Mid-IR SWIFTS : a miniature integrated spectrometer in the L-band

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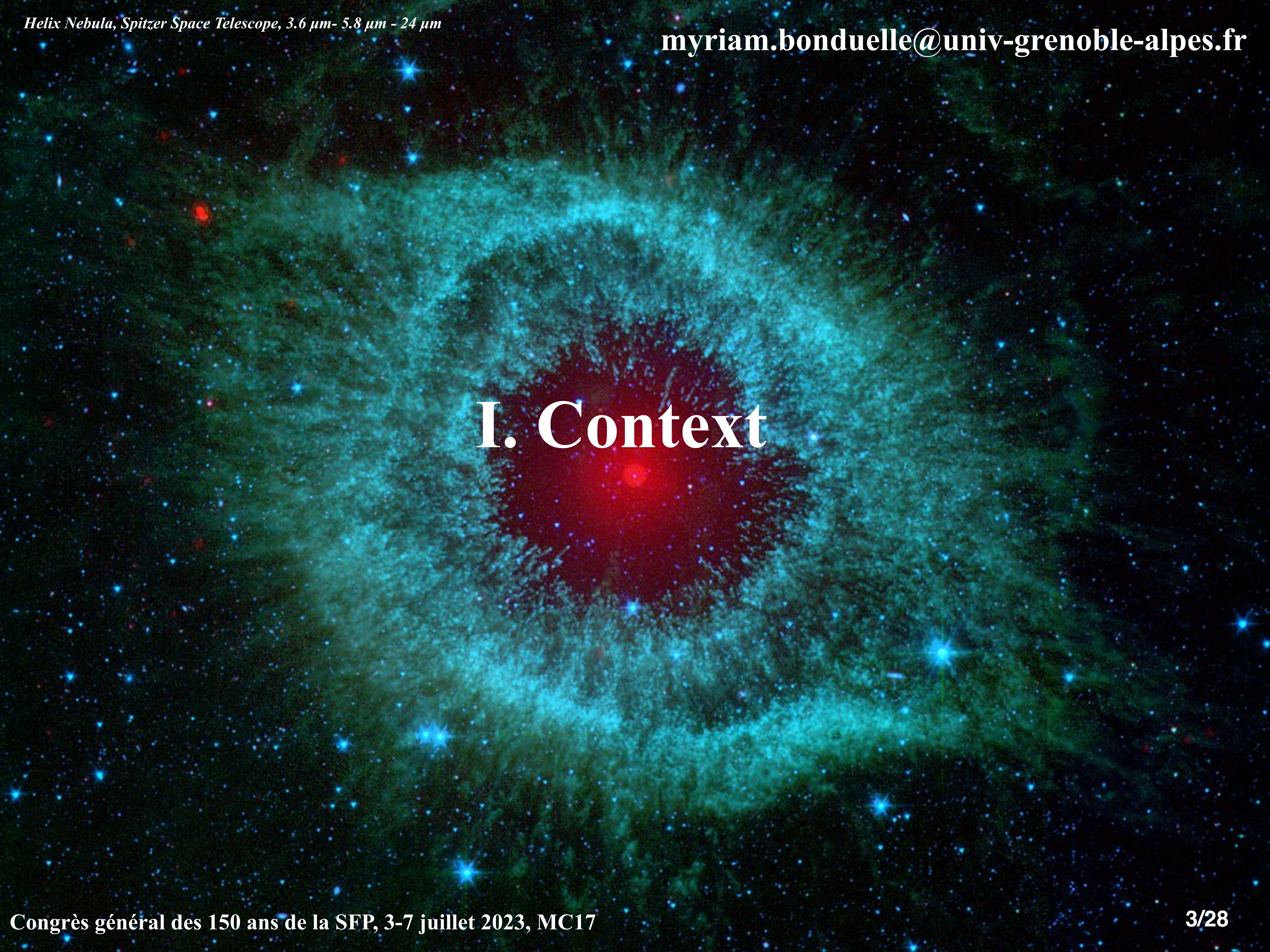
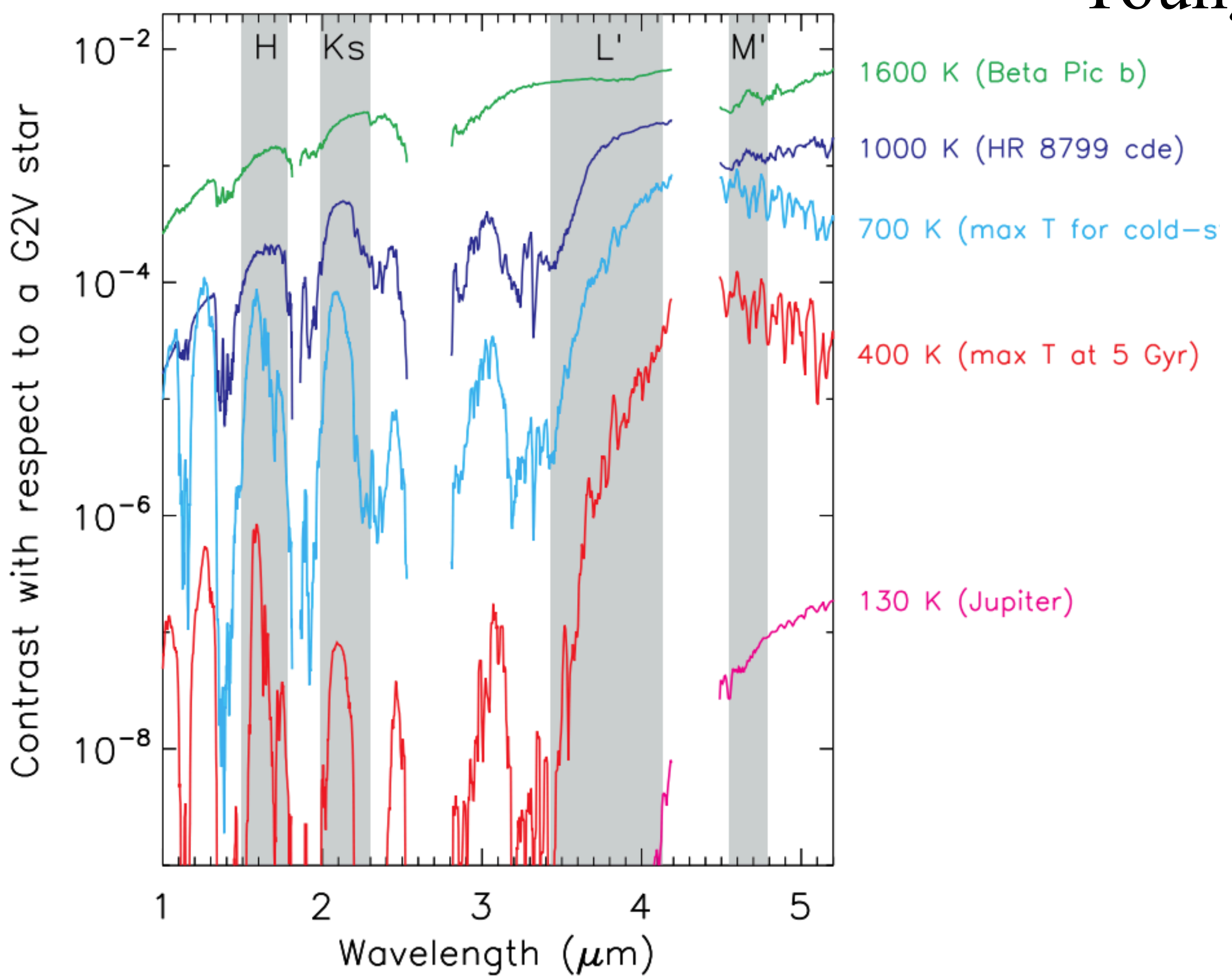


Helix Nebula, Spitzer Space Telescope, 3.6 µm- 5.8 µm - 24 µm

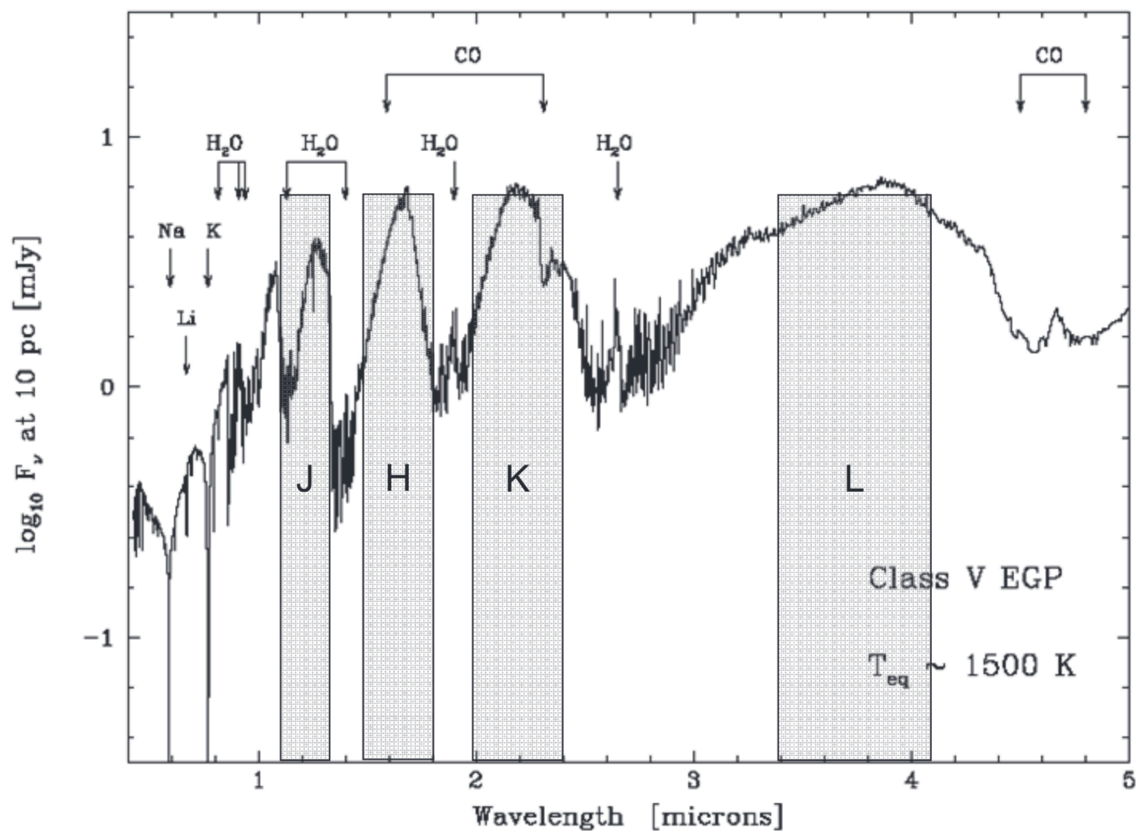
I. Context

L-band (astrophysics) : **3.4 µm to 4.1 µm**

- Dust in exozodiacal disks
- Young exoplanets within the snow line



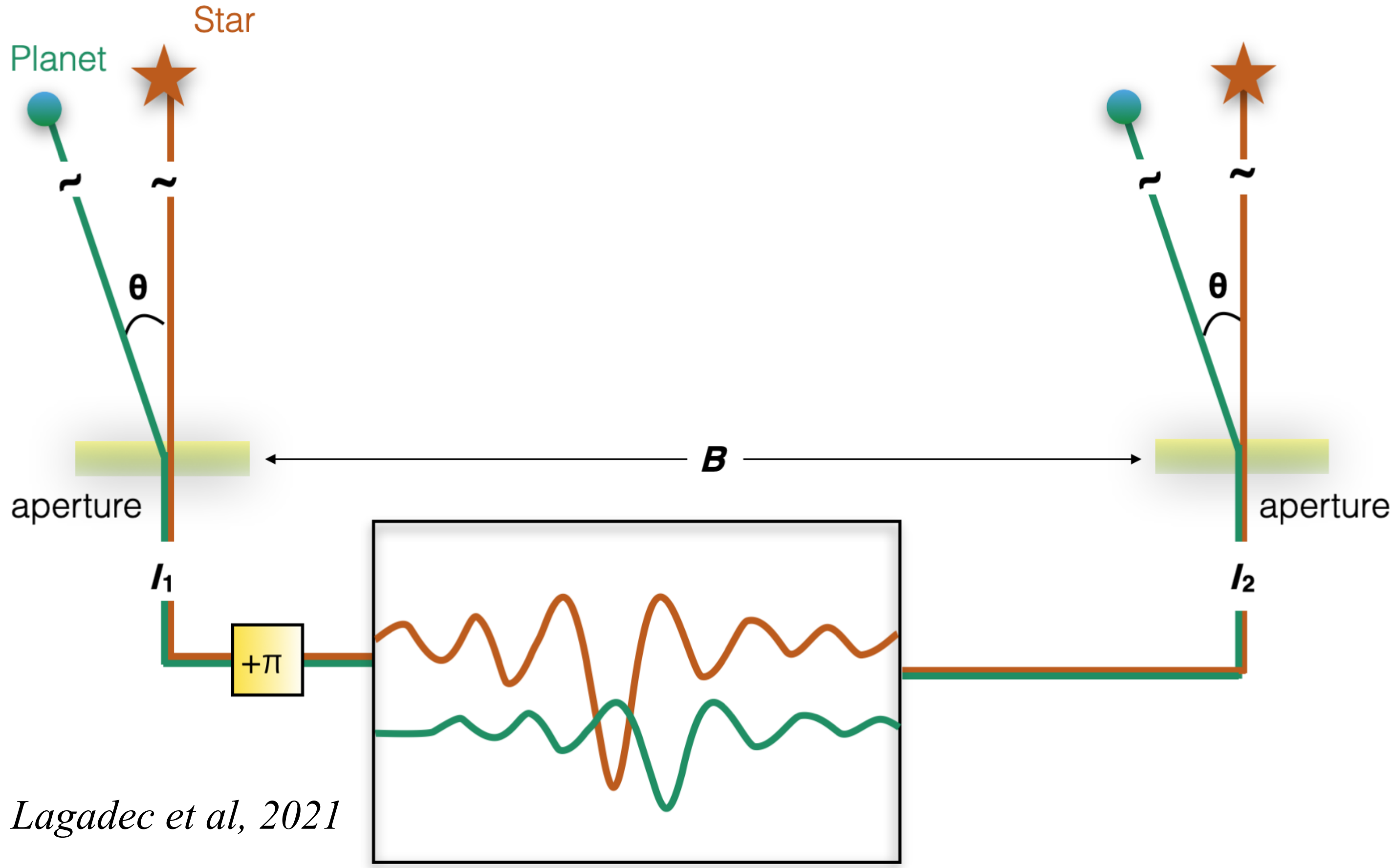
Skemer et al, 2014



Emission spectra of a young hot Jupiter

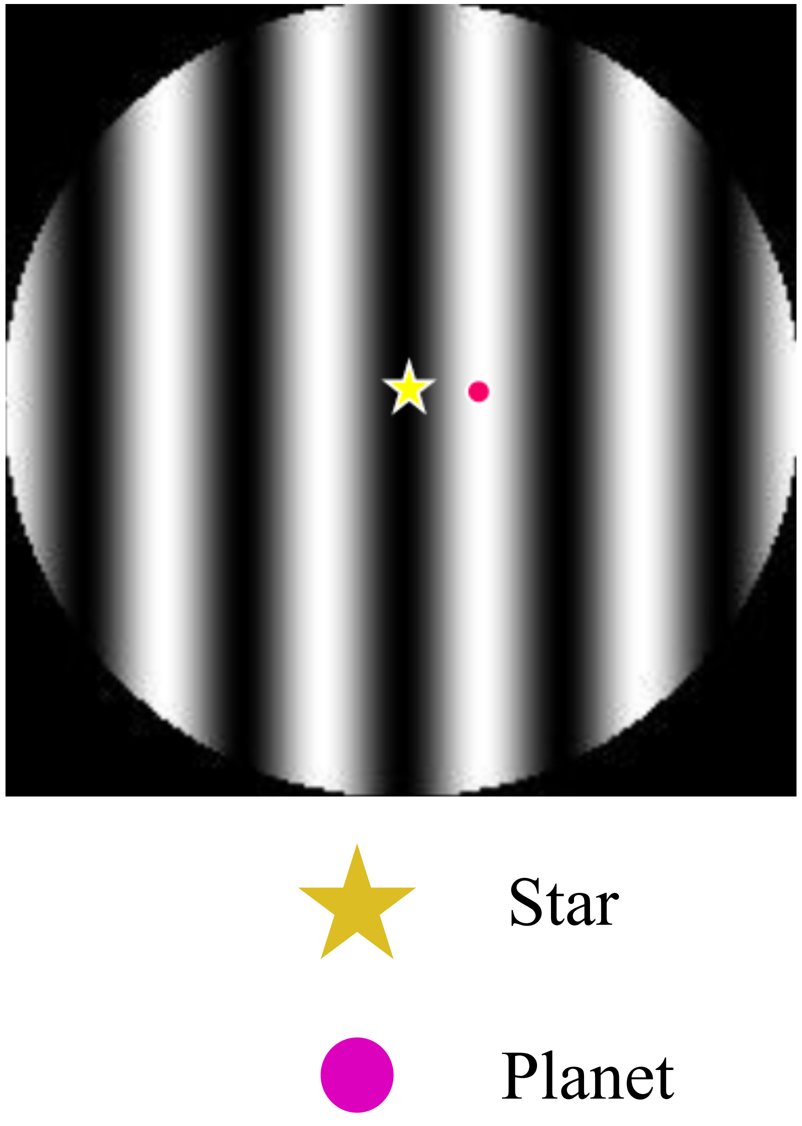
S. Heidmann. Composants actifs en optique intégrée pour l'interférométrie stellaire dans le moyen infrarouge. Optique / photonique. Université de Grenoble, 2013. Français. NNT : 2013GRENT096. tel-01199463v2

I. 1. L-band in astrophysics



T. Lagadec et al, 2021

- **Nulling interferometry : direct detection of exoplanets**

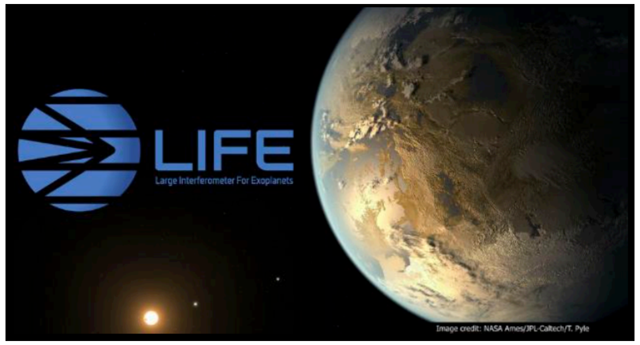


P.I. : D. Defrère (KU Leuven)

ASGARD

HEIMDALLR | Baldr | BIFROST | NOTT

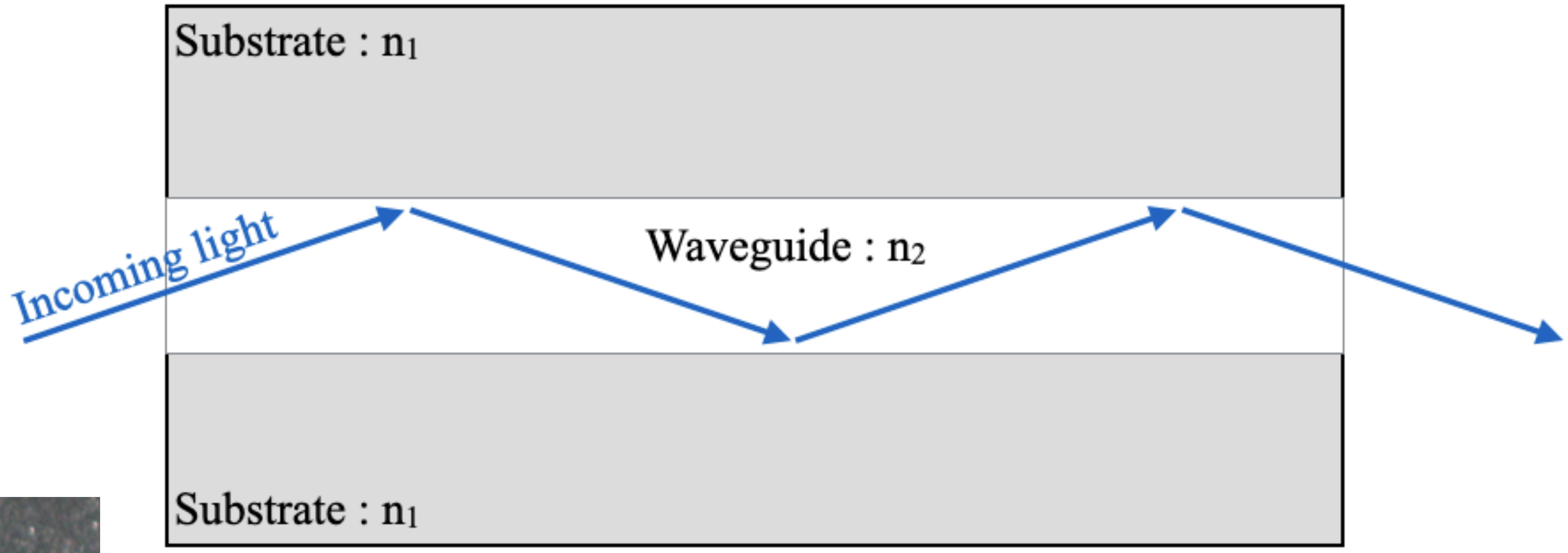
P.I. : S. Quanz (ETH Zurich)



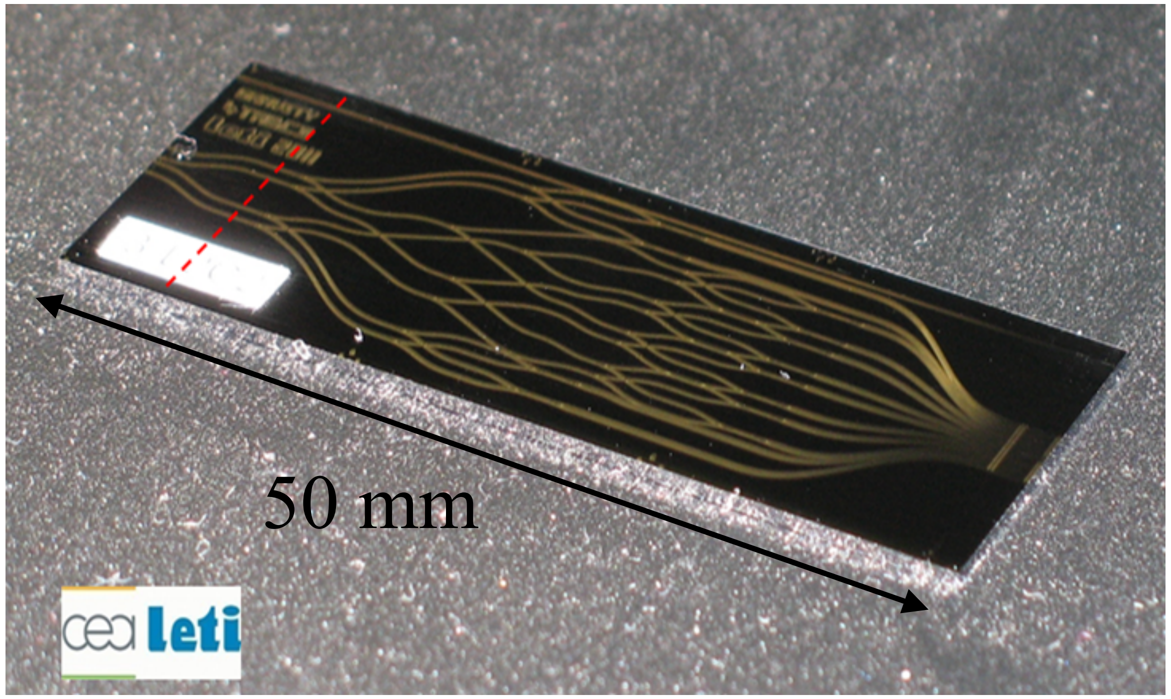
https://life-space-mission.com

• **Waveguide : local change of the refractive index to confine the light**

- Beam splitters
- Directional coupling
- Integrated spectrometers…



$n_1 < n_2$

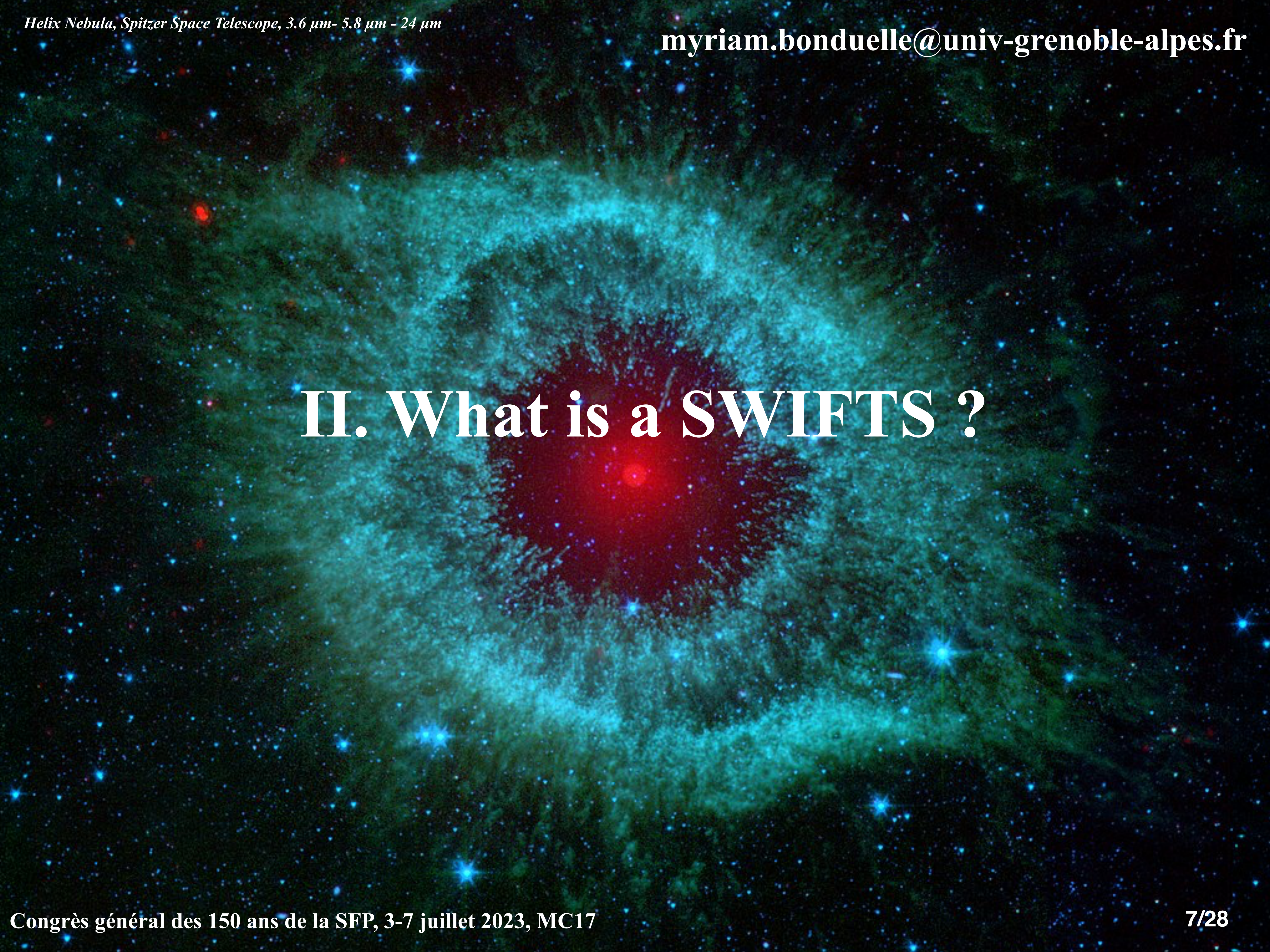


Astrophysical photonic chips :

➡ GRAVITY (4 telescope beam combiner for the VLTI)

➡ Compact, weight reduction…

➡ **<u>Embedded applications</u>** !



Helix Nebula, Spitzer Space Telescope, 3.6 µm- 5.8 µm - 24 µm

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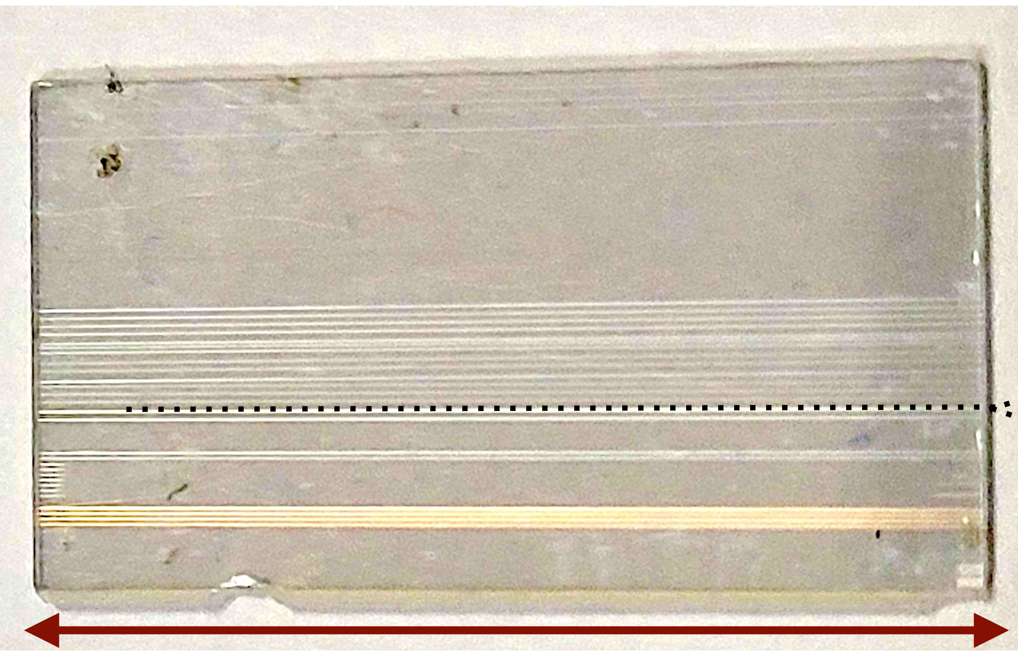
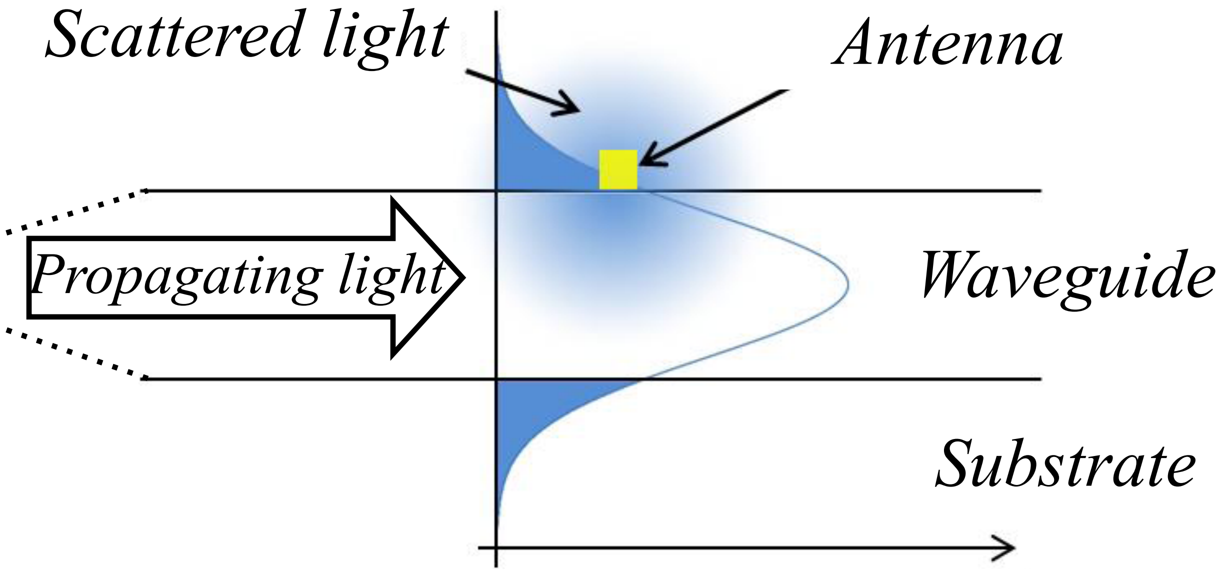
II. What is a SWIFTS ?

- **SWIFTS = Stationary Wave Integrated Fourier Transform Spectrometer**



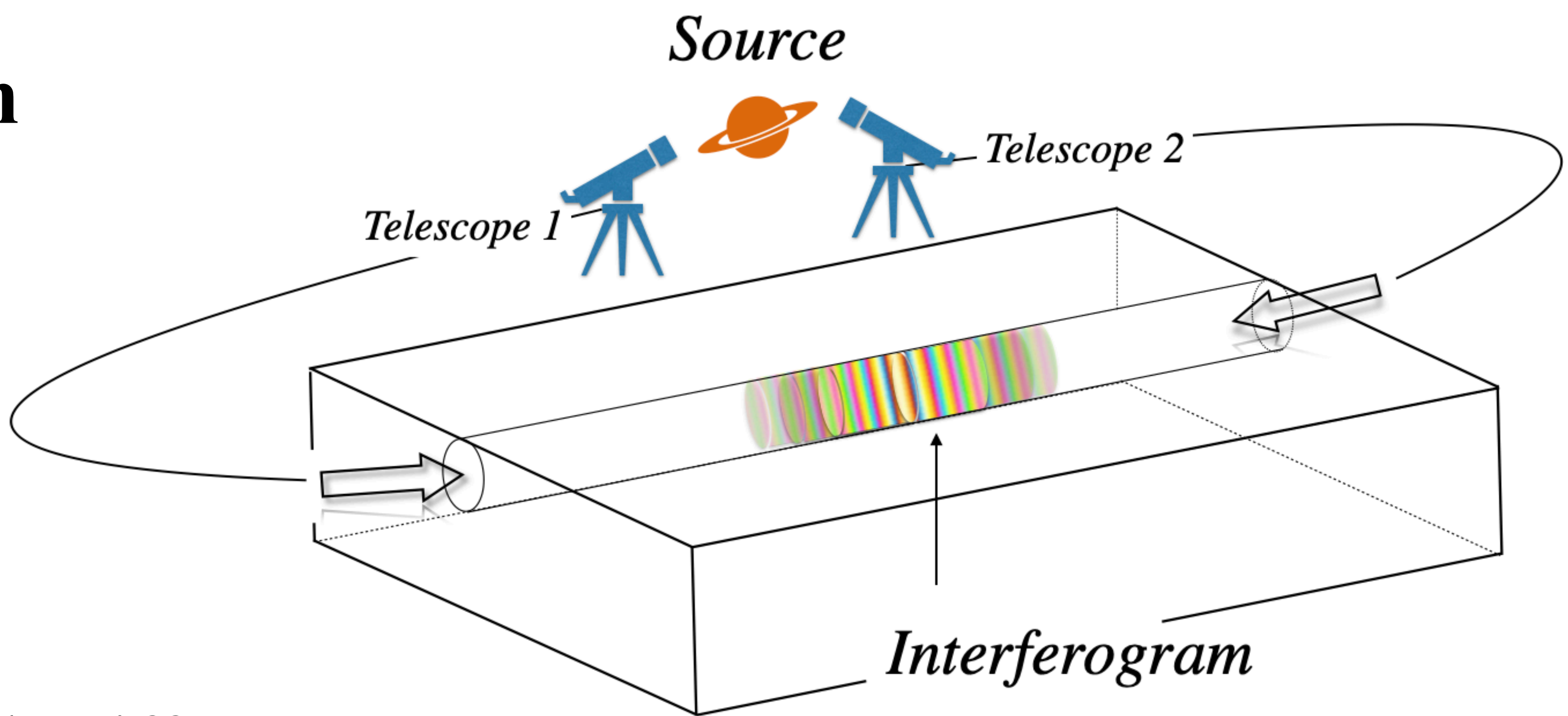
2 cm



- **Principle :** - interferogram in a **<u>waveguide</u>**
  - sample the interferogram via scattering centres : **<u>antennas</u>**
  - collect the information
  - Inverse Fourier Transform => spectrum of the source

- **Principle :** **1. obtain an interferogram in a <u>waveguide</u>**
  2. sample it via scattering centres : **<u>antennas</u>**
  3. Collect the interferogram & Inverse FT => spectrum of the source

"Gabor" configuration

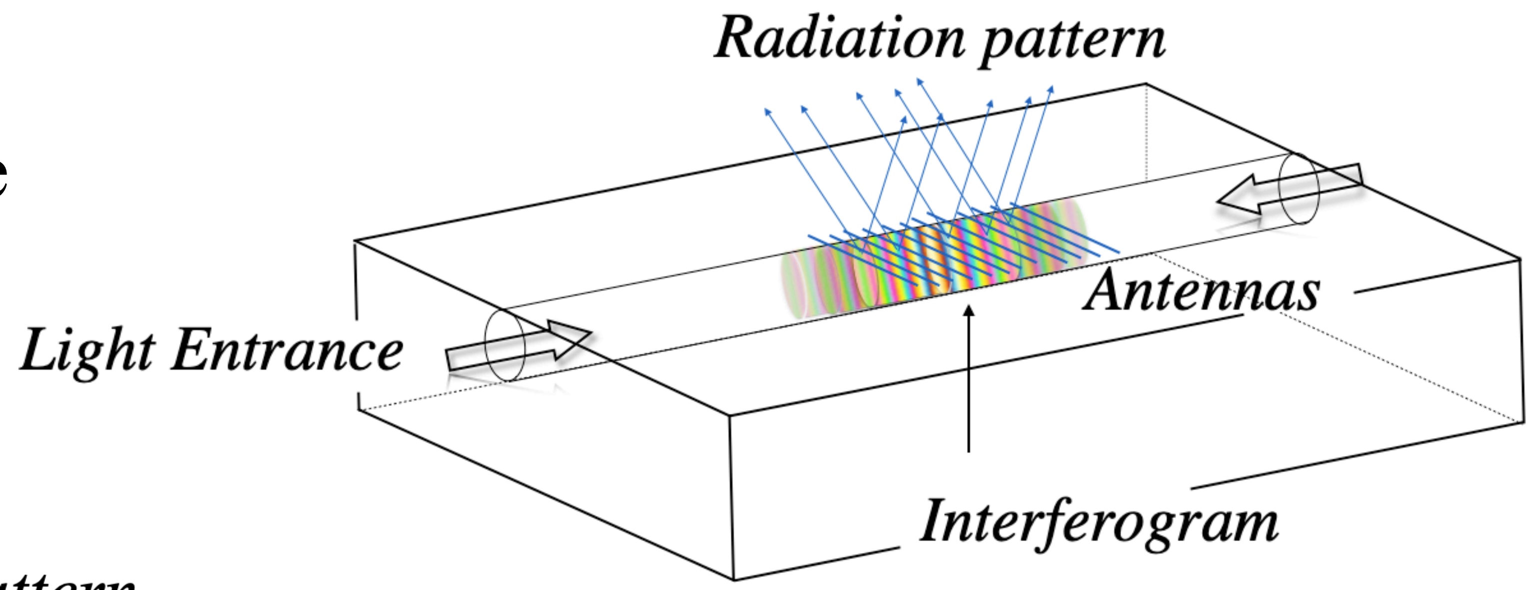


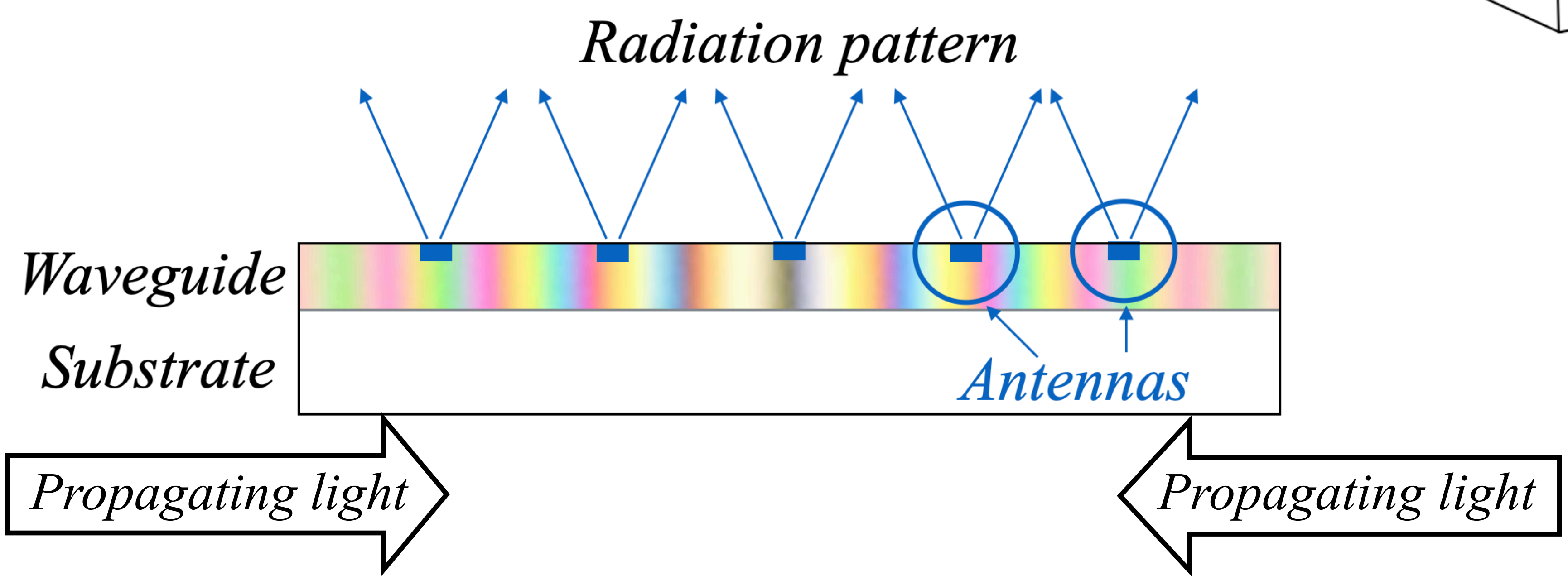
- controllable Optical Path Difference
- complete interferogram, central fringe in the middle of the waveguide

II.3 : Sample the interferogram

- **Principle :** 1. obtain an interferogram in a **waveguide**
  2. sample the interferogram : antennas
  3. Collect the interferogram & Inverse FT => spectrum of the source

- Antennas = "**grooves**"
  (dielectric discontinuities)
  periodically etched in the sample

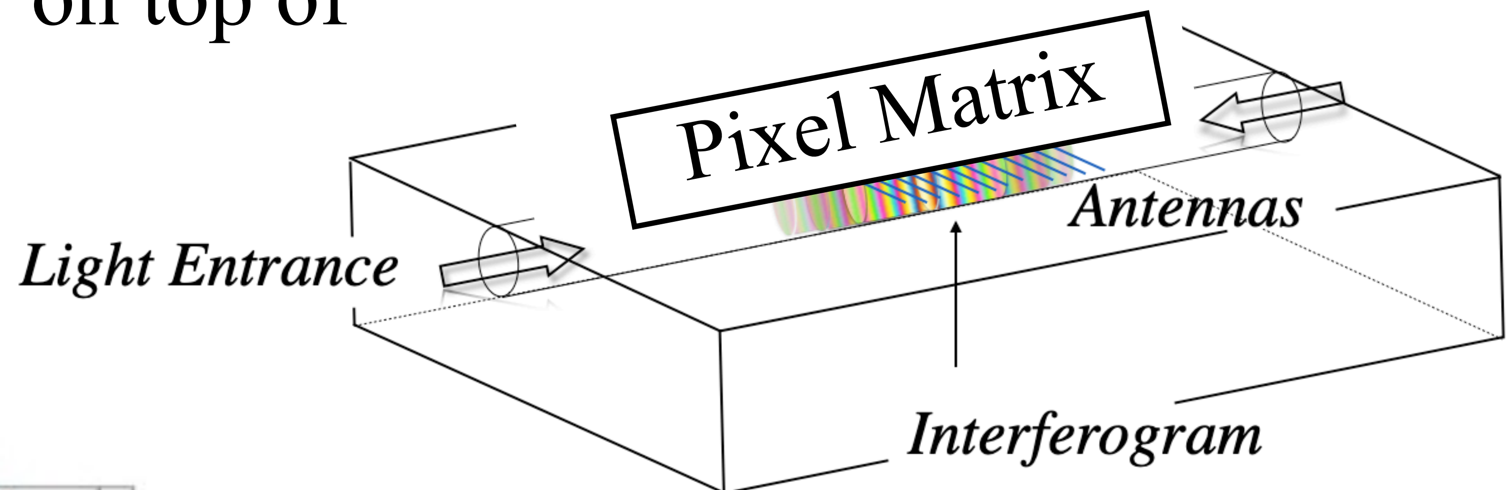


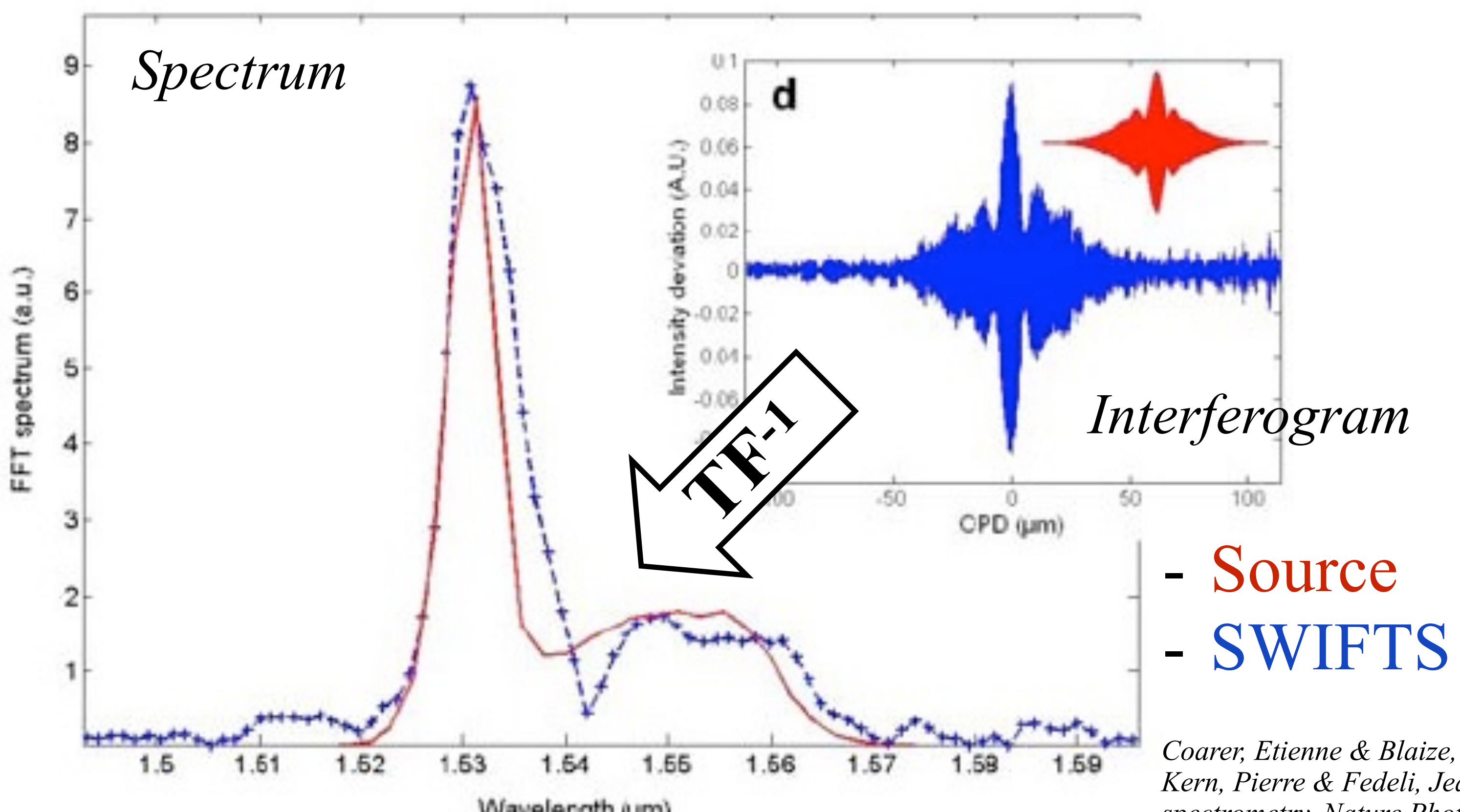


- **Principle :** 1. obtain an interferogram in a **waveguide**
  2. sample the interferogram : **antennas**
  3. Collect the interferogram & Inverse FT => spectrum of the source

- Detector's pixel matrix directly on top of the antennas

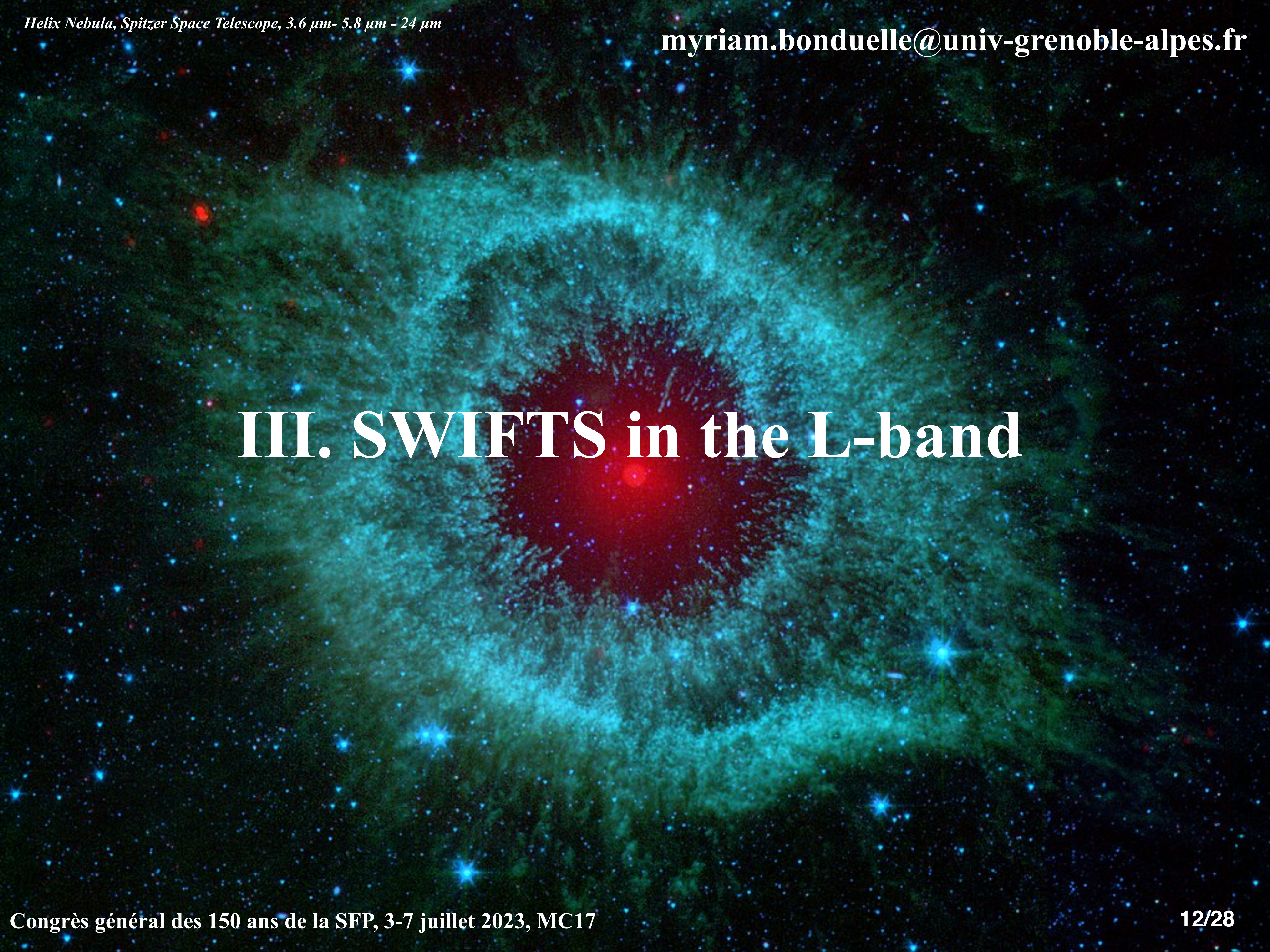
  ➡ **no relay optics**





- Inverse FT {Interferogram} = Spectrum {Source}

Coarer, Etienne & Blaize, Sylvain & Benech, Pierre & Stefanon, Ilan & Morand, Alain & Lerondel, Gilles & Leblond, Grégory & Kern, Pierre & Fedeli, Jean-Marc & Royer, Pascal. (2007). Wavelength-scale stationary-wave integrated Fourier-transform spectrometry. Nature Photonics - NAT PHOTONICS. 1. 473-478. 10.1038/nphoton.2007.138.



Helix Nebula, Spitzer Space Telescope, 3.6 µm- 5.8 µm - 24 µm

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III. SWIFTS in the L-band

III.1 : Mid-IR SWIFTS characteristics

- **Resolution** :

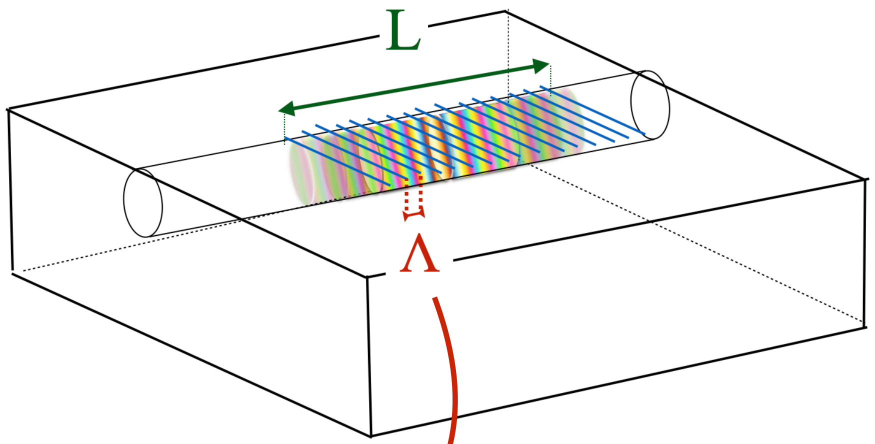
$$R = \frac{\lambda}{\Delta\lambda} = \frac{2 \times n_{eff} \times L}{\lambda}$$

  - L = 1cm => **R > 10 000** ($\Delta\lambda$ ~340pm)

- **Spectral Bandwidth :**

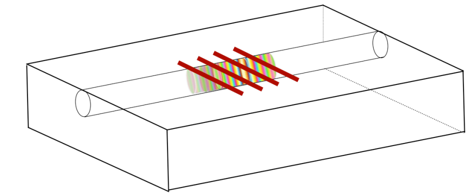
$$\Delta\lambda_{bandwidth} = \frac{\lambda^2}{4 \times n_{eff} \times \Lambda}$$

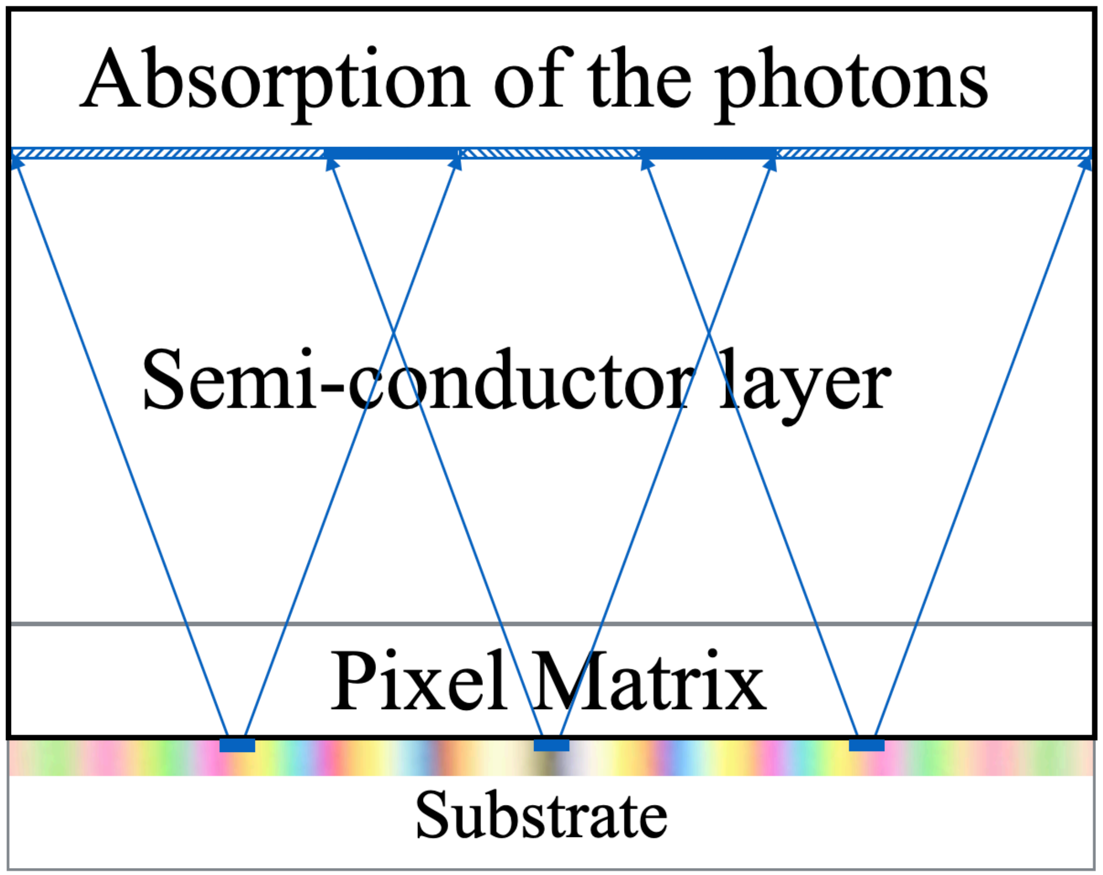
  - Λ = 30 µm => **$\Delta\lambda_{bandwidth}$ ~ 44nm**



➡ **Compact, high resolution spectrometer** : spectral emission, absorption lines

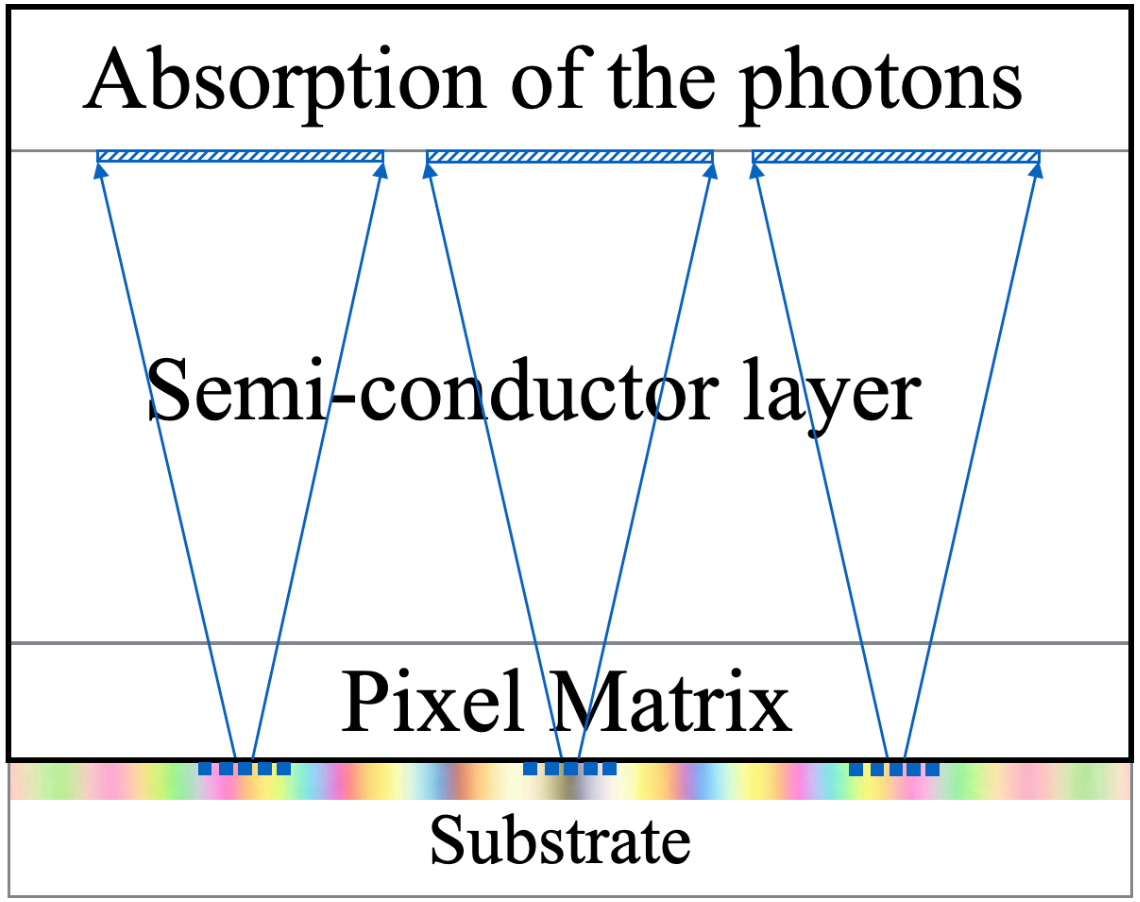
- Mid-IR detectors :



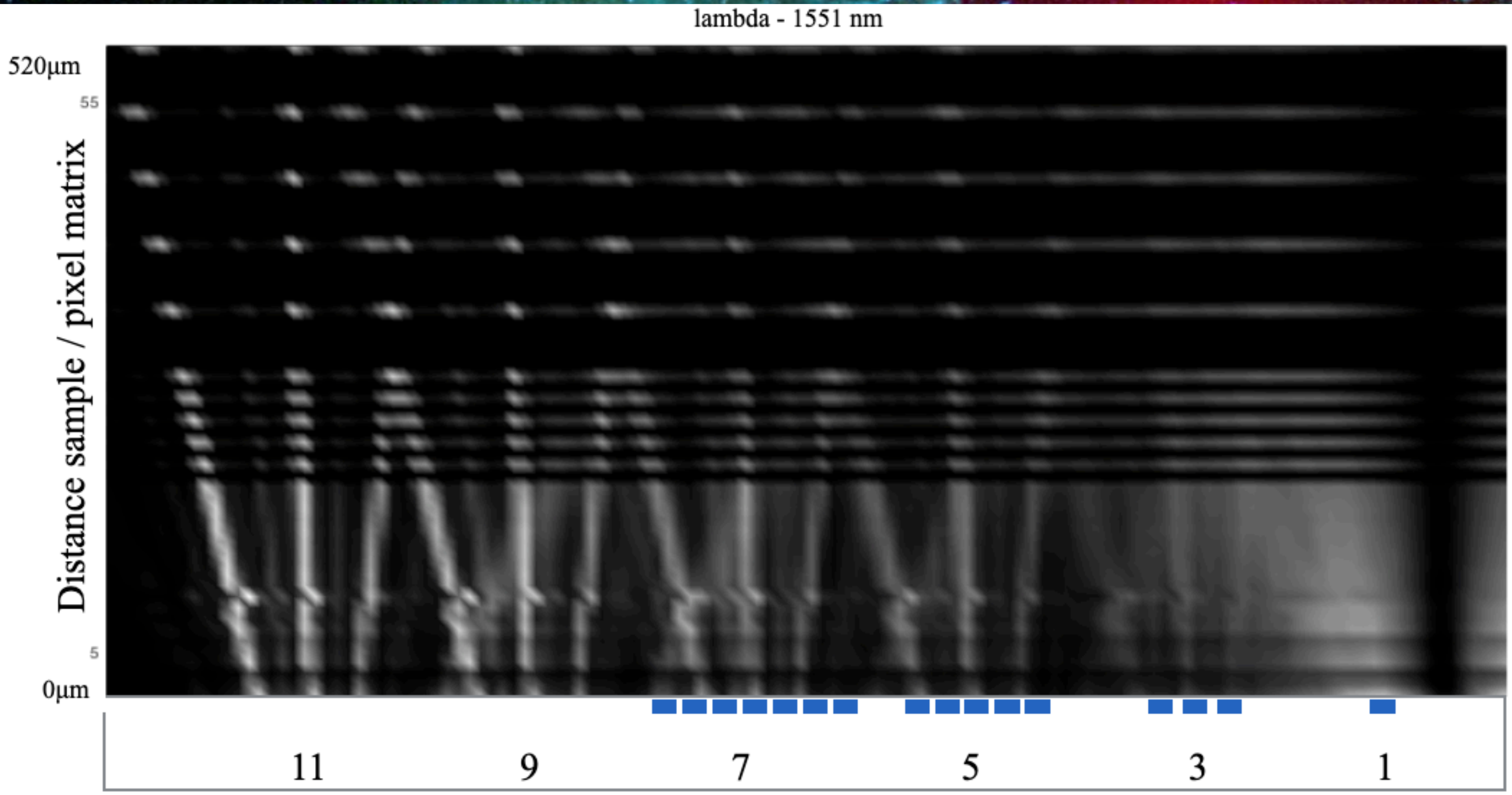


- 1 groove per antenna = crosstalk on the pixels

➡ mini-diffraction gratings : several grooves per antenna



➡ **reduction of the angular diffraction**

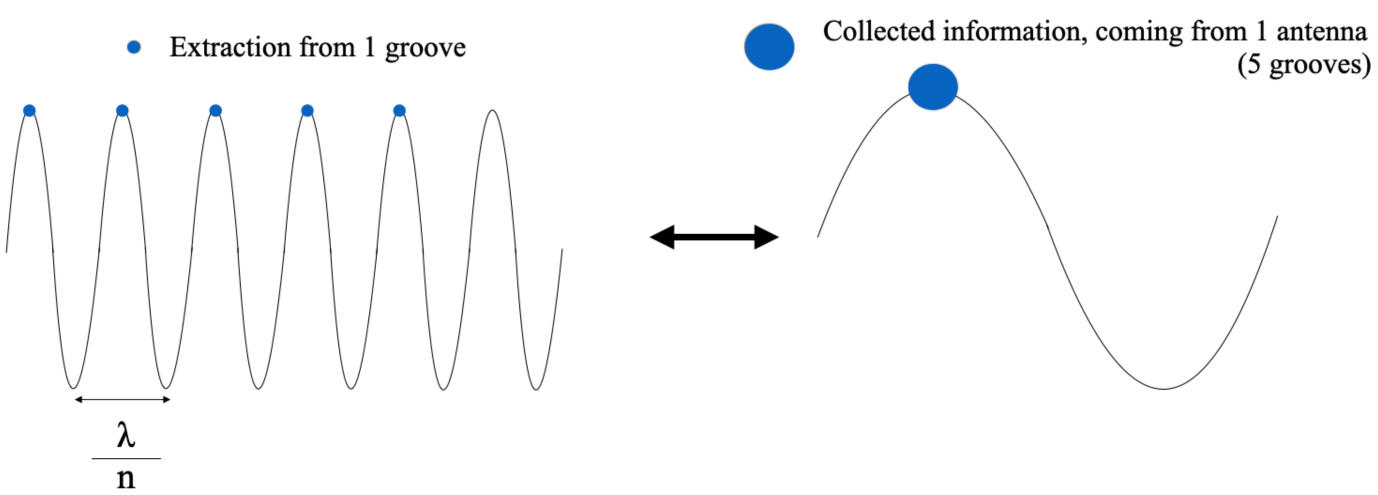


Number of grooves per antenna

➡ *Reduction of the angular diffraction when increasing the number of grooves per antenna*

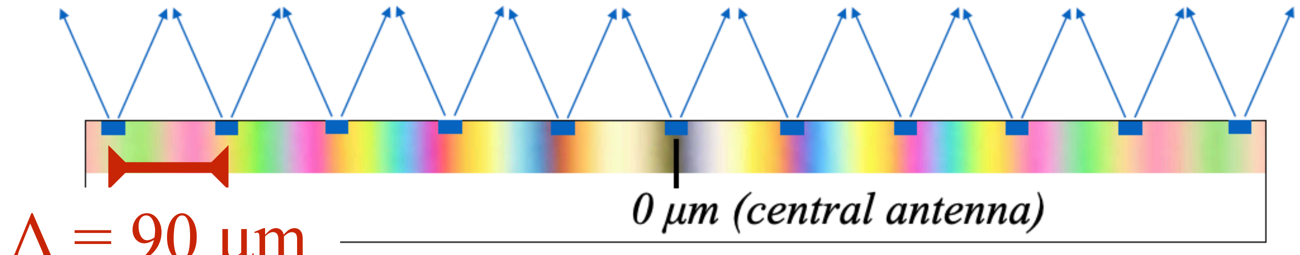
δ = Pitch between two grooves

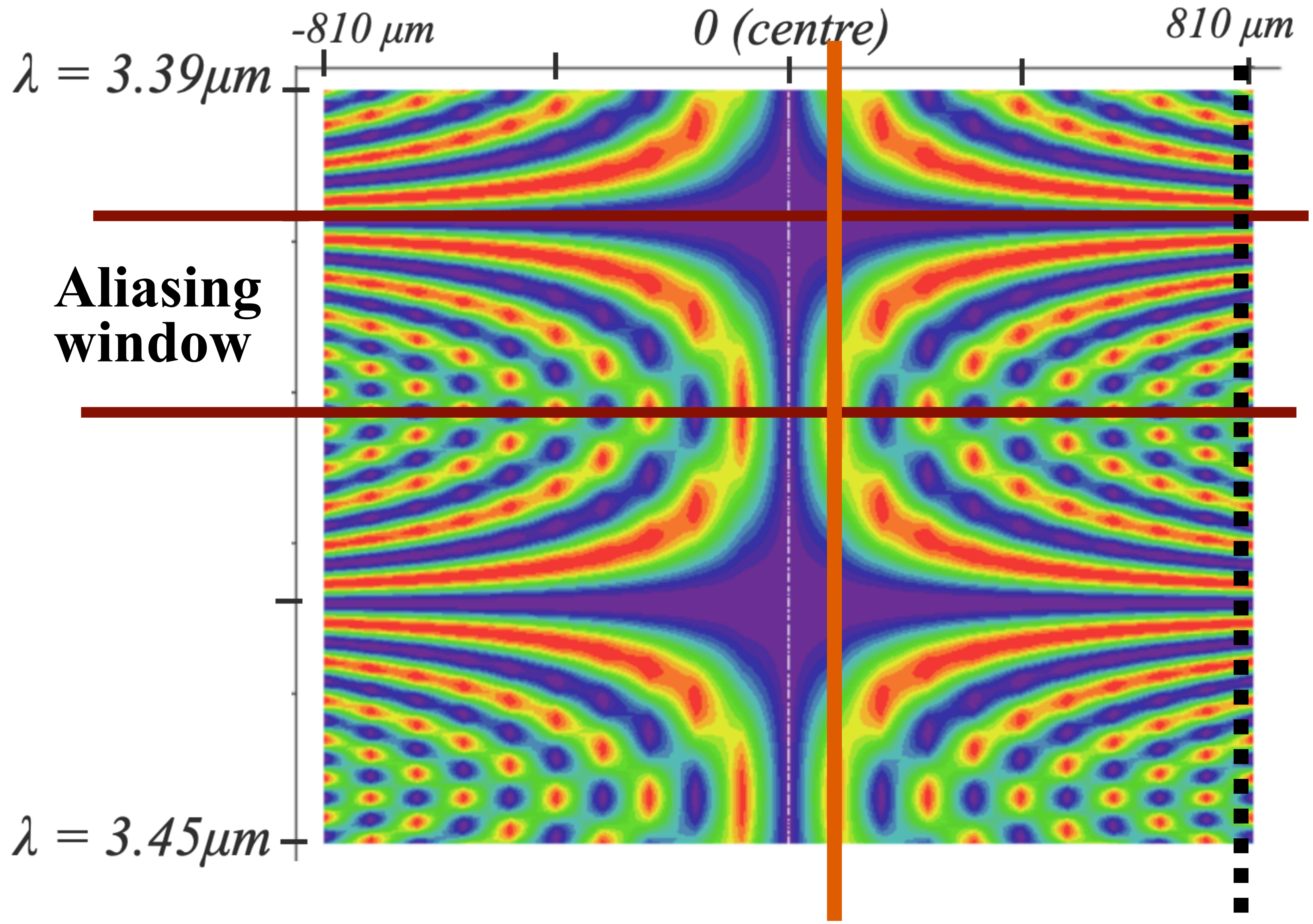
$$\delta \propto \frac{\lambda}{n_{eff}}$$ = Period of the interferogram

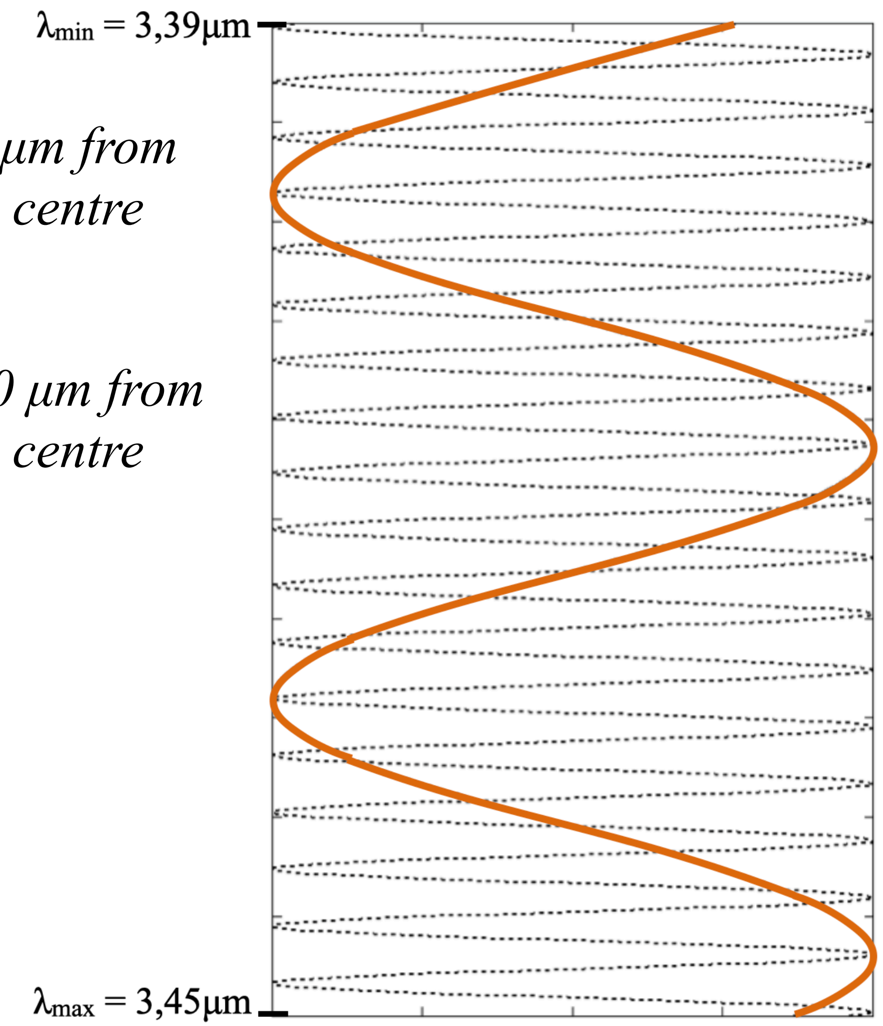


III. 3. What to expect from a mid-IR SWIFTS ?

- Simulation : theoretical sampled signal — 20 antennas

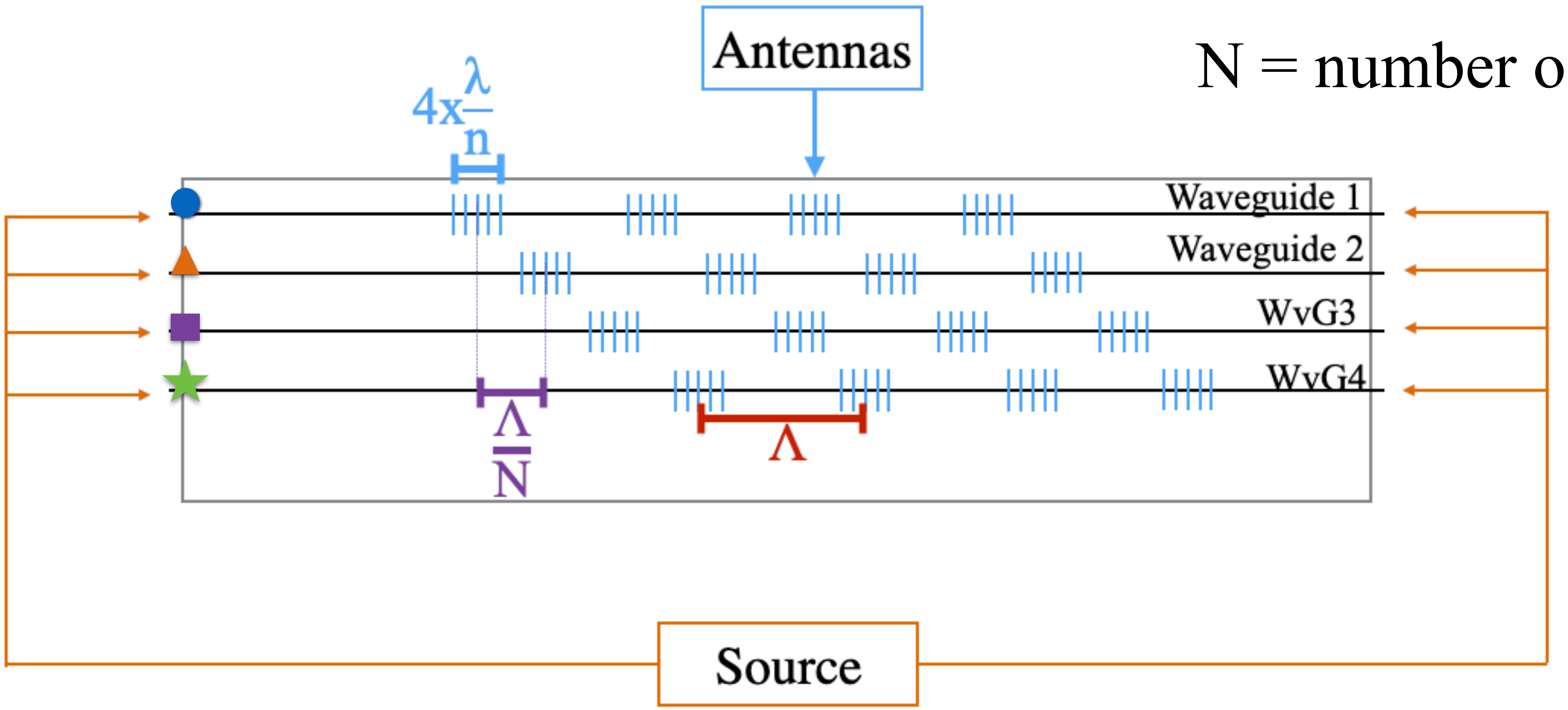


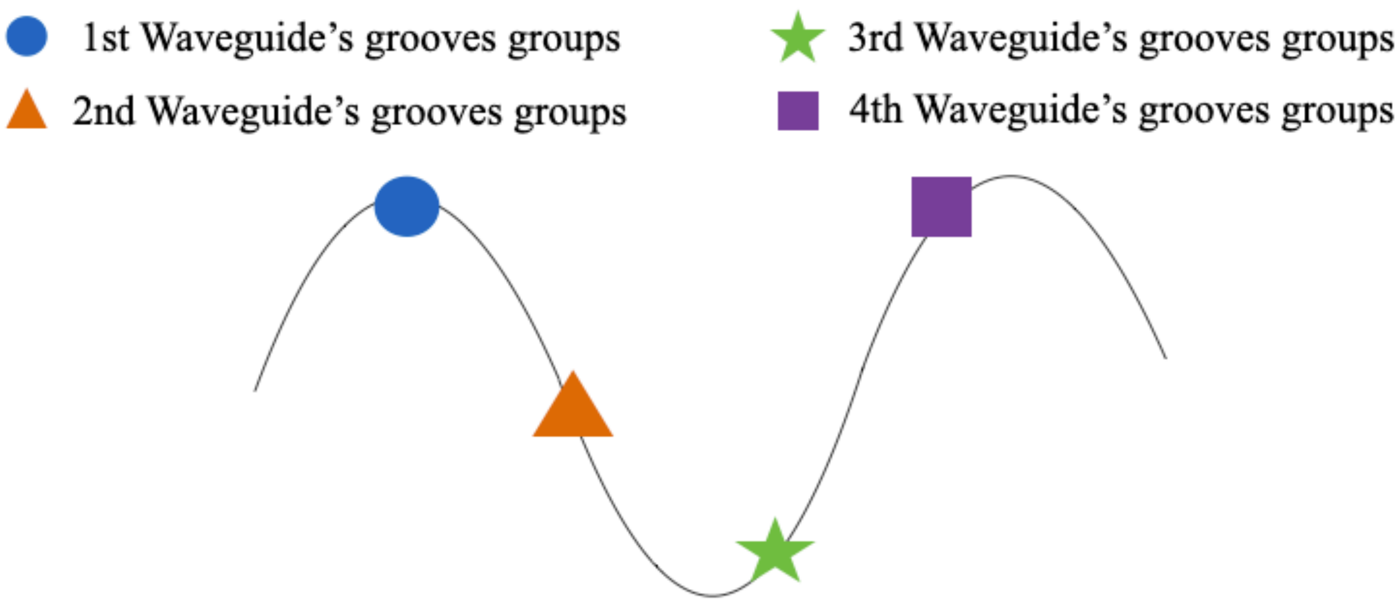




III. 4. Spatial Multiplexing

N = number of waveguides, ex 4





➡ **<u>Increases the bandwidth</u>**

Helix Nebula, Spitzer Space Telescope, 3.6 µm- 5.8 µm - 24 µm

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IV. How do you make a mid-IR SWIFTS ?

- **Lithium Niobate ($LiNbO_3$) :** ➡ Transparent in the Mid-IR
  ➡ **Electro-active** material : Pockels effect

Electro-optic coefficient

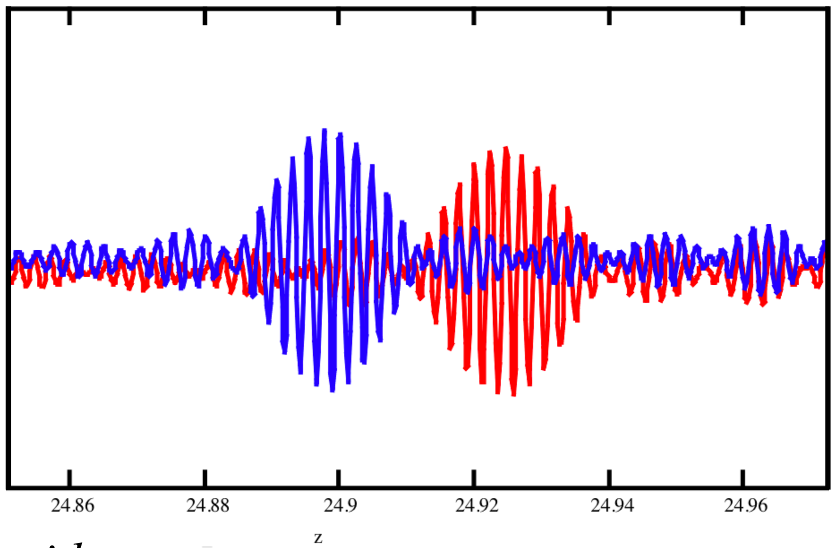
$$\Delta n(E_{app}) = -\frac{1}{2} \times n^3_{LiNbO3} \times r_{33_{LiNbO3}} \times E_{app}$$

Variation of the local refractive index

Applied electric field

➡ Temporal modulation of the fringes : **increases the bandwidth**

$E_{app} = 0V$
$E_{app} = 4V$

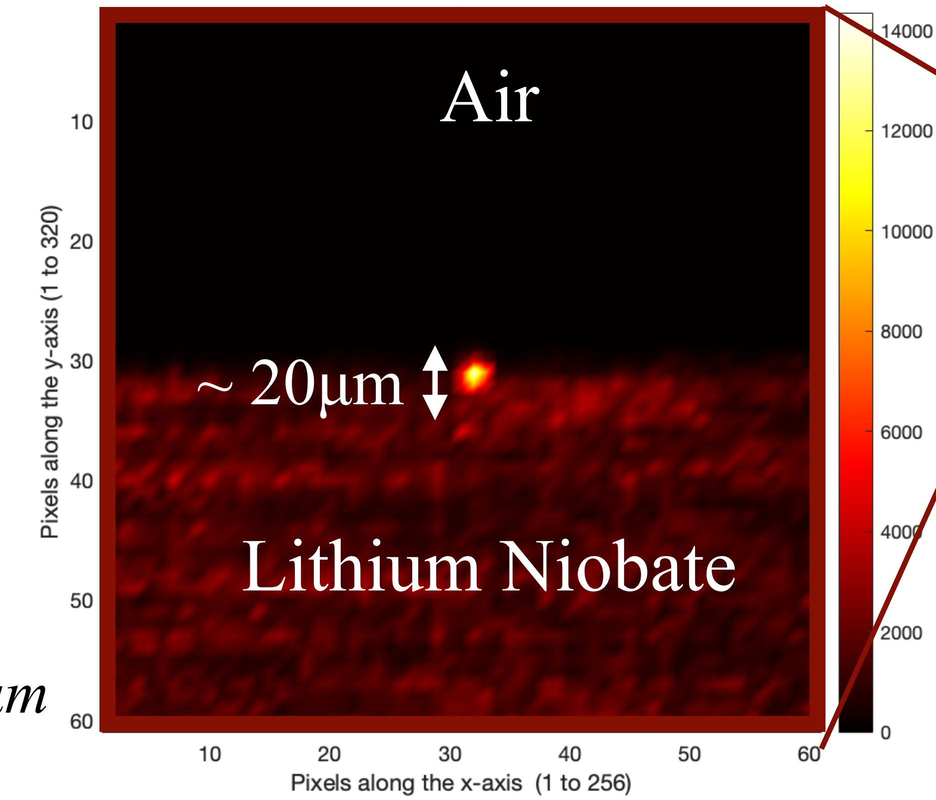


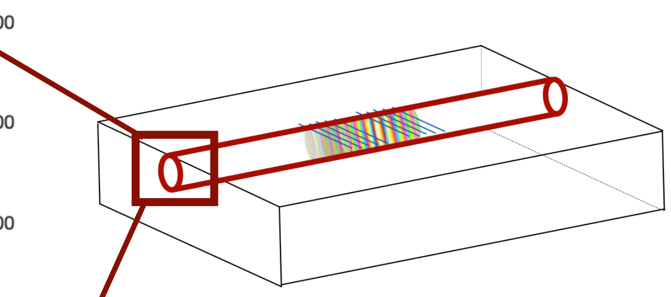
Simulation of the interferogram in the waveguide

- 2 technologies
  - **<u>Titane Diffusion</u>**
  - Direct Laser Writing

- $\Delta n \sim 10^{-2} - 10^{-3}$

Waveguide injected at 3.39 µm





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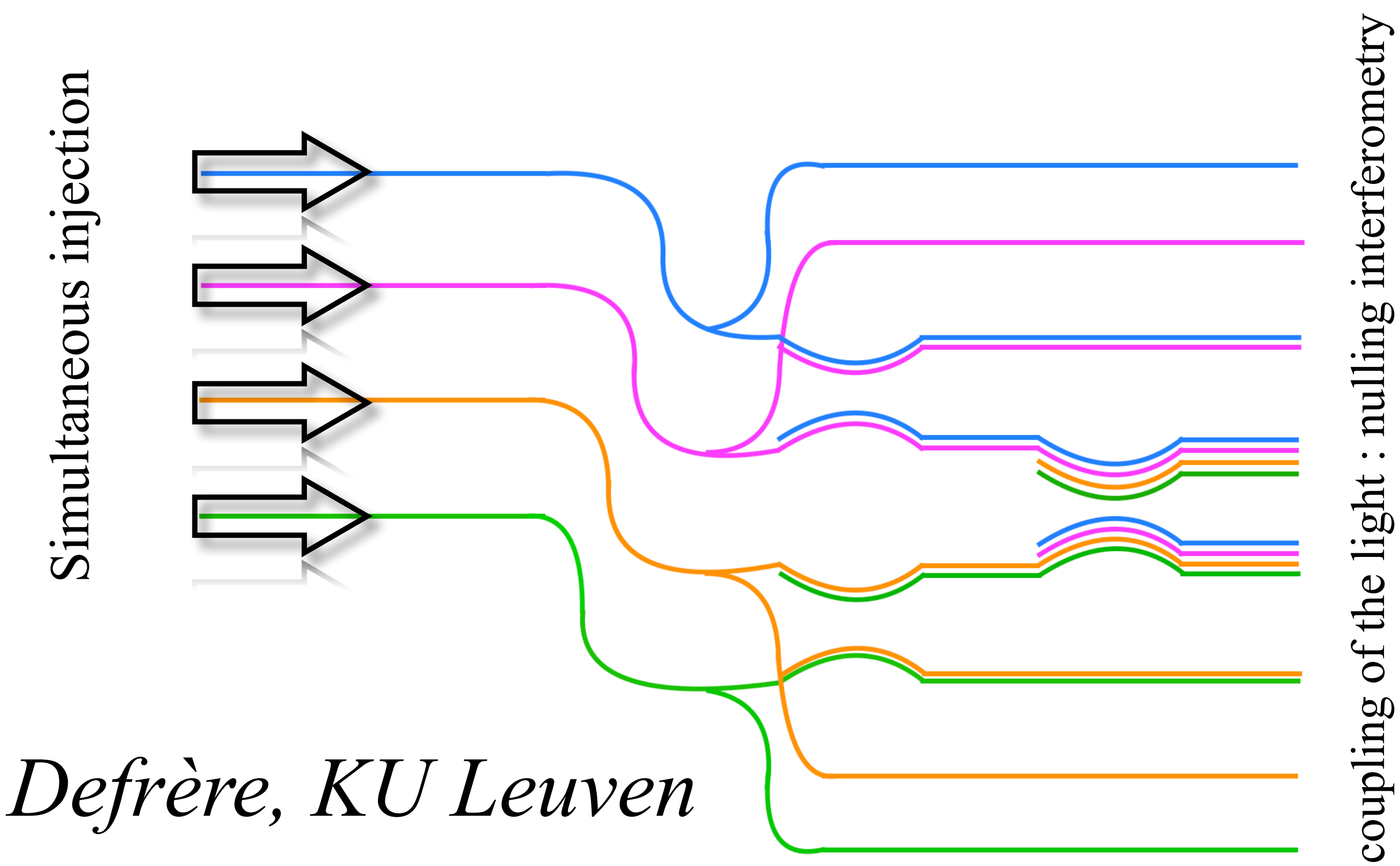
- Complex planar geometries : 4-Telescope recombiner for nulling interferometry

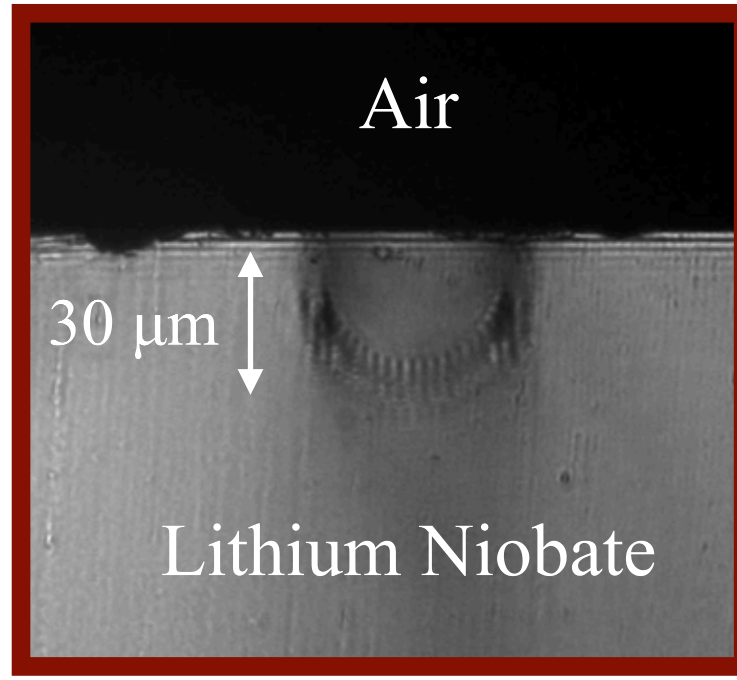


➡ *ASGARD/NOTT project, D. Defrère, KU Leuven*

IV. 2b Make your waveguides : Direct Laser Writing

- 2 technologies
  - Titane Diffusion
  - **<u>Direct Laser Writing</u>**

$\Delta n \sim 5x10^{-4}$ - $1x10^{-3}$
(*Inverse Helmholtz technique*)



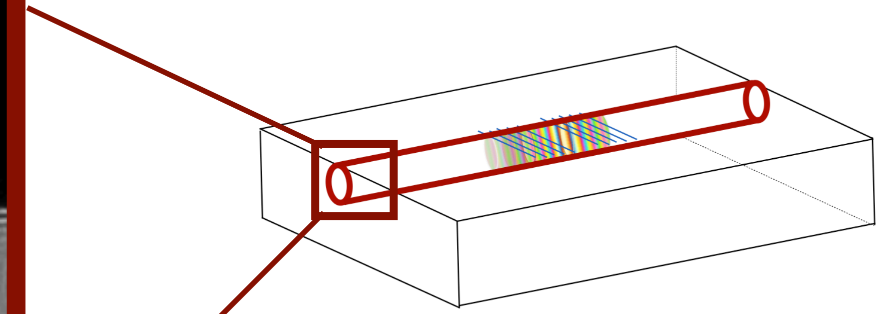
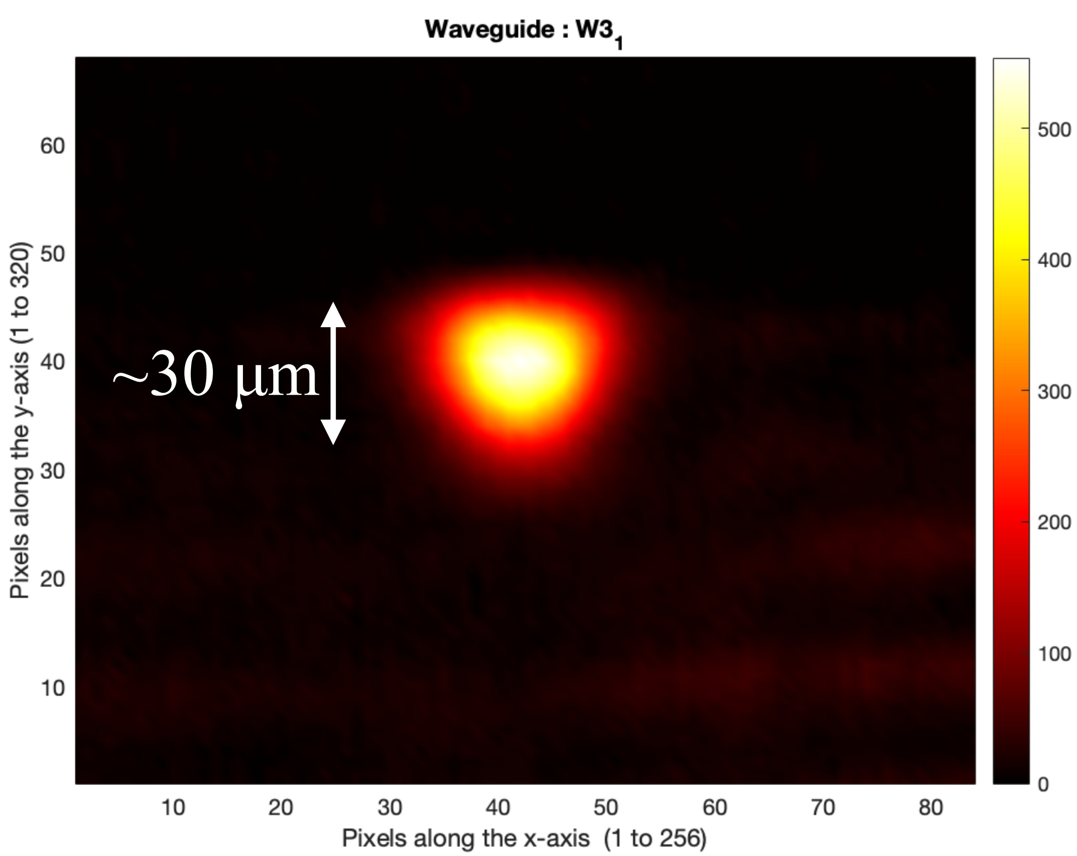


Image of a waveguide in white light



Waveguide injected at 3.39 µm

- **depressed index cladding technique**
- Simple and fast
- 3D geometries

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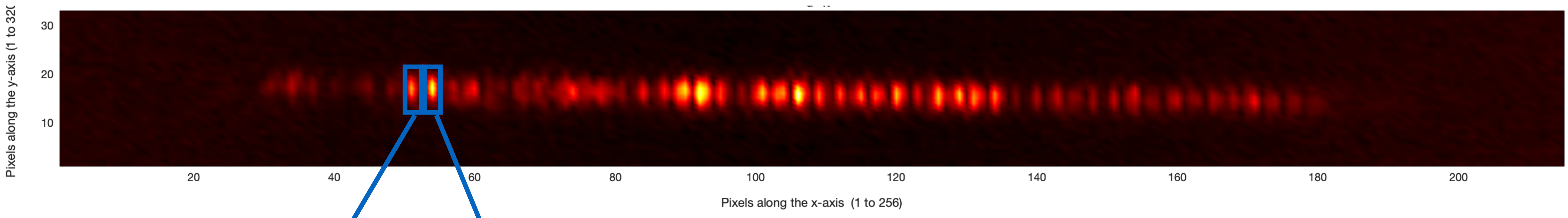
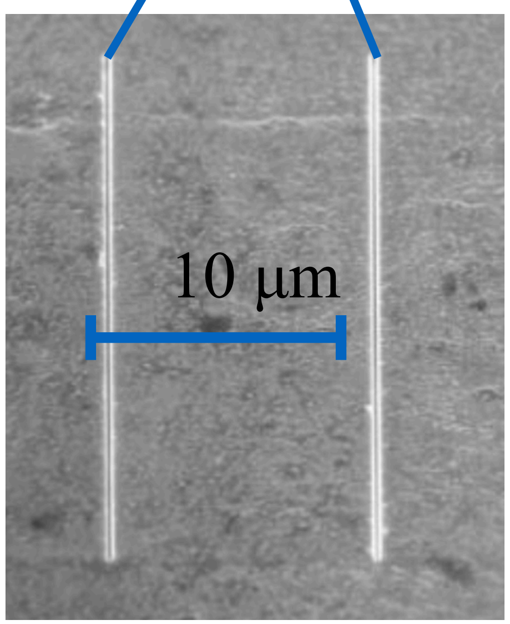
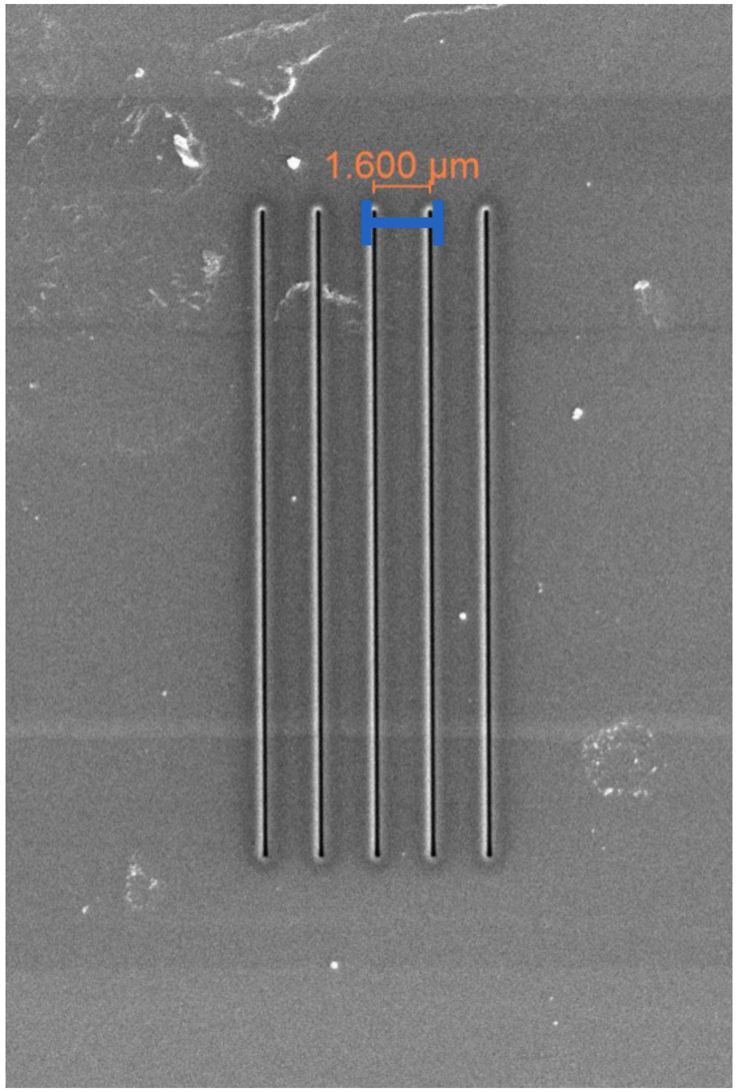
✦ FIB (Focused Ion Beam) :

Diffraction pattern of the antennas (Waveguide injected at 3.39µm)





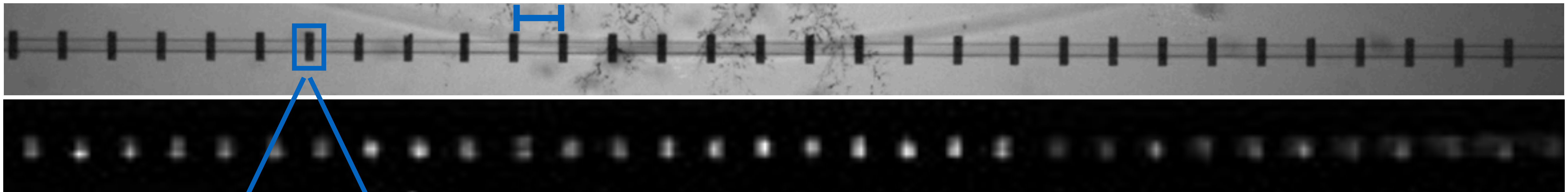
work in progress



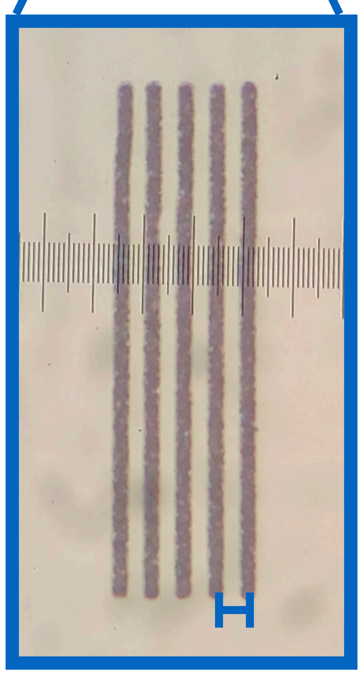
✦ Direct Laser Writing :

90 µm

Image in white light of the antennas

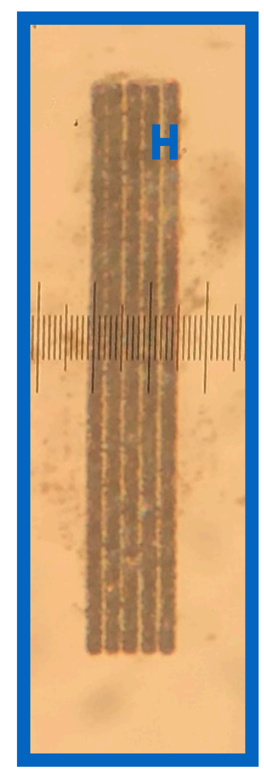


Diffraction pattern of the antennas



$$3.2\mu m = 2 \times \frac{\lambda}{n_{eff}}$$

work in progress ⇨

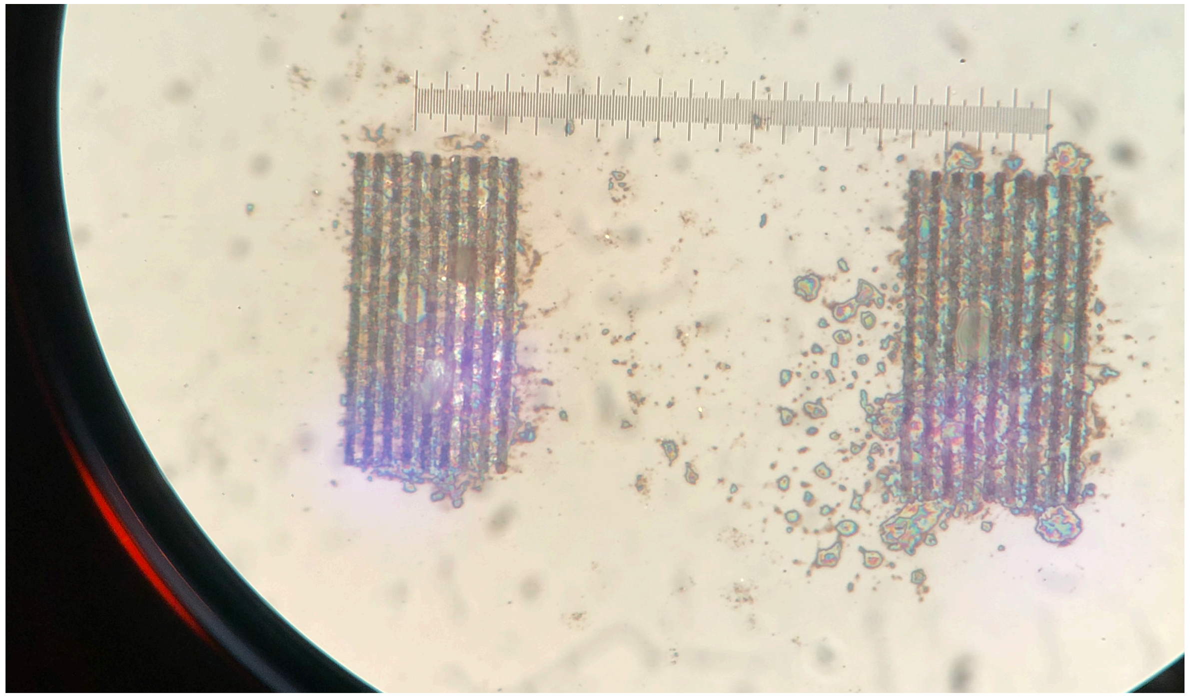


$$1.6\mu m = \frac{\lambda}{n_{eff}}$$

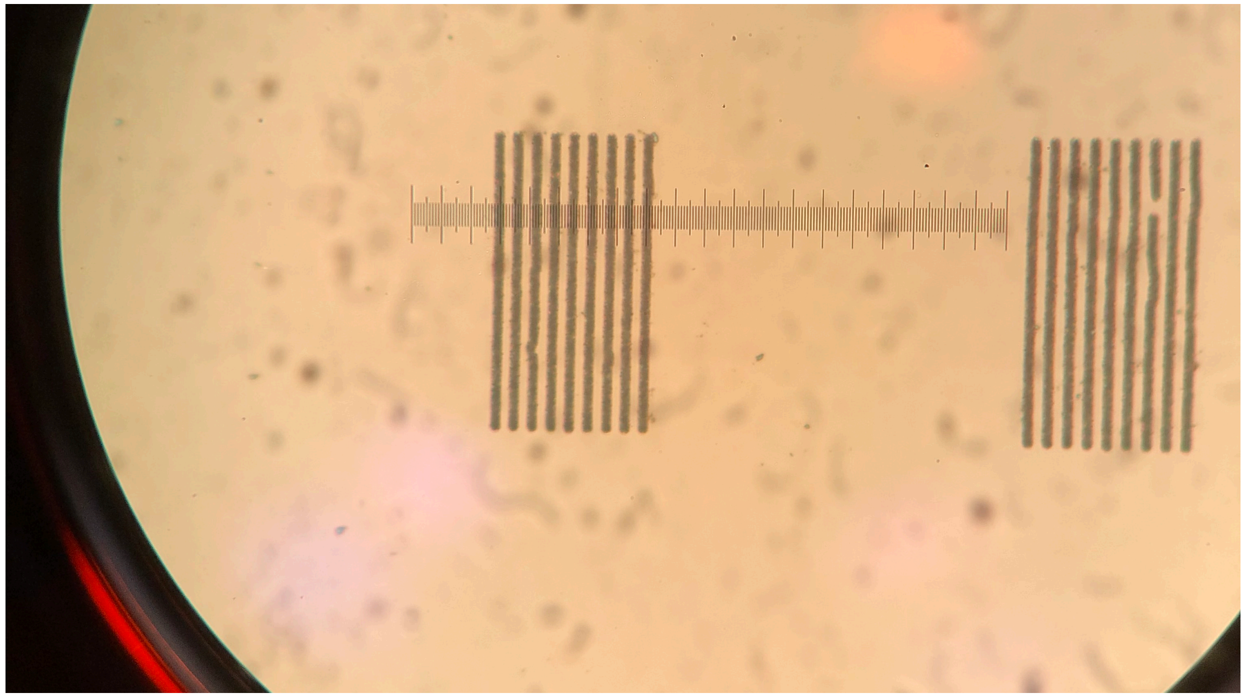
➡ Ideal pitch between the grooves

✦ Direct Laser Writing :

Aplicaciones del Láser y Fotónica



ultra sound cleaning →



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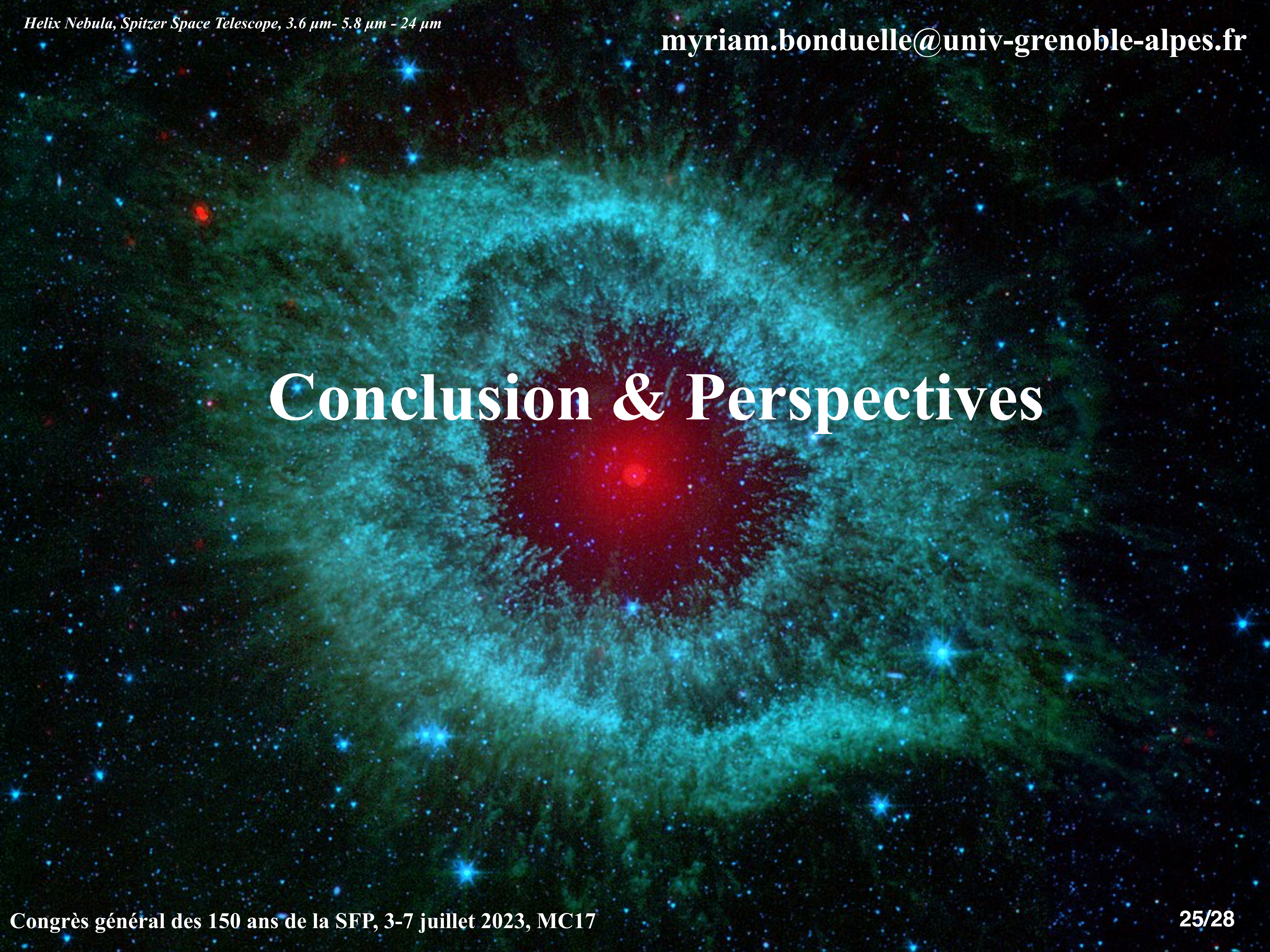


Helix Nebula, Spitzer Space Telescope, 3.6 µm- 5.8 µm - 24 µm

Conclusion & Perspectives

Conclusion & perspectives

- Small and compact high resolution spectrometer in the L-band
  ➡ **embedded applications !** (drones, satellites, rovers…)

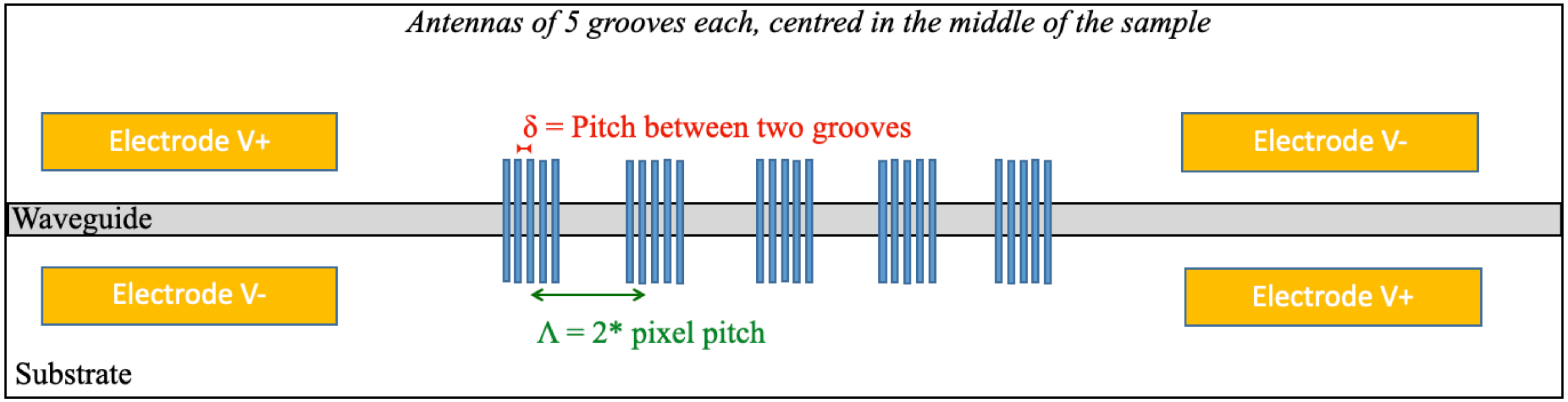
- Different technologies explored :
  - Titane Diffusion + FIB
  - Direct Laser writing

L-band (3.4 µm - 4.1 µm):
- **R >10 000**
- **λ bandwidth ~ 44 nm**
- **Spatial multiplexing**
- **Temporal modulation**

See also :
- *M. Bonduelle, G. Martin, A. Morand, J. R. Vazquez de Aldana, C. Romero Vázquez, N. Courjal, A. Coste, "Development of mid-IR waveguides to implement high resolution spectrometers in integrated optics," Proc. SPIE 12188, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation V, 121885R (29 August 2022)*
- *Martin G, Zhang G, Bonduelle M, Allaw R, Callejo M, Morand A, Rodenas A, Cheng G, Stoian R, d'Amico C. Development of a 3D ultrafast laser written near-infrared spectro-interferometer. Opt Lett. 2023 May 1;48(9):2253-2256. doi: 10.1364/OL.484270. PMID: 37126247.*

Conclusion & perspectives

- New samples on the way in both technologies
- Implementation of the EO effect



- New type of detectors directly grown on the antennas (NIT)

NIT New Infrared Technologies

See also :

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- *Martin G, Zhang G, Bonduelle M, Allaw R, Callejo M, Morand A, Rodenas A, Cheng G, Stoian R, d'Amico C. Development of a 3D ultrafast laser written near-infrared spectro-interferometer. Opt Lett. 2023 May 1;48(9):2253-2256. doi: 10.1364/OL.484270. PMID: 37126247.*

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- Javier R. Vazquez de Aldana
- Carolina Romero Vázquez
- Víctor Arroyo Heras

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- Nadège Courjal
- Roland Salut
- Laurent Robert

Thank you very much !

Questions ?

FOCUS
Focal Plane Array for Universe Sensing
Labex Focus : ANR-11-LABX-0013

ASHRA
Action Spécifique Haute Résolution Angulaire

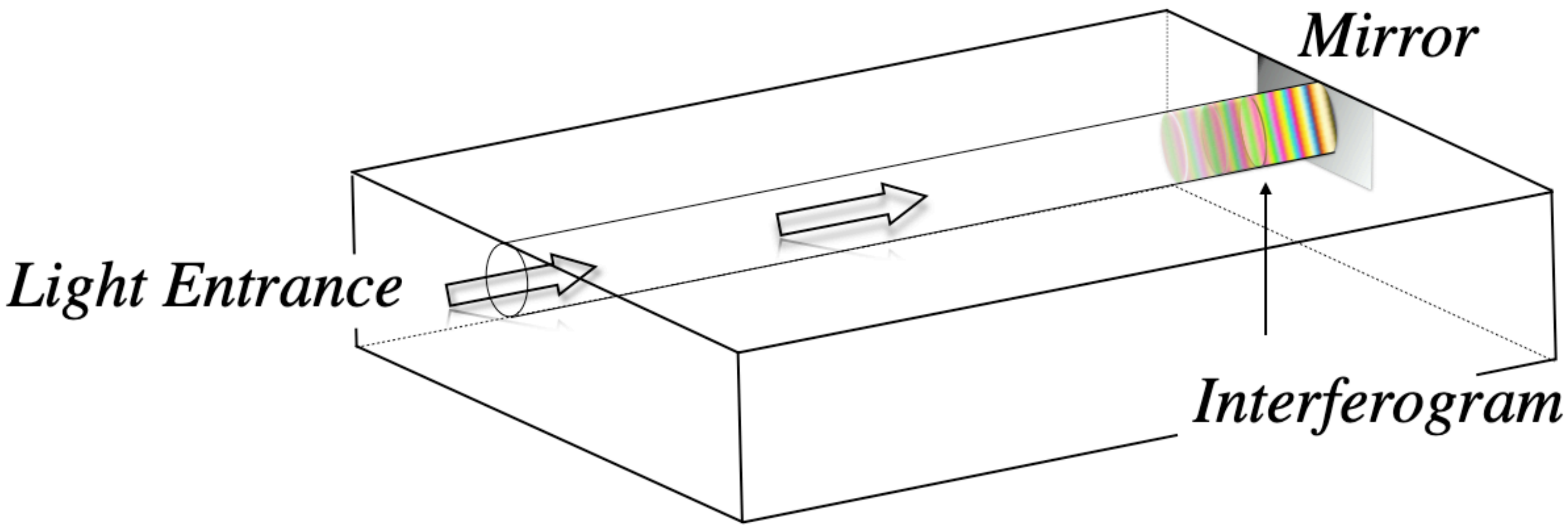
The authors acknowledge funding from ASHRA (Action Specifique Haute Resolution Angulaire) 320 from INSU- CNRS and LabEx FOCUS ANR-11-LABX-0013

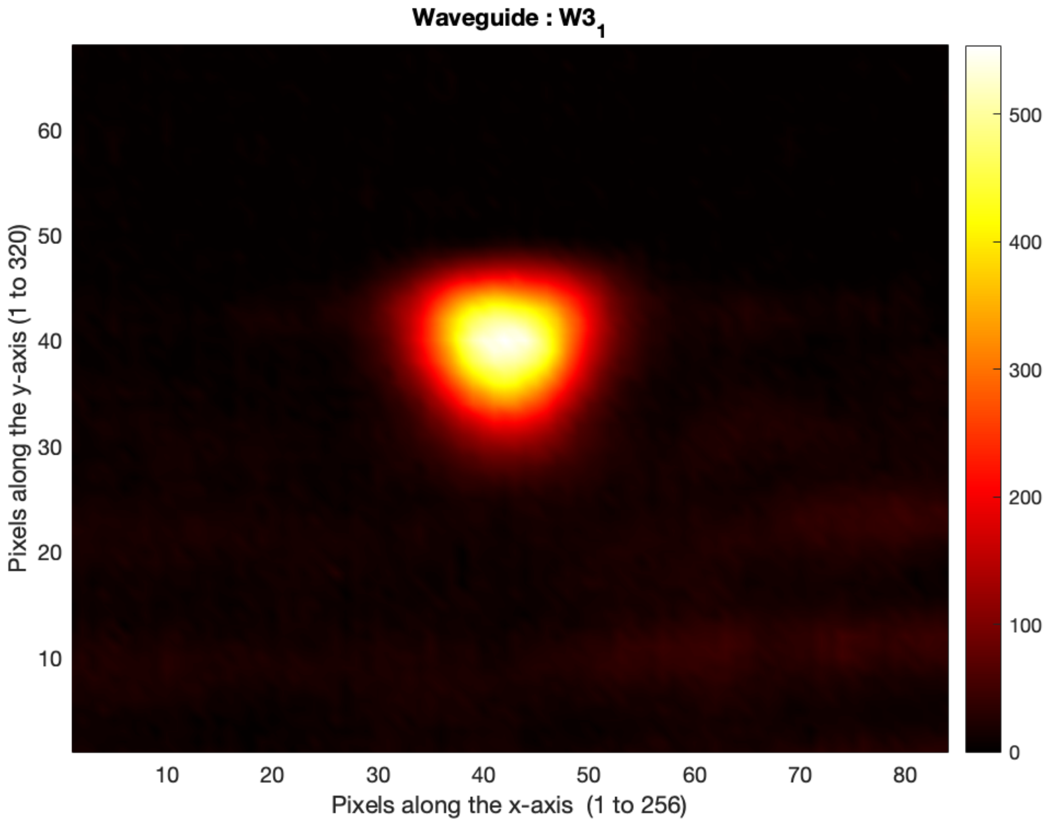
Additional slides

Lippmann configuration

Half-interferogram set near the mirror

No need for a precise control of the OPD





2D Gaussian

$$\Delta n(x,y) = \frac{-\nabla^2 \sqrt{I(x,y)}}{2 n_B k^2 \sqrt{I(x,y)}}$$