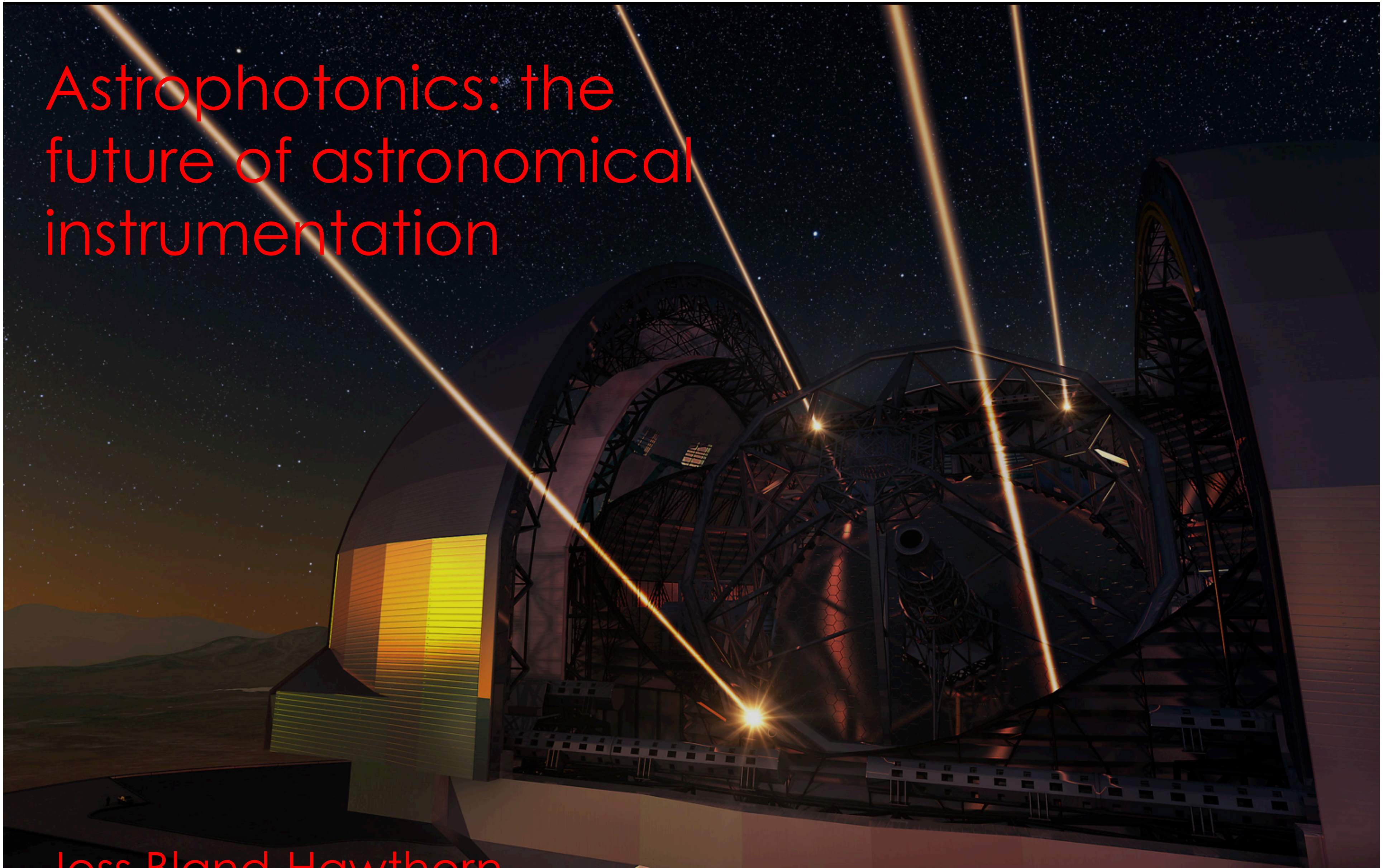
Astrophotonics: the future of astronomical instrumentation

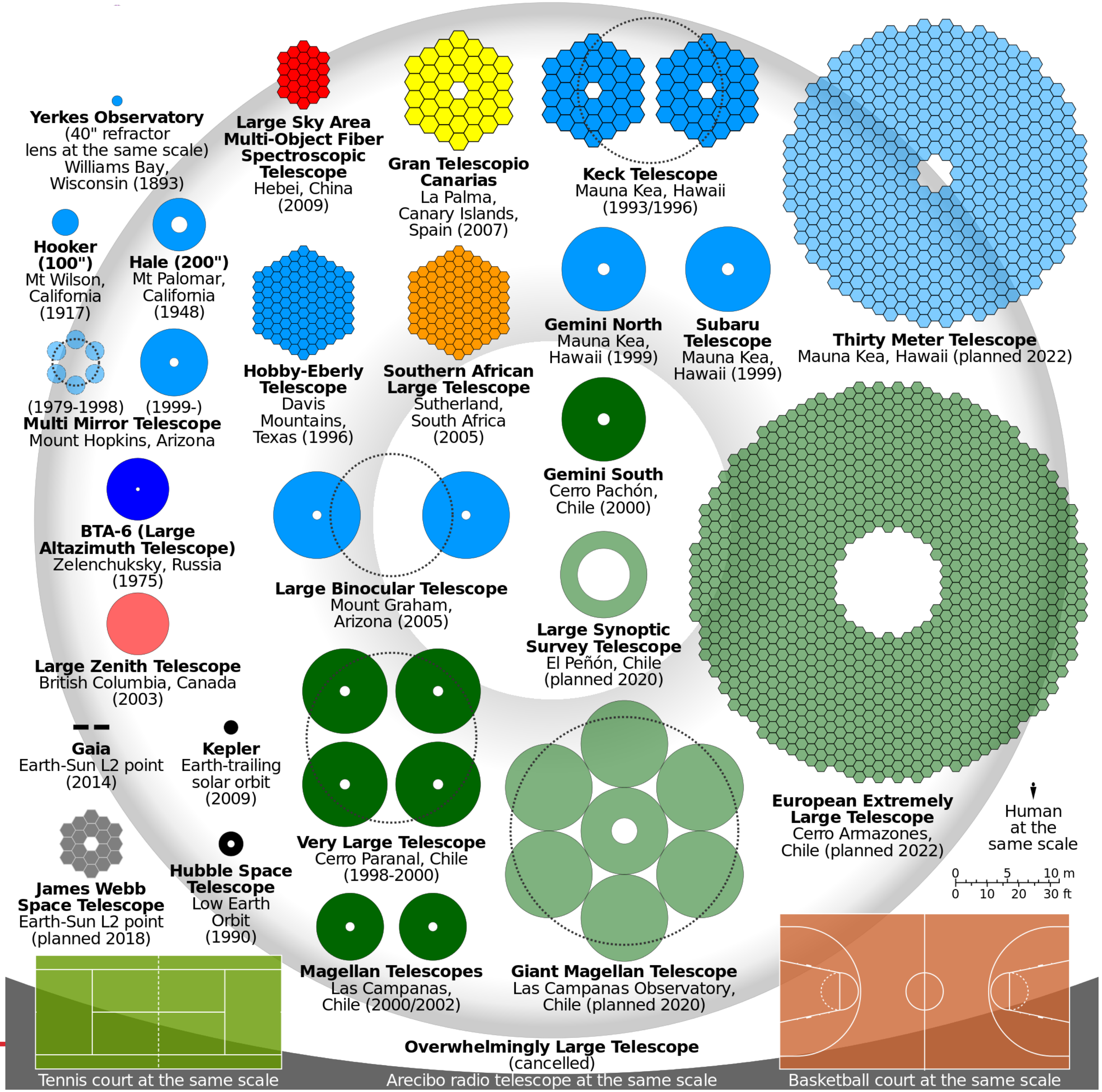


Joss Bland-Hawthorn
Institute of Photonics & Optical Science
Sydney Astrophotonic Instrumentation Lab
Sydney Institute for Astronomy

SAIL
Sydney Astrophotonic Instrumentation Laboratory

THE UNIVERSITY OF SYDNEY

Inexorable rise of massive telescopes…



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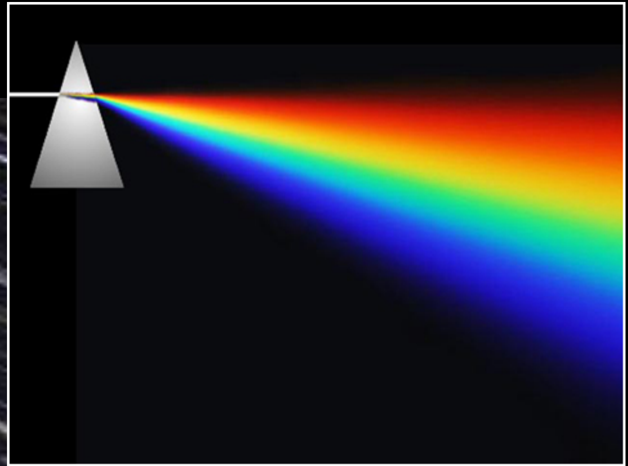
Telescopes gather light from space...



Light gathered and focused by a telescope must often be refocused onto spectrographs and other complex instruments. To such ends, astronomers are coming to realize the benefits of photonics.

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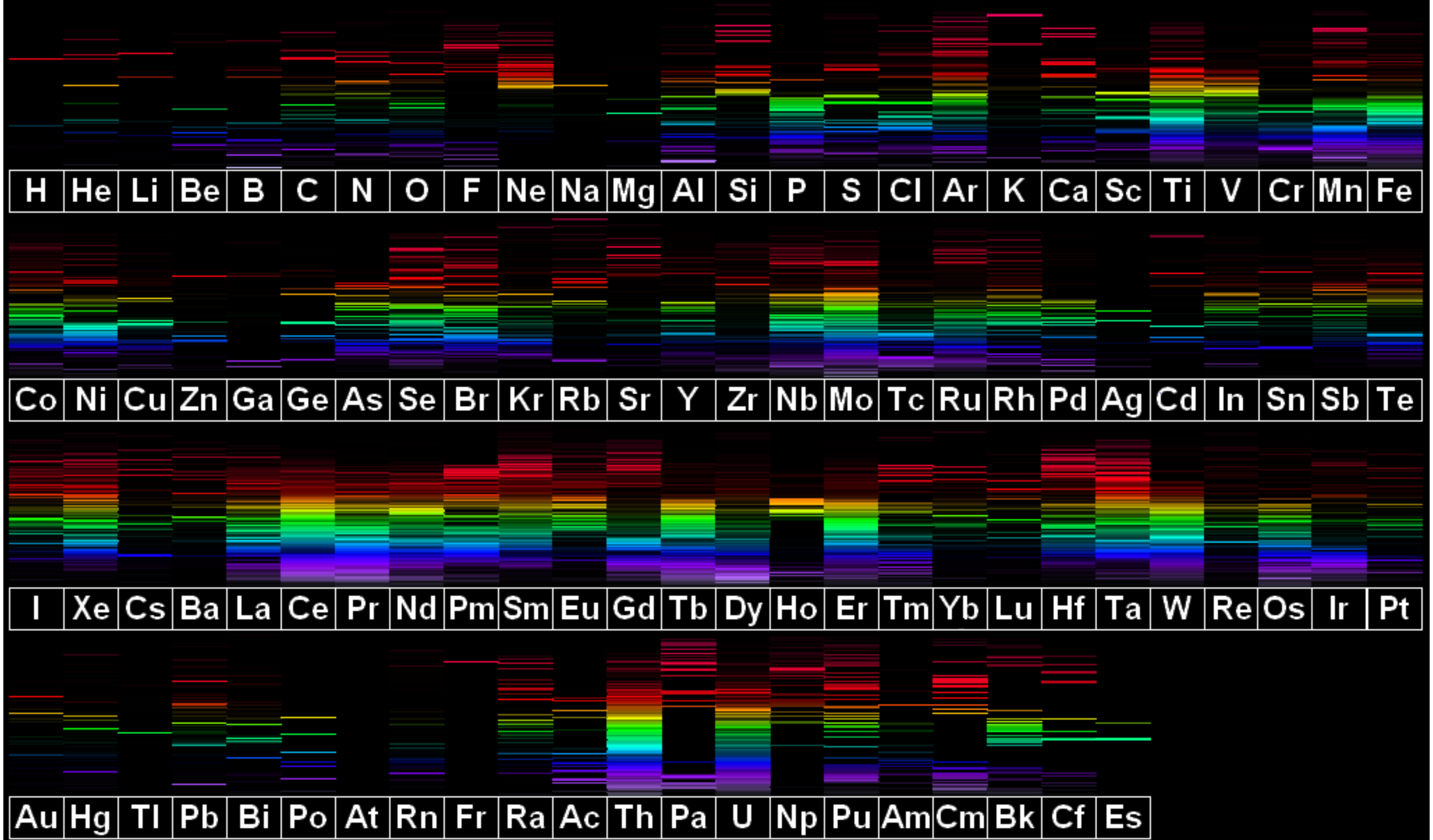
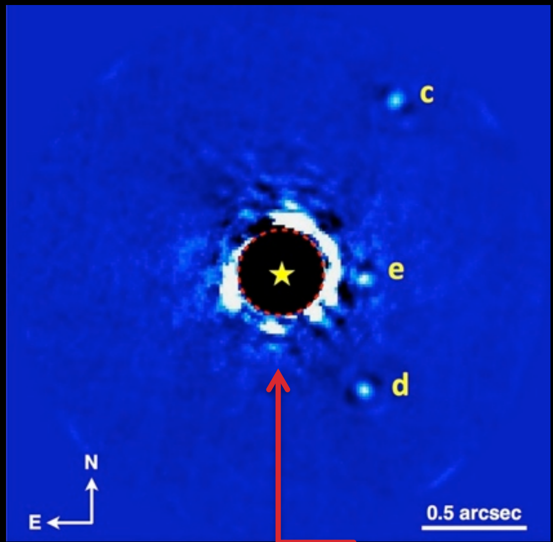
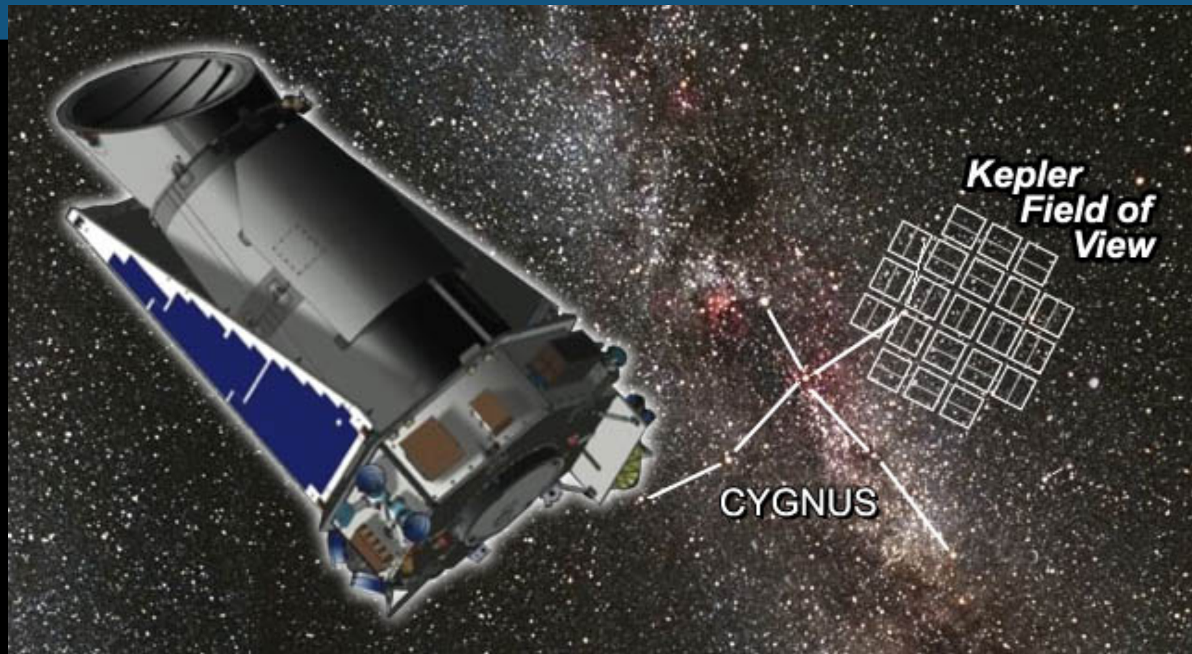
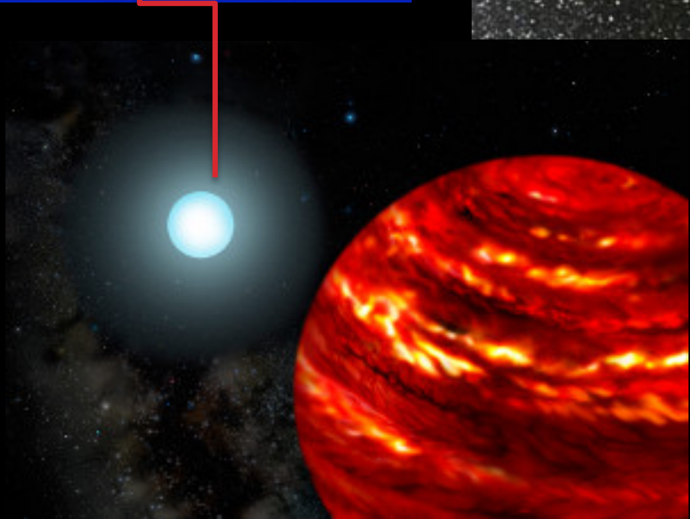
...and tell us the Universe is full of matter



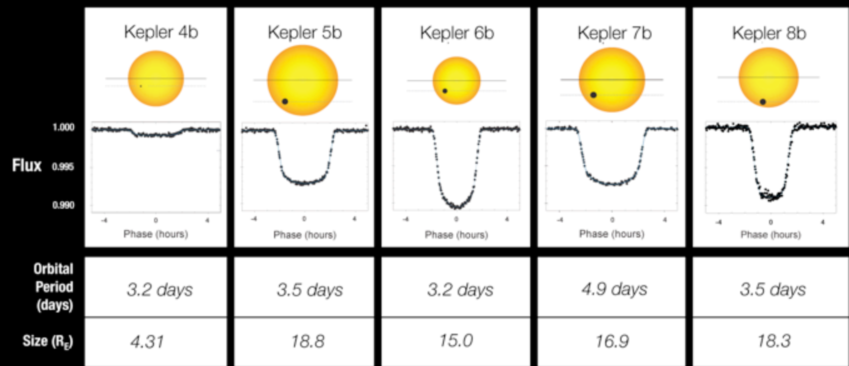
Some of the biggest questions nearby & far away

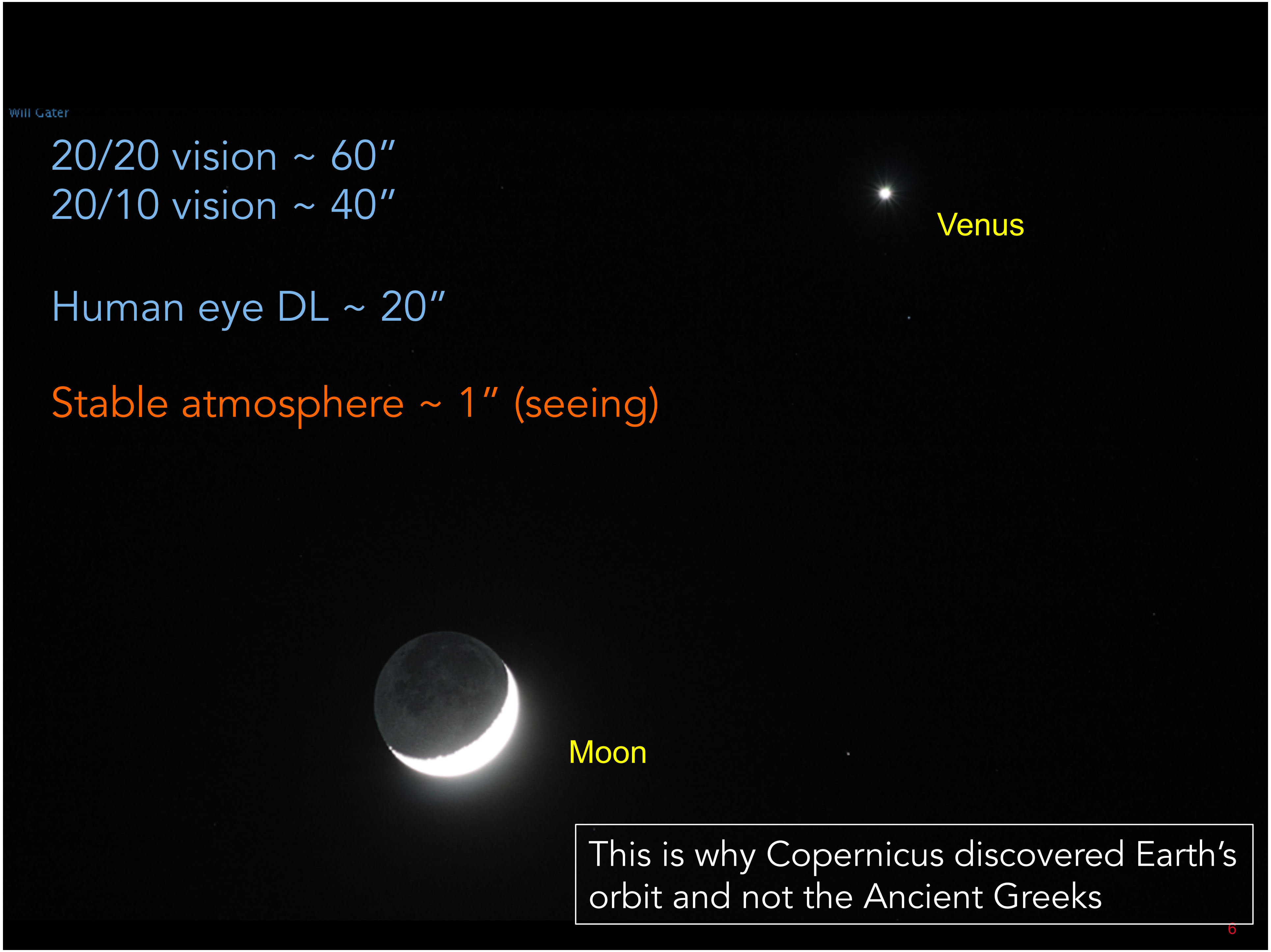






Transit Light Curves





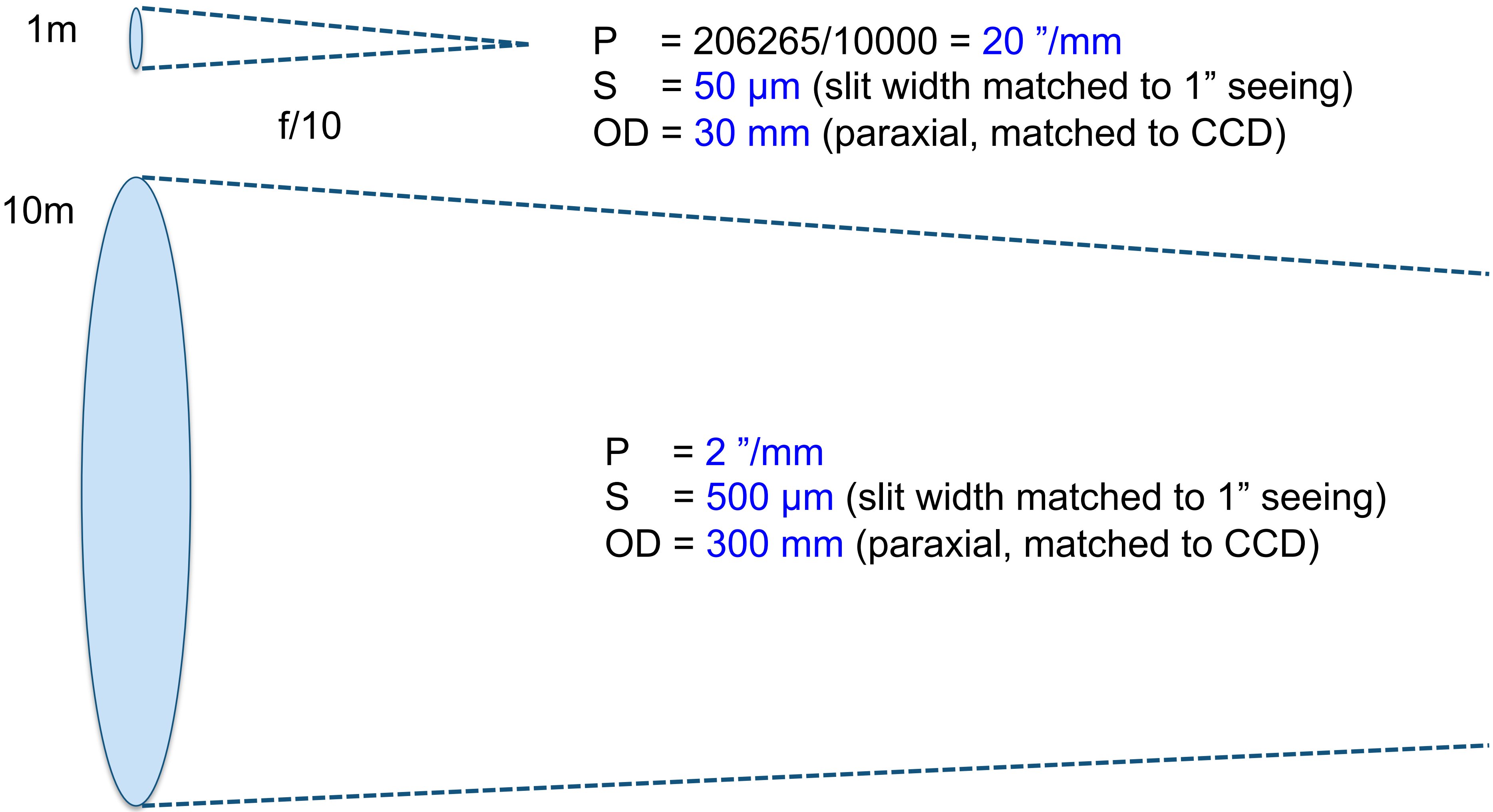
20/20 vision ~ 60″
20/10 vision ~ 40″

Human eye DL ~ 20″

Stable atmosphere ~ 1″ (seeing)

This is why Copernicus discovered Earth's orbit and not the Ancient Greeks

The problem with bigger telescopes

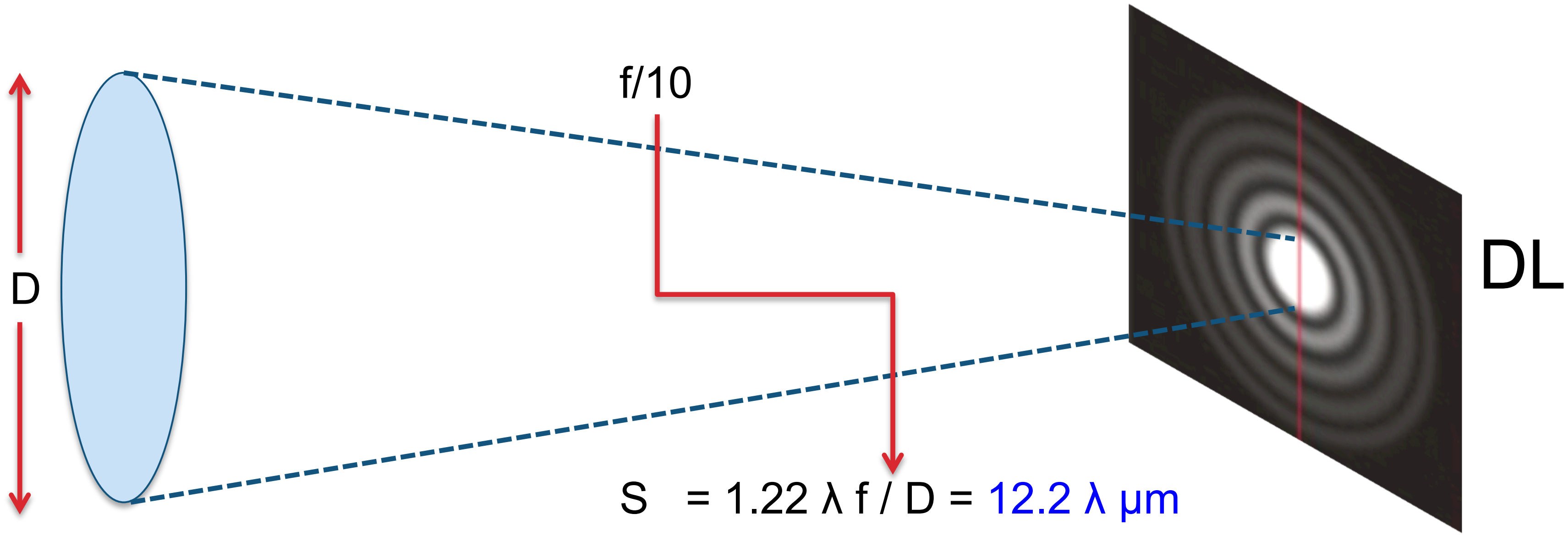


P = 206265/10000 = 20 ”/mm
S = 50 μm (slit width matched to 1” seeing)
OD = 30 mm (paraxial, matched to CCD)

P = 2 ”/mm
S = 500 μm (slit width matched to 1” seeing)
OD = 300 mm (paraxial, matched to CCD)

JBH & Horton 2006; JBH et al 2010; JBH & Kern 2012

Is there any way to break this ?



S = 1.22 λ f / D = 12.2 λ μm

This has no dependence other than f-ratio, and within range of photonics.

But not well matched to SMF modal diameter since NA = D / 2 f = 0.05

Note that f/2.5 to f/5 is ideal for photonics.

JBH & Horton 2006; JBH et al 2010; JBH & Kern 2012

Coupling efficiency into SMF

Coupling starlight into single-mode fiber optics

Stuart Shaklan and Francois Roddier

We have calculated the efficiency with which starlight can be coupled into a single-mode fiber optic that is placed in the focal plane of a telescope. The calculations are performed for a wide range of seeing conditions, with and without rapid image stabilization, and for a wide range of wavelengths. The dependence of coupling efficiency on the f-ratio of the incident beam is explored. Also, we calculate the coupling efficiency as a function of displacement for a perfect Airy pattern. We have also used a computer program which simulates atmospheric wavefronts to determine the variance of instantaneous coupling efficiency as a function of seeing. In perfect conditions, the maximum efficiency at the LP_{11} mode cutoff is 78% due to the mismatch of the Airy pattern and the nearly Gaussian mode of the fiber. Maximum total coupled power is attained at $d/r_0 = 4$ with rapid image stabilization.

Theory (1988): Airy disk ➔ SMF ~ 78% maximum (LP_{11} mode cut-off)

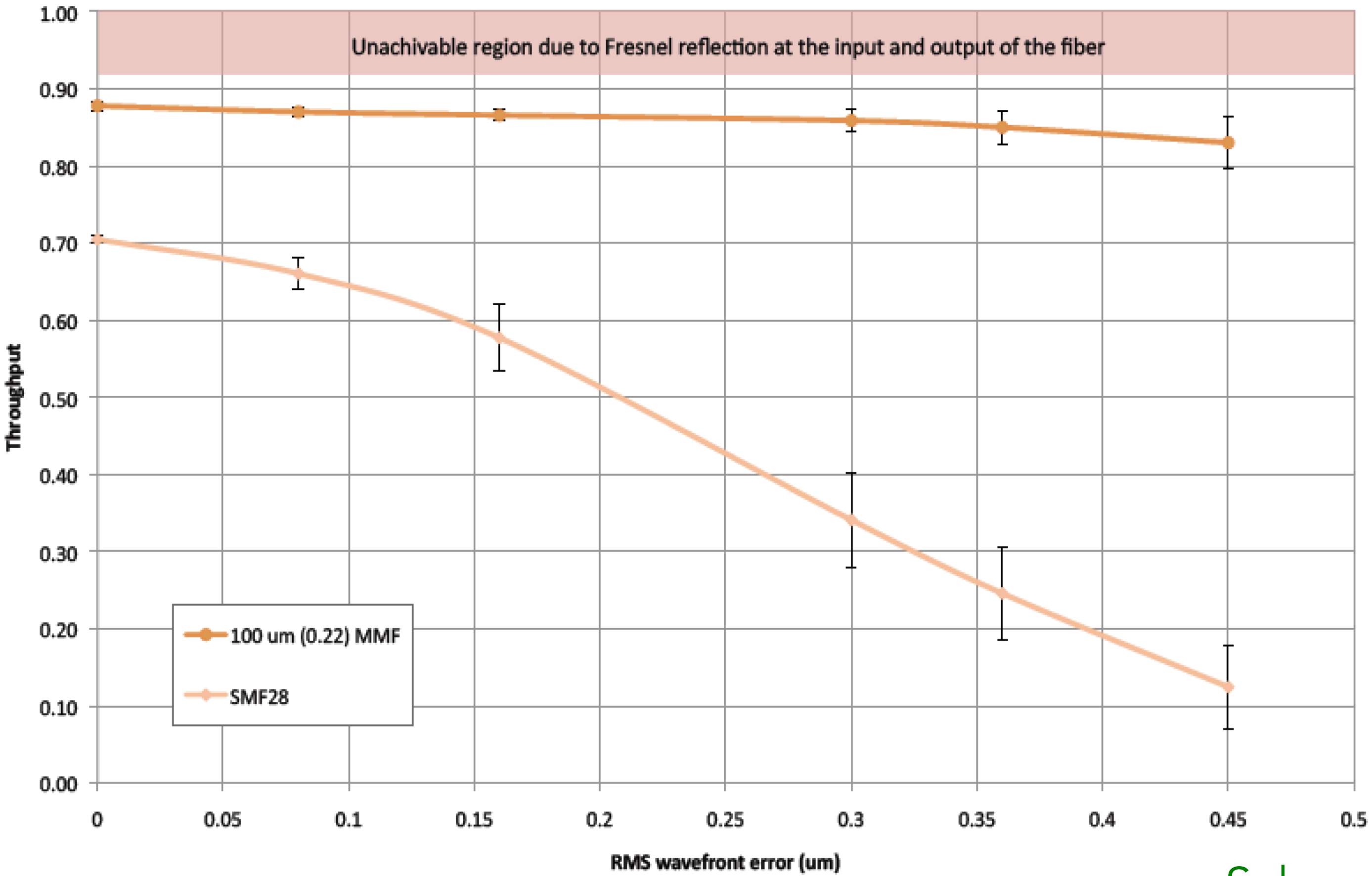
Practical (2000): La Silla 3.6m team found 5% coupling at best without AO

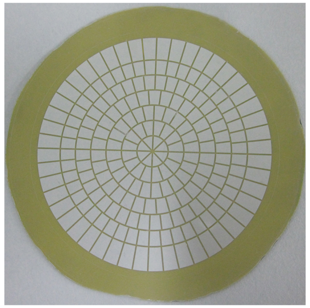
Practical (2015): Subaru 8m team now achieving 60+% with AO + new PIAA

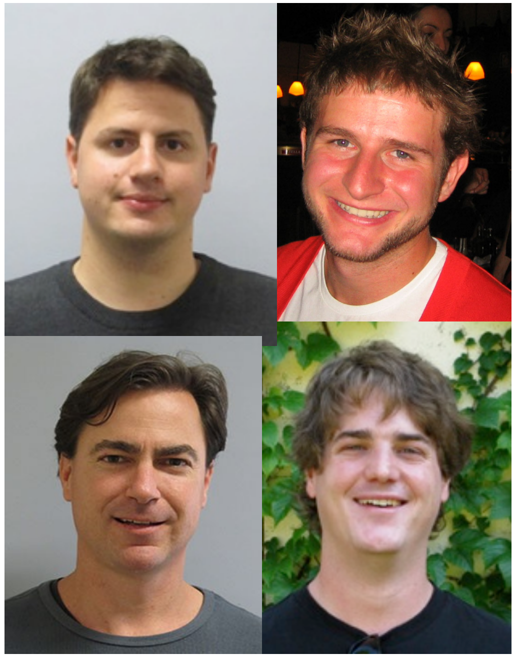
Shaklan & Roddier 1988; Coudé du Foresto et al 2000; Guyon 2003; Jovanovic et al 2015

Direct coupling of 8m telescope to SMF

Required two breakthroughs: **(a) AO, 2000 DM actuators**





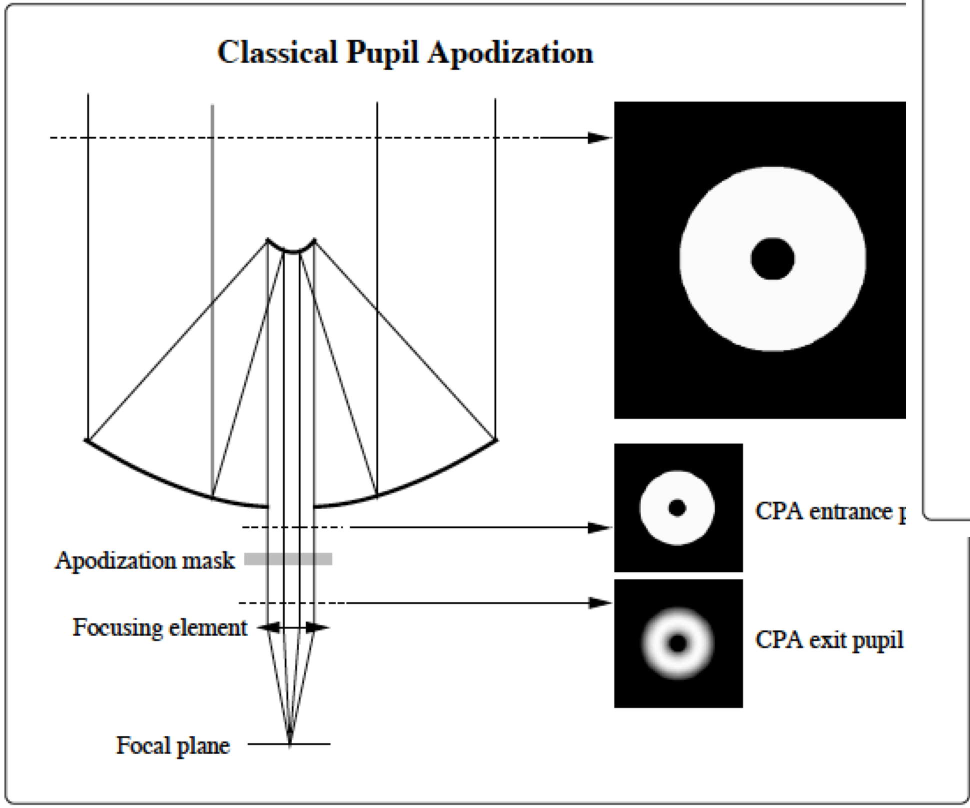


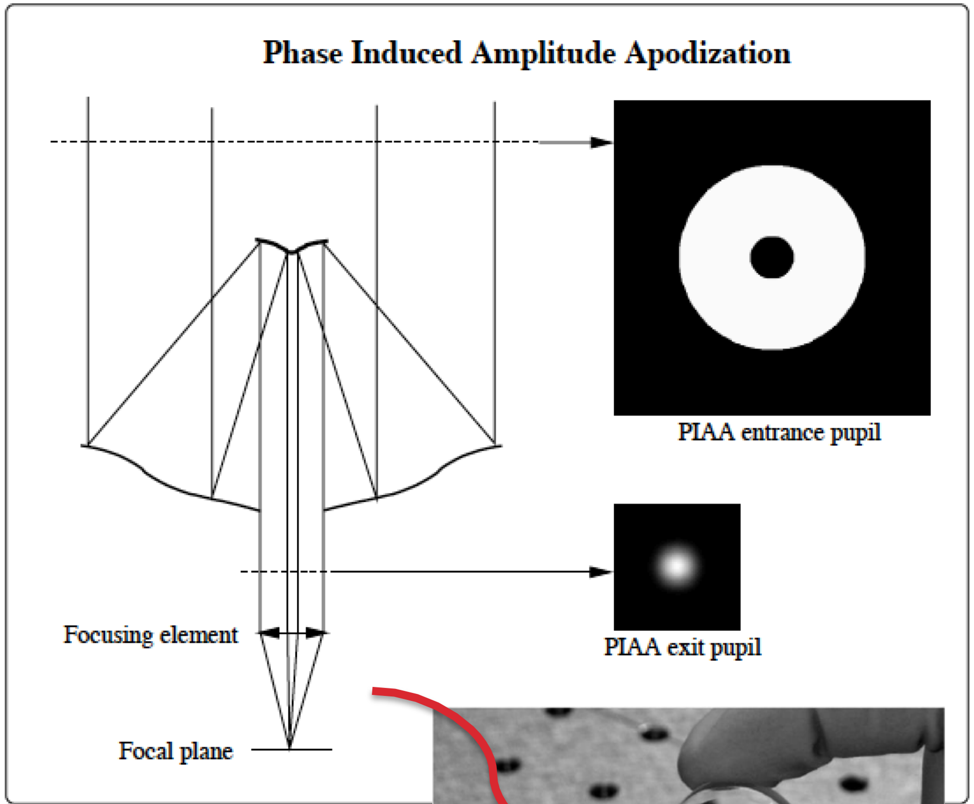
Subaru 8m Telescope, Hawaii

Jovanovic et al (2015)

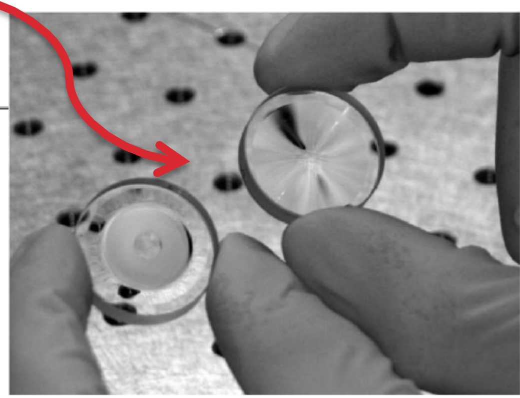
(b) phase-induced amplitude apodization

Big telescopes have central holes,
but can now fill in with PIAA lens pair
➔ Gaussian beam





Equivalent to this lens pair



Guyon 2003

AO simplified:

Now used routinely on-axis with a single laser guide star.

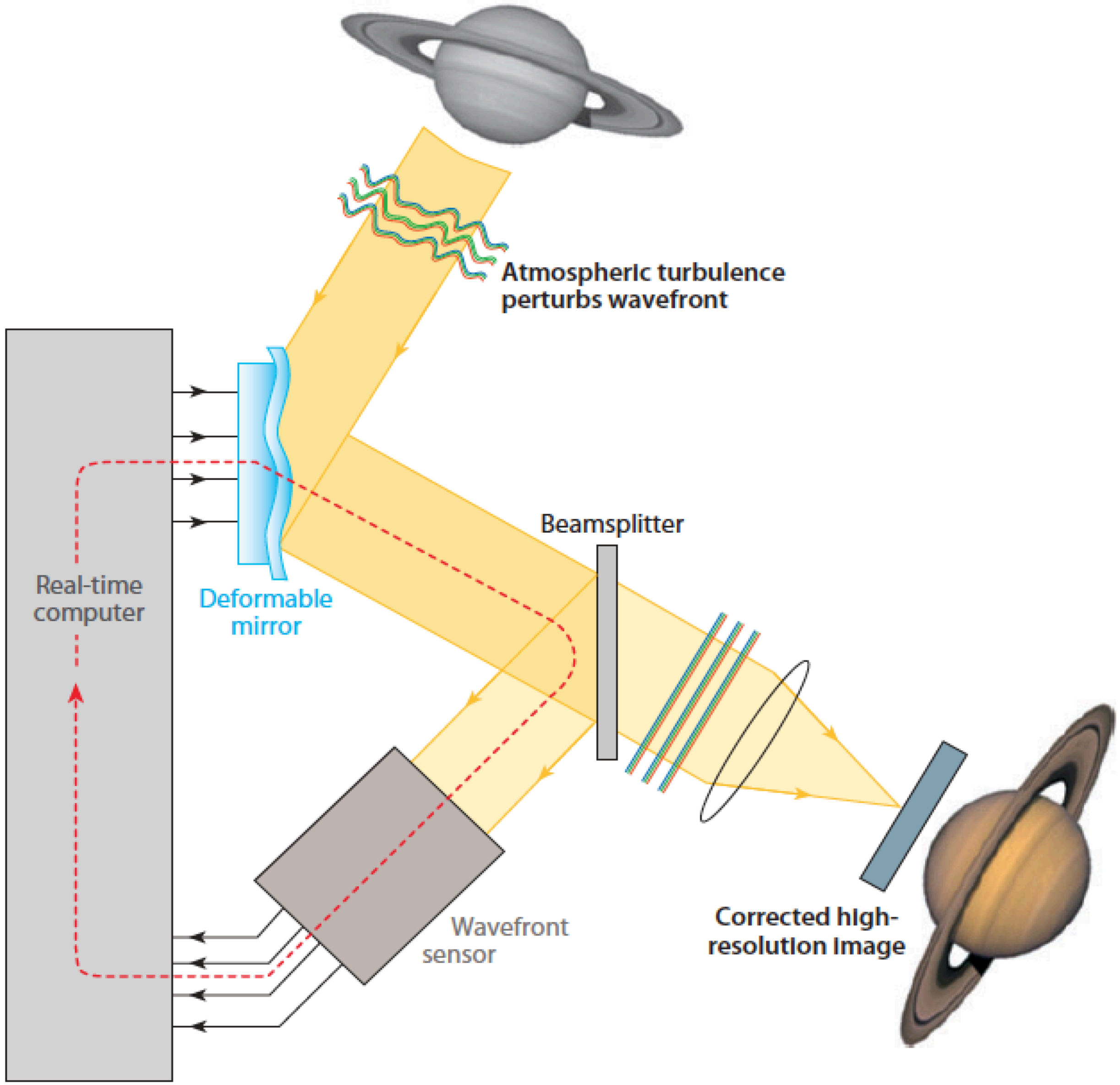
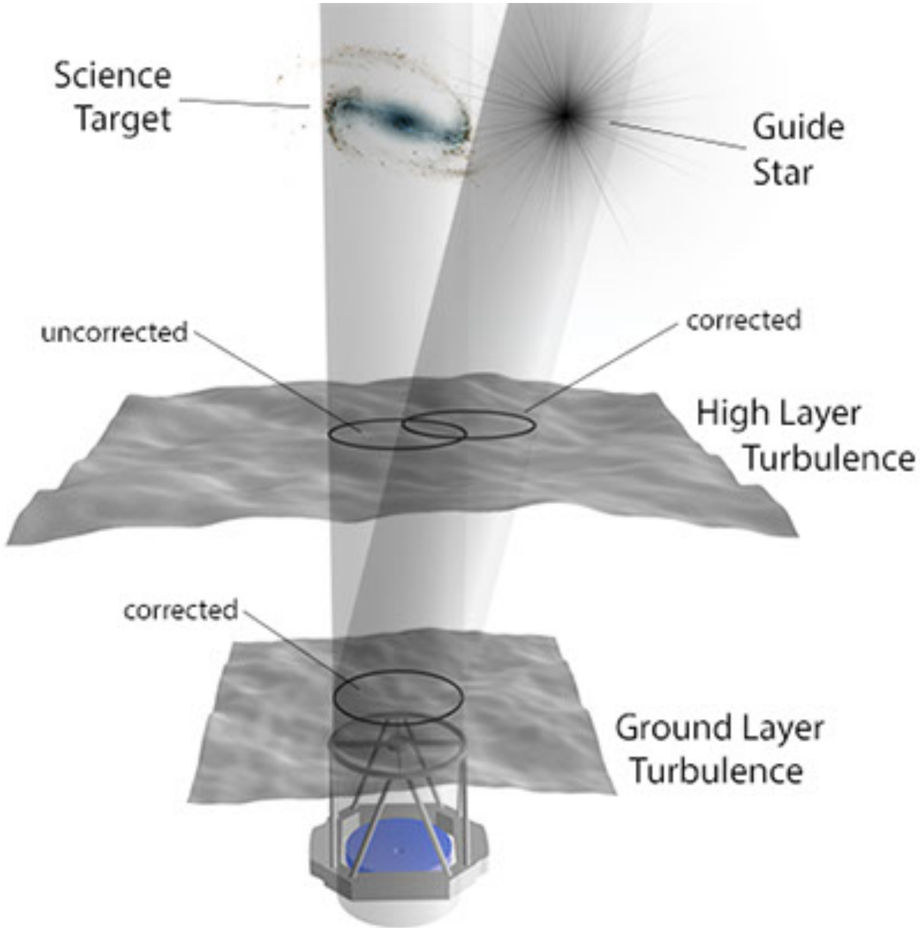


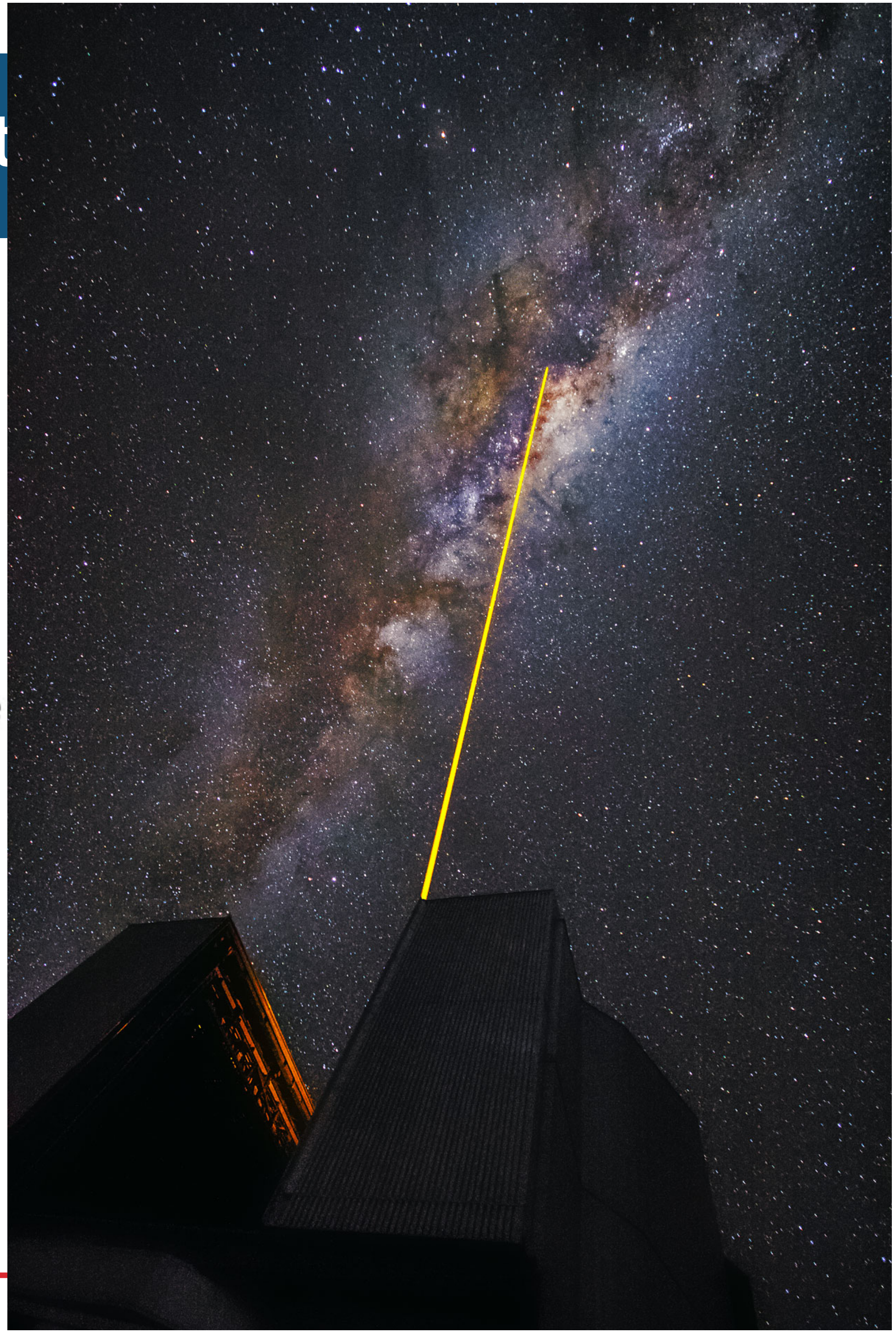
Figure 3

Adaptive optics working principle (courtesy of *Sterne und Weltraum* and S. Hippler).

Adaptive opt

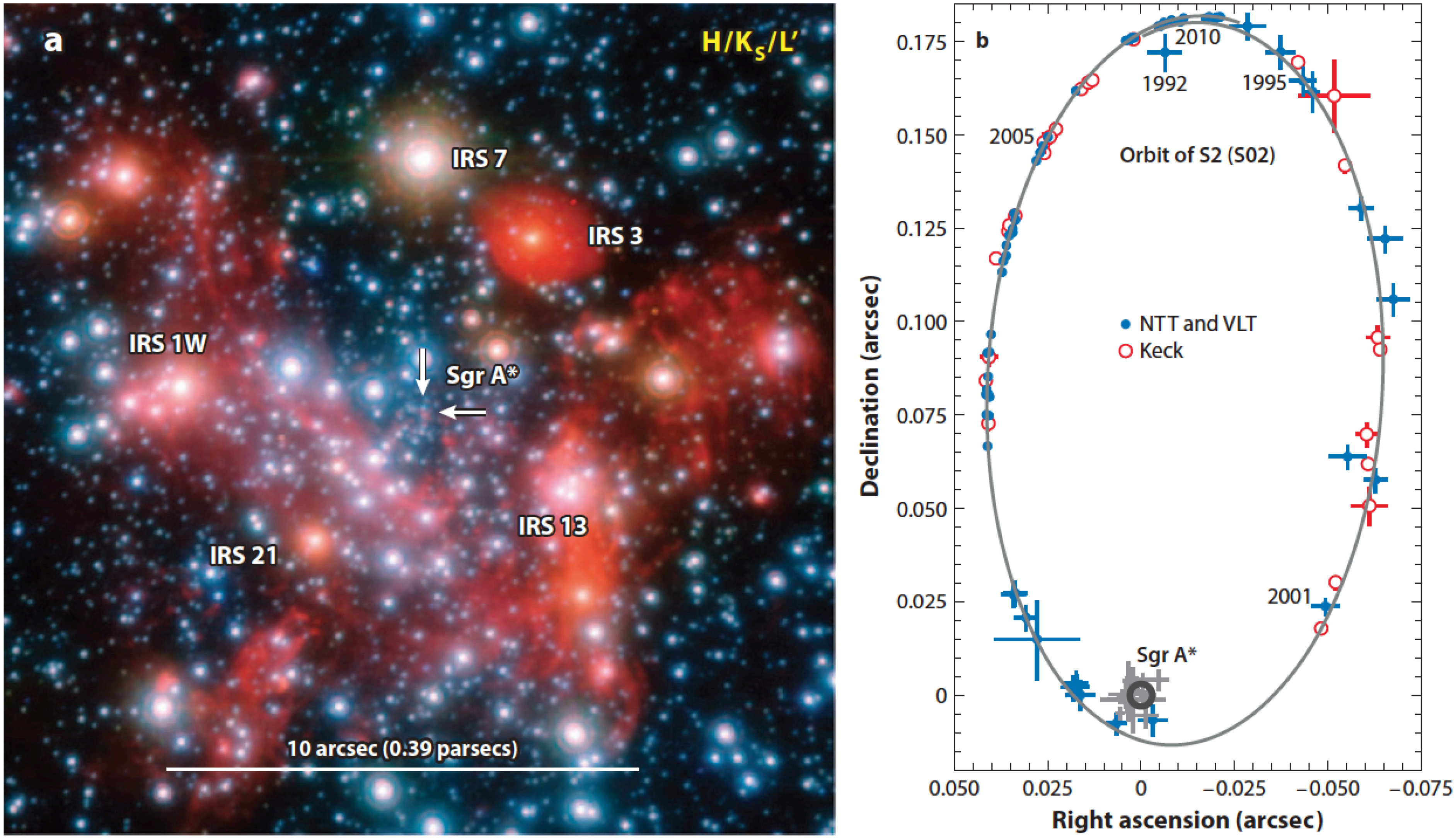


Single-Conjugate Adaptive Optics



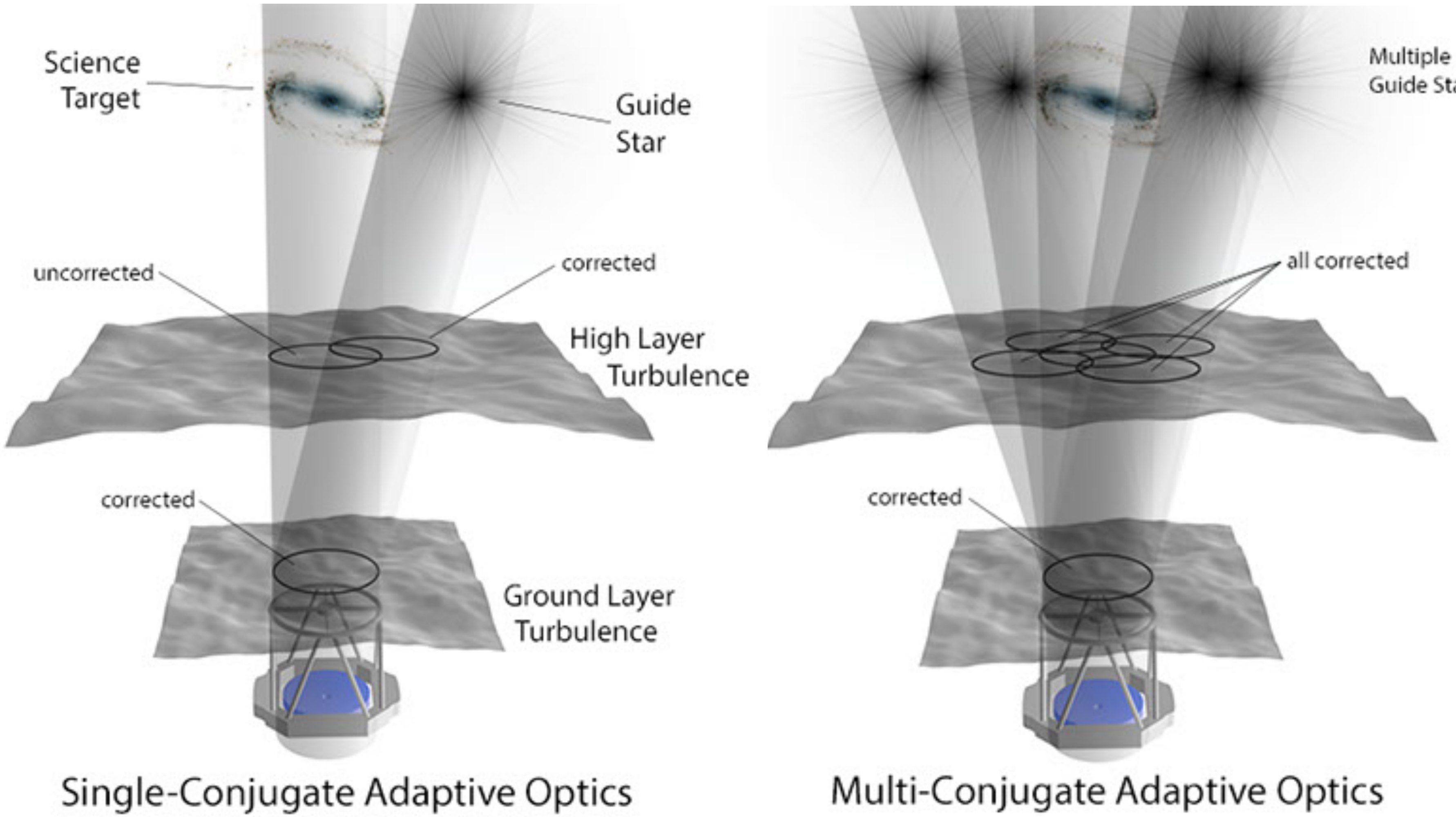
Wizinowich et al 2003; van Dam et al 2003

Discovery of 4 x 10^6 $M_\odot$ black hole

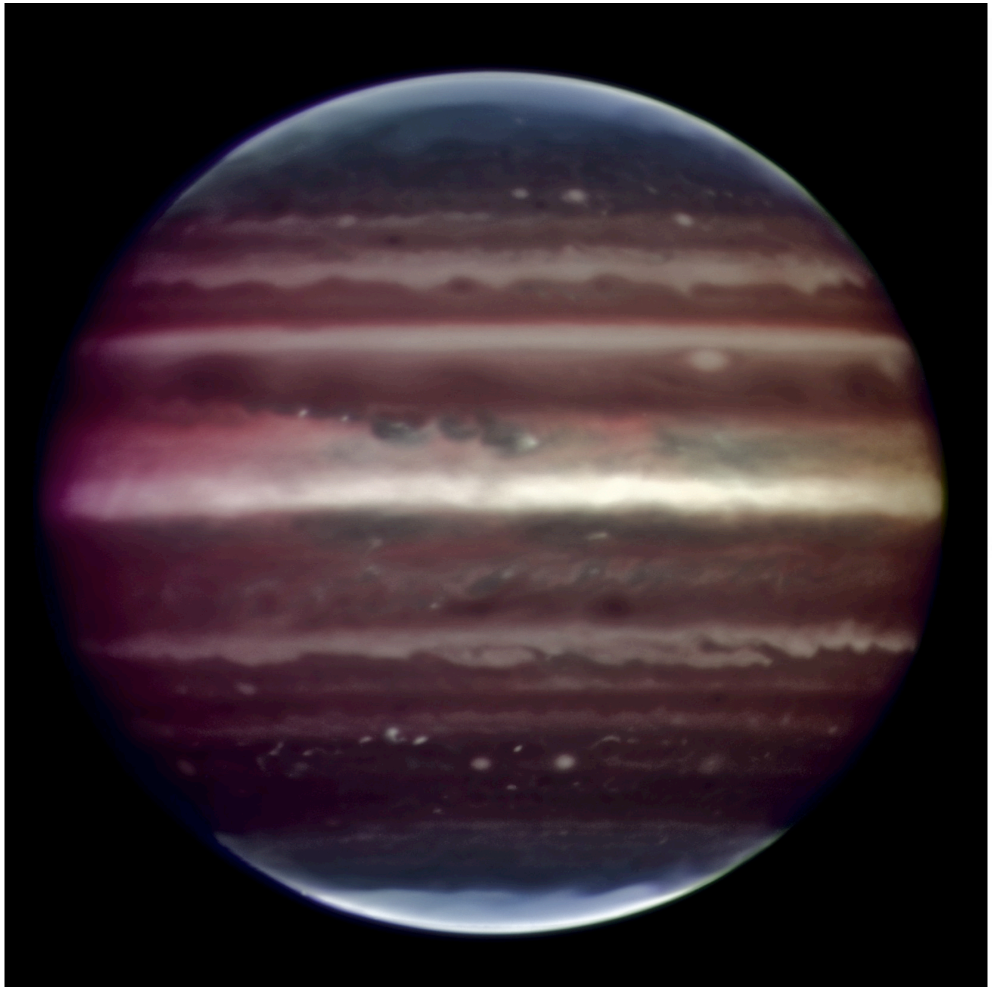


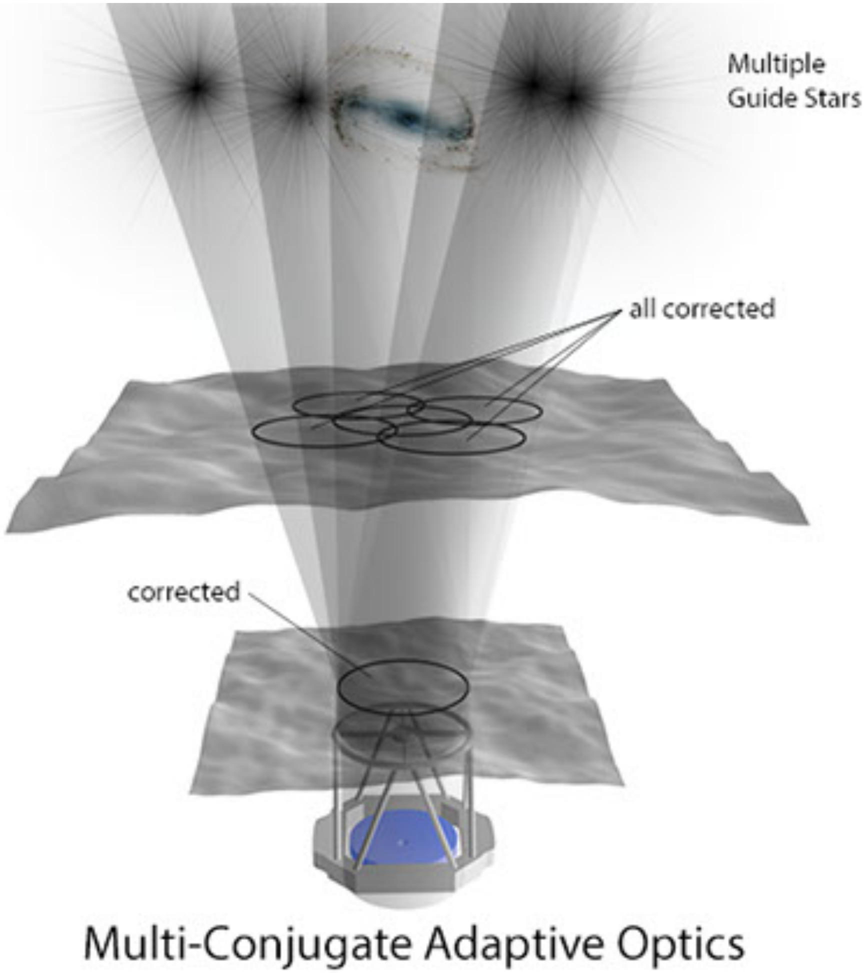
Genzel et al 2003; Ghez et al 2005; Ghez et al 2008; Genzel et al 2010

Adaptive optics: SCAO vs MCAO



Adaptive optics: SCAO vs MCAO

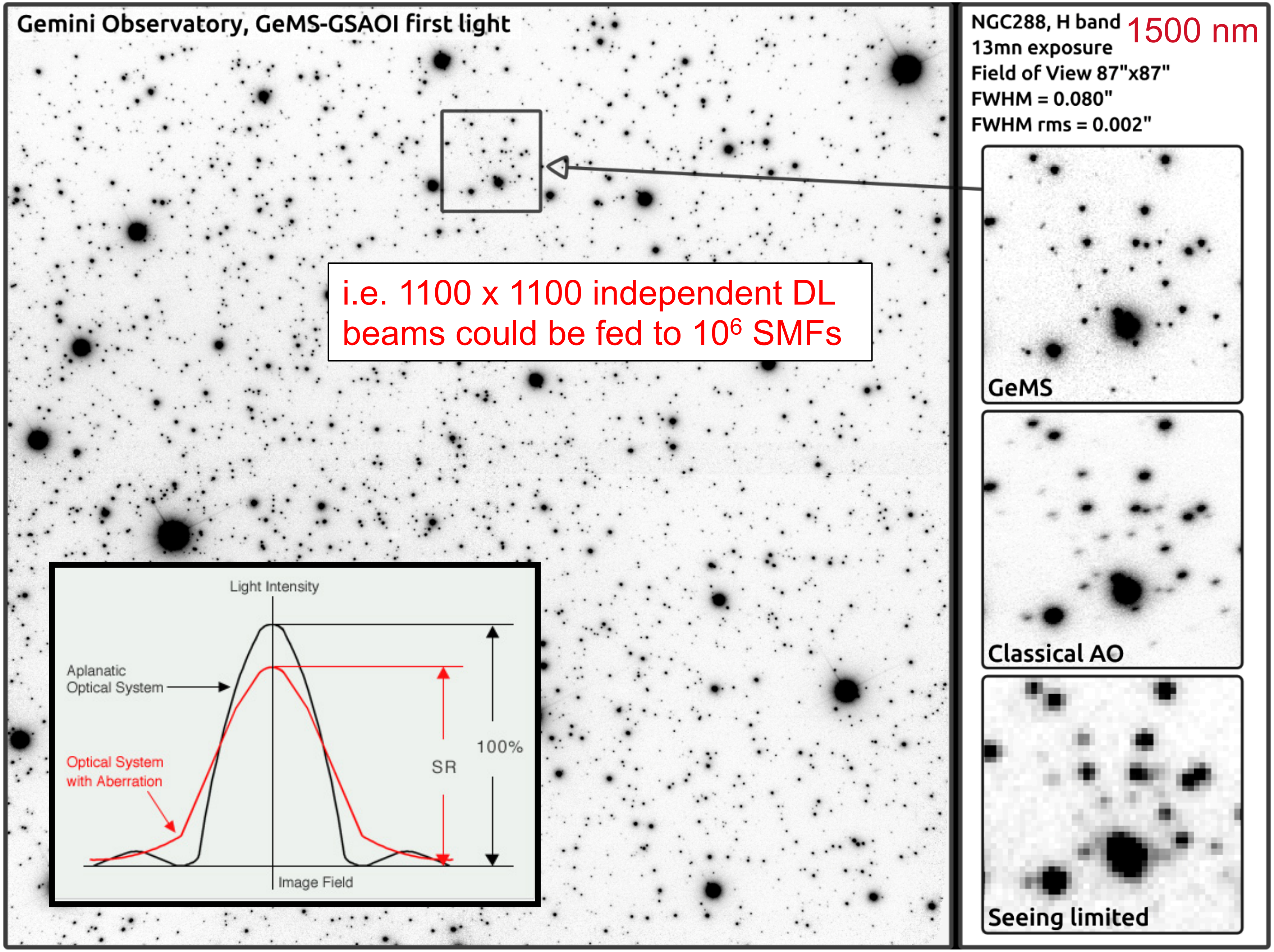




2100 nm; ESO Very Large Telescope, Chile

Marcis et al 2008

Figure 5. GeMS first light: NGC288 in H band



McGregor et al 2004; Neichel et al 2014

Instruments without optics: an integrated photonic spectrograph

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

2006

A perfect DL telescope can image onto one or more SMF.

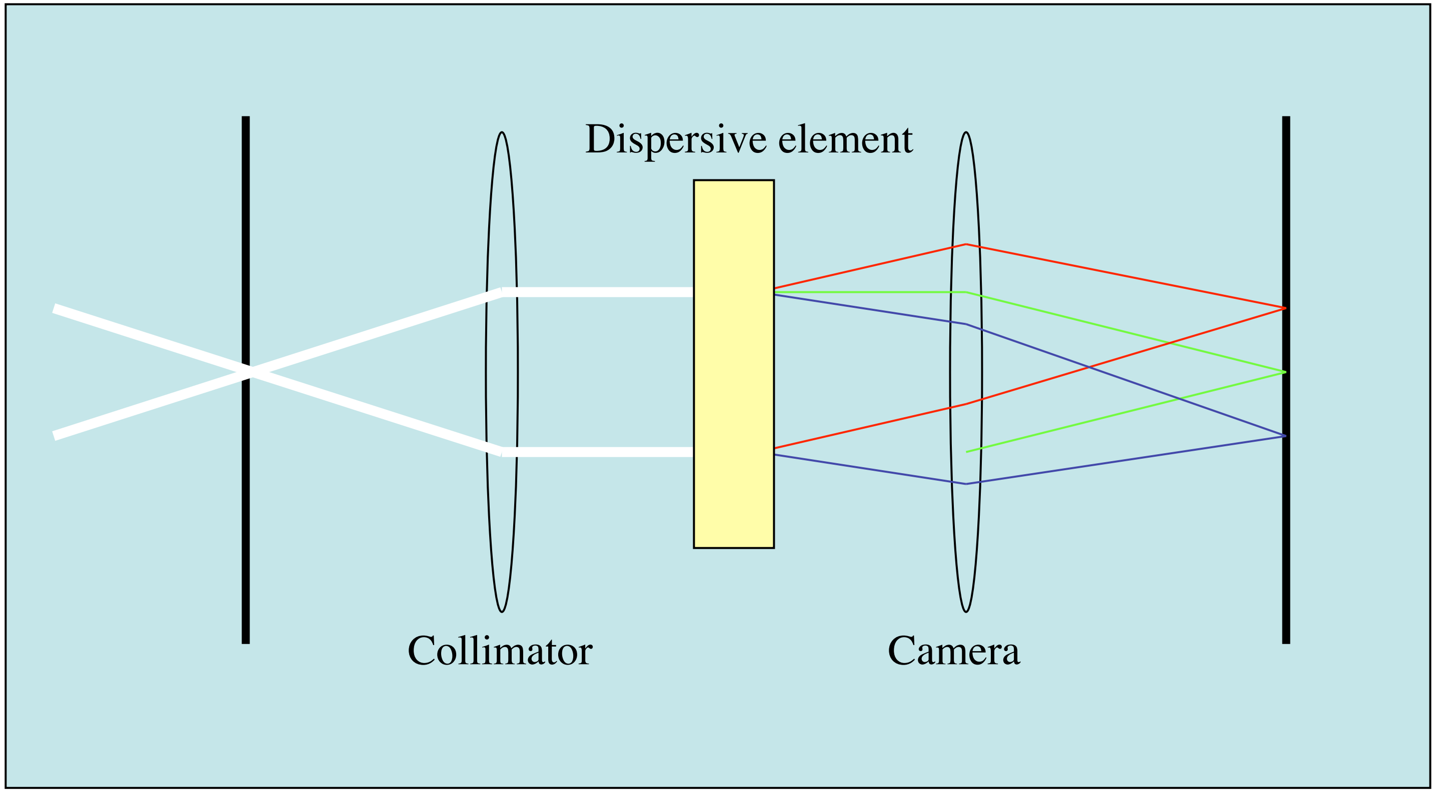
This can feed a spectrograph in its minimum (DL) configuration.

But can telescopes + AO can ever achieve this ideal (90^+ %) ?

DL spectroscopy:

$R = m\,N$

m = interf. order
N = # of beams



Why are spectrographs so far removed from the ideal?

Medium resolution spectrograph has pupil $D_P \sim 30$ mm, say

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

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

$R = m\,N = m\,D_P\,\rho = 30{,}000$

...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. collapse an instrument to its DL configuration.

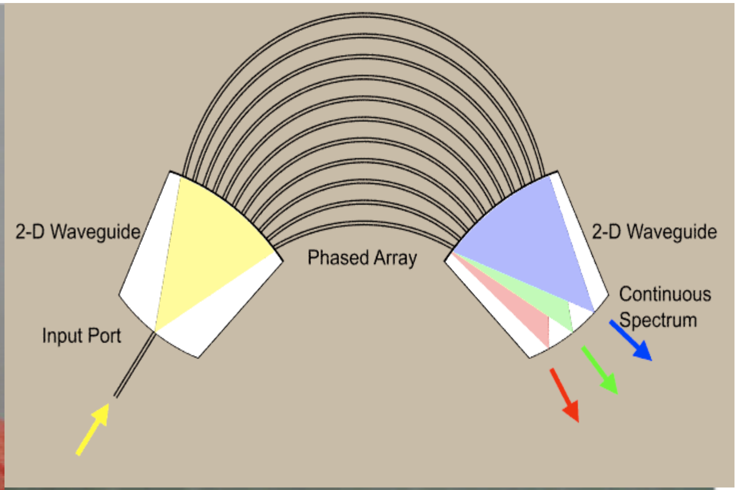
1st photonic (DL) spectrograph with broadband spectrum

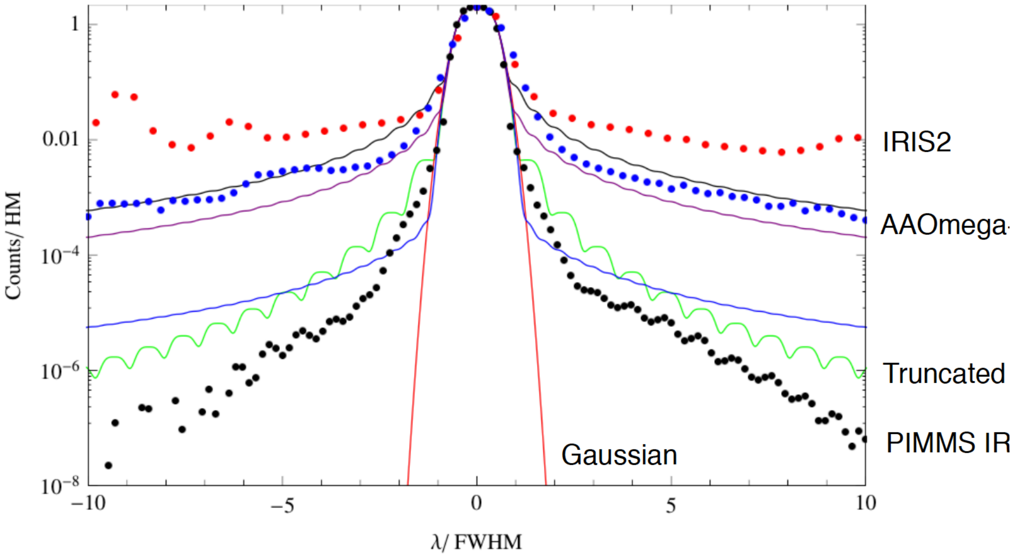
R = 8000, m ~ 20, N = 440

Δλ = 1300-1700 nm

T = 85% throughput, end-to-end

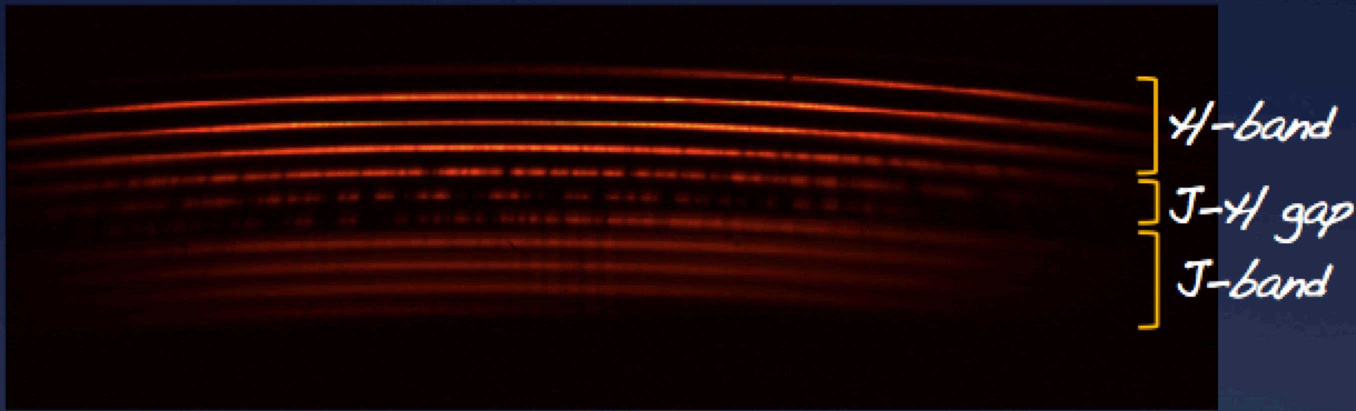
Apodised, X-dispersed, Cooled





Cvetojevic et al 2009, 2011; Betters et al 2014; Jovanovic et al 2014

On-sky: Results



Metadata:

Date: 9th April 2015

Seeing: $<0.5''$

Strehl: 60%

Estimated coupling efficiency: 40-60%

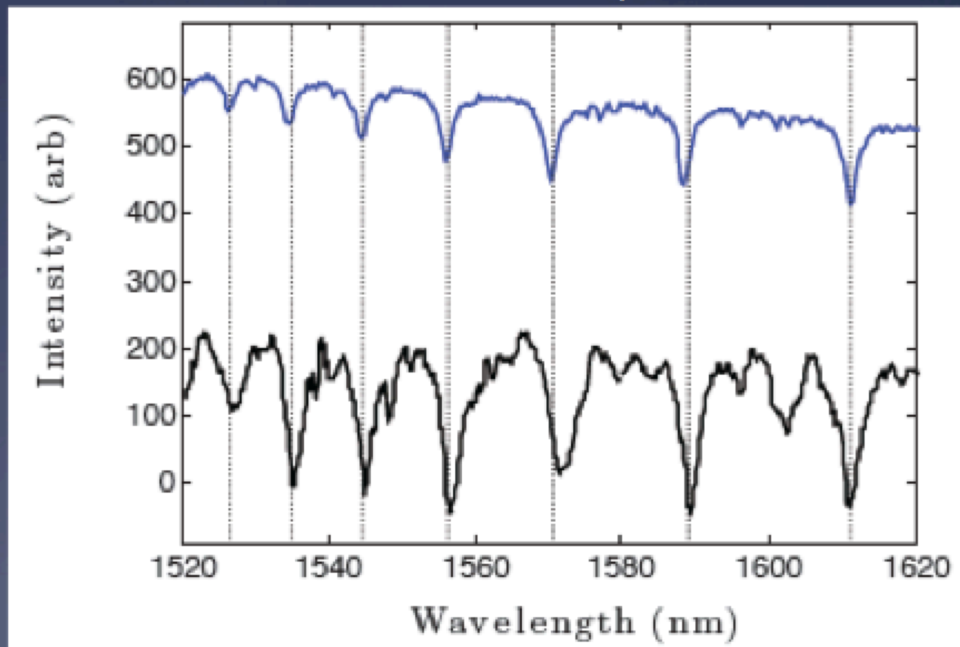
Star: HD135153

Spectral type: F1

Spectrograph throughput: 40% in H-band

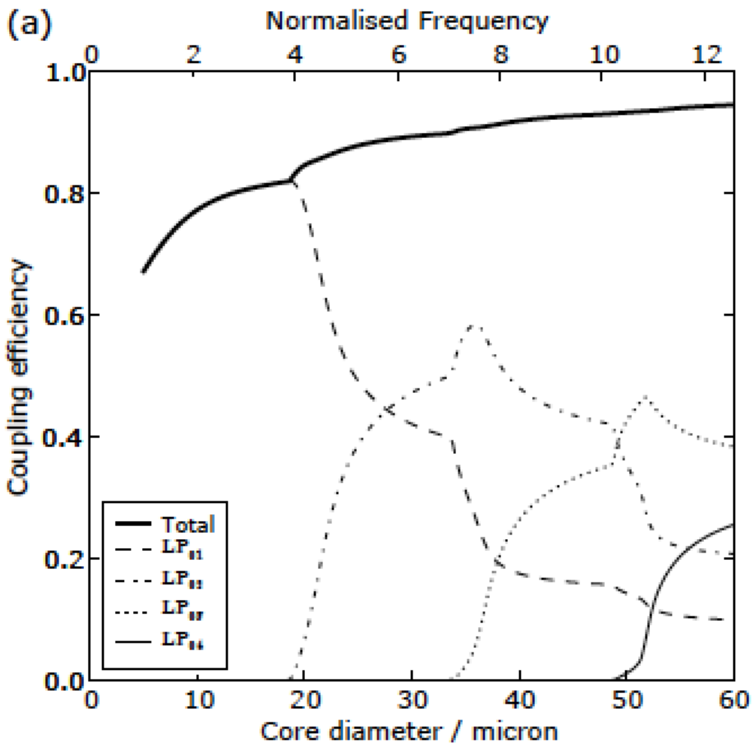
Best AO systems are
<u>not</u> perfectly stable yet

Preliminary data reduction

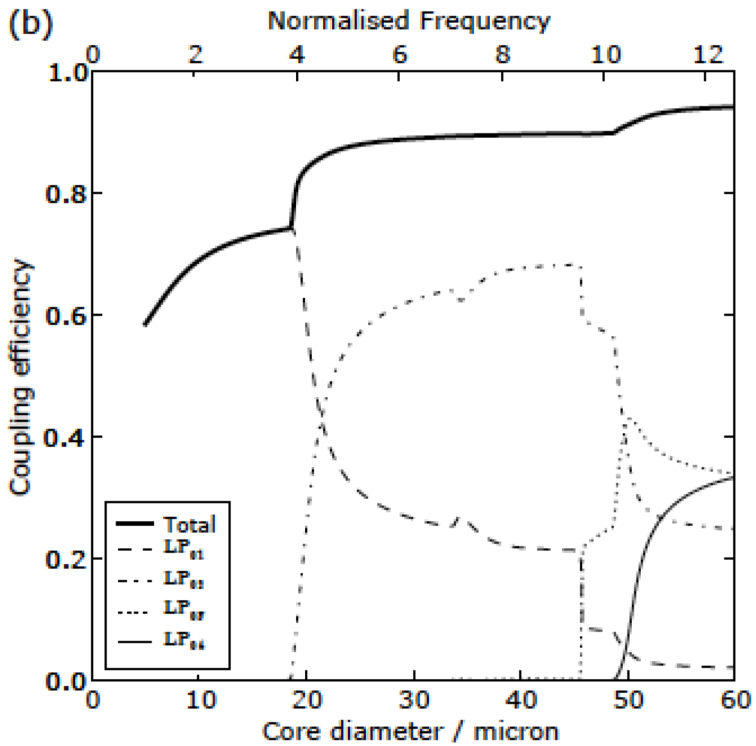


So what if we fall short with AO?

Coupling light into few mode fibres, Horton & JBH (2007), Optics Express



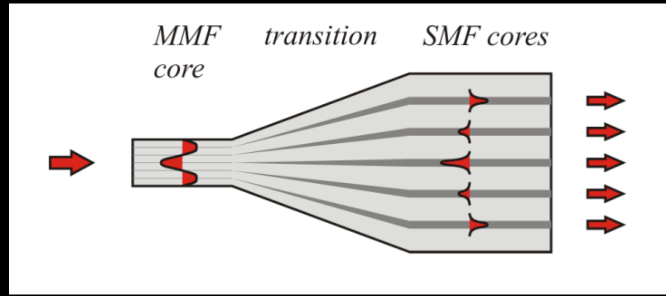
No hole in mirror

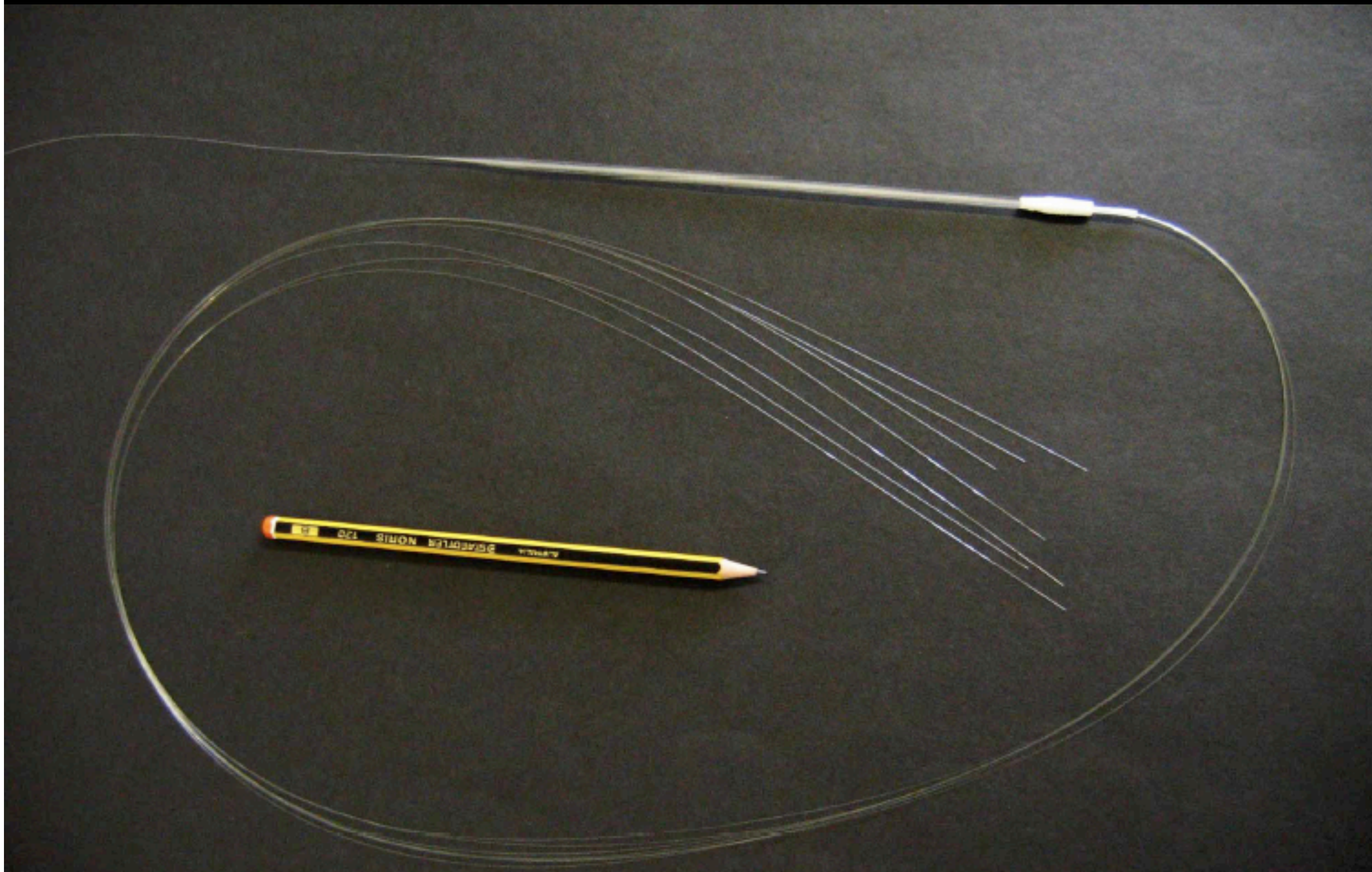


20% hole in mirror

The photonic lantern:

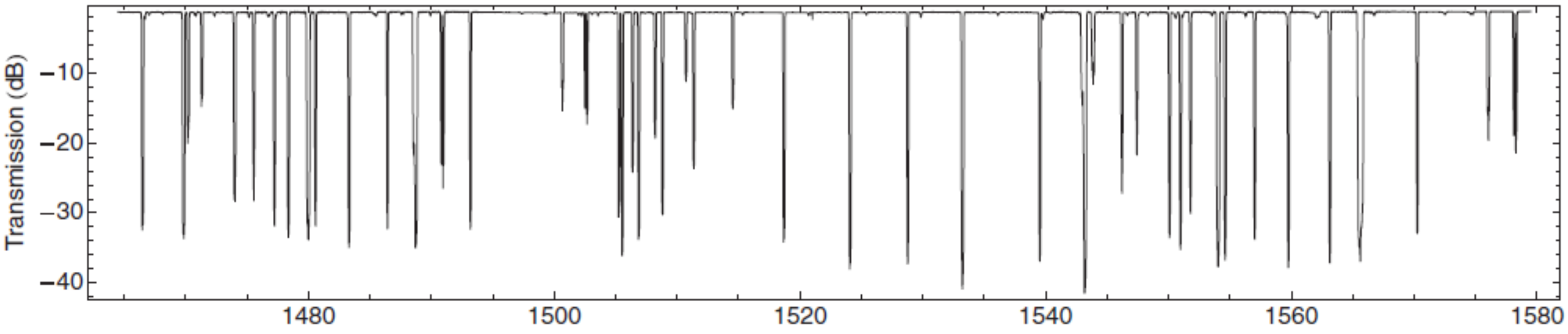
Efficient coupling to SMF
Single mode action in MMF



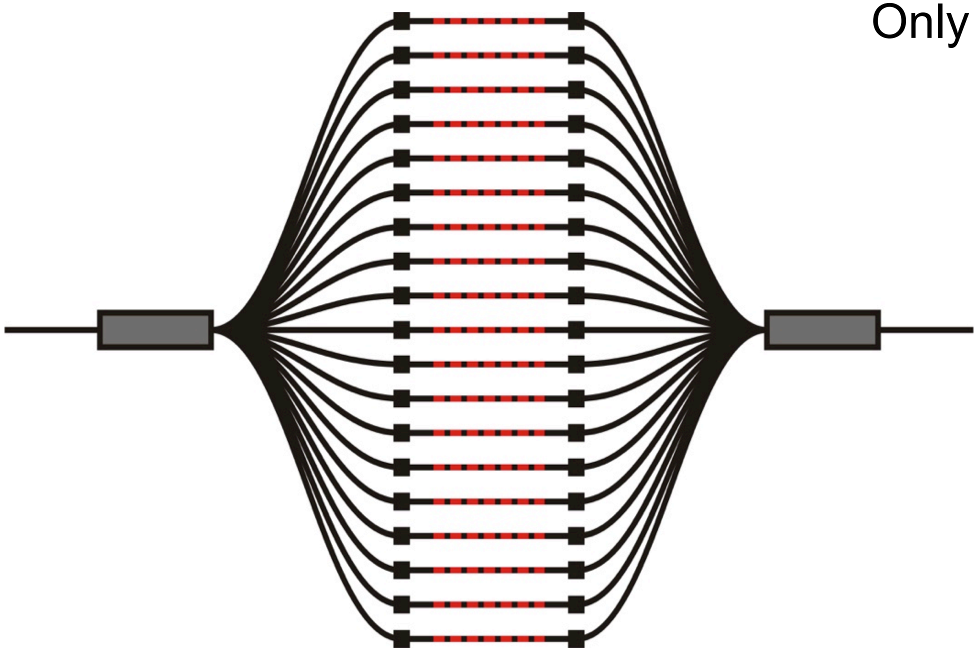


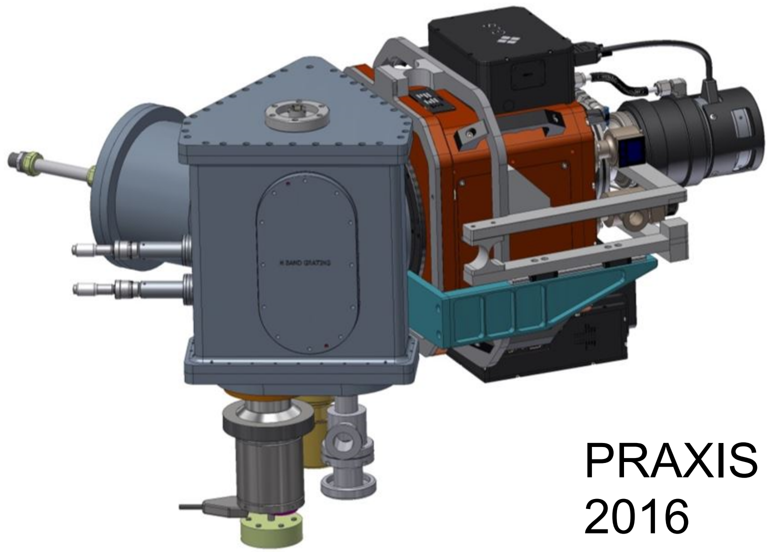
Leon-Saval, Birks & JBH 2005; Leon-Saval, Argyros & JBH 2010; Birks et al 2015

Example: complex filtering in an MMF



Only half of the spectrum

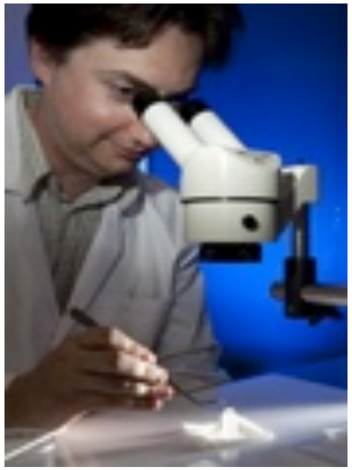


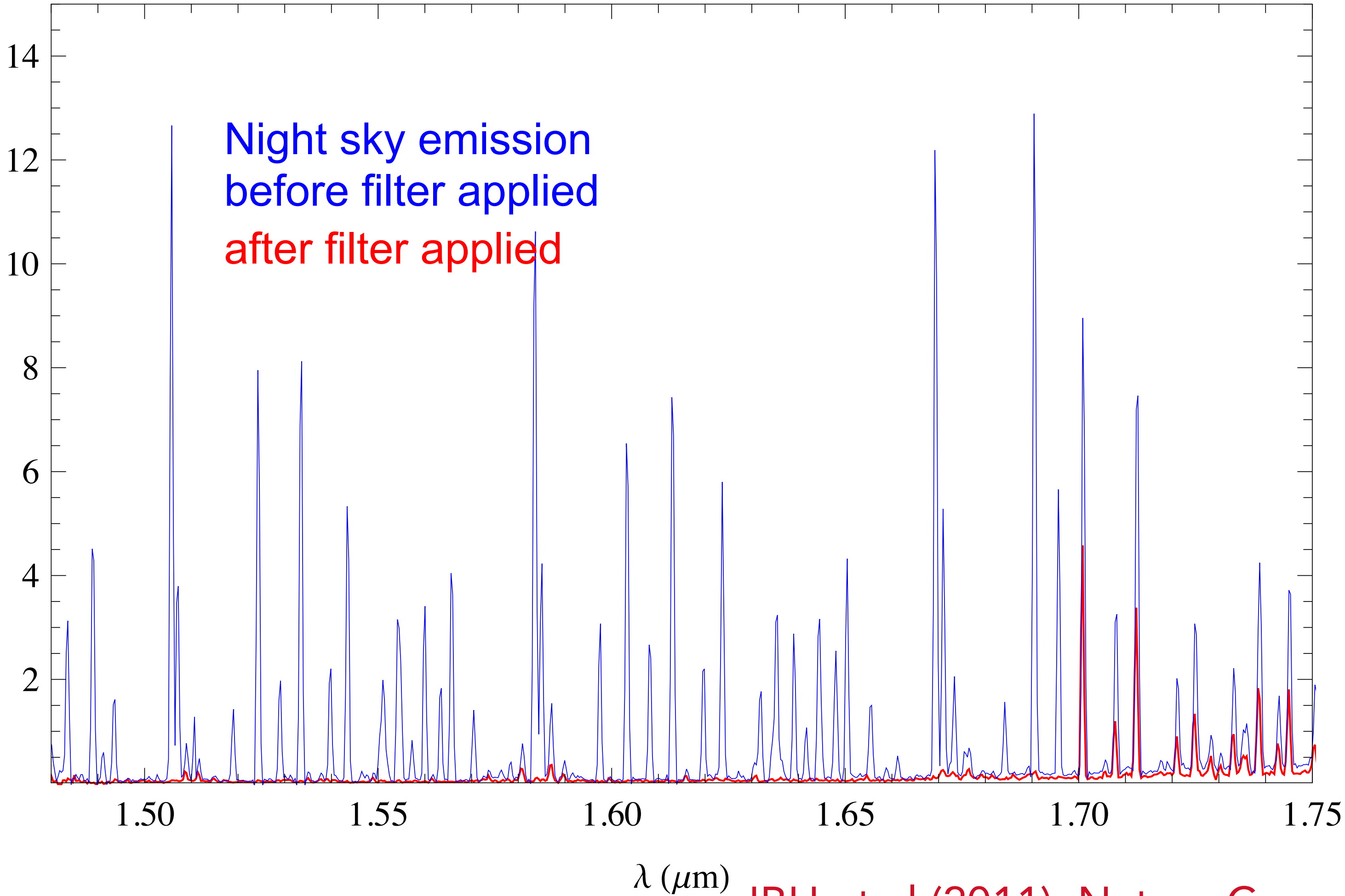


PRAXIS
2016

Example: complex filtering in an MMF

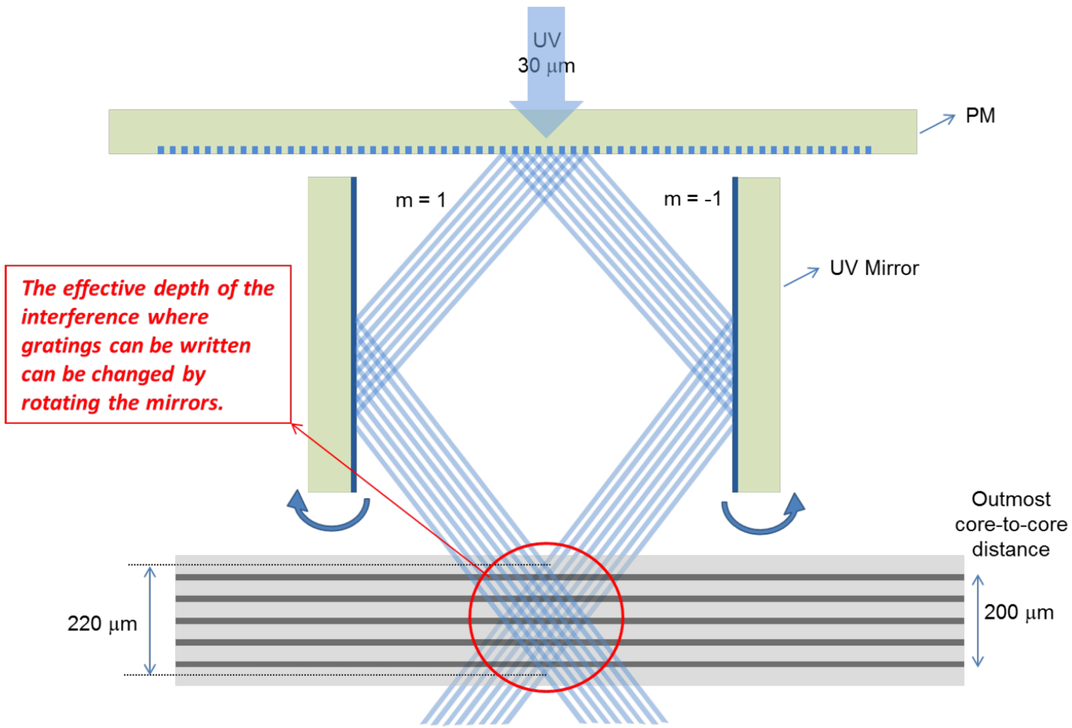
- Complex aperiodic FBGs to remove unwanted frequencies <u>in MMFs</u>

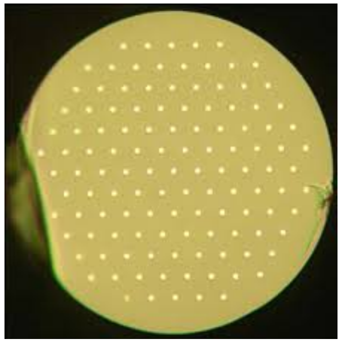




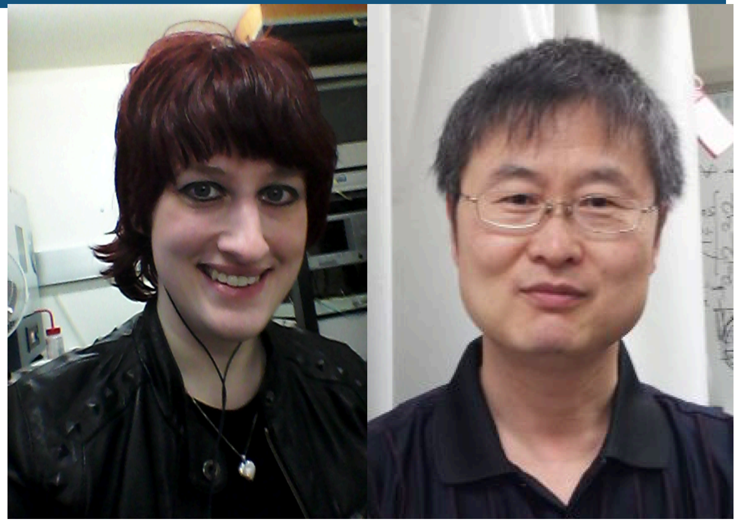
JBH et al (2011), Nature Comms.

Printing FBGs into Multi Core Fibres

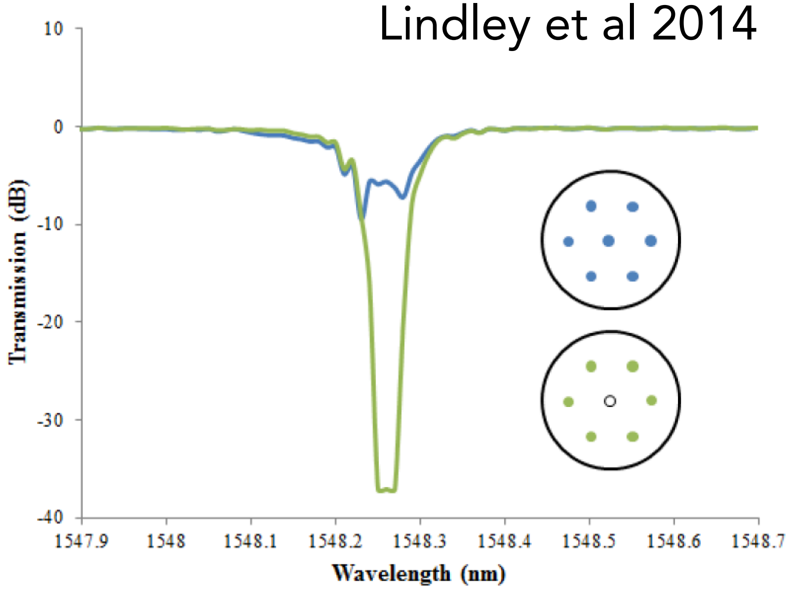




120-core fibre

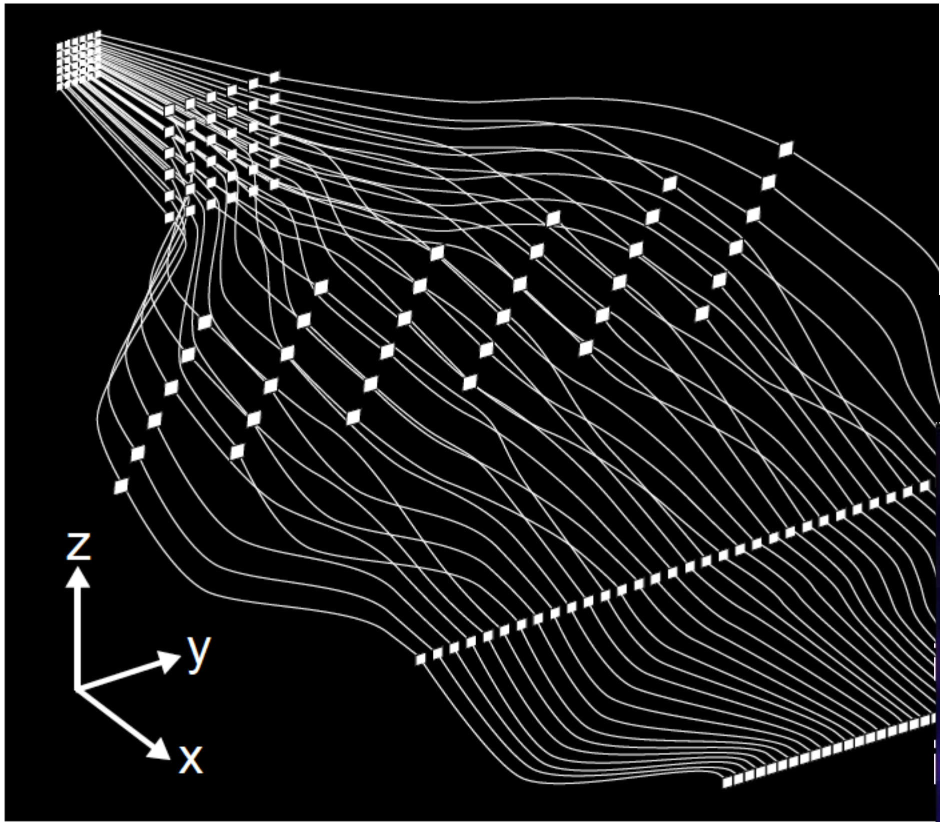


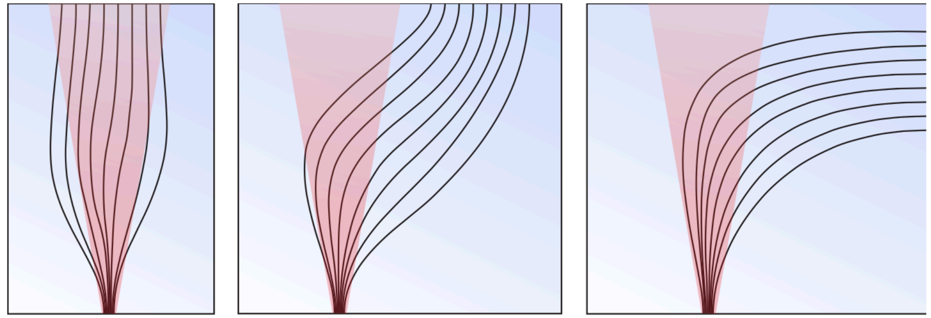
Lindley et al 2014

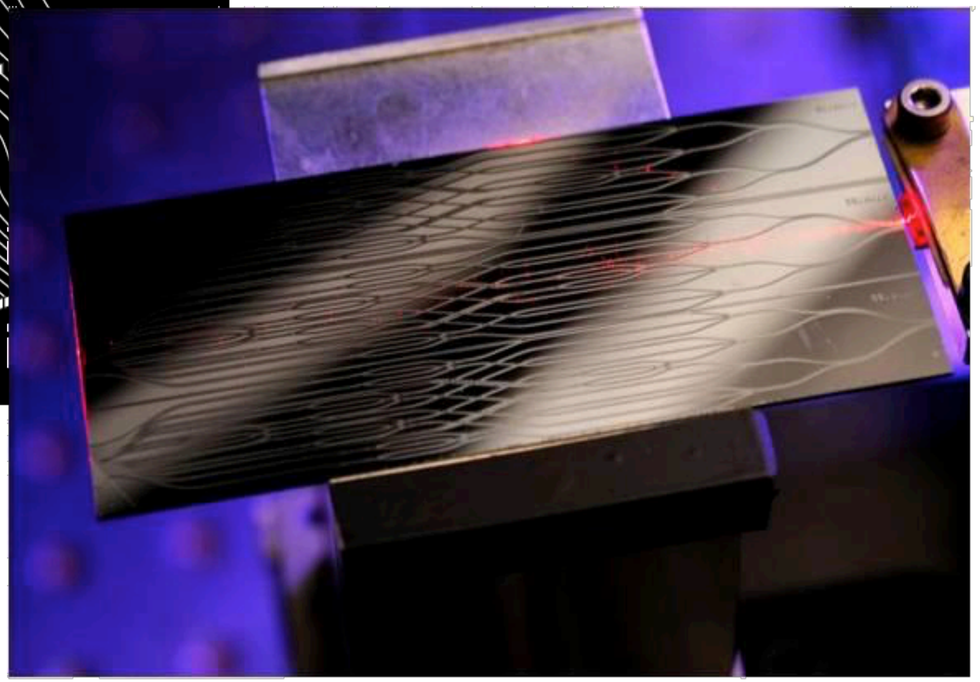


Lindley et al 2014, 2015

2D & 3D lantern, beam combining, reformatting







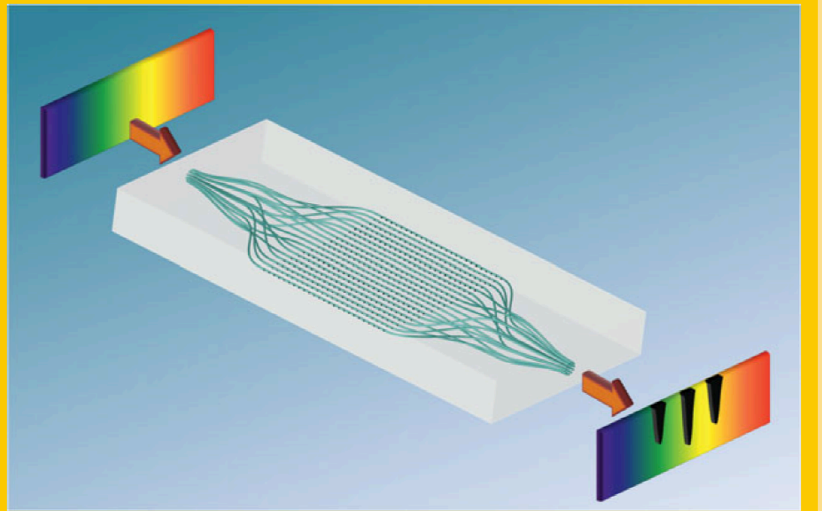
Sketch shown because many ULI tracks in Eagle glass are hard to photograph.

Thomson et al 2011, 2012; Norris et al 2014; MacLachlan et al 2015

Laser Photonics Rev. **8,** No. 1, L1–L5 (2014) / **DOI** 10.1002/lpor.201300129

LASER & PHOTONICS REVIEWS

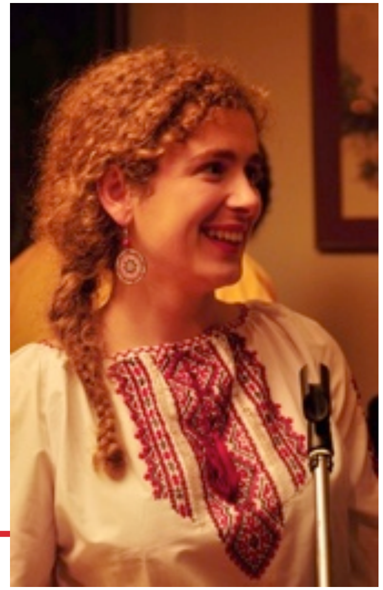
Abstract The first demonstration of narrowband spectral filtering of multimode light on a 3D integrated photonic chip using photonic lanterns and waveguide Bragg gratings is reported. The photonic lanterns with multi-notch waveguide Bragg gratings were fabricated using the femtosecond direct-write technique in boro-aluminosilicate glass (Corning, Eagle 2000). Transmission dips of up to 5 dB were measured in both photonic lanterns and reference single-mode waveguides with 10.4-mm-long gratings. The result demonstrates efficient and symmetrical performance of each of the gratings in the photonic lantern. Such devices will be beneficial to space-division multiplexed communication systems as well as for units for astronomical instrumentation for suppression of the atmospheric telluric emission from OH lines.



LETTER ARTICLE

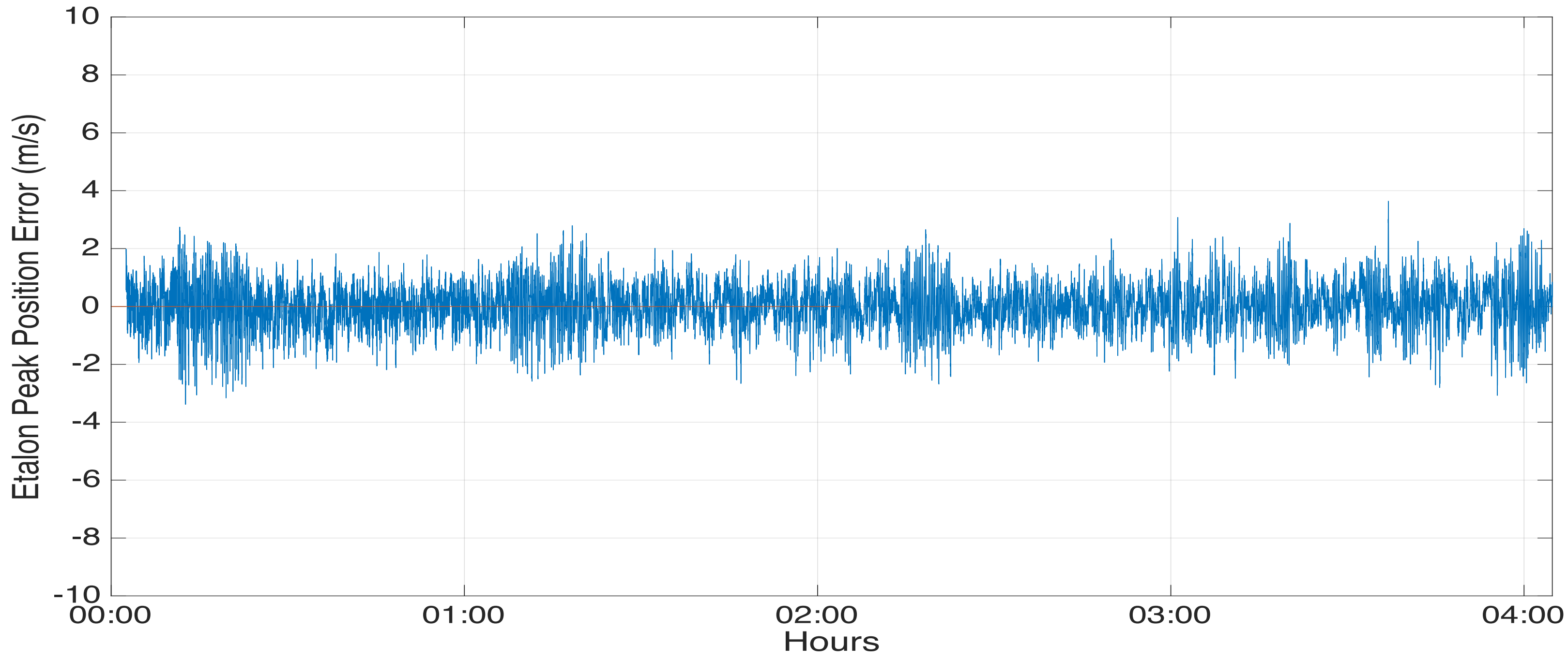
Multiband processing of multimode light: combining 3D photonic lanterns with waveguide Bragg gratings

Izabela Spaleniak[1,2,*], Simon Gross[1,3], Nemanja Jovanovic[4], Robert J. Williams[1], Jon S. Lawrence[1,2,5], Michael J. Ireland[1,2,5], and Michael J. Withford[1,2,3]

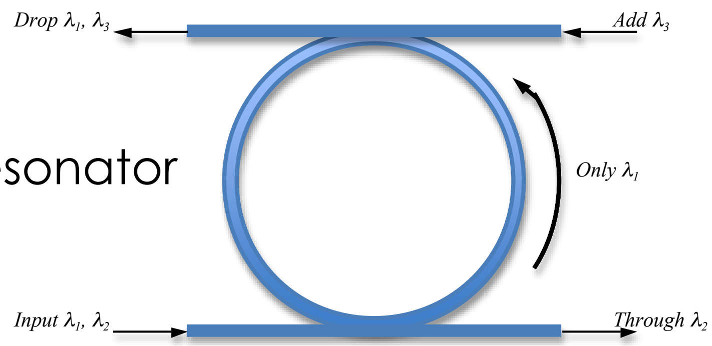


Spaleniak et al 2015; Douglass et al 2015

Many new integrated functions: e.g. laser combs



ring resonator



Our latest approach is to lock a fibre etalon to a Rb laser diode.

We achieve < 80 cm s^{-1} stability, or < 20 cm s^{-1} (co-adding).

Chu et al 2012; Schwab et al 2014

Astrophotonics groups are developing many other photonic technologies

Fibres, bundles

Multicore fibres

Photonic lanterns, solid lanterns, dicers

Fibre Bragg gratings

Waveguides, array waveguides

Laser combs

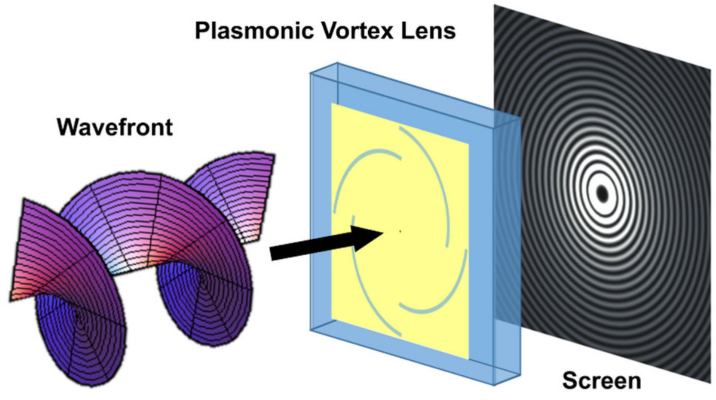
Ring resonators

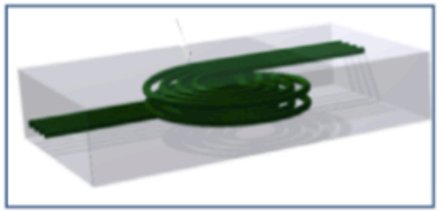
Optical vortex generation, OAM

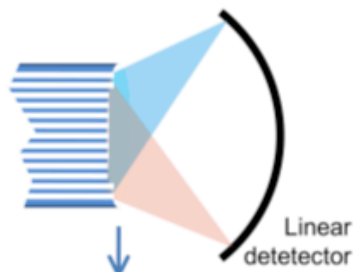
Optical circulators

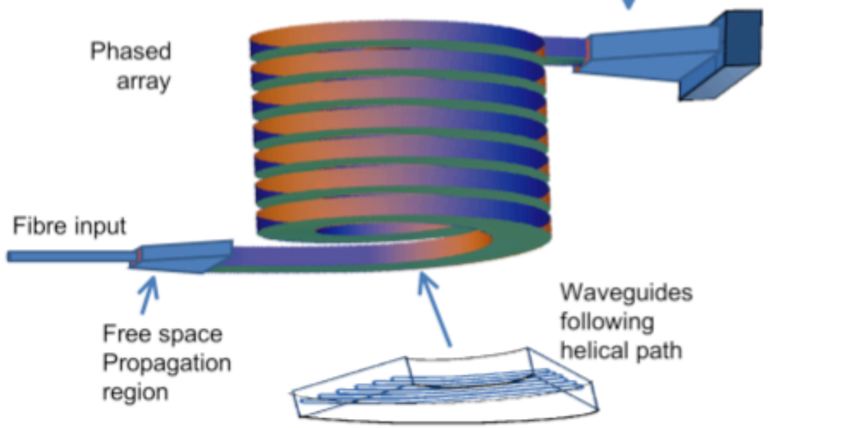
Raman microfluidic spectroscopy

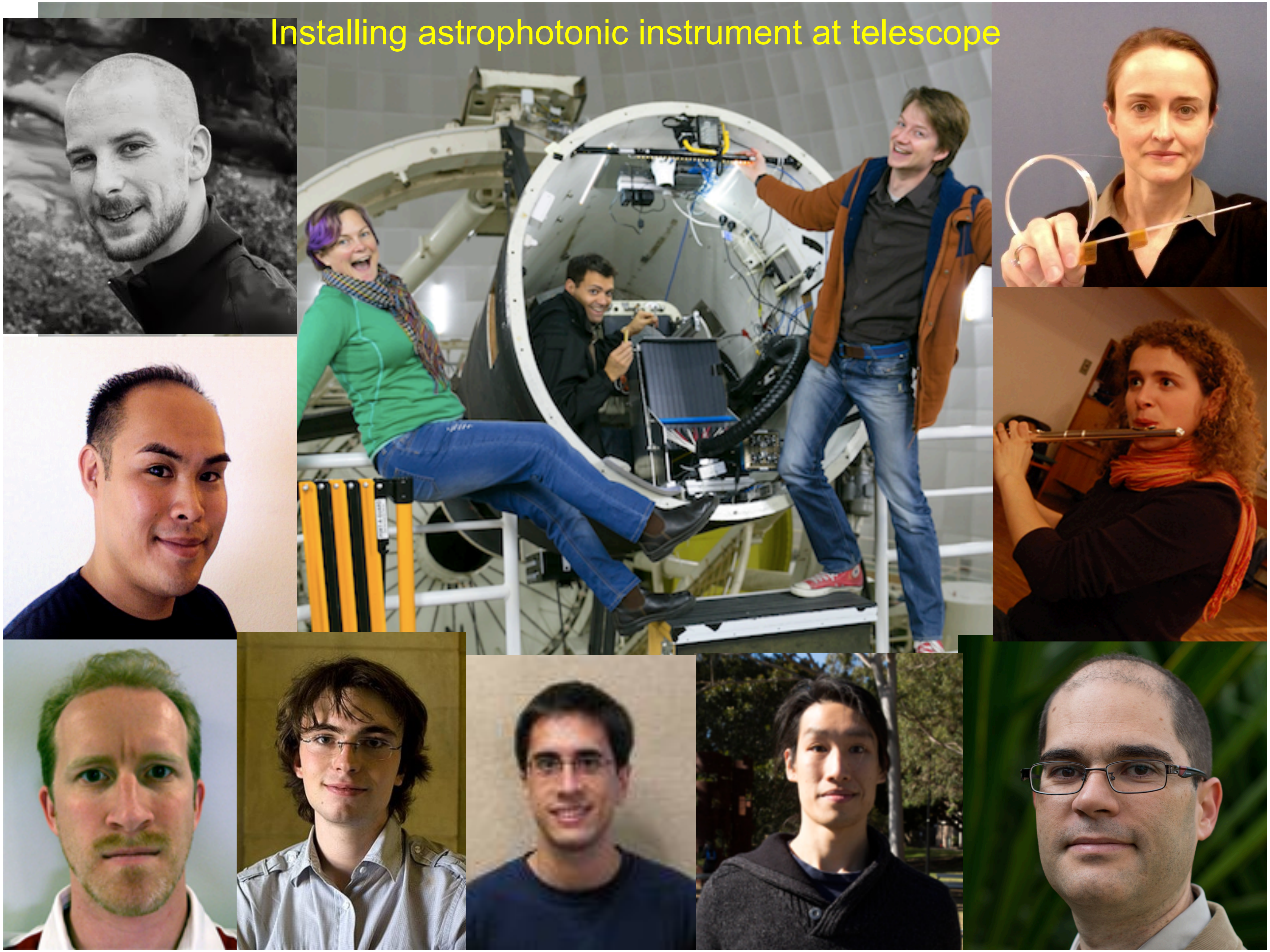
Interferometry



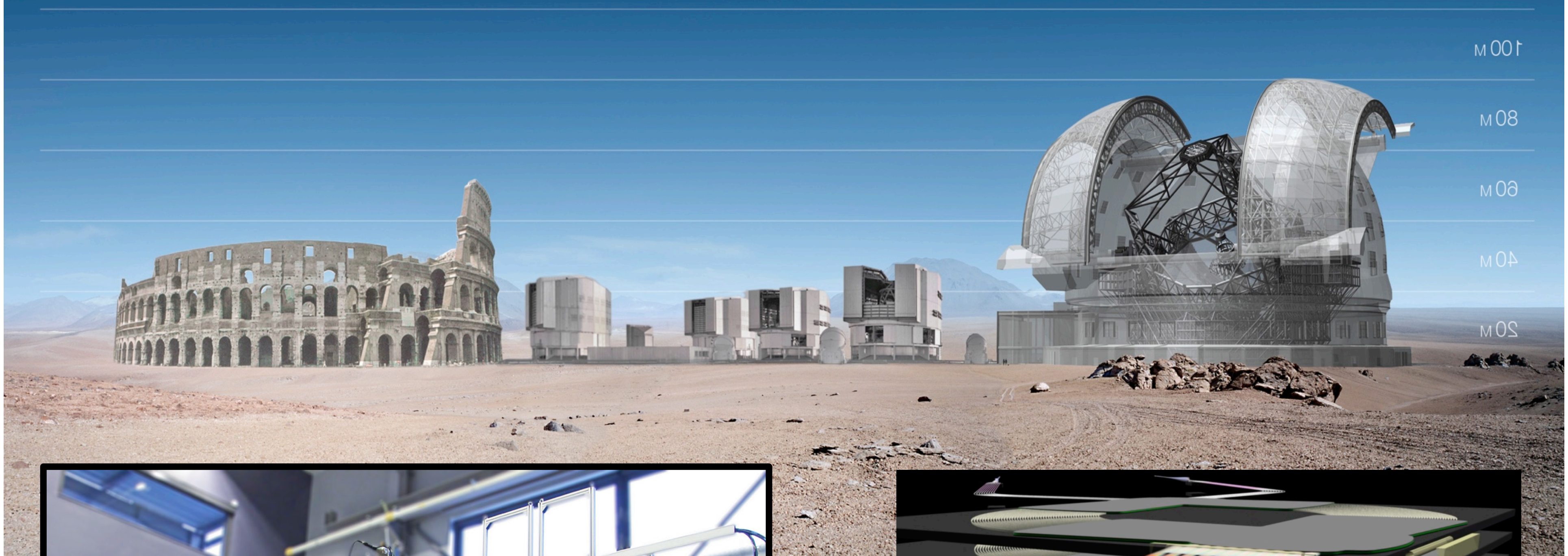


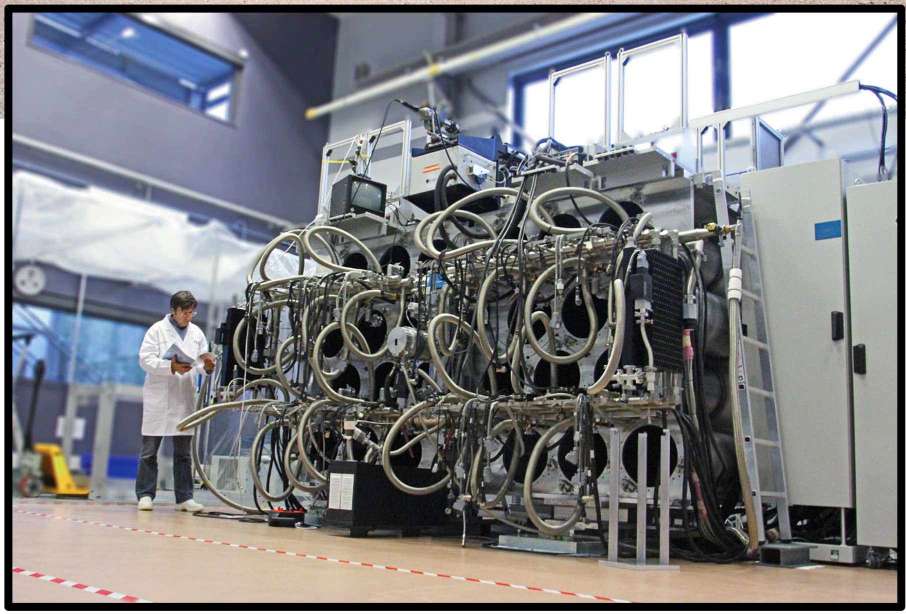


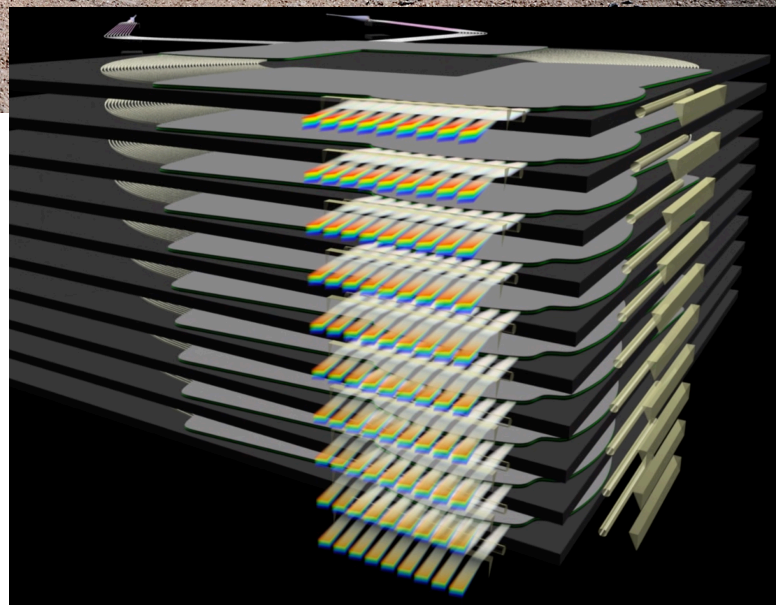



Installing astrophotonic instrument at telescope

A future dominated by DL instruments & telescopes





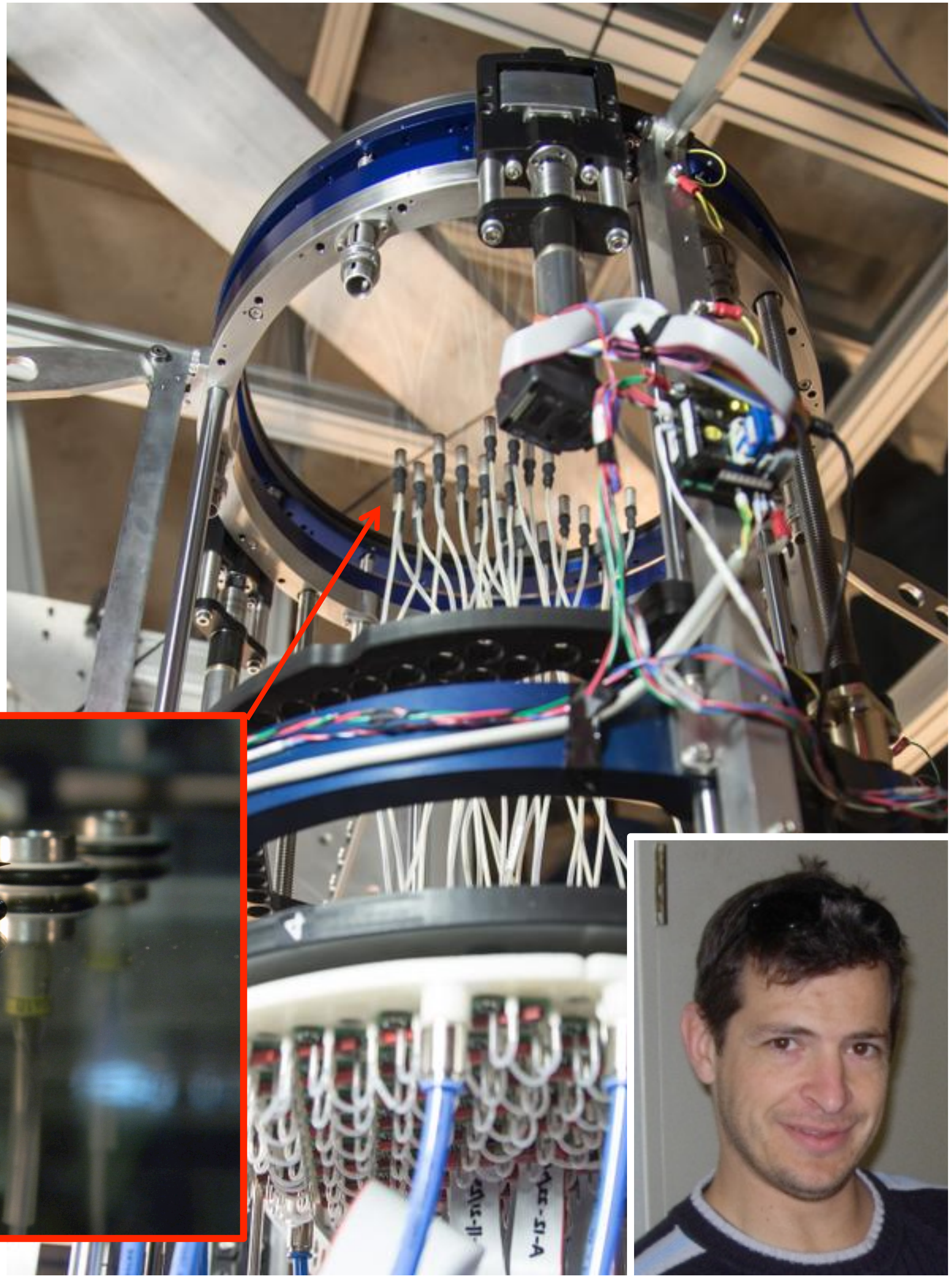


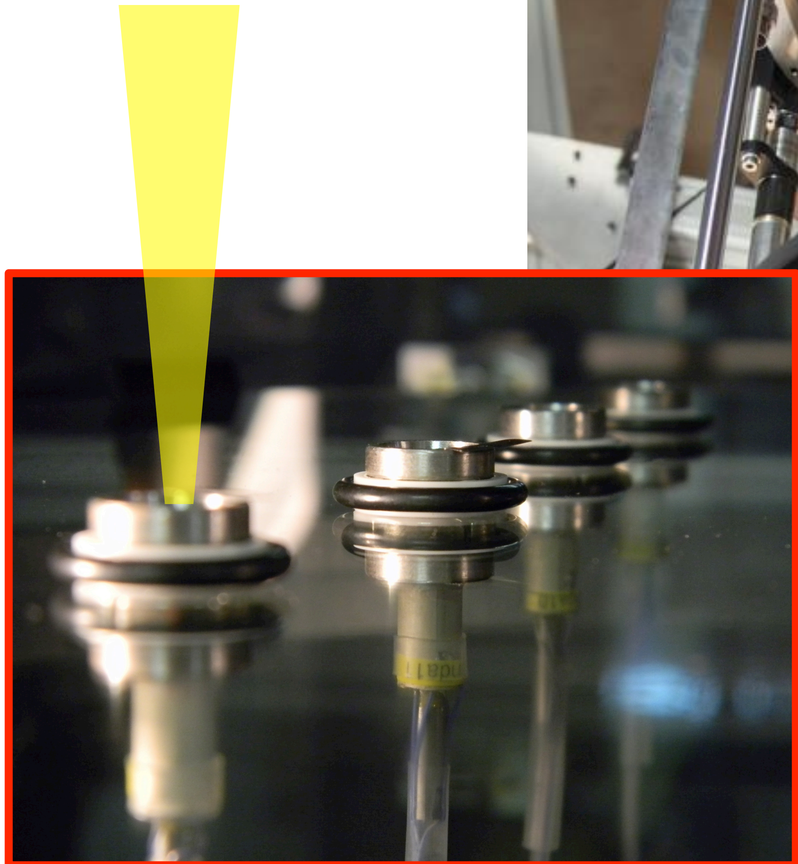
Bacon et al 2006; JBH et al 2010

Australian Astronomical Observatory (AAO)

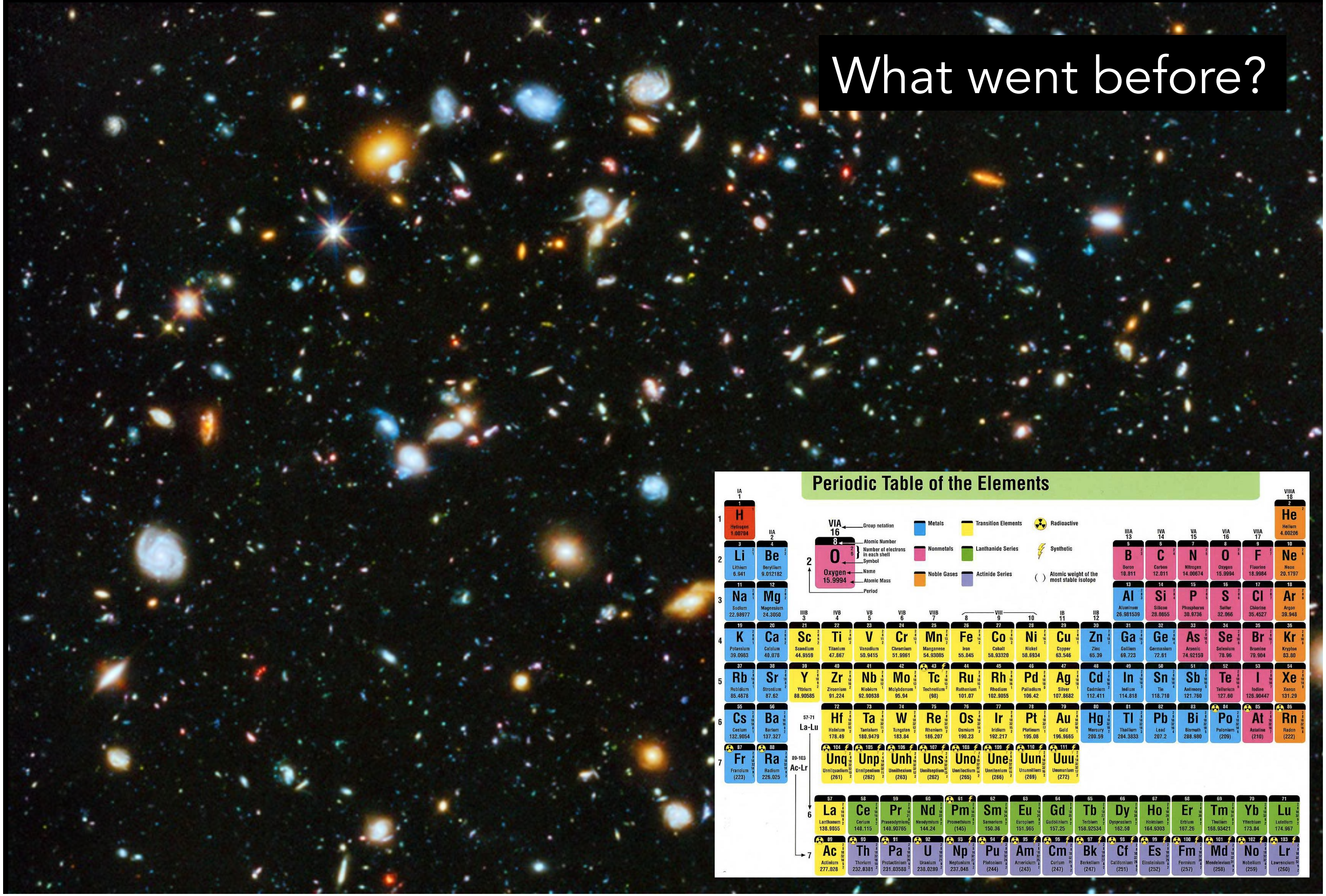
World leaders in autonomous robotic fibre positioning

Target many objects simultaneously





Hubble shows us galaxies were smaller in the past.



The next generation of huge telescopes will achieve direct coupling into single-mode waveguides, or close to it.

The $100M investment in advanced AO is paying off.

Astrophotonic instrumentation will dominate the future.