



MULTIPLEXING HETERODYNE INTERFEROMETRY WITH TELECOM FIBERS AND ULTRAFast TECHNOLOGIES IN THE H-BAND

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Stellar Intensity Interferometry, La Palma, 08/10/2026

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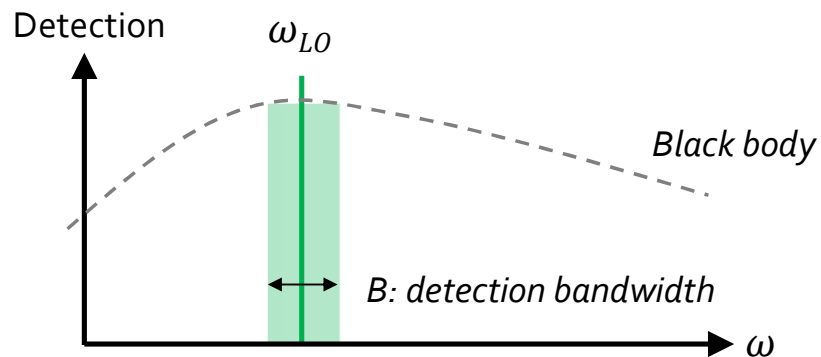


In this talk :

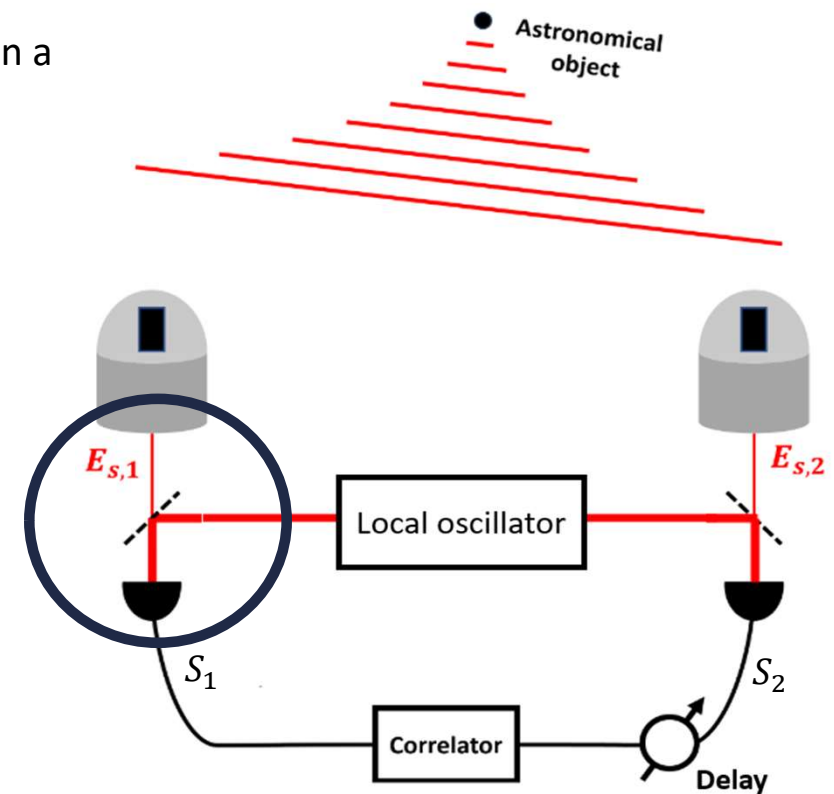
1. New approach : serrodyne stellar interferometry
2. Single channel proof of concept
3. Experimental demonstration of multiplexing
4. Monomode fiber injection with AO

0. Heterodyne Stellar Interferometry

- The weak stellar field is mixed with a strong local oscillator (laser) on a fast photodetector => beat note
- The signal is down converted to an intermediate frequency (RF) :
 - The correlation gives g^1
=> Complex visibility and closure phase are accessible



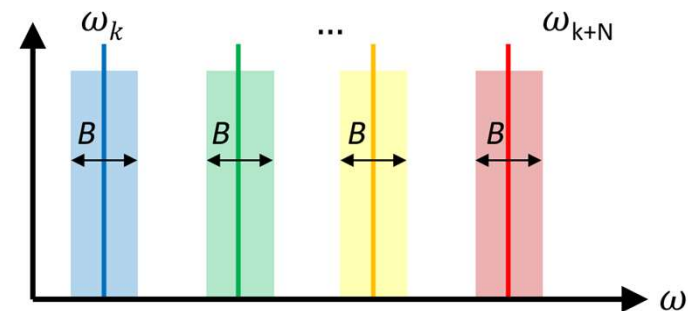
- Only starlight within bandwidth B around the LO frequency is measured ($B \approx \text{GHz}$, against THz for the star's spectrum).



0. Heterodyne Stellar Interferometry

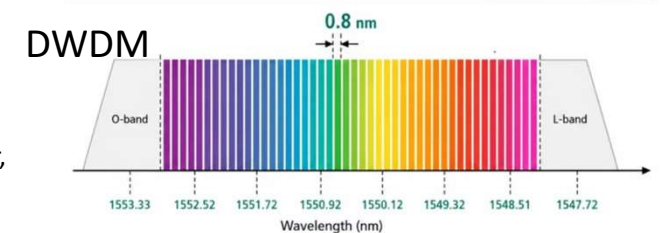
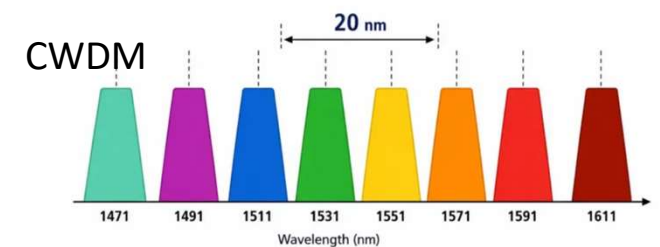
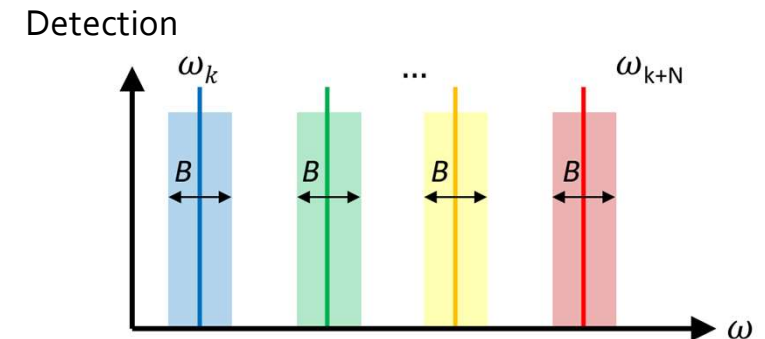
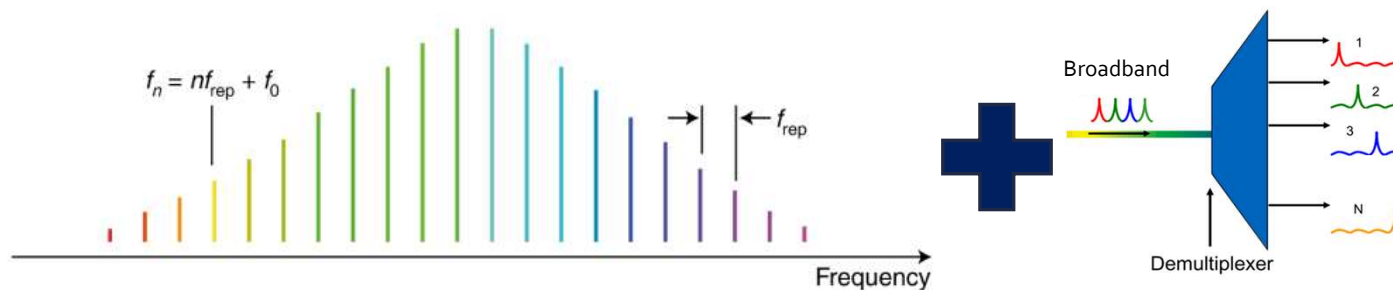
Method	Advantages	Disadvantages
Intensity interferometry (HBT) measures $ V ^2$, no phase	- No delay lines, no beam transfer - Tolerates low-quality optics - Effective in blue	- SNR set by detector timing and photon flux - Few photons per coherence time
Heterodyne interferometry complex V , closure phase	- Electronic delay lines/ post-processing N telescopes without SNR losses - More sensitive	- LO quantum noise ($h\nu$) at short λ - LO phase to distribute Limited by detector elec bandwidth $\approx$ GHz

Multiplexing (N parallel channels, $SNR \propto \sqrt{N}$)



1. Spectral multiplexing : frequency comb ?

- Multiple frequencies LO : **frequency comb**
- **Spectral demultiplexers** and N detectors allows parallel detection
- Well studied in quantum and laser metrology as “multiheterodyne” [4][5]



[4] D.A Long and all, Multiheterodyne spectroscopy with optical frequency combs generated from a continuous-wave laser, Optics Letters, 2014, 39,9

[5] Cole and all, Frequency Comb Calibrated Laser Heterodyne Radiometry for Precision Radial Velocity Measurements, 2024, arXiv

1. Spectral multiplexing : frequency comb ?

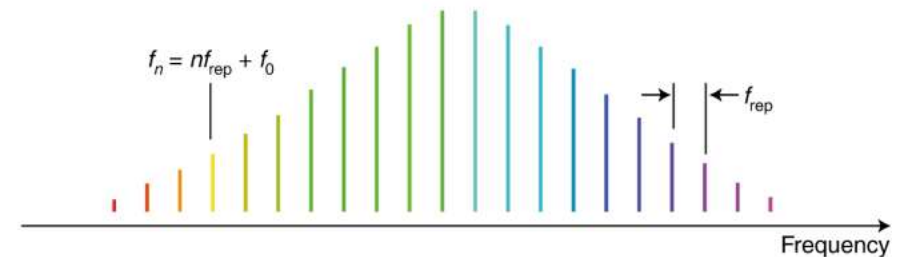
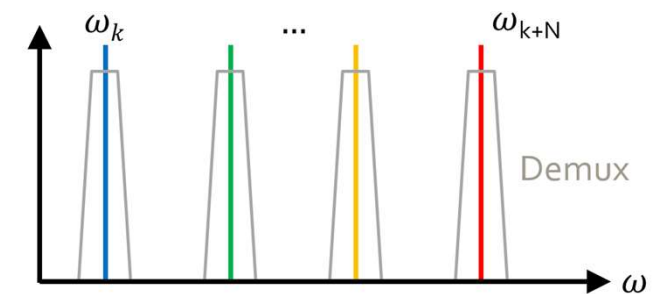
A known path to improve Stellar Heterodyne Interferometry [6]:

1. Requires infrared combs with enough power per tooth
2. Demultiplexer and frequency comb need to be perfectly matched



- Still in the « discussion part » of very recent papers [7][8]

Detection



[6] Ireland MJ, Monnier JD. 2014. Proc. SPIE Conf. Ser. 9146:914612

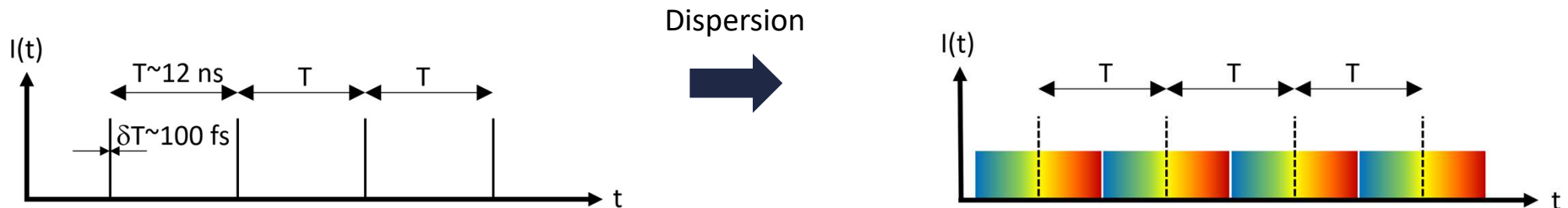
[7] G. Bourdarot, and all "Toward a large bandwidth photonic correlator for infrared heterodyne interferometry" A&A, 639,A53 (2020)

[8] T.Allain, and all "Proof of concept of heterodyne interferometry at 10.6 μm using photonic correlator", A&A, 712, A81 (2026)

1. Spectral multiplexing : swept source

Our new approach → Heterodyne detection with stretched pulses

- Use a commercial unstabilized telecom femtosecond laser
- Start from a train of femtosecond pulses
- Propagate through a long **dispersive fiber** [6]
 - stretch the pulse duration up to the repetition period : “the red frequencies travel faster than the blue ones”
 - quasi-continuous-wave swept source

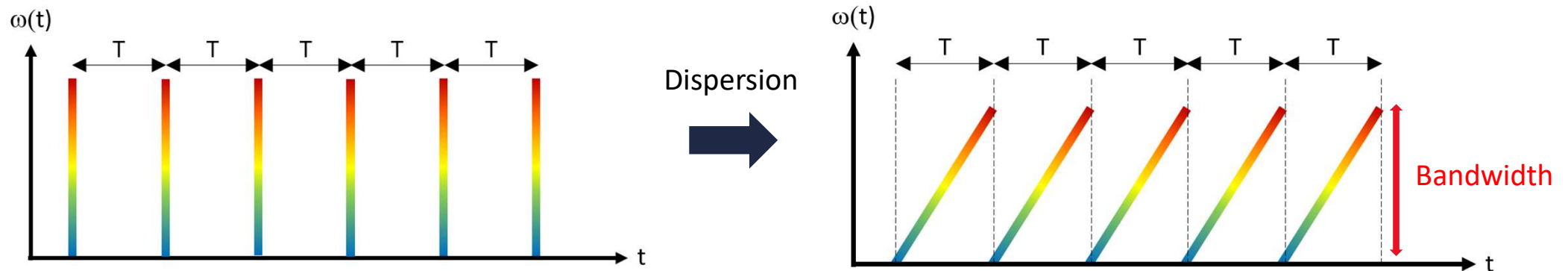


1. Spectral multiplexing : swept source

Our new approach → Heterodyne detection with stretched pulses

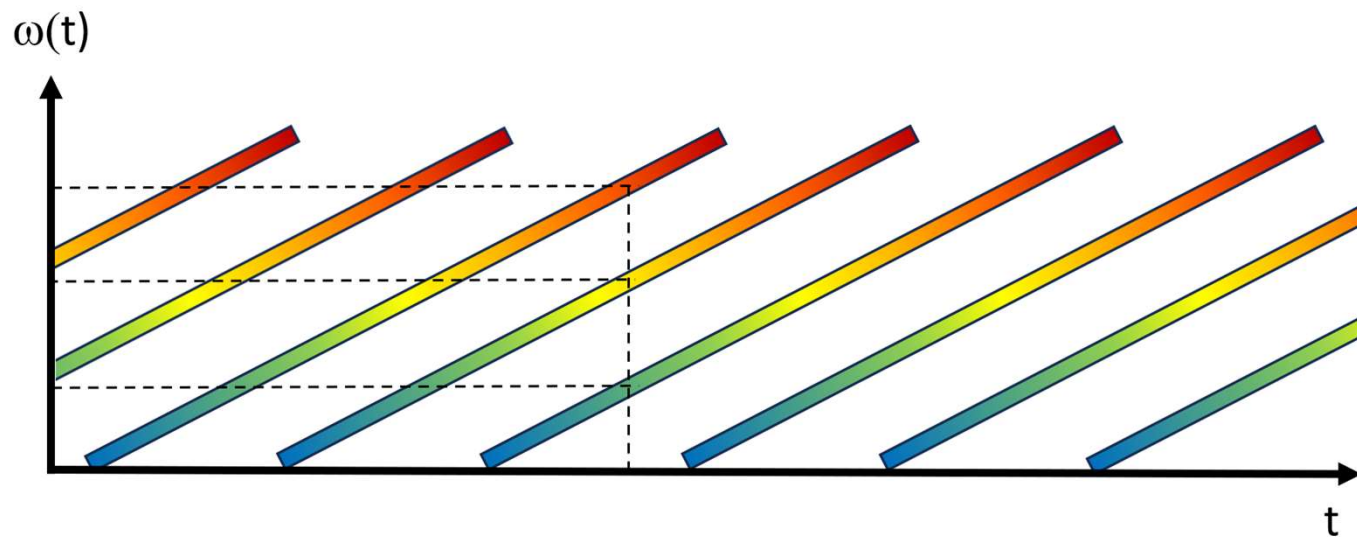
“The red frequencies travel faster than the blue ones”

- This shift of frequencies create an ultrafast ($\sim \text{ns}$) swept-source
- Tunable by bandwidth and amount of dispersion



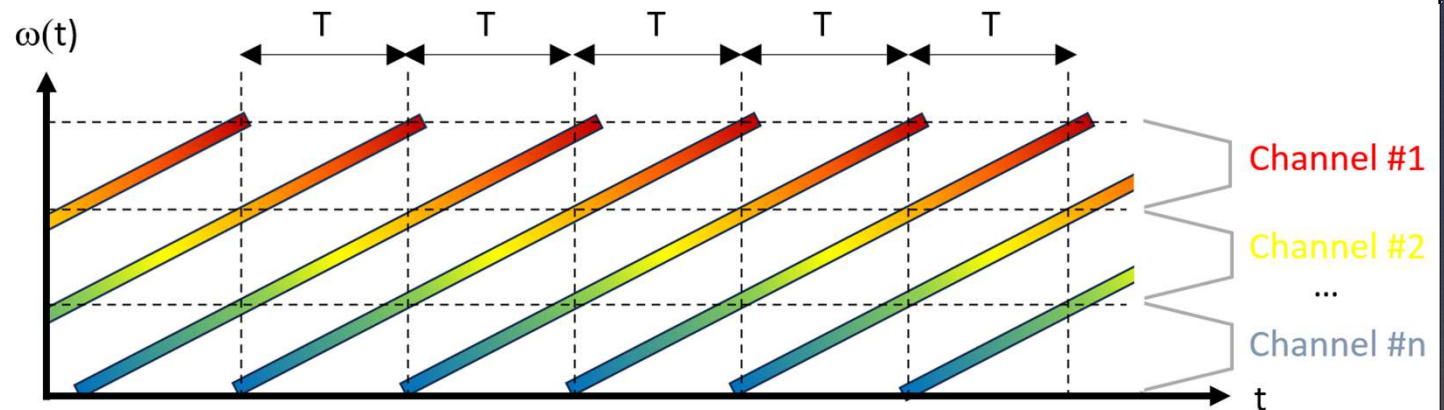
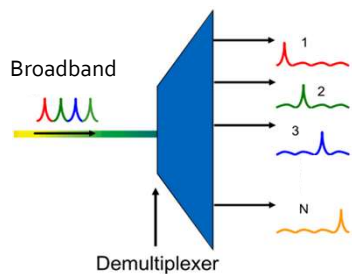
1. Spectral multiplexing : swept source

- Propagate through a **longer** dispersive fiber OR **larger bandwidth**
 - stretch the pulse duration up to **more than** the repetition period ($1/f_{rep}$)
 - **Several discrete frequencies at each time**



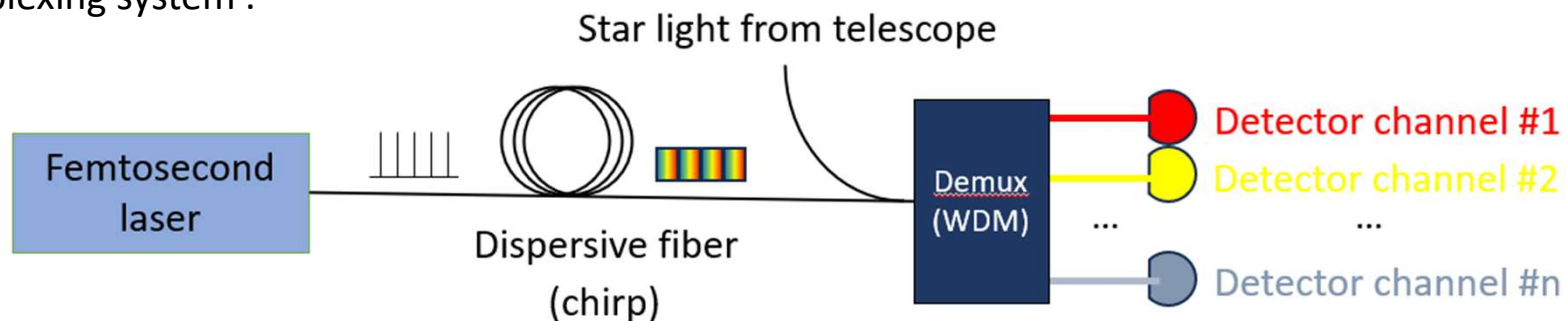
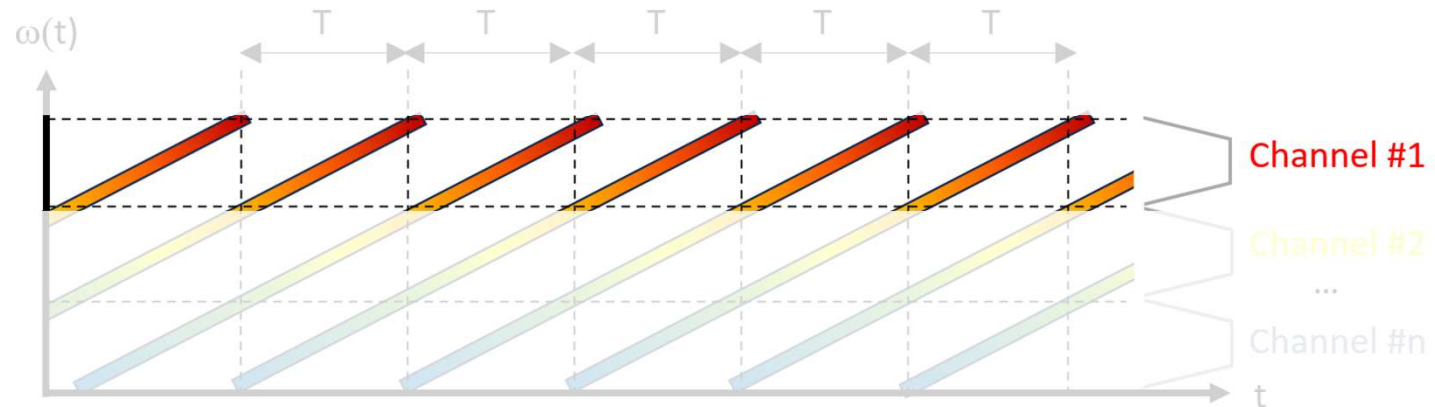
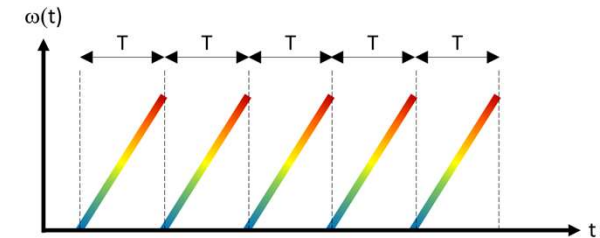
1. Spectral multiplexing : swept source

- Adding a demultiplexer (CWDM) to create N channels

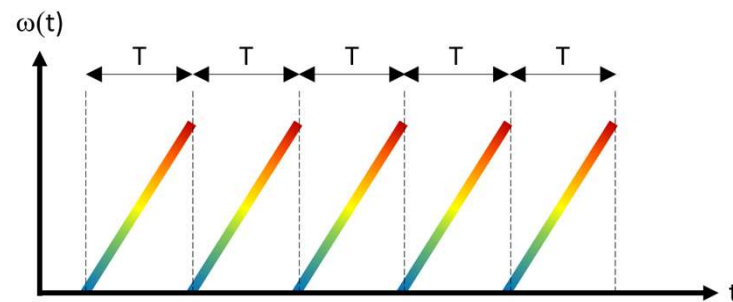


1. Spectral multiplexing : swept source

- Adding a demultiplexer to create n channels
- At each channel : a swept source and a narrow bandwidth (1 freq at each time)
- Allows for a very simple demultiplexing system :



Feasibility of this new **SERRODYNE** stellar interferometry ?

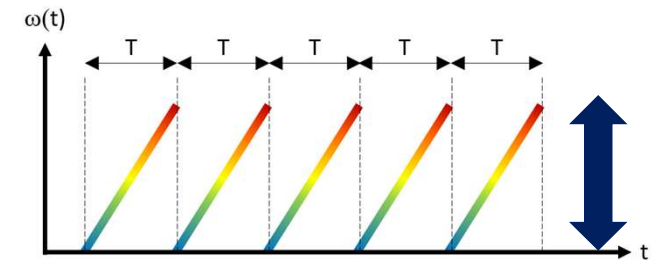
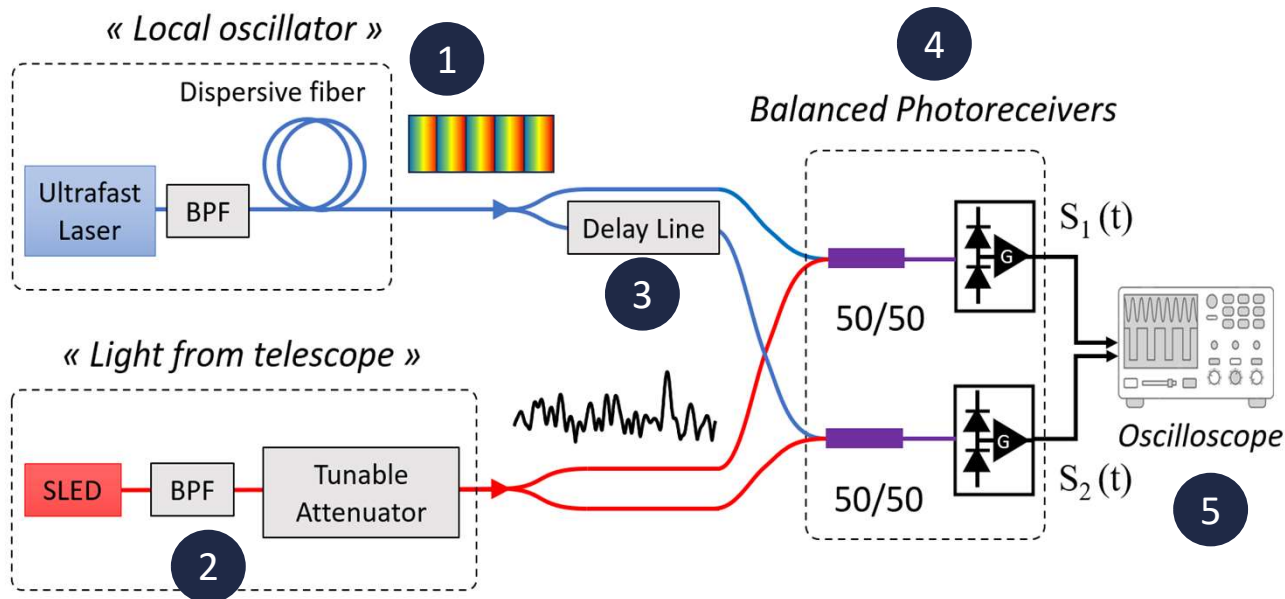


Serrodyne = the Latin **Serra**
"saw" for sawtooth + ...**dyne** for
heterodyne

In the H-band to rely on all the photonic components and mature technologies (ultrafast laser, fast and large band detectors, telecom fibers)

2. Single channel Proof of concept :

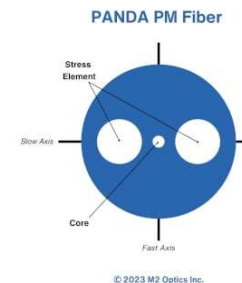
A two-arm all-PM-fiber serrodyne interferometer with telecom components :



Multi-function Integrated Optical Chip (MIOC)



Fiber couplers



Balanced 22GHz photodiodes

2. Single channel Proof of concept :

Temporal correlation measurement (noiseless) :

- At each delay $\tau \Rightarrow$ Pearson correlation coefficient :

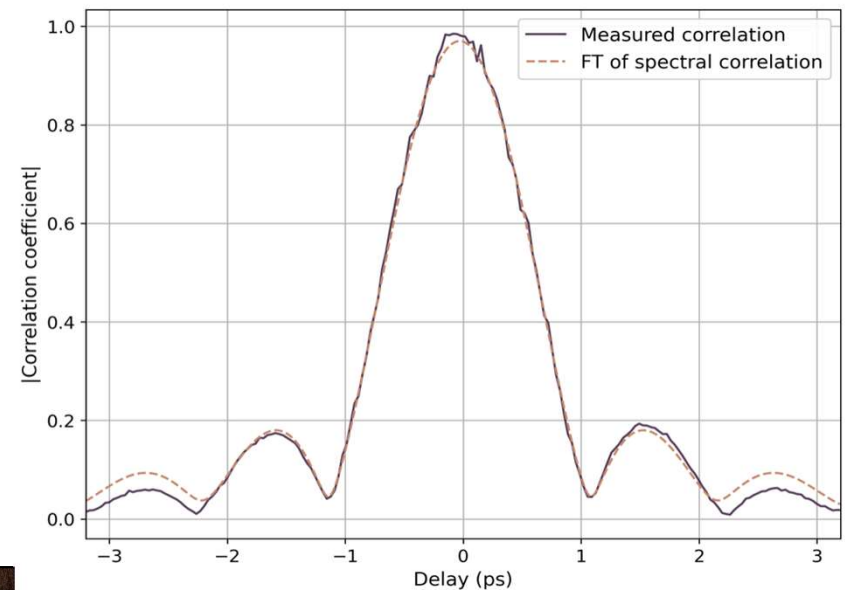
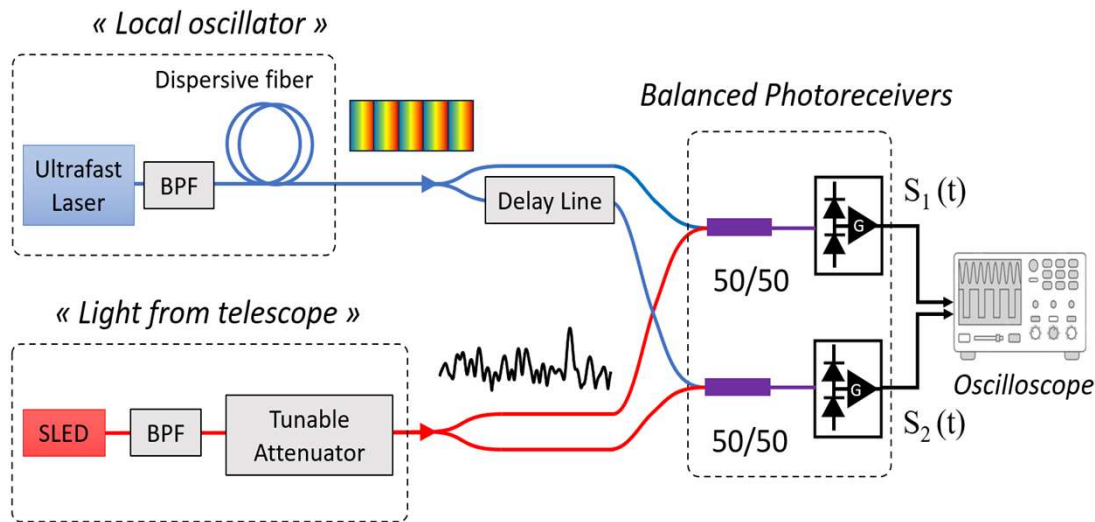
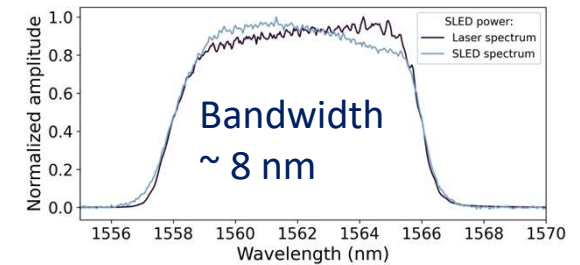
$$\rho_{1,2}(\tau) = \frac{\langle S_1(t) S_2(t - \tau) \rangle}{\sqrt{\langle S_1^2 \rangle \langle S_2^2 \rangle}} \sim \frac{\text{Re} \langle E_S(t) E_S^*(t - \tau) \rangle}{\langle I_S(t) \rangle}$$

Electric field of the signal
Delay

$$g_1(\tau, 0)$$

FT (artificial star spectrum)

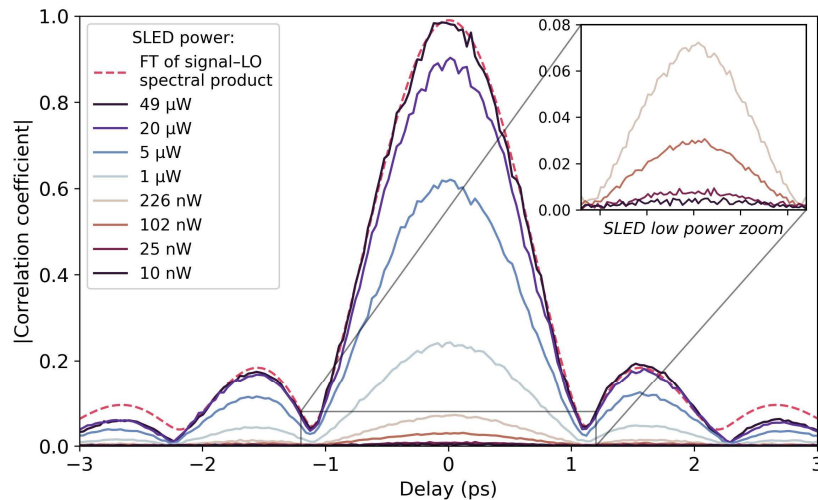
Sharp bandwidths $\Rightarrow \rho_{1,2}$ is a sinc^2



2. Single channel Proof of concept :

Detection limits :

- As the SLED power is reduced => coherent beatnote signals are dominated by uncorrelated noises and instrumental visibility decrease



- For a **400 μs** acquisition time per point, the limit astronomical flux is **1.5nW** per detector (i.e per telescope) over 8nm or 188pw/nm or 23,5 Gphotons/s

Broadband heterodyne interferometry in the H-band with chirped femtosecond laser

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ABSTRACT

Context. Infrared heterodyne interferometry offers a scalable alternative to direct interferometry for long-baseline telescope arrays. However, at near-infrared wavelengths, its sensitivity is limited by the electronic detection bandwidth and by the shot noise of the optical reference. Parallel detection via spectral multiplexing has long been identified as a potential means to increase the signal-to-noise ratio of heterodyne interferometers.

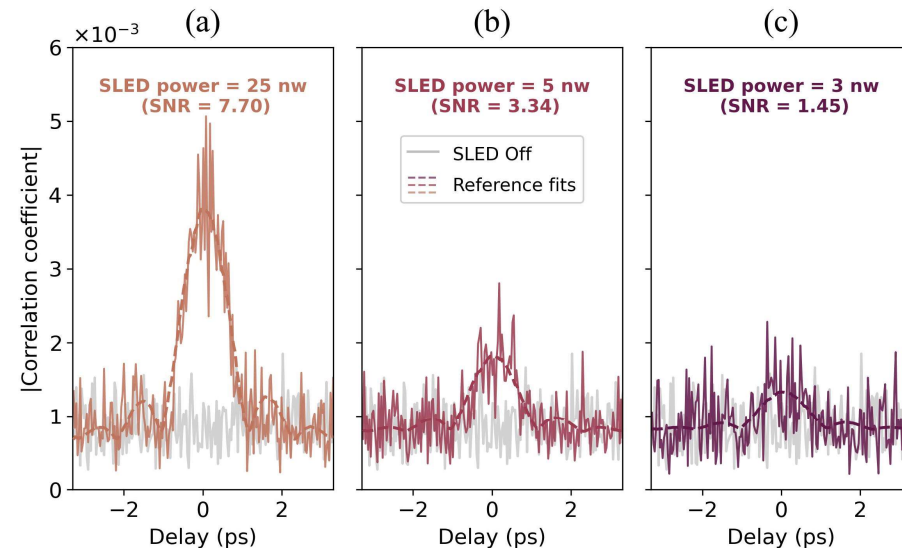
Aims. We propose a novel heterodyne detection architecture based on highly dispersed broadband pulses from a mode-locked laser, fast InGaAs photoreceivers, and numerical correlation. This enables straightforward spectral multiplexing with commercial components to increase the signal-to-noise ratio (SNR), while extending instantaneous wavelength coverage to simultaneous J- and H-band operation. The scheme also supports high-resolution spectroscopic imaging ($R = 10^3 - 10^4$).

Methods. We derive the SNR of a two-arm heterodyne interferometer based on balanced photodetection and apply the model to the proposed scheme, using measurements from a single-spectral-channel, all-fiber, polarization-maintaining interferometer operating at 1.56 μm over an 8 nm bandwidth.

Results. We experimentally demonstrate an SNR exceeding 2 for a spectral flux density of 188 pW nm^{-1} at 1.56 μm , with an integration time of 0.4 ms. Scaling the integration time and number of spectral channels suggests that fringe visibility of the brightest H-band stars could be achieved with 1 m² telescopes within the typical atmospheric coherence time.

Conclusions. These results represent a significant step toward broadband, scalable heterodyne interferometers, demonstrating the potential of ultrafast laser and telecommunications technologies for astronomical interferometry in the J+H bands. By combining broadband spectral multiplexing with numerical correlation, the architecture also opens a route to direct spectro-imaging without an additional spectrometer.

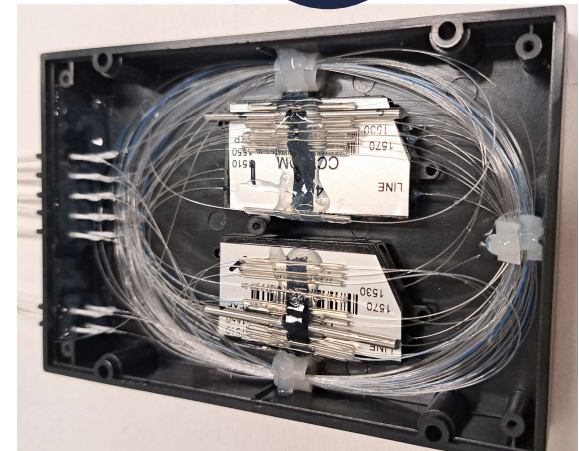
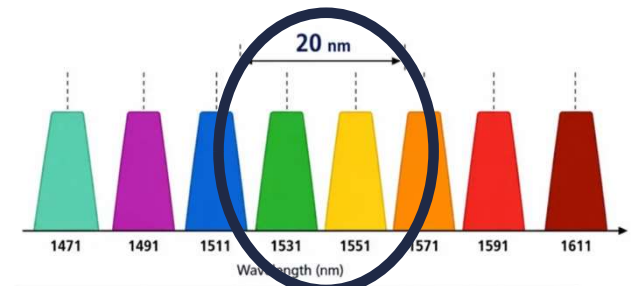
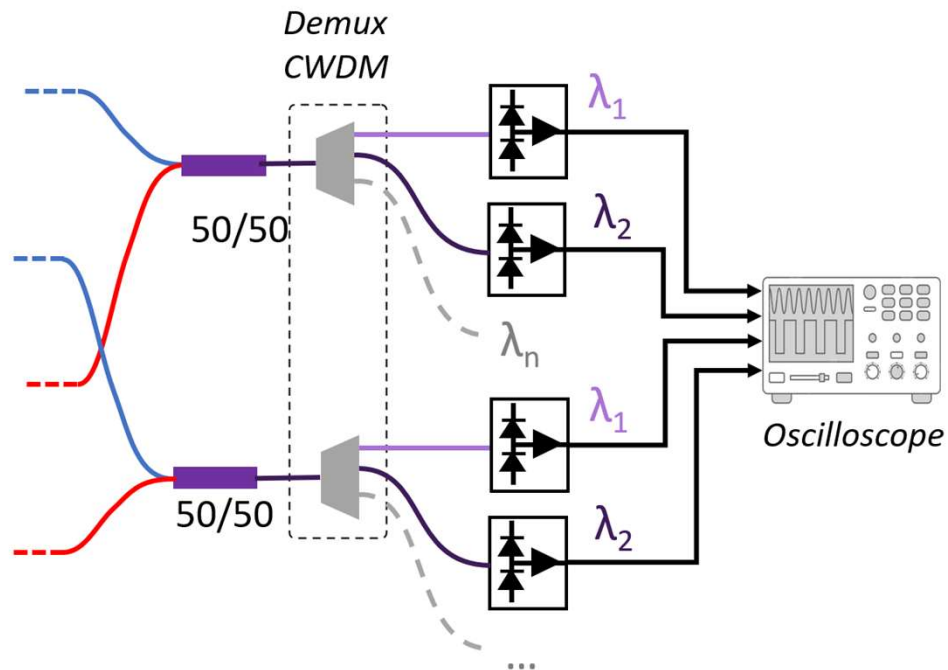
Pre-print : arXiv:2608.28098



3. Multiplexing demonstration :

Two-channel multiplexing for a 16 nm wide total bandwidth :

- Commercial CWDM, 4 channels, 20nm each, around 1540 nm, insertion loss 1.5 dB, uniformity 0.6 dB

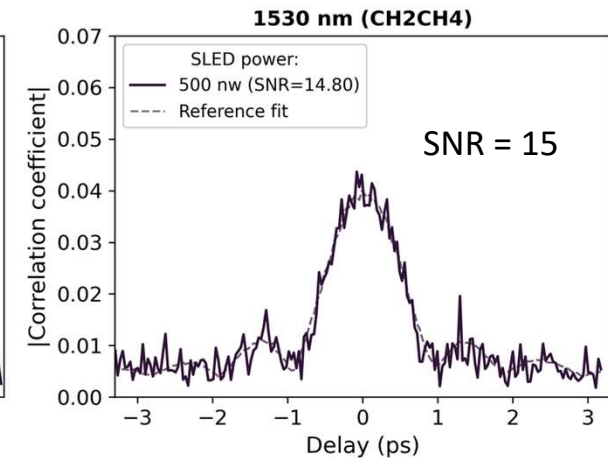
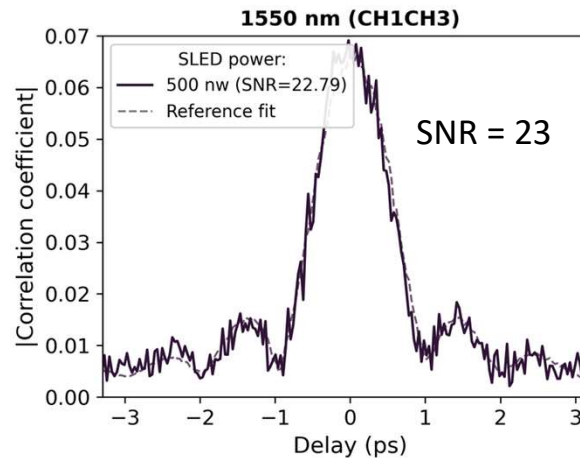
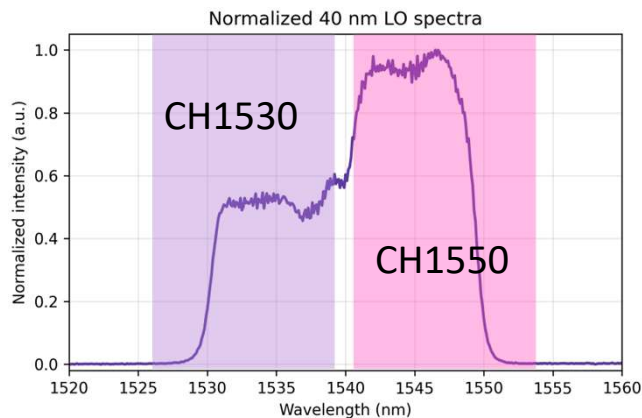
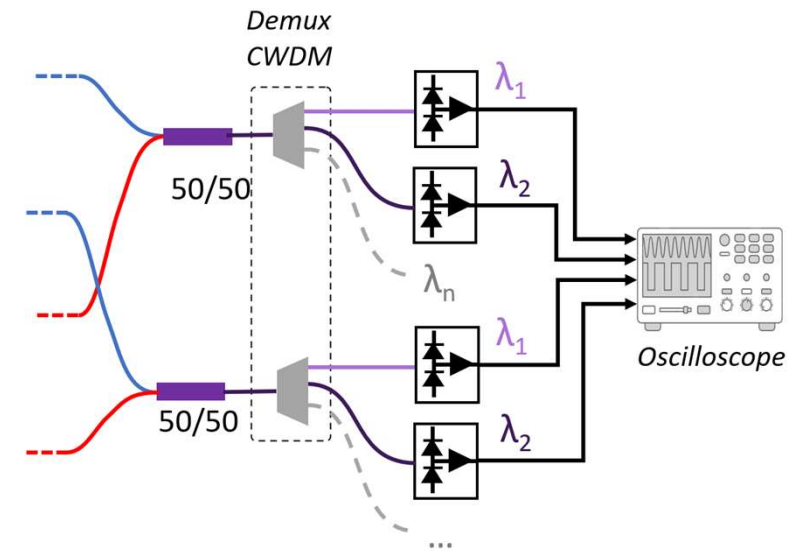


Inside each CWDM : cascaded thin-film filters give non-uniform loss across channels

3. Multiplexing demonstration :

Two-channel multiplexing for a 16 nm wide total bandwidth :

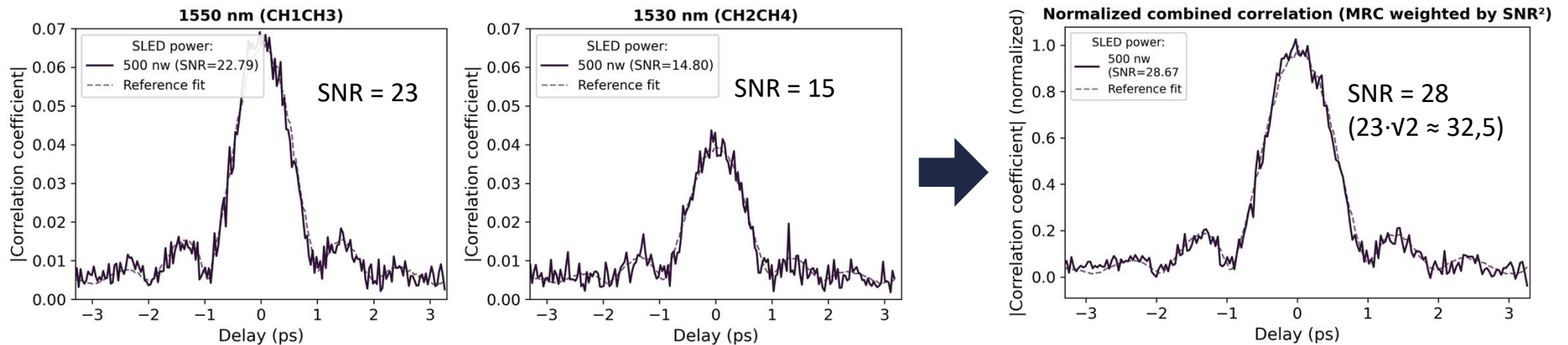
- Two parallel temporal correlations :
 - At each astronomical flux : different visibilities ?
 - Variable optical losses per channels
 - laser non-flat spectral profile : optical power is unequally distributed



3. Multiplexing demonstration :

A two channels multiplexing for a 16 nm wide total bandwidth :

- Maximum Ratio Coupling (MRC) : $SNR_{MRC} = \sqrt{(SNR_1)^2 + (SNR_2)^2} = \sqrt{2} SNR$ for equal SNRs



- BUT due to CWDM losses and non-flat LO spectrum : not better SNR than single channel prototype
- First demonstration of multiplexed stellar heterodyne interferometry system

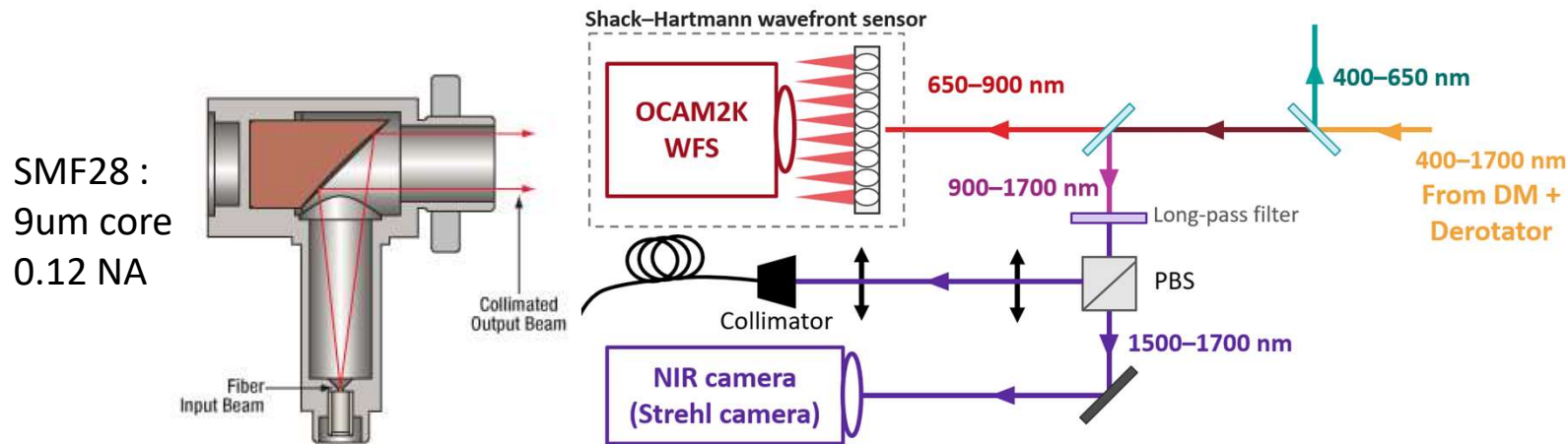
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On-sky viability : what about single mode fiber injection ?

4. Single mode fiber injection :

Injection in the H band with AO :

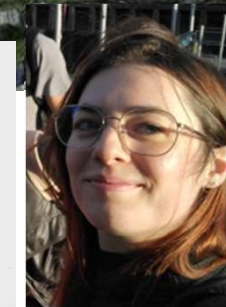
- Already operational AO system “AOC” @ C2PU, Calern
- Strehl ratio (AO efficiency metric) : how close the AO-corrected PSF is to the ideal diffraction-limited PSF.
- AOC On-sky Strehl: $\sim 40\% \rightarrow \sim 66\%$
- Setup :



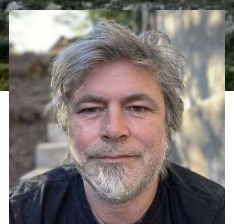
M. Carbillet



L. Abe



E. Lefebvre



O. Lai

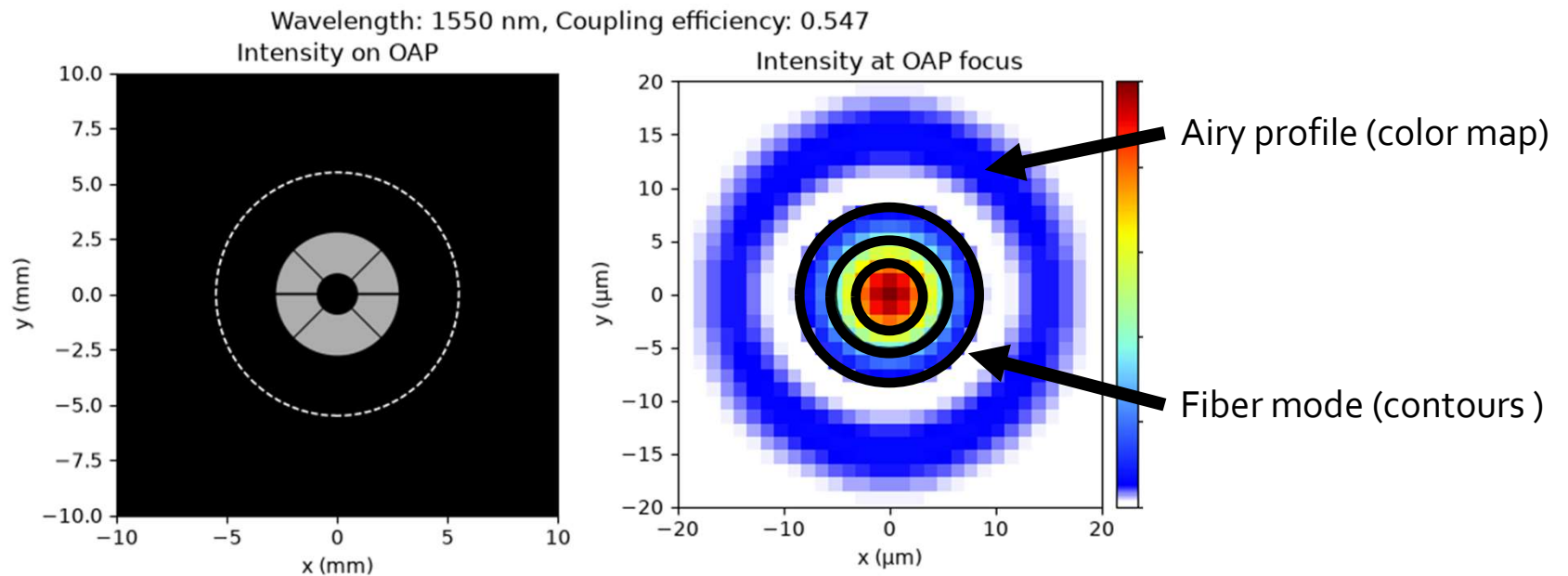
AO team @ C2PU



4. Single mode fiber injection :

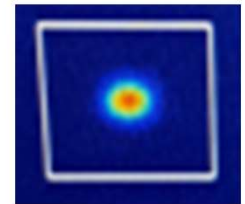
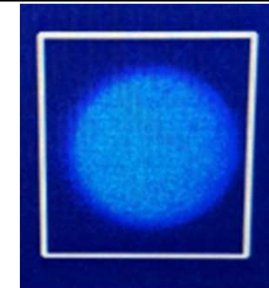
Injection in the H band with AO :

- Due to the telescope obscuration and spiders, : max injection of 54% of the light into the SMF



4. Single mode fiber injection :

MM output

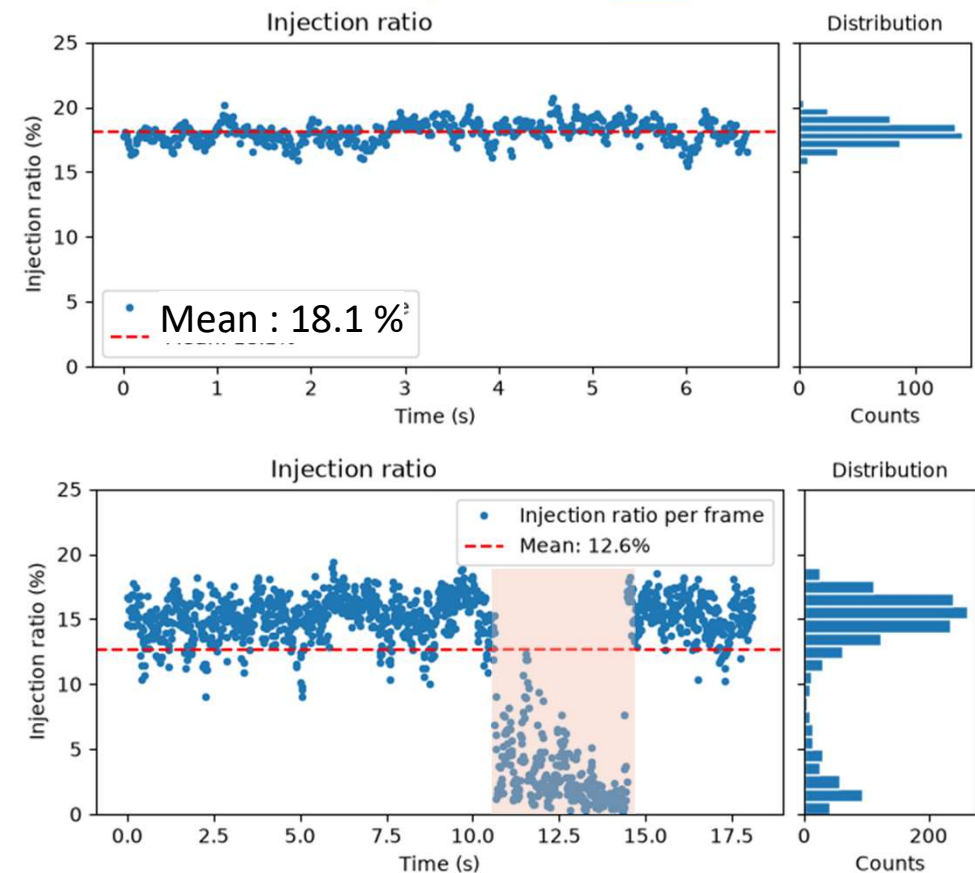


SM output

Injection in the H band with AO :

- **SMF injection: 10–18%** for **40–50% Strehl**
(max injection 54% due to PSF)
- **AO OFF:** injection drops to **1–2%**
- **Key point:** higher Strehl → better PSF quality → higher SMF coupling
- **Betelgeuse ($H \approx -4$):** **~ 0.16 nW** over 200 nm
 - equivalent to ~ 0.8 pW/nm , 6.4 M photon/s

For 400us : limit is **1.5nW** over 8nm or 188pw/nm
 → **22 s** for single channel, **1,4 s** for 16 channel



4. Conclusions :

- Proof of concept for the Stellar Serrodyne Interferometry : same detection limit than continuous LO [8]
- First lab demonstration of a multiplexed heterodyne interferometry for astronomy
- Monomode fiber injection with AO :
 - Calern's plateforme : planned collaboration with Nulling Interferometry photonics chips J.Calderon-Gomez, F.Martinache and N. Cvetojevic

Spectro-imaging + second-scale measurements + km baseline

Revival of the heterodyne interferometry ?

Thanks for your attention !

Searching for a Postdoc in 2027 !

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Photo : Serge Brunier