26ème Congrès général de la SFP
Mini-colloque Astrophonique : optique moderne pour l’instrumentation astronomique

Astrophotonics for visible interferometry

Elsa Huby

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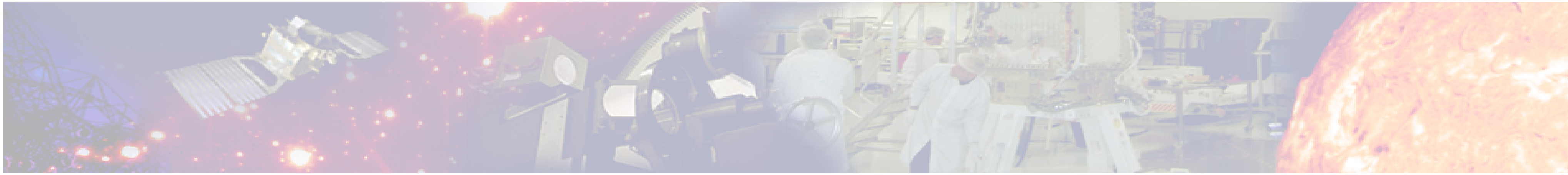
S. Vievard, **O. Guyon**, N. Jovanovic, J. Lozi, N. Cvetojevic, **T. Kotani**,
F. Marchis, G. Duchêne, J. Woillez, É. Choquet, L. Gauchet, P. Fédou, O. Lai

IPAG Institut de Planétologie et d'Astrophysique de Grenoble
LESIA l'Observatoire de Paris | PSL
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique
Subaru Telescope – National Astronomical Observatory of Japan
SCExAO Subaru Coronagraphic Extreme Adaptive Optics すばるコロナグラフ極限補償光学装置



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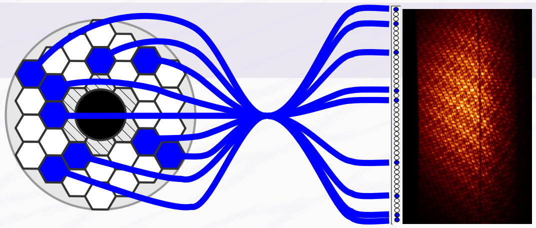
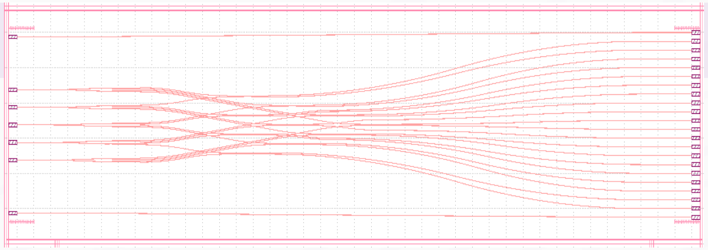
Université de Paris
PSL UNIVERSITÉ PARIS

Outline

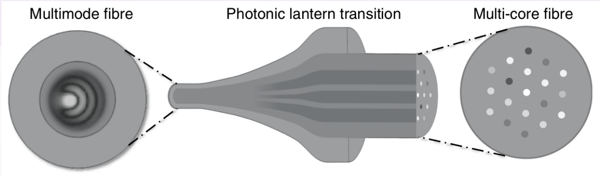
- **The FIRST instrument, visible spectro-interferometer**
  - Direct detection of exoplanets
  - Instrument principle: pupil masking / pupil remapping
  - Science case: detection of protoplanets



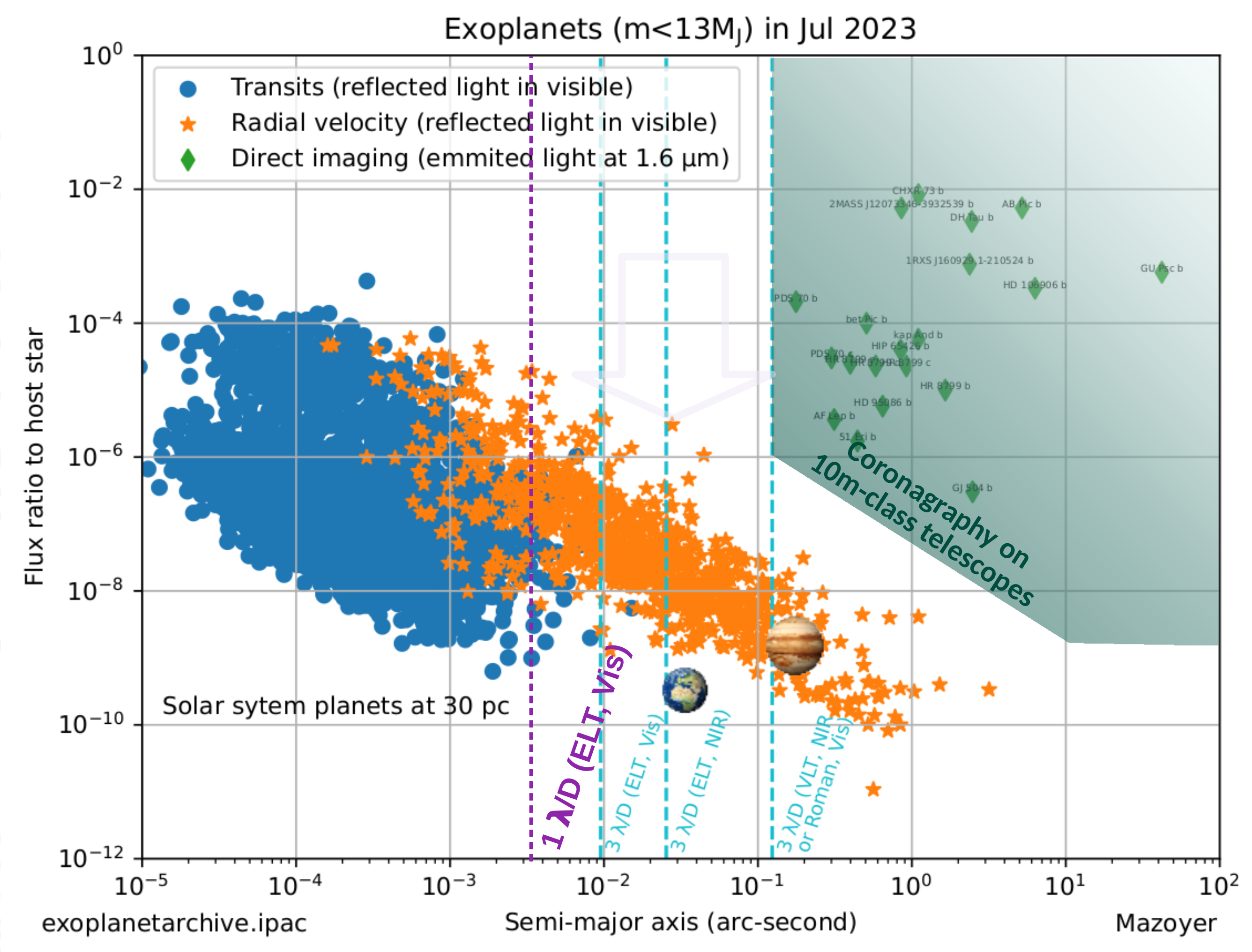
- **Planar combiners for the visible**
  - 5-input chip prototypes
  - Low vs high contrast index chip
  - Laboratory characterization



- **Photonic developments in the visible**
  - Active phase shifters
  - 3D chip
  - Photonic lantern



Direct detection of exoplanets



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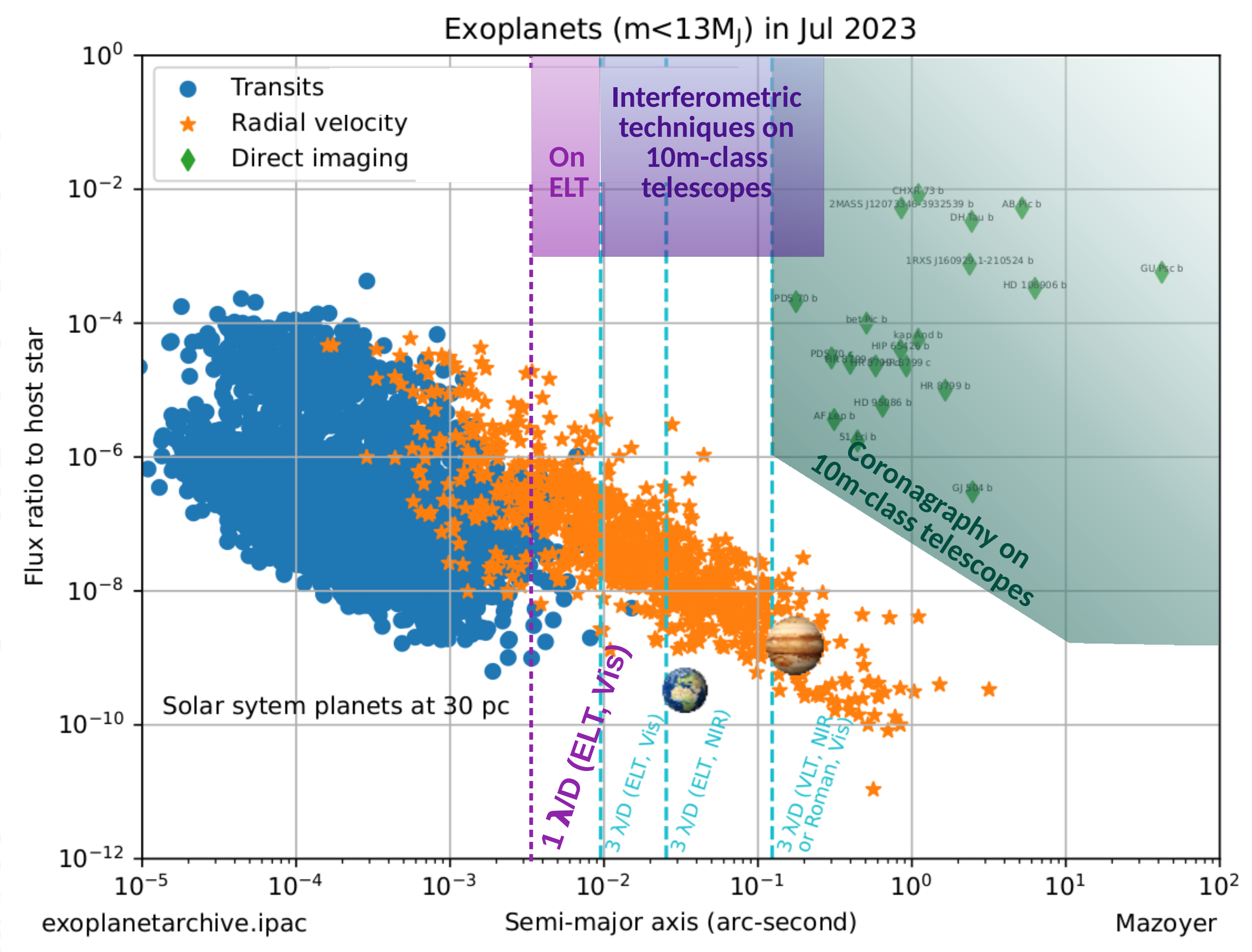
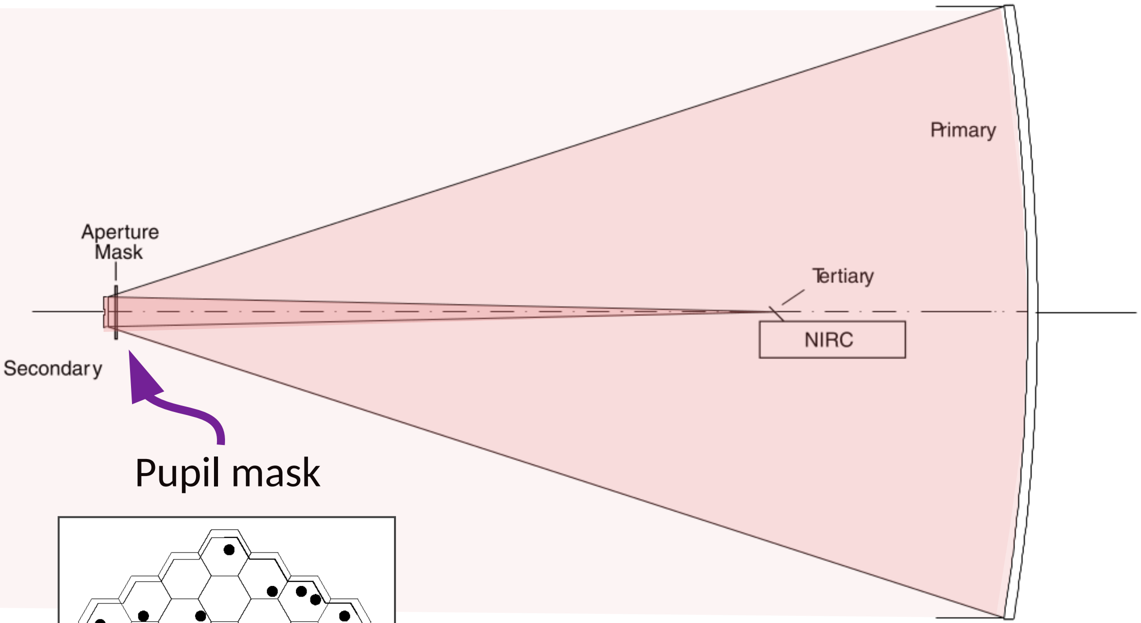
Direct detection of exoplanets

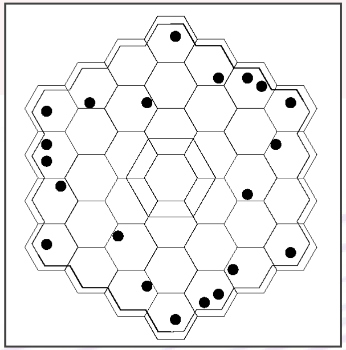


Interferometric technique on monolithic telescopes
Sparse Aperture Masking (SAM) / Non Redundant Masking (NRM)

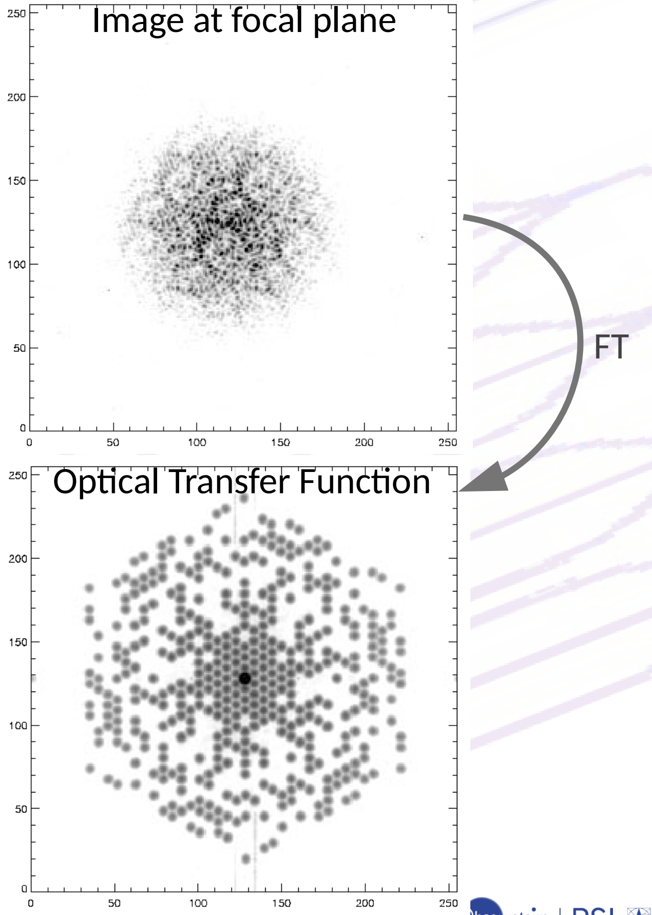
Baldwin et al., 1986
Haniff et al., 1987



Pupil mask

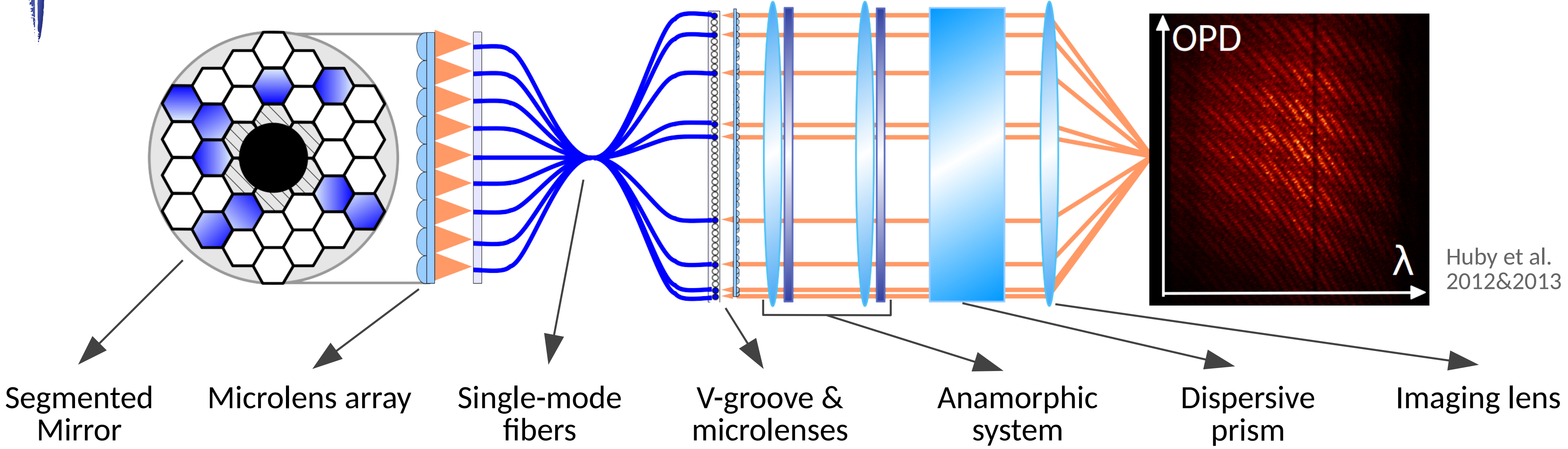


Tuthill et al. 2000



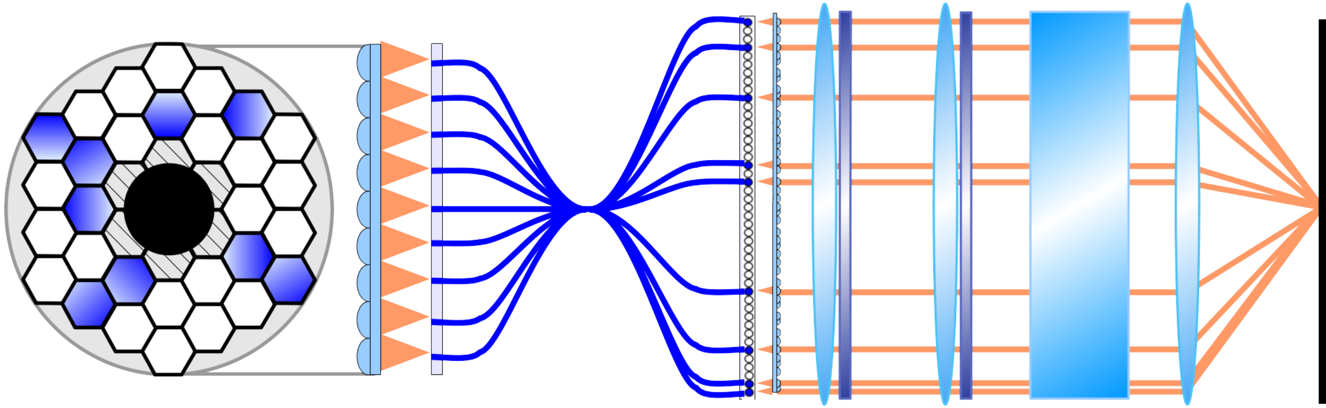
The FIRST instrument: spectroscopy at the diffraction limit (and below)

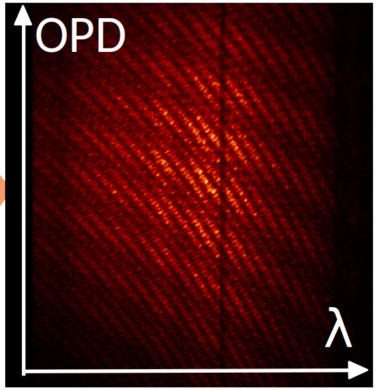
Pupil remapping



The FIRST instrument: spectroscopy at the diffraction limit (and below)

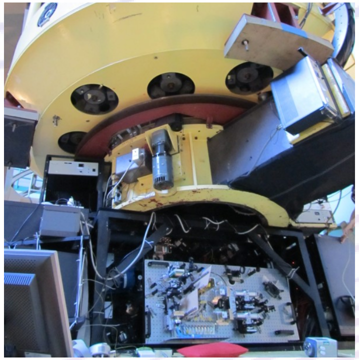
FIRSTv1

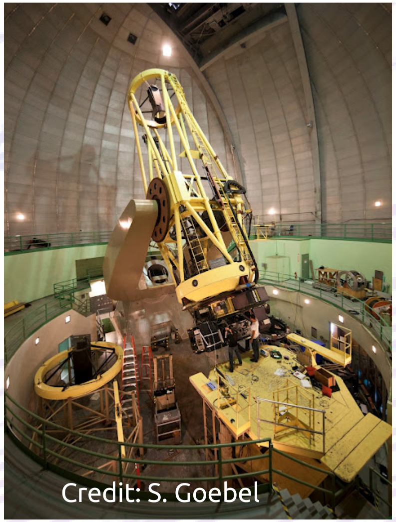




Huby et al. 2012&2013

2010 - 2013:
Lick Observatory
3m-Shane telescope

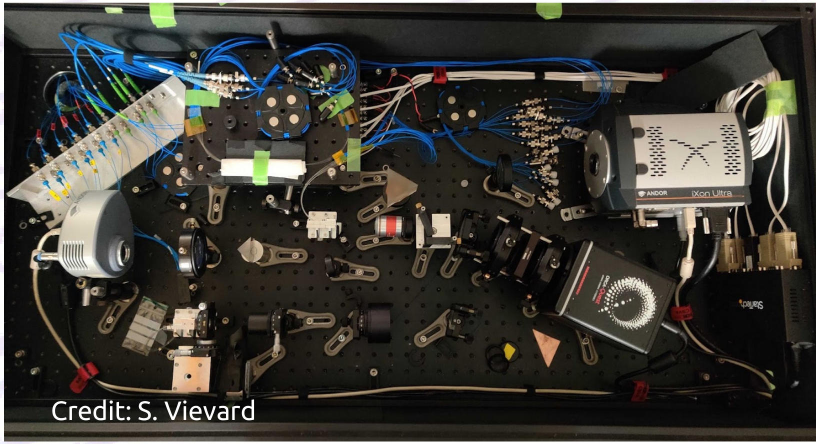




Currently:
Subaru Telescope
8m-Subaru telescope
→ SCExAO platform

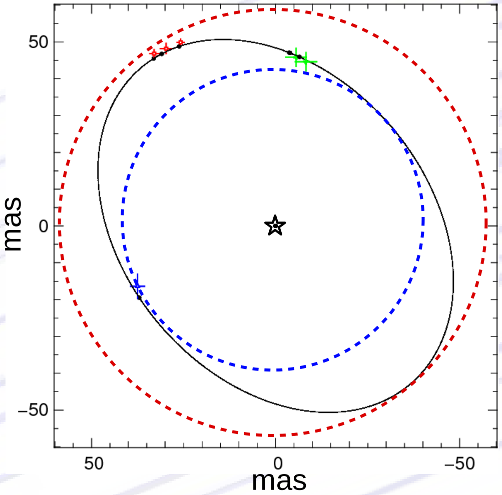
Vievard et al. submitted

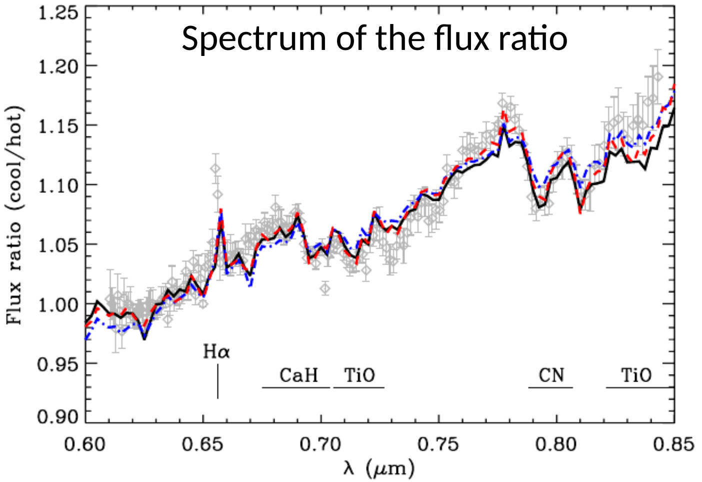
2023 July 7th



The FIRST instrument: spectroscopy at the diffraction limit (and below)
FIRSTv1

At the diffraction limit:
Capella results on the **3-m Shane telescope**





Huby et al. 2013

The FIRST instrument: spectroscopy at the diffraction limit (and below)

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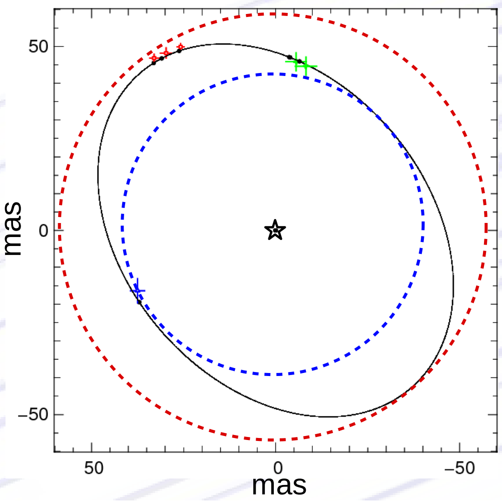
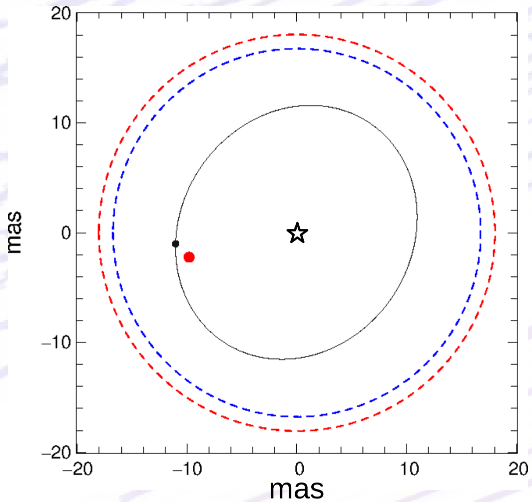
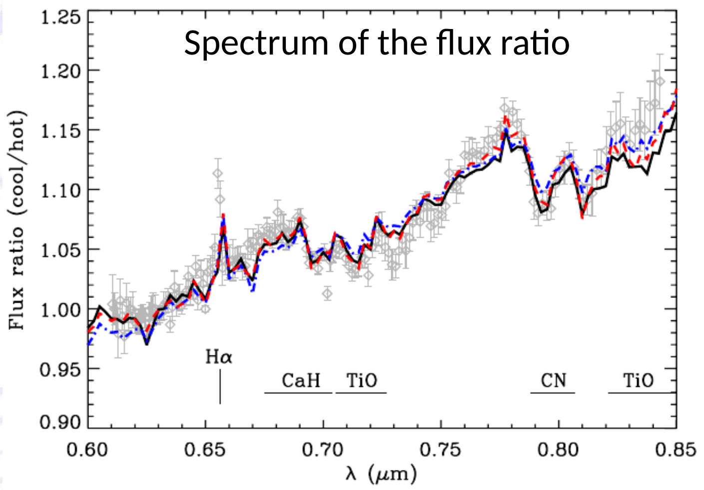
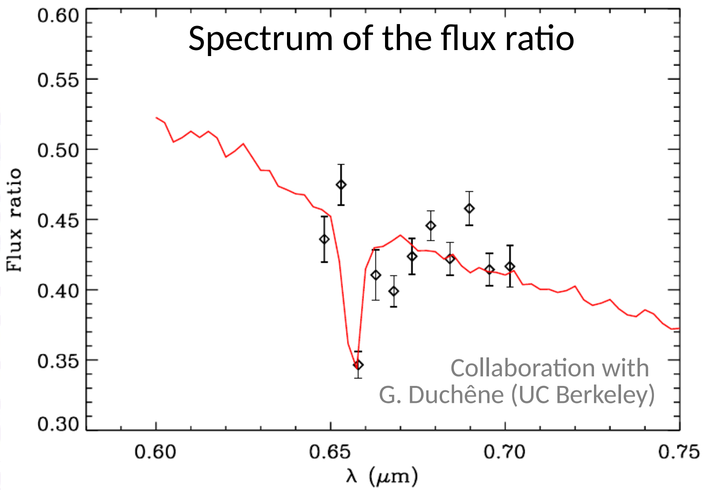




Below the diffraction limit: Alpha Equu results on the **8-m Subaru telescope**

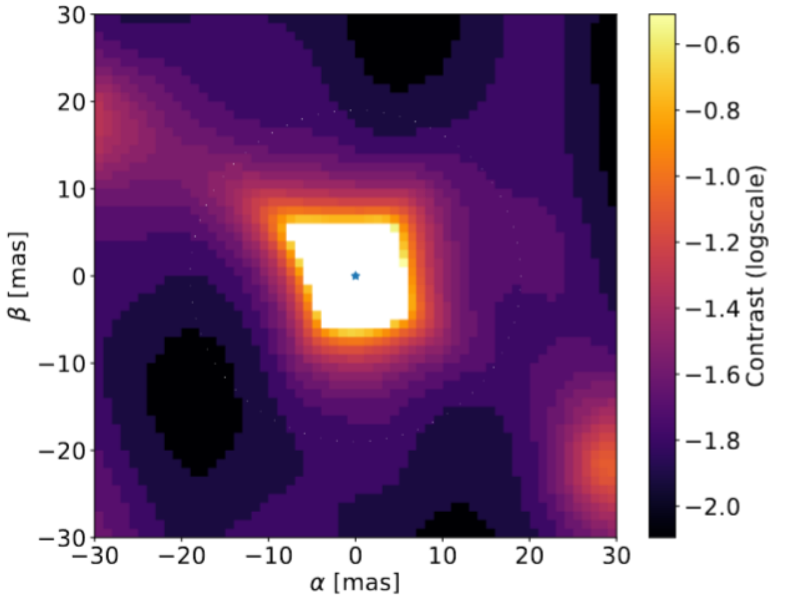


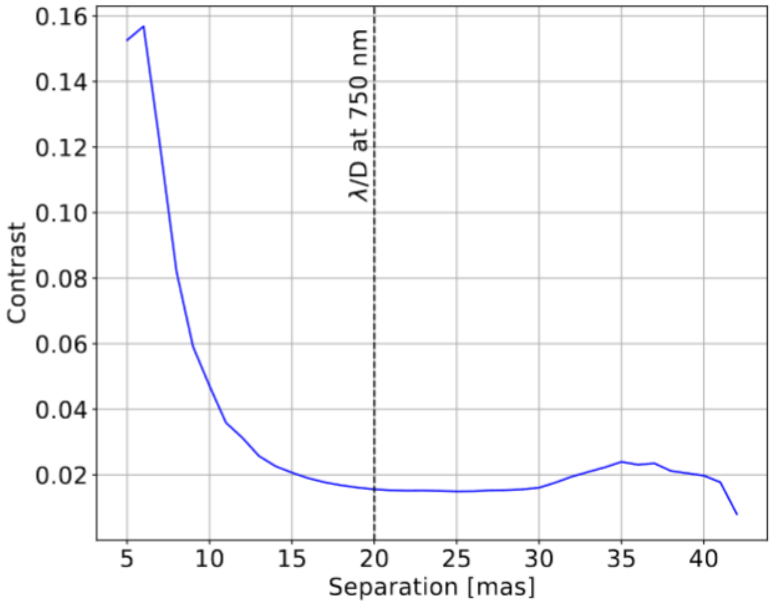
Huby et al. 2013



The FIRST instrument: spectroscopy at the diffraction limit (and below)
FIRSTv1

Sensitivity map at the 8m-Subaru telescope



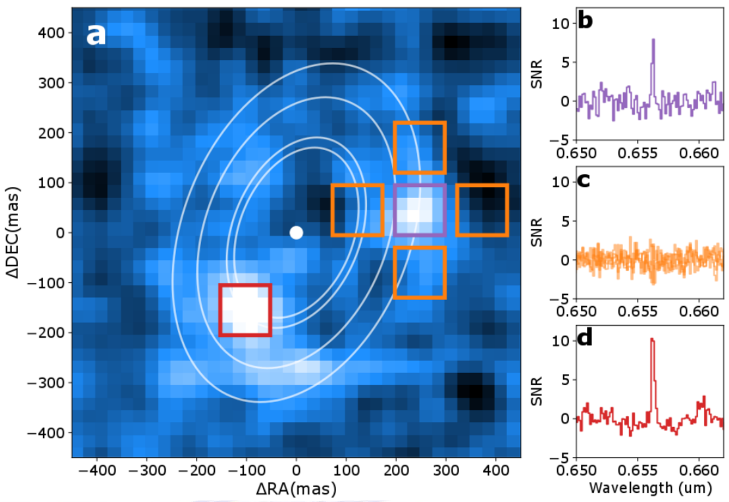


3-σ sensitivity map around **Keho'oea (*Vega*)**
Total integration time of 500s on target

Vievard et al. submitted

FIRSTv2

- Hα emission, a signature for accreting matter



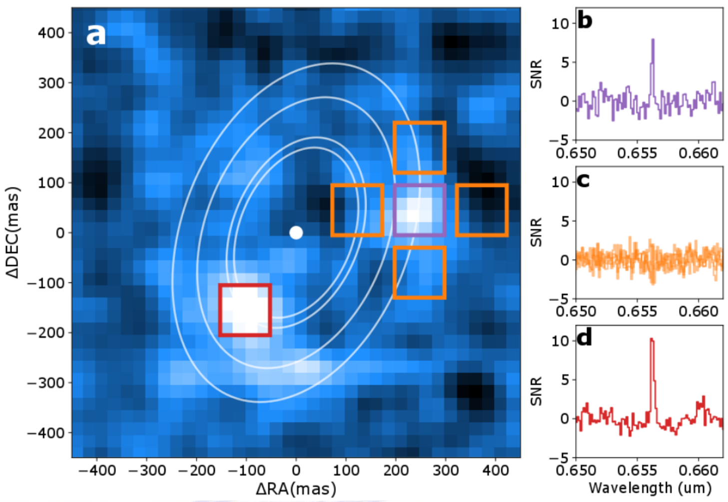
Haffert et al. 2019

MUSE observations:

- Integral field spectroscopy
- Spectral resolution ~ 3000
- Hα Spectral Differential Imaging (subtraction of the continuum)

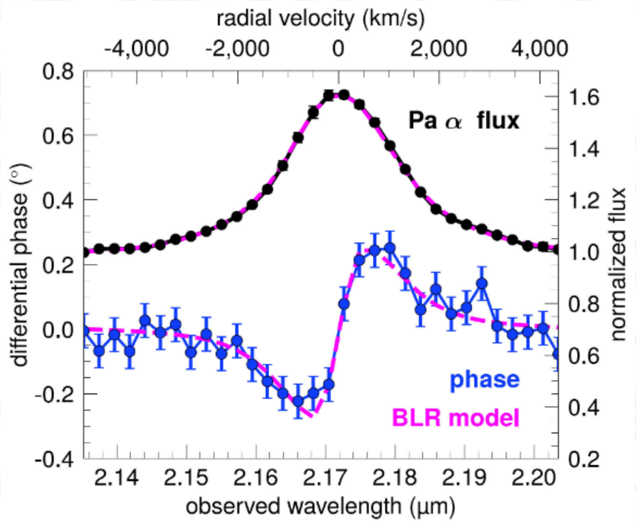
The FIRST instrument: the detection of protoplanets
FIRSTv2

- Hα emission, a signature for accreting matter



Haffert et al. 2019

- Interferometric equivalent: **differential phase**



GRAVITY collab., Sturm et al. 2018

MUSE observations:

- Integral field spectroscopy
- Spectral resolution ~ 3000
- Hα Spectral Differential Imaging (subtraction of the continuum)

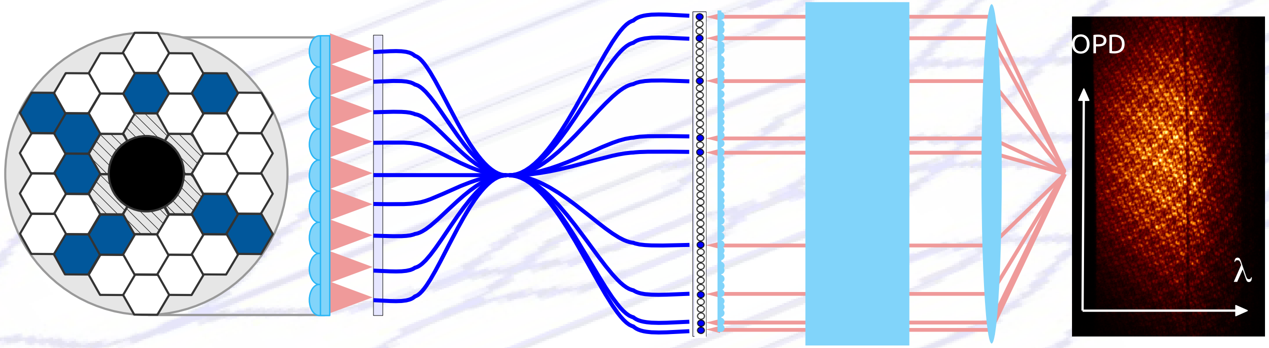
FIRSTv2 objectives:

- High **spectral resolution: ~3000**
- Improve the **contrast: 10^{-2} - 10^{-3}**
- Improve the **sensitivity**: **Rmag 7** (AB Aur), **Rmag 11-12** (PDS70)

FIRSTv2: the move to photonics

FIRST**v1**

Path length matched single mode fibers | Non redundant array | Anamorphic syst. + Disp. prism | Focal plane recombination



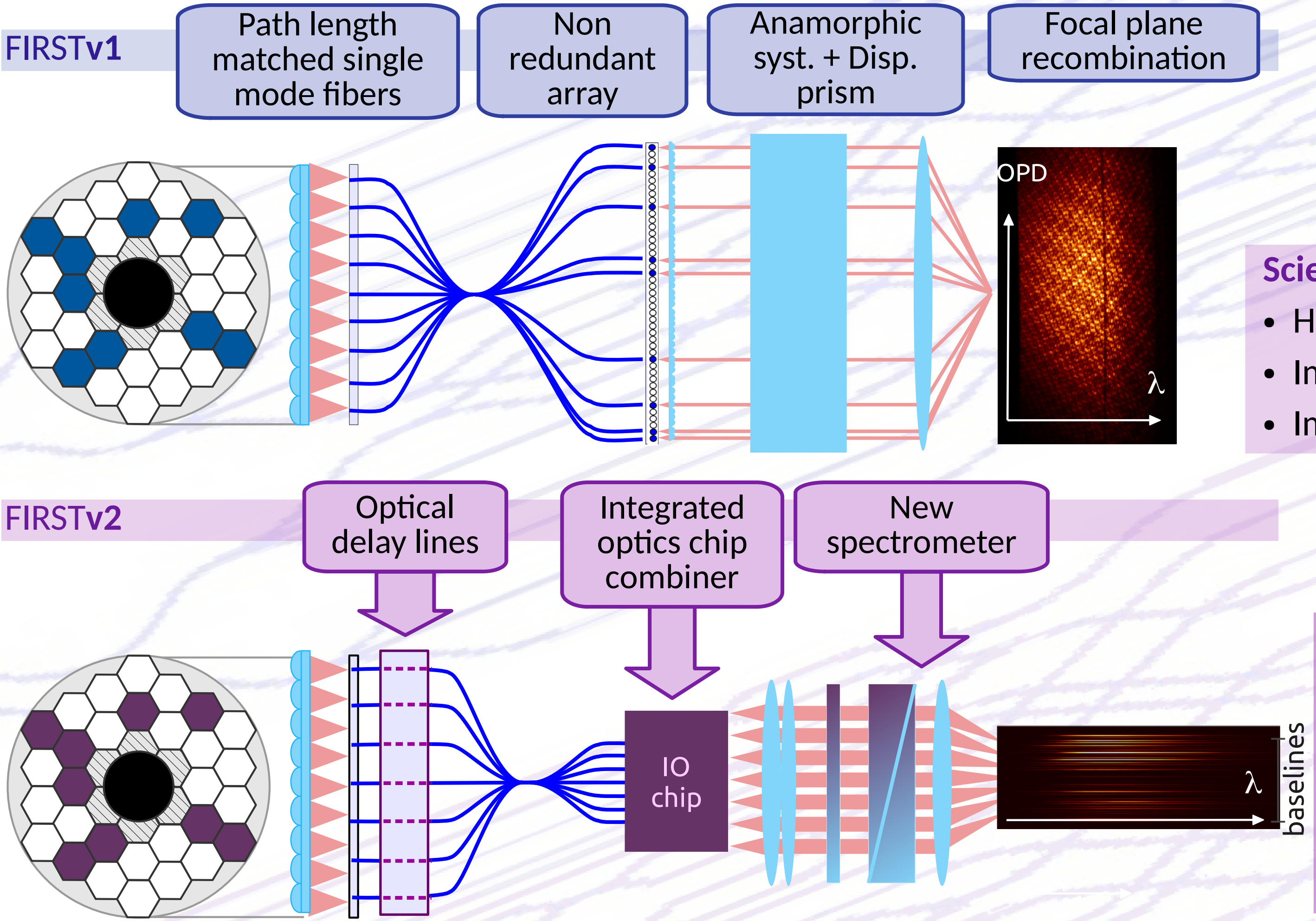
Science case objectives:

- High **spectral resolution: ~3000**
- Improve the **contrast: 10^{-2} - 10^{-3}**
- Improve the **sensitivity**: **Rmag 7** (AB Aur)

Photonic Integrated Circuit

- Stability to mechanical and temperature variations
- Flux concentration
- Scalable to more inputs
- Active phase control

FIRSTv2: the move to photonics



Science case objectives:

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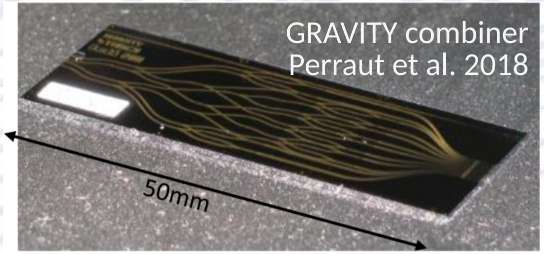
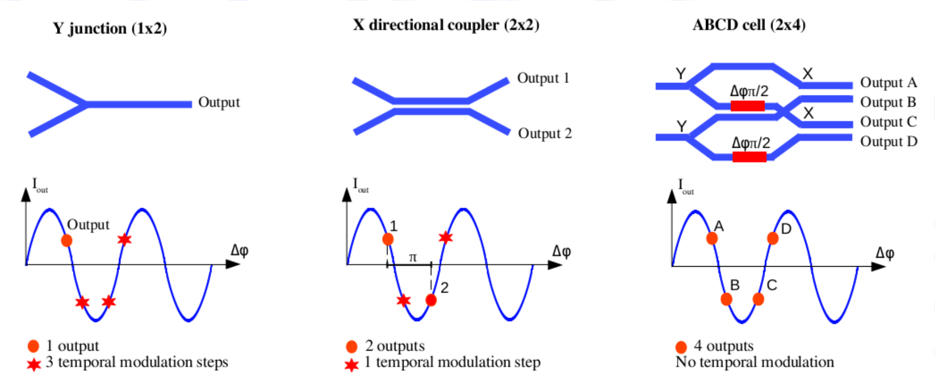
Photonic Integrated Circuit



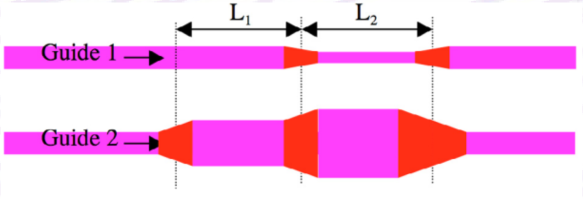
GRAVITY combiner
Perraut et al. 2018

Waveguides are created within a piece of glass (silicon)
→ Kern et al. 1996, Berger et al. 1999, Malbet et al. 1999

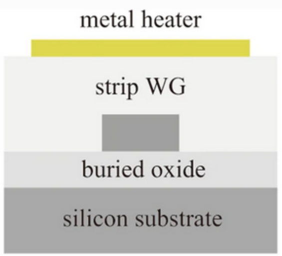
- Straight and curved waveguides
- Splitters: Y junctions
- Combiners:
  - Reverse Y-junction
  - X-junction
  - Directional coupler or evanescent wave coupler
  - Tricouplers
  - Multimode Interference (MMI) Coupler
- Phase shifters
- Thermo-electric phase shifter / Electro-optic phase shifter



Lallement et al. 2023



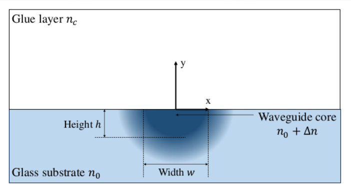
Benisty et al. 2009

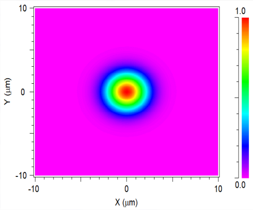


Liu et al., 2022

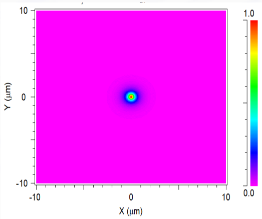
Photonic developments for the visible

Low index contrast

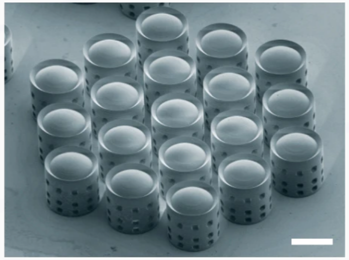




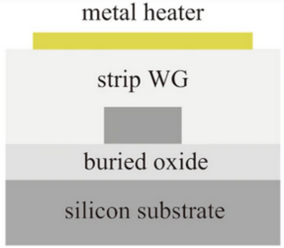
High index contrast



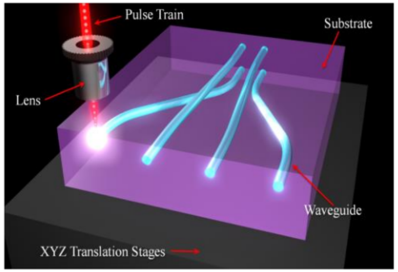
Printed microlenses



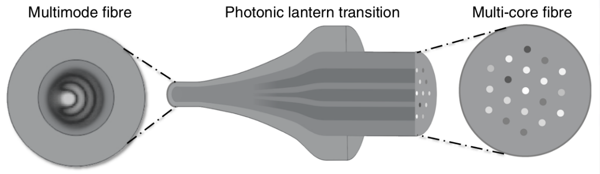
Active phase shifters



3D-chips



Photonic lantern

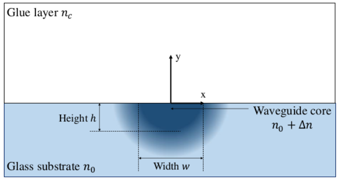


Low vs **high** refractive index contrast

Low index contrast

TEEM photonics

- Diffused material: ion diffusion



- Low index contrast ≈ **0.023**
- Bend Radius = **30 mm**
- Waveguide mode size (MFD equivalent) = **5.4x3.2 µm**
- Expected insertion loss ~ **10%** (0.5 dB)
- Material loss = 0.24 dB/cm

Good fiber coupling
High bend radius
→ large chip

High index contrast

LioniX

- Step index: etching

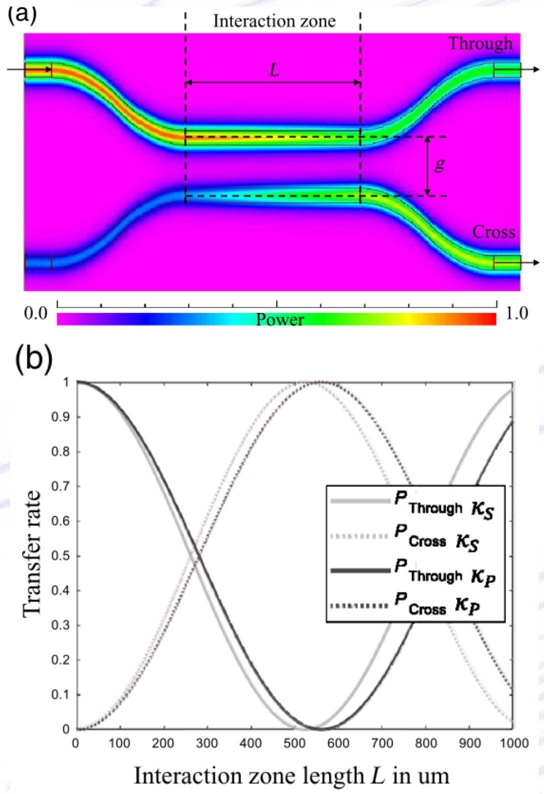
- High index contrast = **0.137**
- Bend Radius ≈ **150 µm**
- Waveguide mode size (MFD equivalent) = **0.7 to 0.9 µm**
- Expected insertion loss ~ **50%** (3 dB)
- Material loss = 0.1 to 0.5 dB/cm

Bad fiber coupling
Low bend radius
→ compact & complex chip

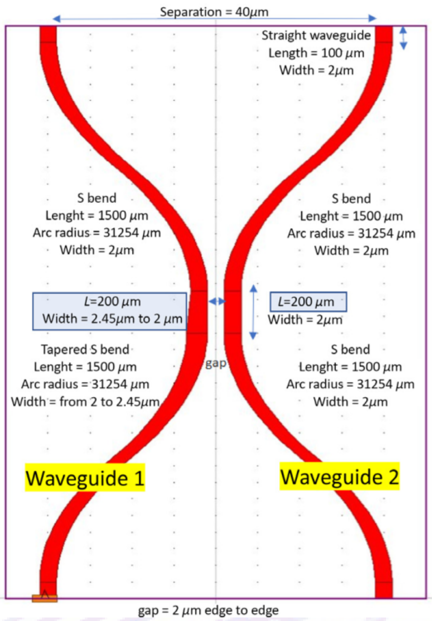
Low refractive index contrast
TEEM Photonics

- Beamprop modeling and design optimization by **Manon Lallement**

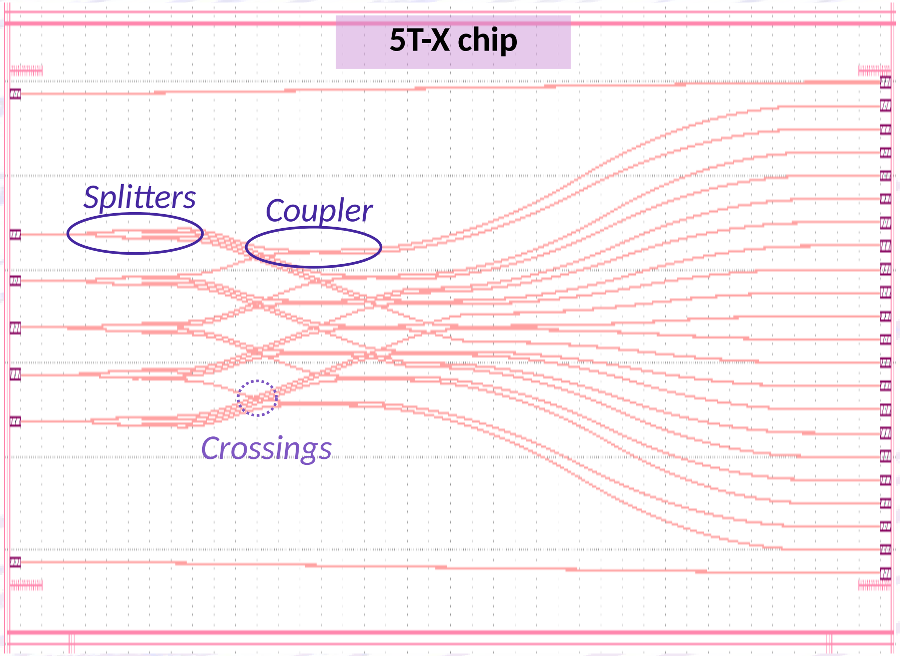
Symmetric coupler



Asymmetric coupler



Lallement et al. 2023



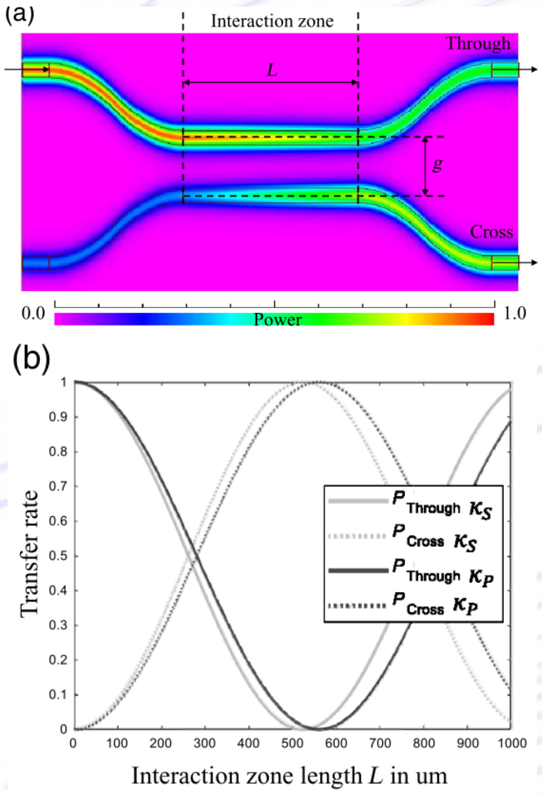
Technology: Ka+/Na+ ion exchange in glass
Single-mode spectral range: 530 nm - 820 nm
Propagation loss: 0.24 dB/cm @656 nm
0.3 dB/cm @ 780 nm
Insertion loss (SM630) : 0.13 dB @ 635nm (97% coupling)

Low refractive index contrast
TEEM Photonics

- Beamprop modeling and design optimization by **Manon Lallement**

5T-X chip

Symmetric coupler



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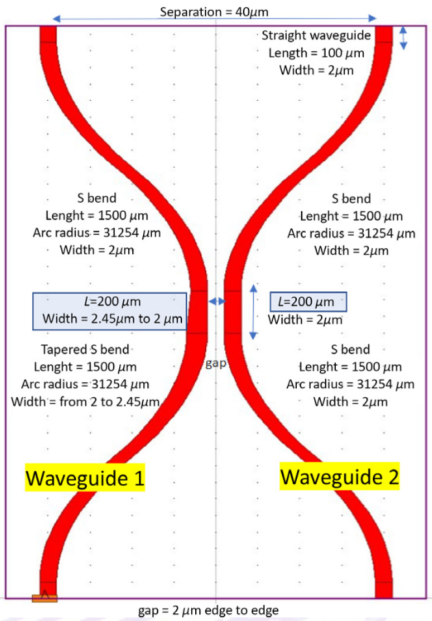
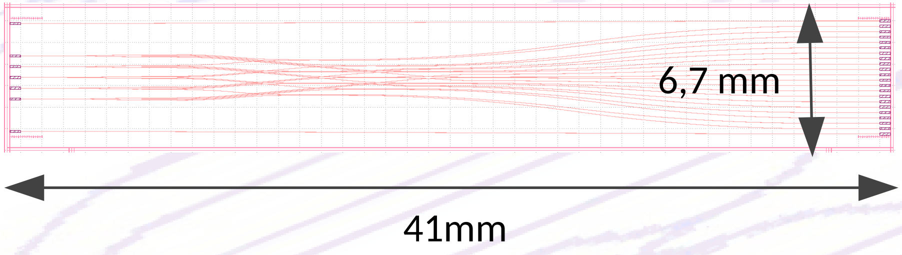


Lallement et al. 2023



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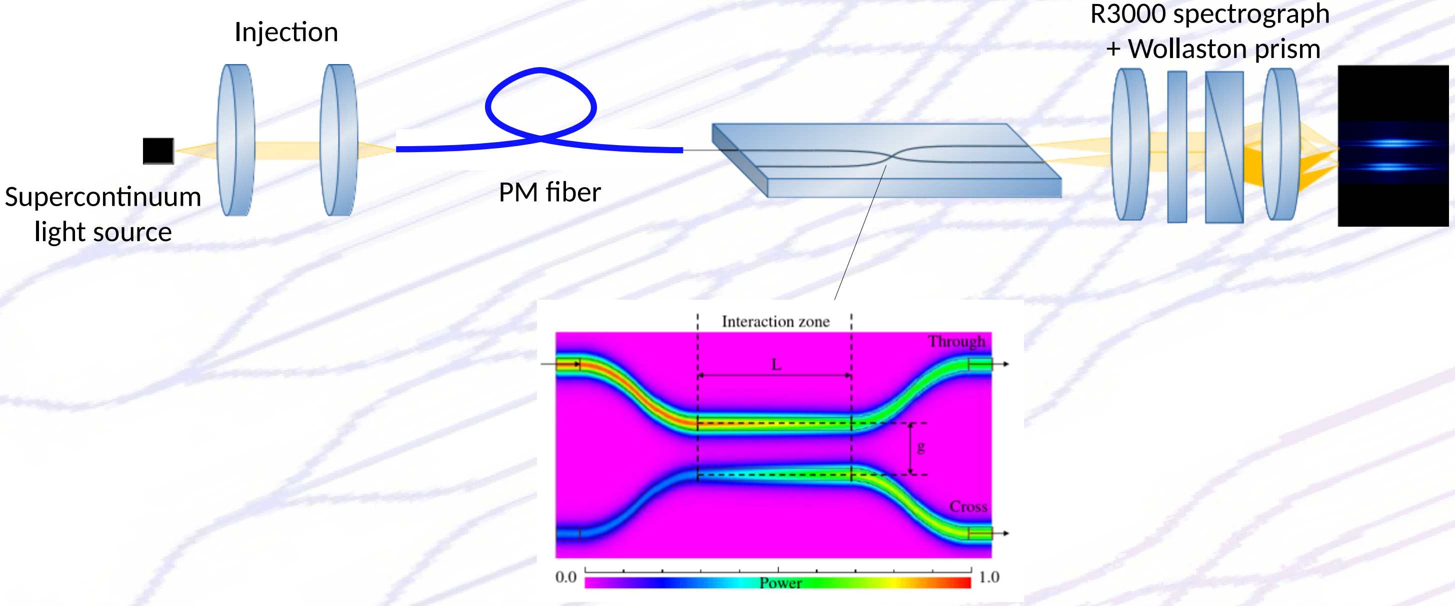
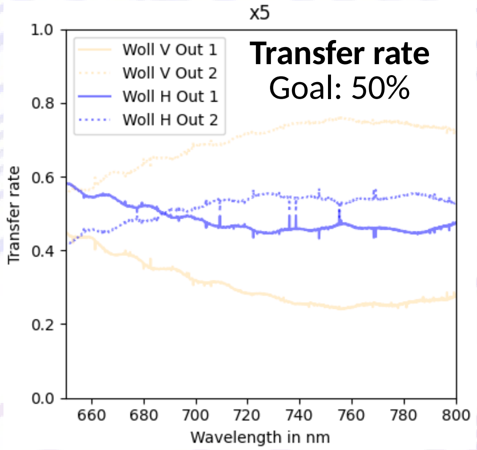
Low refractive index contrast

Polarization study



Lallement et al. (in prep)



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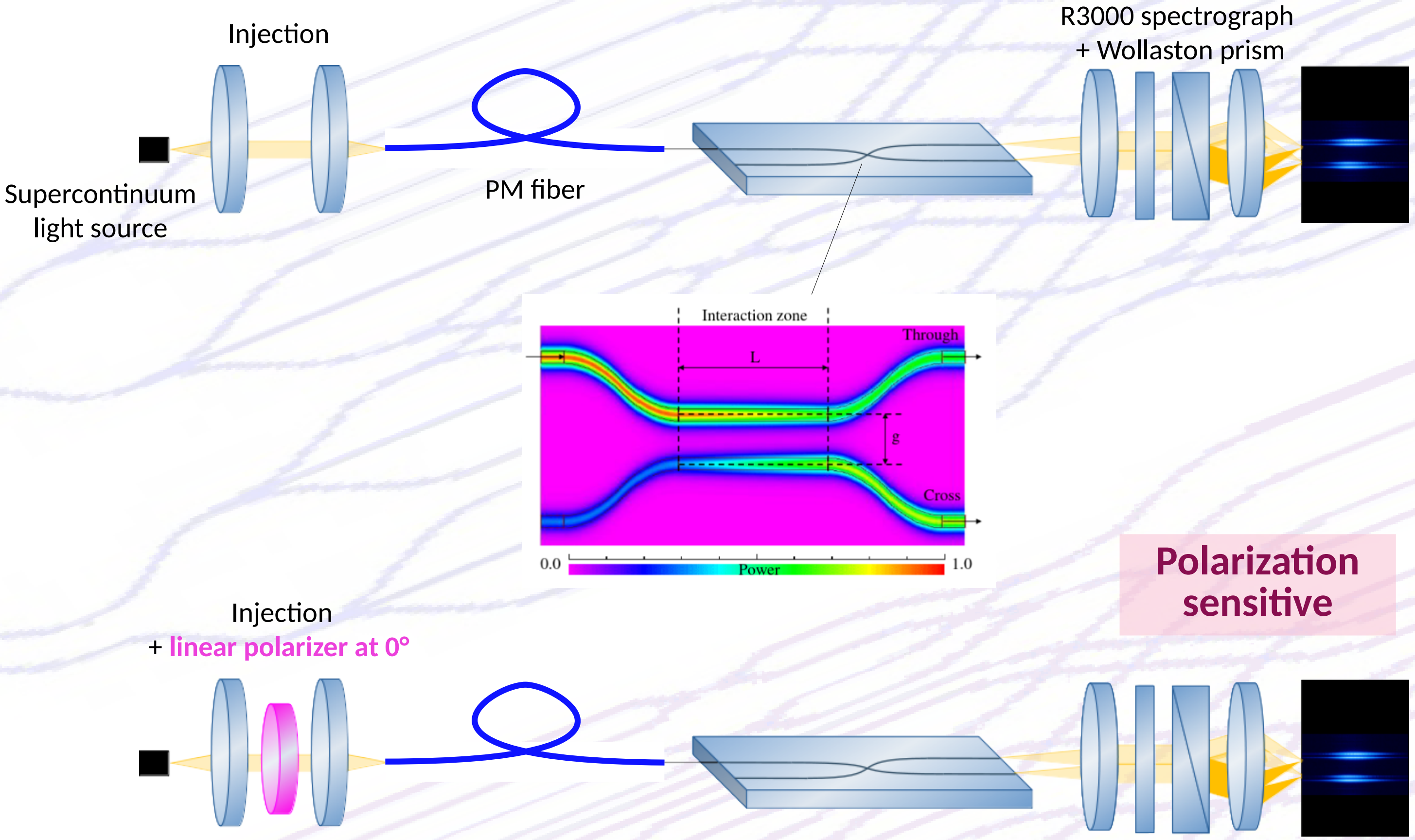
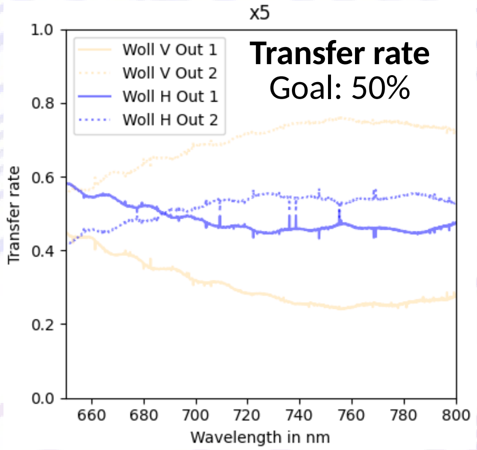
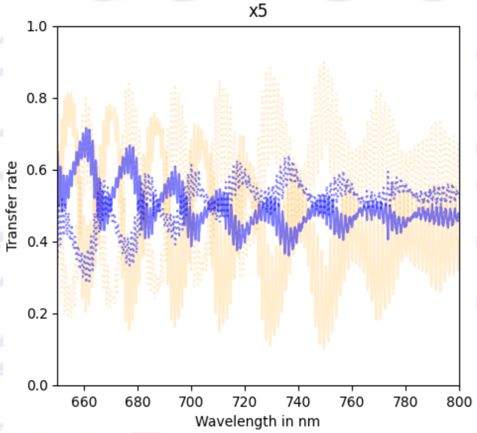
Low refractive index contrast

Polarization study

Lallement et al. (in prep)





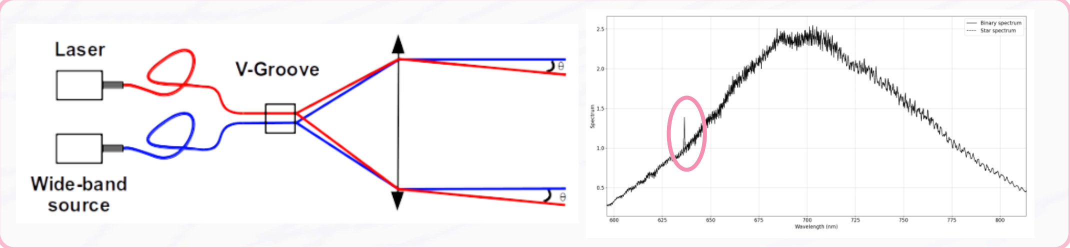


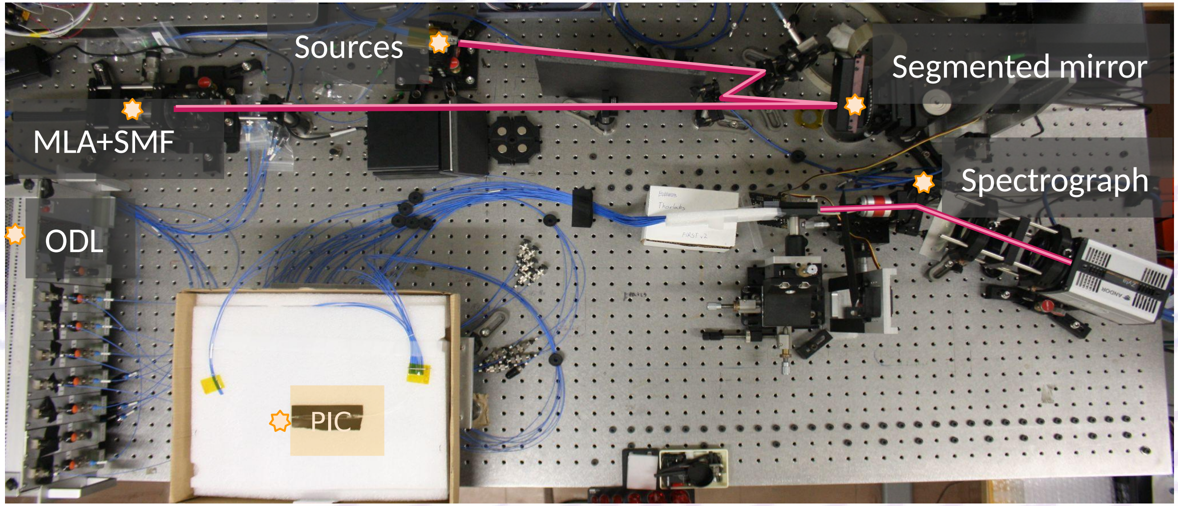
Polarization sensitive

Low refractive index contrast
TEEM Photonics

- Laboratory characterization with a **binary simulator** (K. Barjot's PhD thesis)

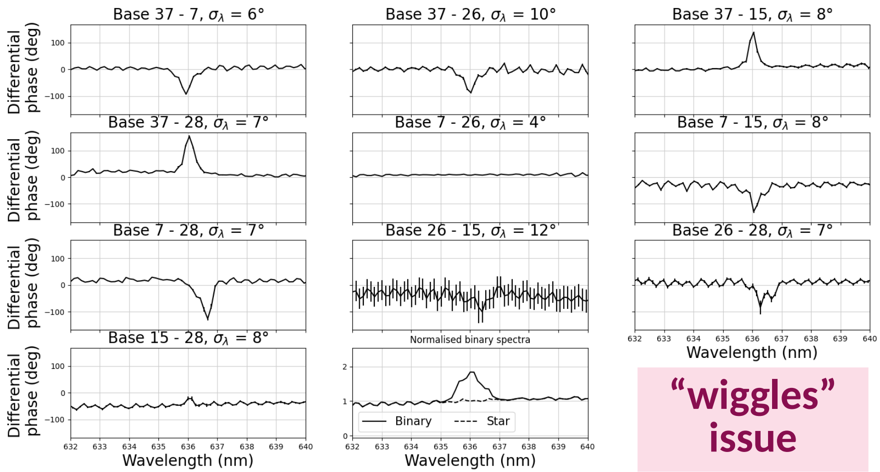
__Star__: supercontinuum light source
__Companion__: LASER @ 635nm





K. Barjot' PhD thesis

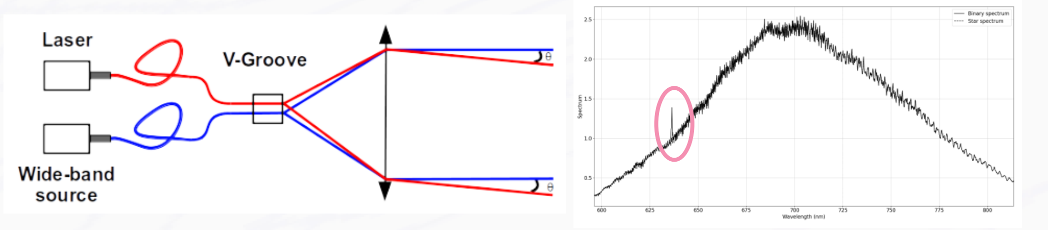
Differential phase measurement



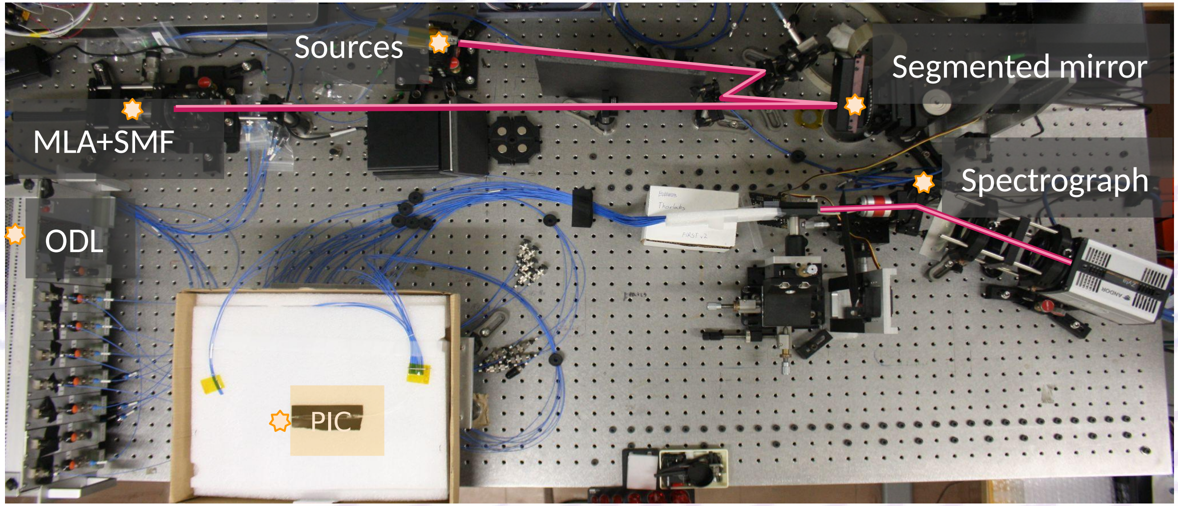
"wiggles" issue

Low refractive index contrast
TEEM Photonics

- Laboratory characterization with a **binary simulator** (K. Barjot's PhD)

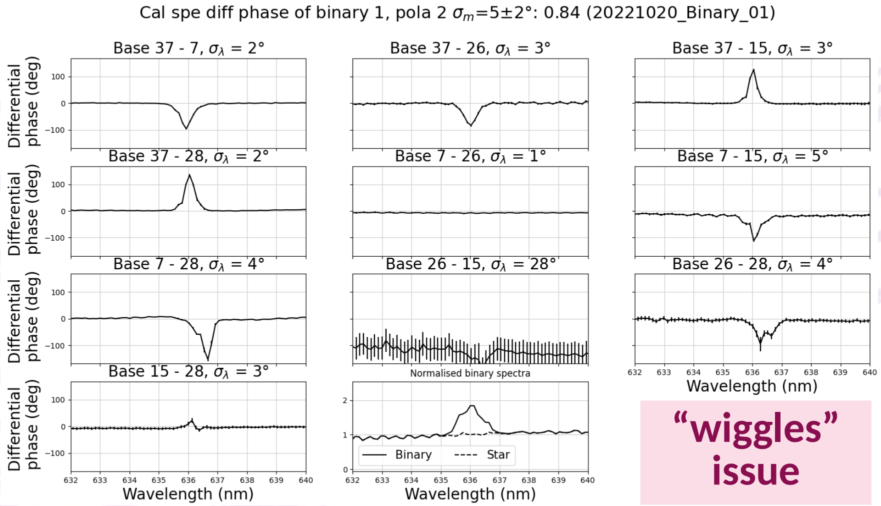


***Star**: supercontinuum light source*
***Companion**: LASER @ 635nm*



K. Barjot' PhD thesis

Differential phase measurement



"wiggles" issue

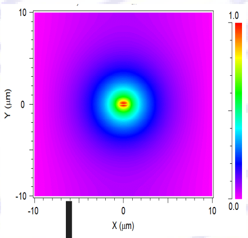
High refractive index contrast
LioniX

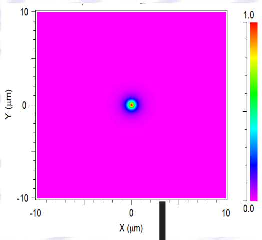
- Design optimization by **Harry-Dean Kenchington Goldsmith**

Insertion loss: tapers required

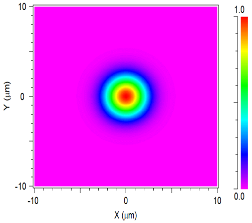
Low confinement TE:TM
MFD = 2.7 µm : 6 µm
Δn_{eff} = 0.002 : 0.008

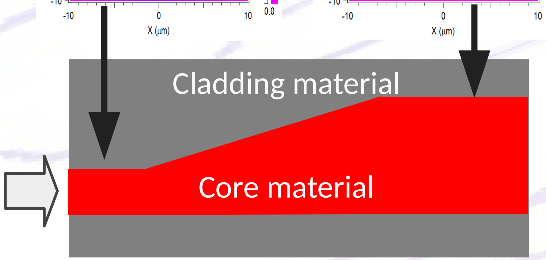
High confinement TE:TM
MFD = 1.2 µm : 1.8 µm
Δn_{eff} = 0.049 : 0.021





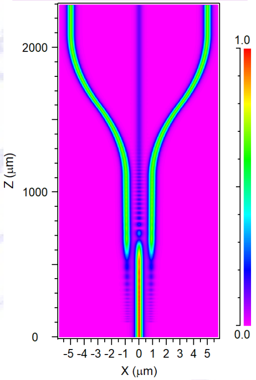
Fibre mode
MFD = 4.5 µm



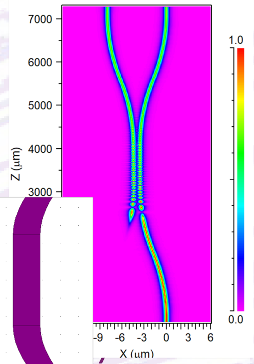


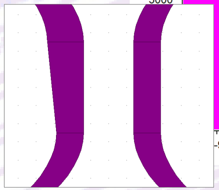
Simulations by H.-D. Kenchington Goldsmith using RSoft FemSIM & BeamPROP

Splitter

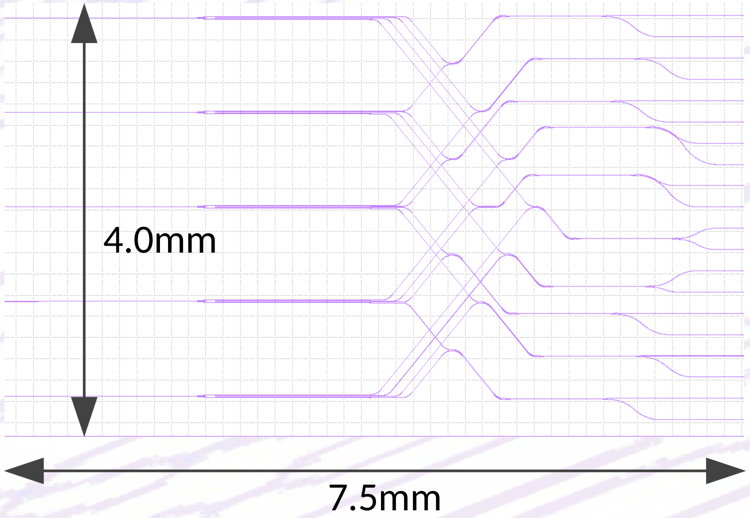


Coupler





5T design

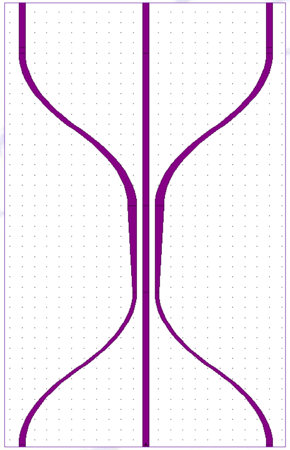


Technology: TripleX
Single-mode spectral range: ~600 nm - 850 nm
Propagation loss: 0.1 to 0.5 dB/cm
Insertion loss (SM630) : 3 dB (50% coupling)

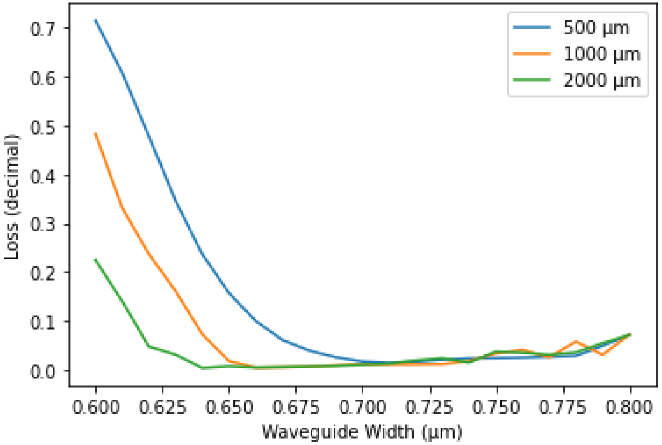
High refractive index contrast
LioniX

- Design optimization by **Harry-Dean Kenchington Goldsmith**

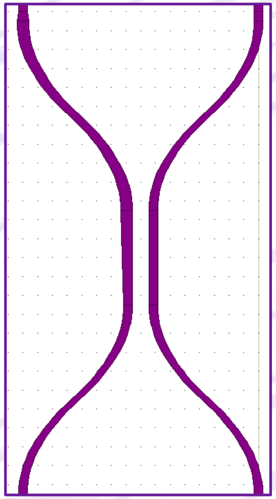
Tricoupler design (splitter)	**Tapered coupler design**

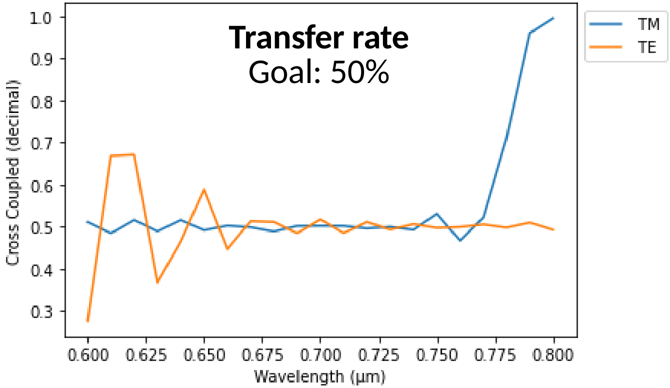


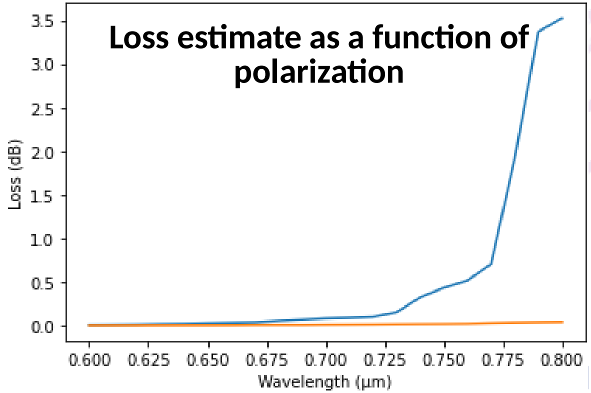
Loss estimate (output in the center wg)
Changing the interaction length



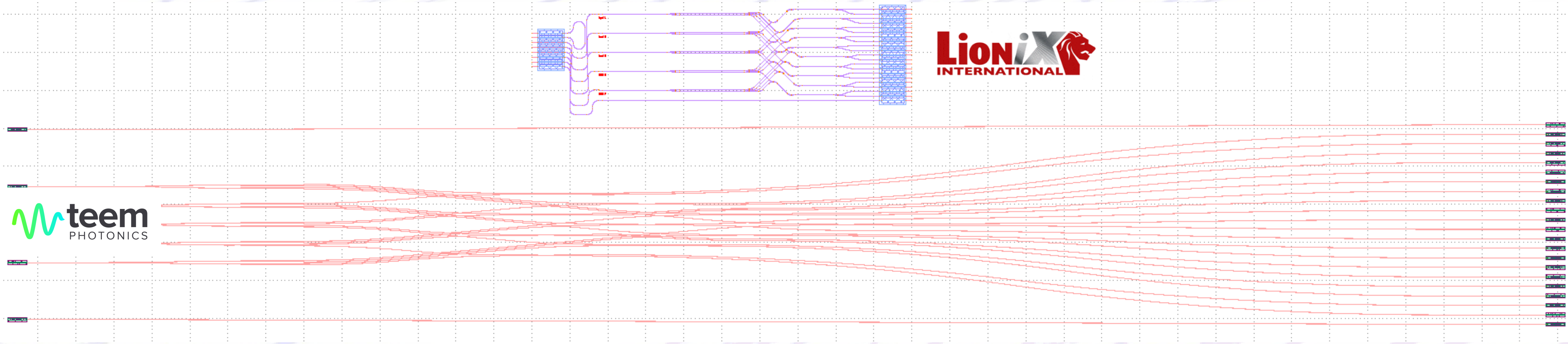
→ Equal splitting by design and low loss







Low vs **high** refractive index contrast



Low index contrast
Good fiber coupling
High bend radius
→ large chip

High index contrast
Bad fiber coupling
Low bend radius
→ compact & complex chip

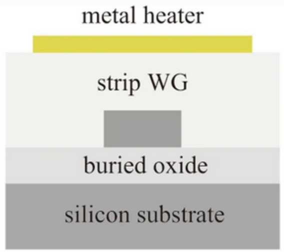
Photonic developments for the visible

Low index contrast

High index contrast

Printed microlenses

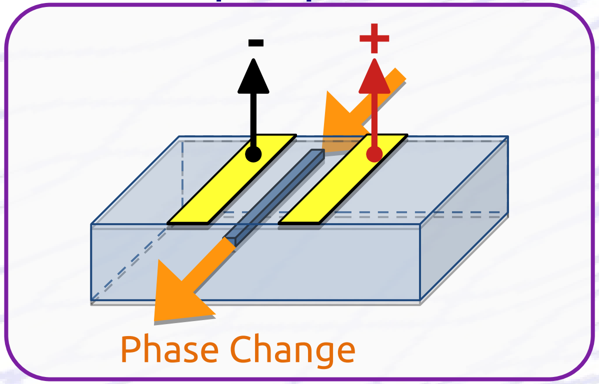
Active phase shifters



3D-chips

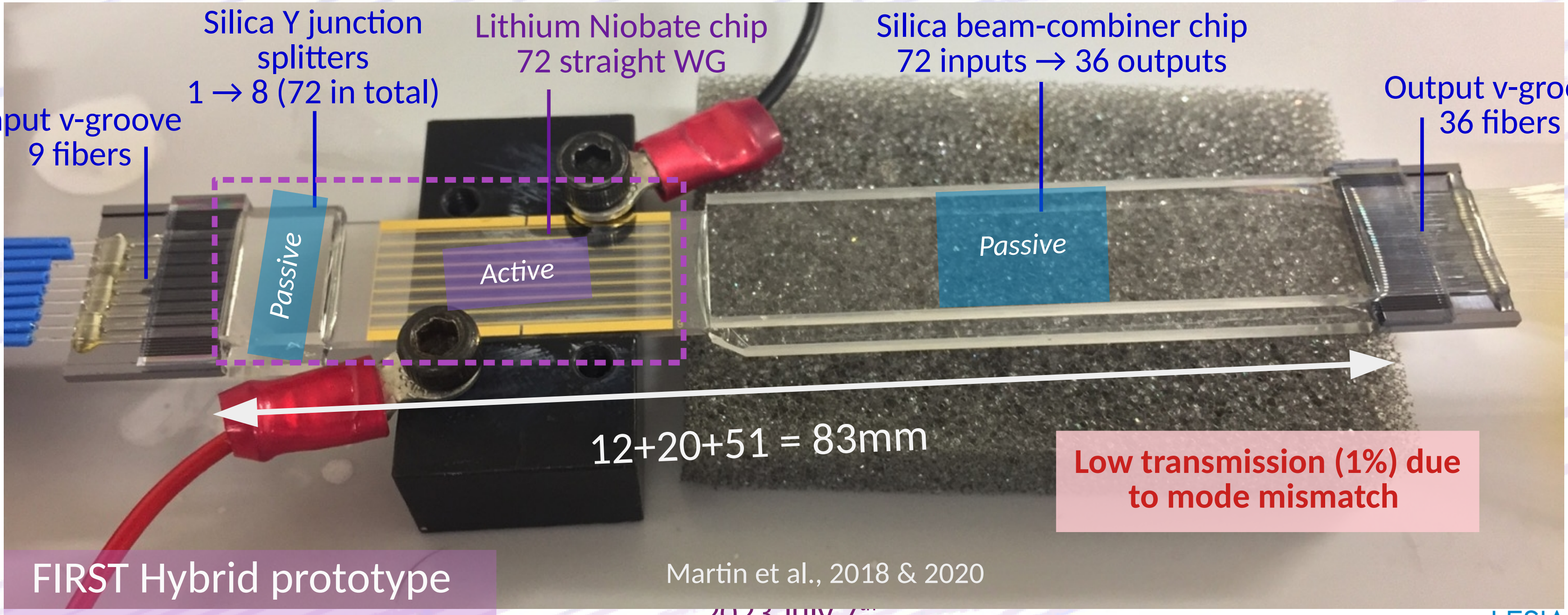
Photonic lantern

Electro-optic phase shifter



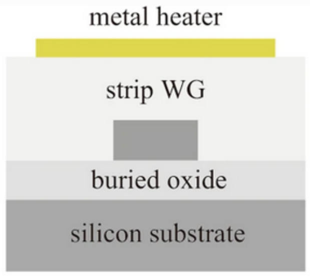
- **Electro-optic material:**
  Lithium Niobate Crystal – LiNbO2.
  Voltage changes the effective refractive index

Low transmission (1%) due to mode mismatch



Thermo-optic phase shifter

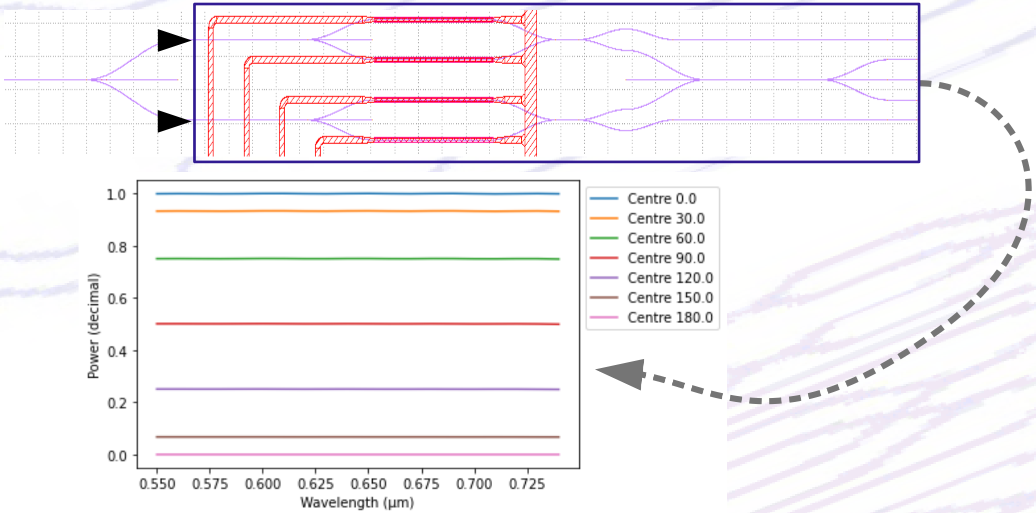
- **Metal heater** above the waveguide to change the refractive index



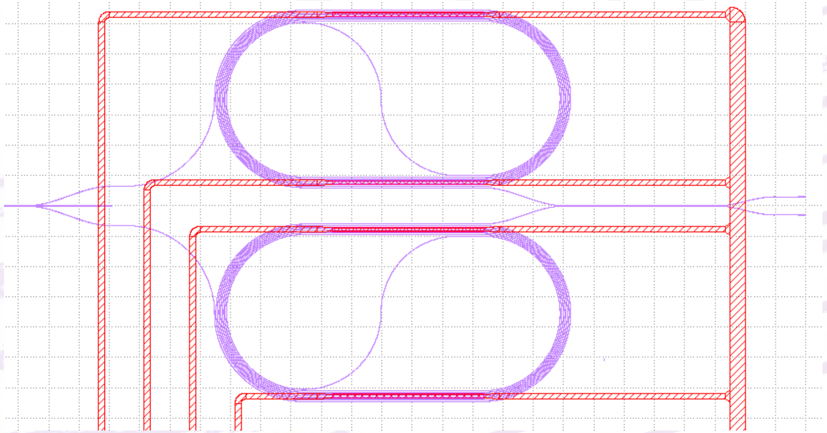
Liu et al., 2022

Chip prototype will be manufactured by October 2023

Nuller design proposed by H.D. Kenchington Goldsmith



On-chip ODL proposed by H.D. Kenchington Goldsmith



Photonic developments for the visible

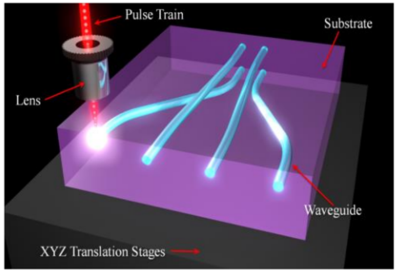
Low index contrast

High index contrast

Printed microlenses

Active phase shifters

3D-chips



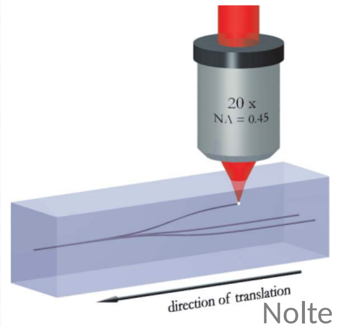
Photonic lantern

2023 July 7th

LESIA l'Observatoire de Paris | PSL

Laser writing: enabling 3D design

- **Ultra-short laser pulses** focused inside the substrate
→ non linear absorption
Collab. C. D'Amico, R. Stoian (Laboratoire Hubert Curien)

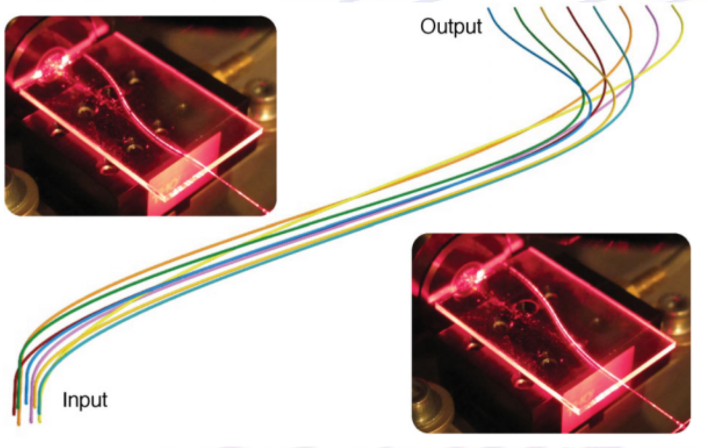


Nolte et al. 2003

5T-3D chip characterization on interferometric bench in Meudon's lab

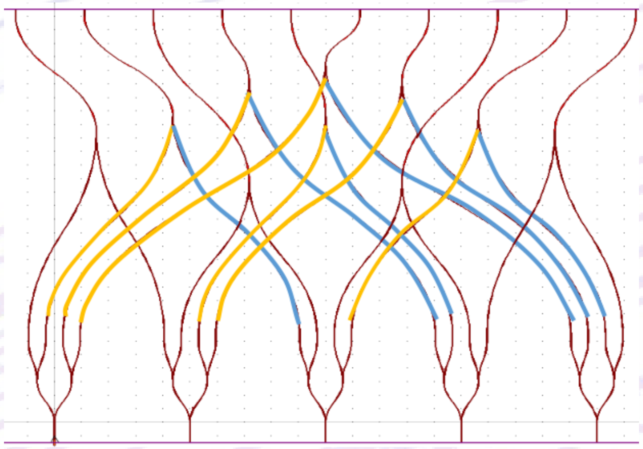
Data analysis in progress

Dragonfly 3D pupil remapper (IR)
2D array → 1D array

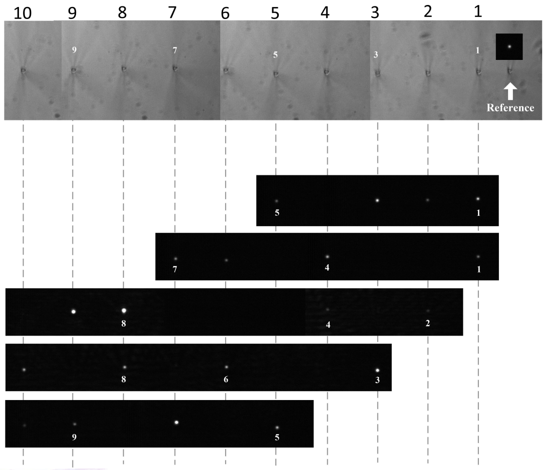


Jovanovic et al. 2012

FIRST 3D 5-beam combiner (visible)
1D array → 1D array
No in-plane guide crossing



Martin et al. 2022



Photonic developments for the visible

Low index contrast

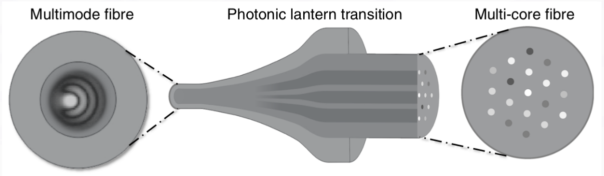
High index contrast

Printed microlenses

Active phase shifters

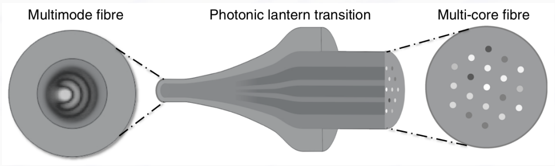
3D-chips

Photonic lantern



Photonic lantern

- Visible photonic lantern: **another way to sample the wavefront**
  Collab. **S. Leon-Saval**, **C. Betters** (University of Sydney)
- Wavefront sensing demo



Norris et al. 2020

Increased throughput

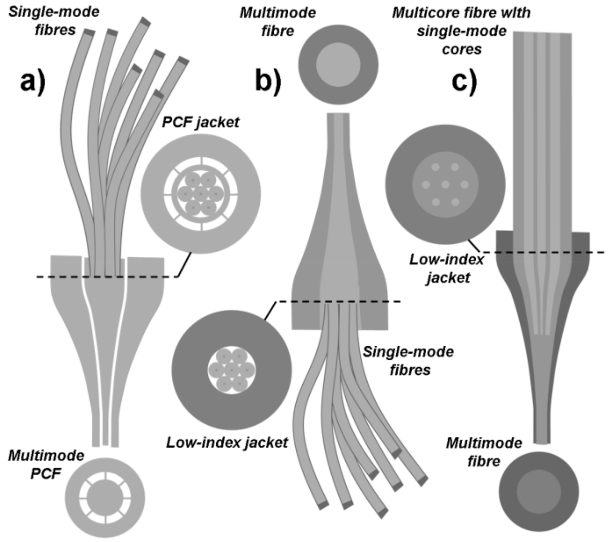
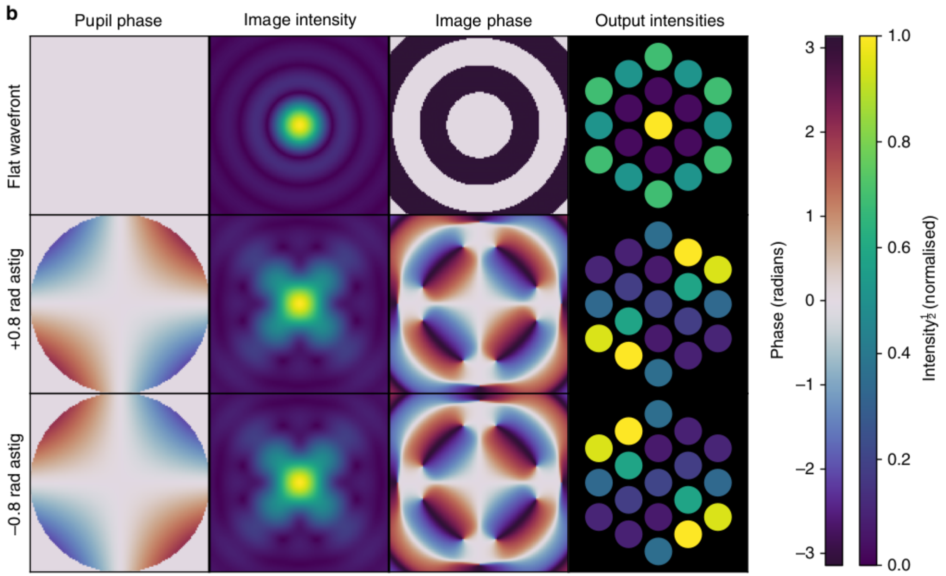


Fig. 1. Schematic representation of the three different approaches for the fabrication of Photonic lanterns; a) PCF technique; b) Standard single-mode fibre combiner/splitter technique; and c) Multicore fibre approach.

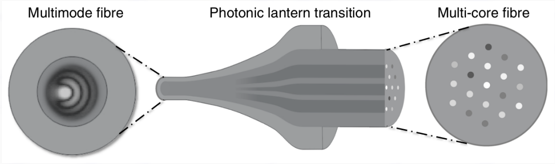
Leon-Saval et al. 2010



Norris et al. 2020

Photonic lantern

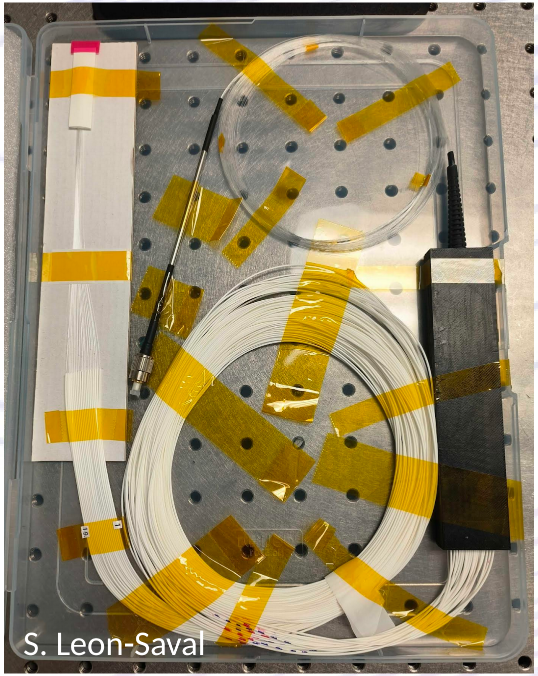
- Visible photonic lantern: **another way to sample the wavefront**
Collab. **S. Leon-Saval**, **C. Betters** (University of Sydney)

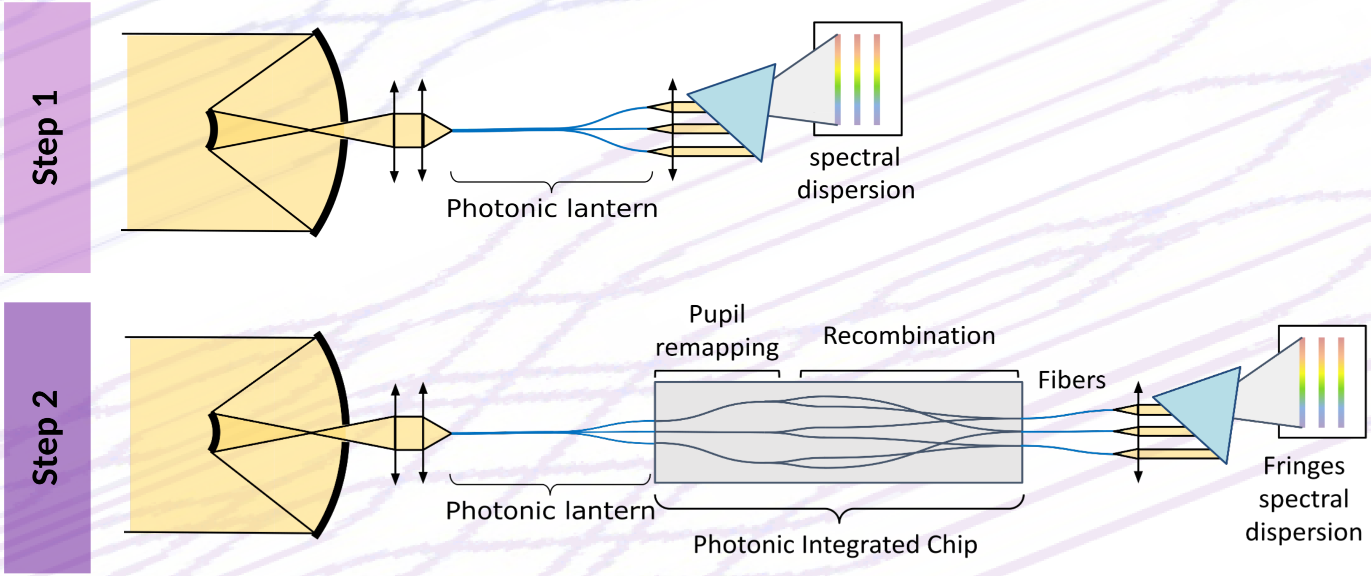


Norris et al. 2020

Increased throughput

Visible Photonic lantern (19 SMF) soon to be integrated and tested with FIRST spectrometer (at Subaru)



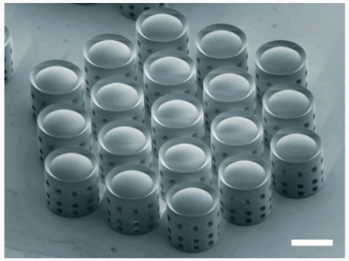


Photonic developments for the visible

Low index contrast

High index contrast

Printed microlenses



Active phase shifters

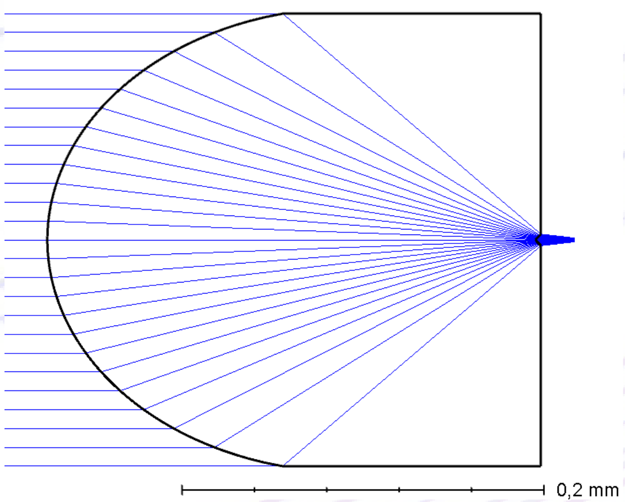
3D-chips

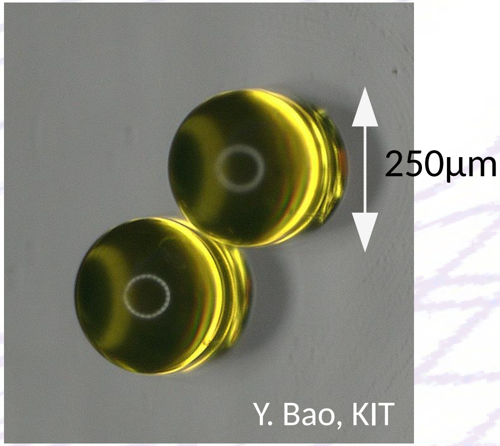
Photonic lantern

3D-printed microlens array

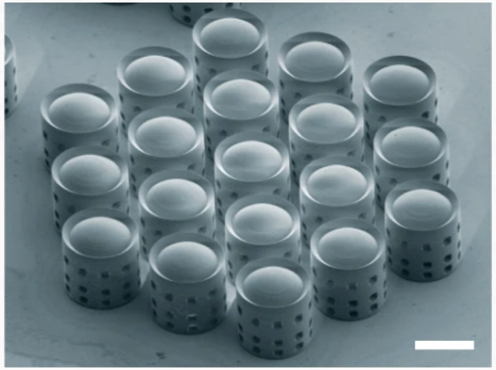
- Optimization of the coupling into the single mode fibers
  Collab. **R. Harris** at MPIA, now at Durham University, and
  Y. Bao at Karlsruhe Institute of Technology

Optical design by Manon Lallement

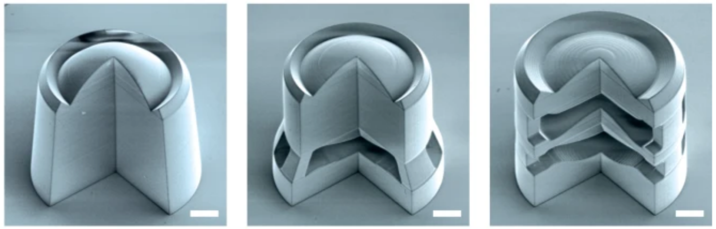




Two-photon direct laser writing of ultracompact multi-lens objectives, Gissibl et al. 2016

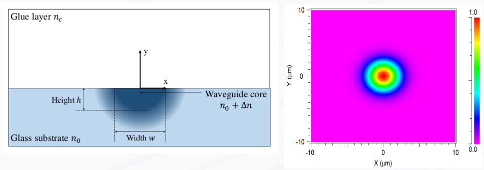


Scale bars, 20 µm.

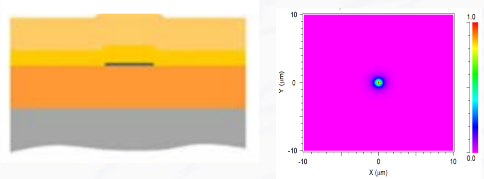


Photonic developments for the visible…

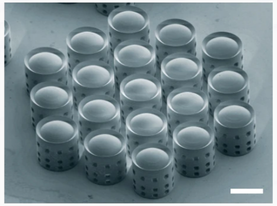
Low index contrast



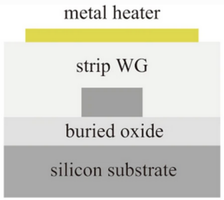
High index contrast



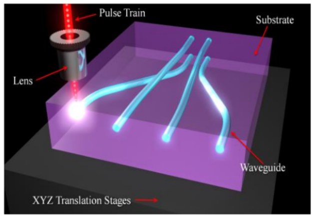
Printed microlenses



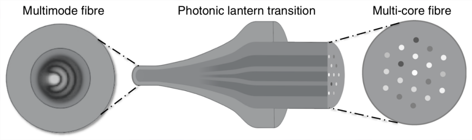
Active phase shifters



3D-chips



Photonic lantern



Visible Photonic devices under development for FIRST:

- Increased **throughput**
- Better control of their **polarization** behavior
- Less **chromaticity**
- New **functionalities** (active functions, photonic lantern)

… to be continued!

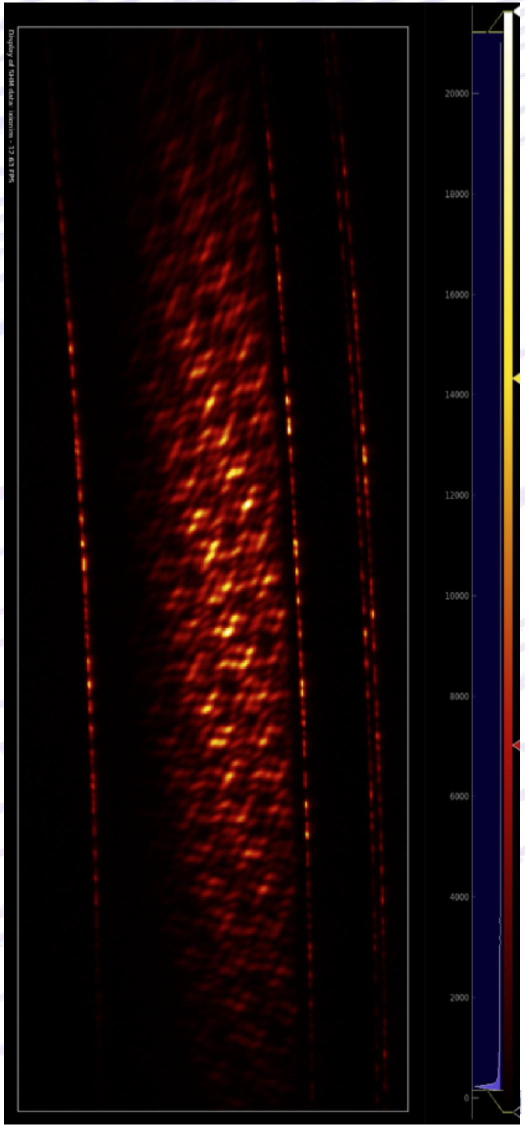
Thank you!

What's next for **FIRST**

- **Wavefront sensing**
  - Measurement of the complex coherence
    → complex visibility
    → incoherent fluxes
    → differential phase between sub-apertures

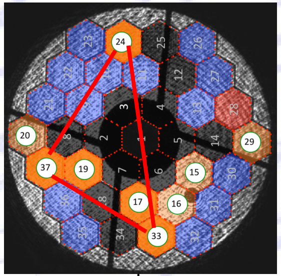
    $$\mu_{ij} = V_{ij} e^{i \Psi_{ij}} \quad A_i A_j \quad e^{i \Delta \phi_{ij}}$$

    → Wavefront sensing!
  - Sense aberration modes related to the segmented nature of the aperture: "Petal modes", island effects
  - In FIRST:
    - Spectrally dispersed fringes: measurement of the path length difference
    - Injection of internal laser sources to disentangle the phase variations due to the AO residuals

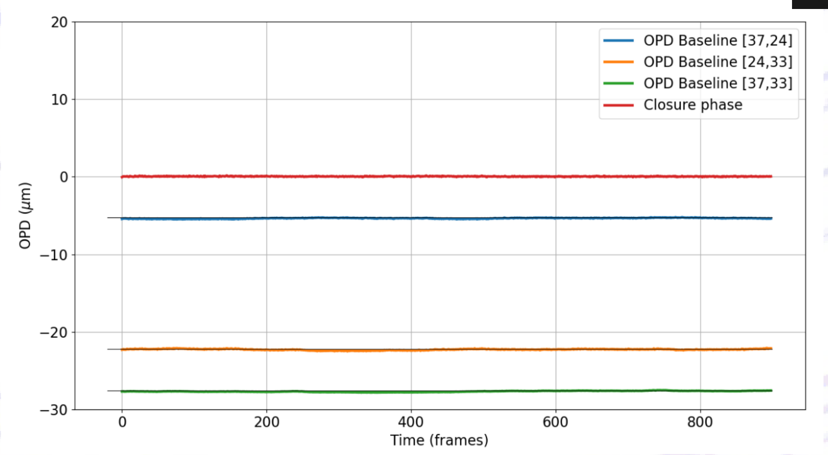


What’s next for **FIRST**

Laboratory testing with internal source

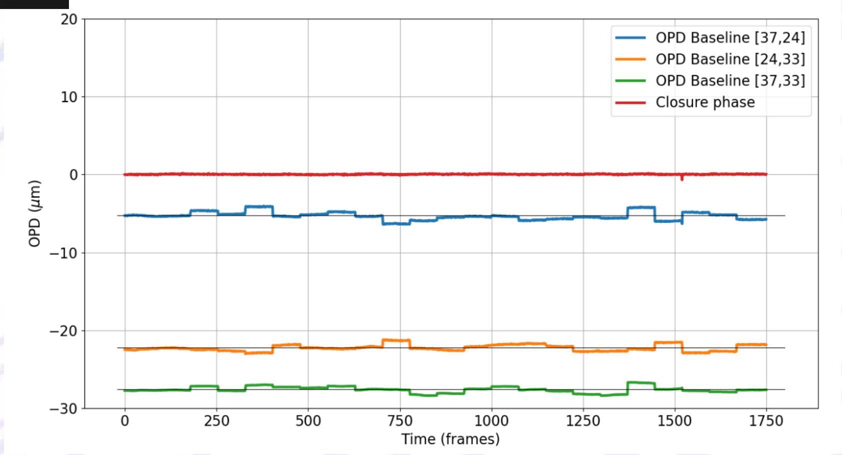


Case 1 : no perturbation on the SCExAO DM



- Large static OPD
- Few microns of perturbation due to fiber instabilities

Case 2 : Petal modes applied on the SCExAO DM



- Confirm sensitivity to petalling modes
- Analysis in progress…

Work of Sébastien Vievard

Why taking a PIC?
Photonic Integrated Circuit

- How is a PIC manufactured?
  - Ion exchange or diffusion
  - Ion etching
  - Laser writing

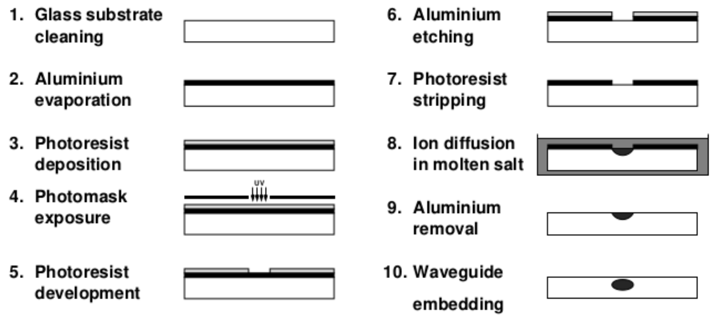


Fig. 4. Waveguide manufacture by ion exchange technique (Schanen-Duport et al. 1996).

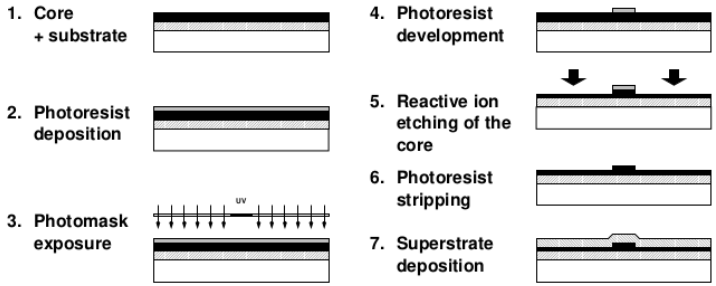


Fig. 5. Waveguide manufacture by etching technique (Mottier 1996).

Malbet et al. 1999

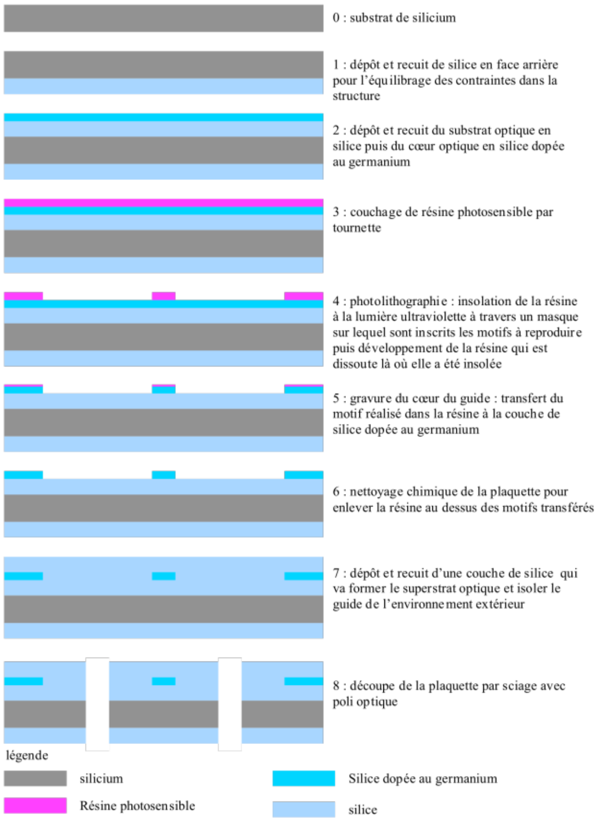
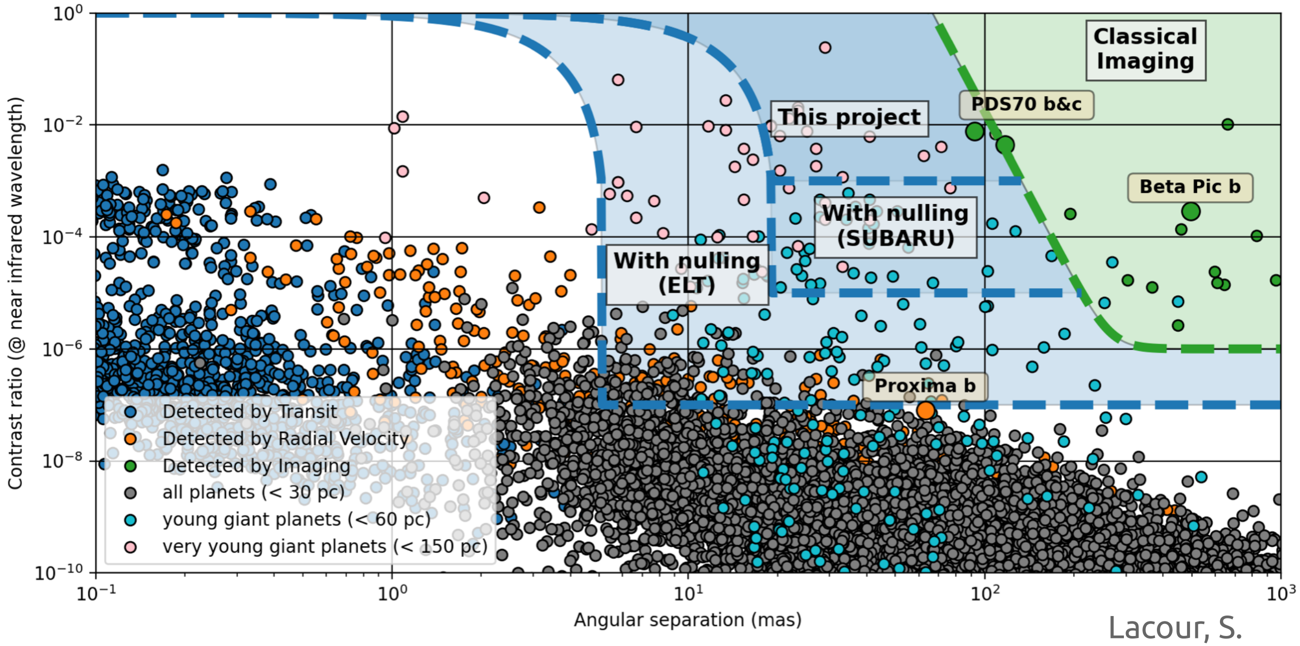


Figure III-1 : empilement technologique de réalisation des guides d'onde optique en silice sur substrat de silicium.

Labeye PhD, 2008

Conclusions & prospects

- **Integrated instrument for an ELT:**
  - some kind of nulling interferometer with tens of apertures
  - angular resolution < 4mas in the visible
  - providing wavefront sensing capability
  - including on-chip phase modulation
  - centimeter-size
  - stable
  - with little alignment



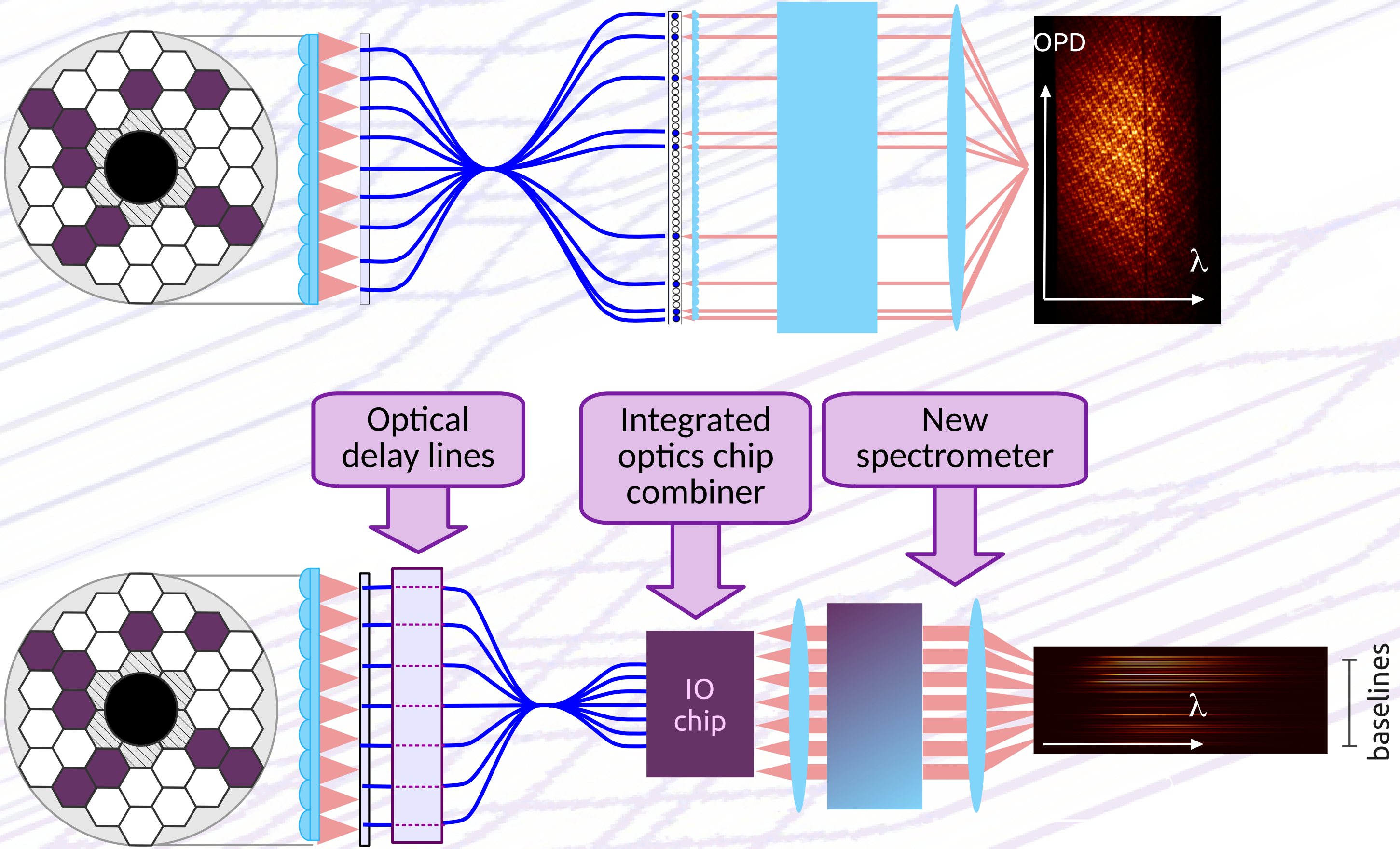
Lacour, S.

The move to photonics

- **Contrast** performance is directly proportional to the **error on the interferometric observables**:

$$\text{Dynamic range} \propto \frac{\sqrt{n}}{\sigma}$$

- Current limitations:
  ~1deg error on the phase
  → achievable **contrast of ~10**
- We want to improve our sensitivity **by a factor >10 in contrast**



- Stability to mechanical and temperature variations
- Flux concentration
- Possible densification
- Active phase control

FIRSTv2 in practice

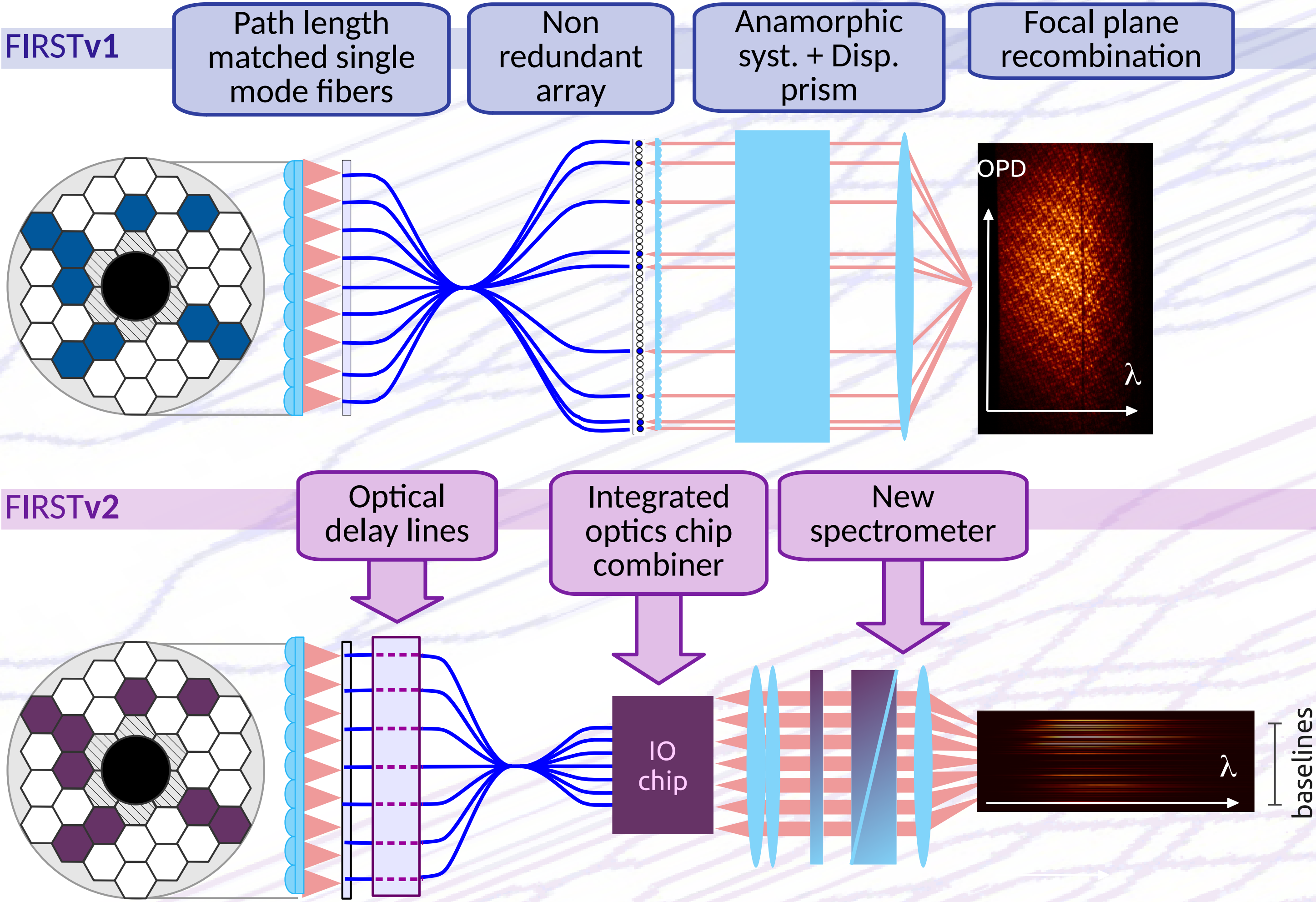
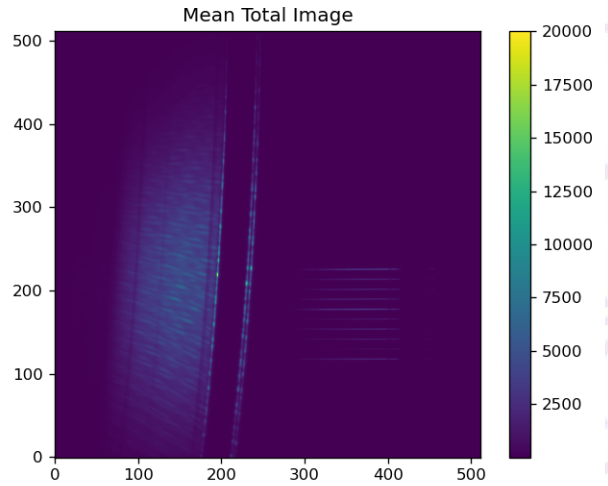


Image with FIRSTv1 and FIRSTv2 running in parallel



FIRSTv2 in practice

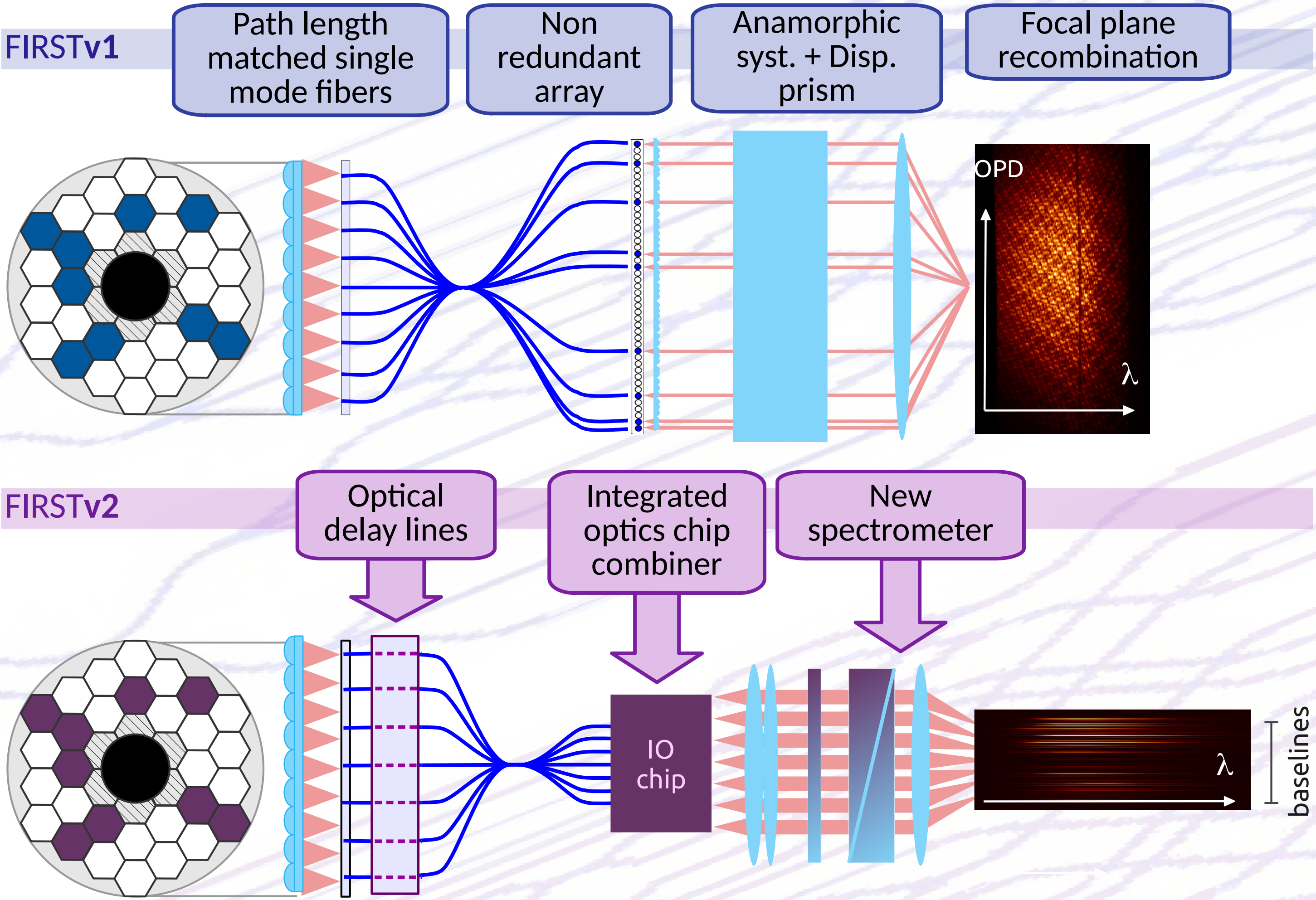
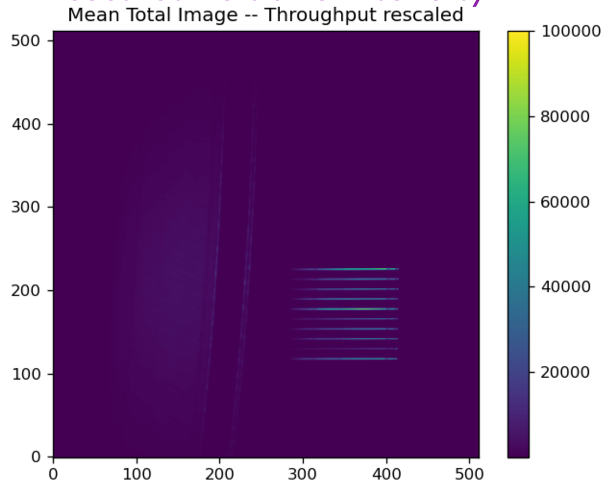
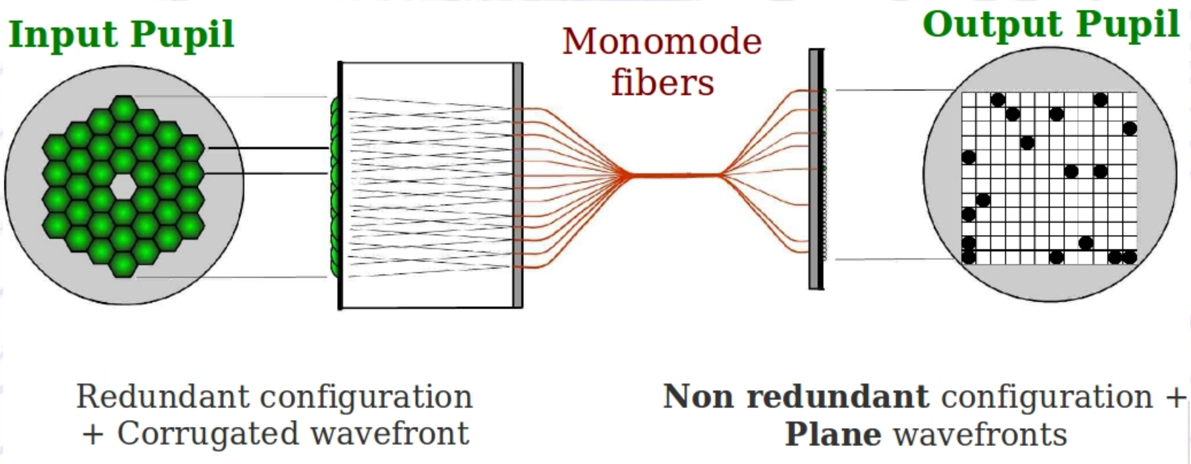


Image with FIRSTv1 and FIRSTv2 running in parallel

Rescaled relative intensity



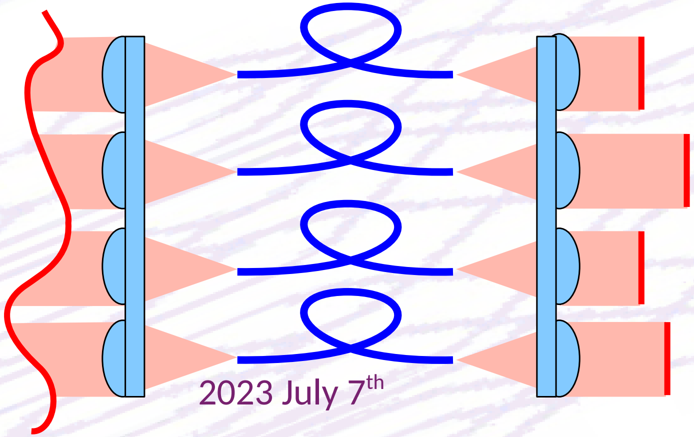
Interferometric techniques on monolithic telescopes
Pupil remapping



Perrin et al. 2006
Lacour et al. 2007
Kotani et al. 2009

Single-mode fibers: **spatial filtering of the wavefront**

Wavefront with aberrations

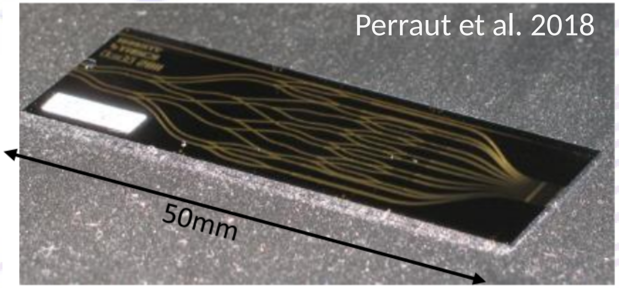


- Coherent wavefronts across the sub-pupil areas
- Differential phase terms remain (piston)

Why taking a PIC?
Photonic Integrated Circuit

- What is a PIC?
  - Analogue to an electronic integrated circuit for photons instead of electrons

  - Waveguides are created within a piece of glass (silicon)



- How is a PIC manufactured?
  - Ion exchange or diffusion
  - Ion etching
  - Laser writing

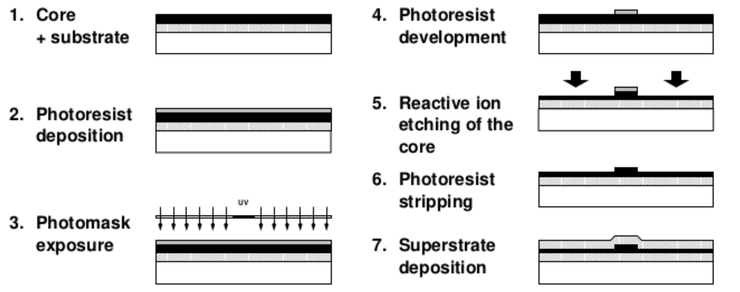


Fig. 5. Waveguide manufacture by etching technique (Mottier 1996).

Malbet et al. 1999