New technologies for aperture synthesis with mid-infrared heterodyne interferometry

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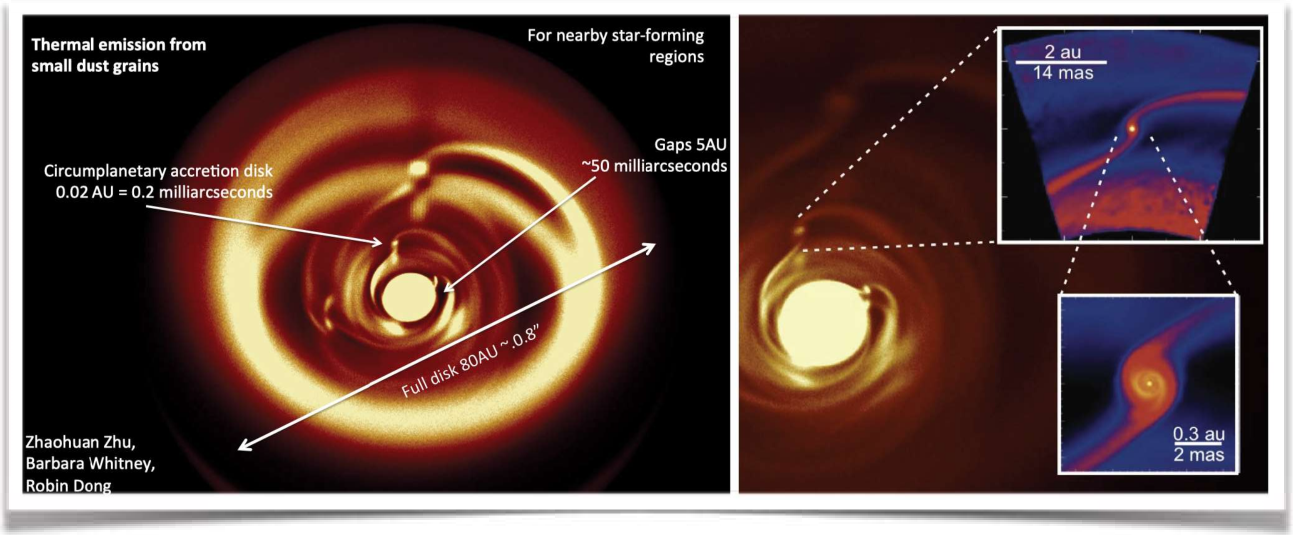


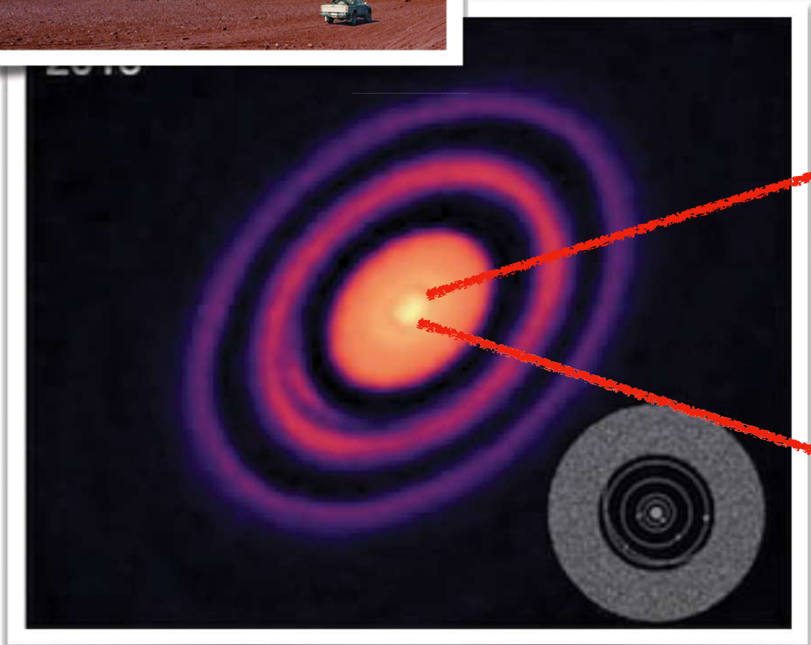
Stellar intensity interferometry workshop, Porquerolles 2024

Funding

Motivation for a multi-telescope imaging array

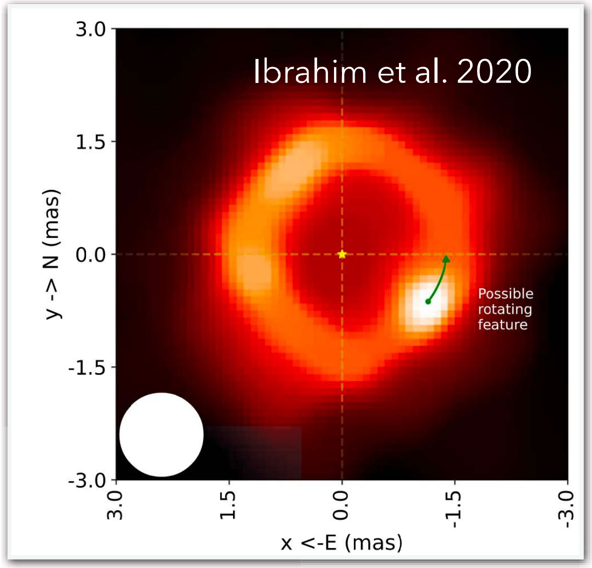
Infrared interferometry image complexity is limited by the number of telescopes

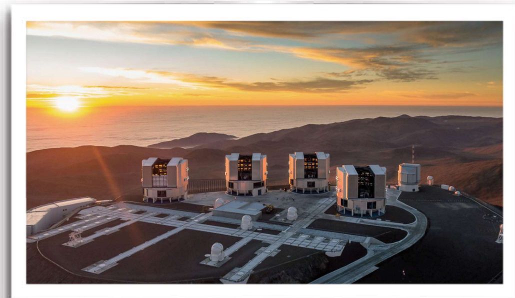
ALMA



Isella et al. 2018

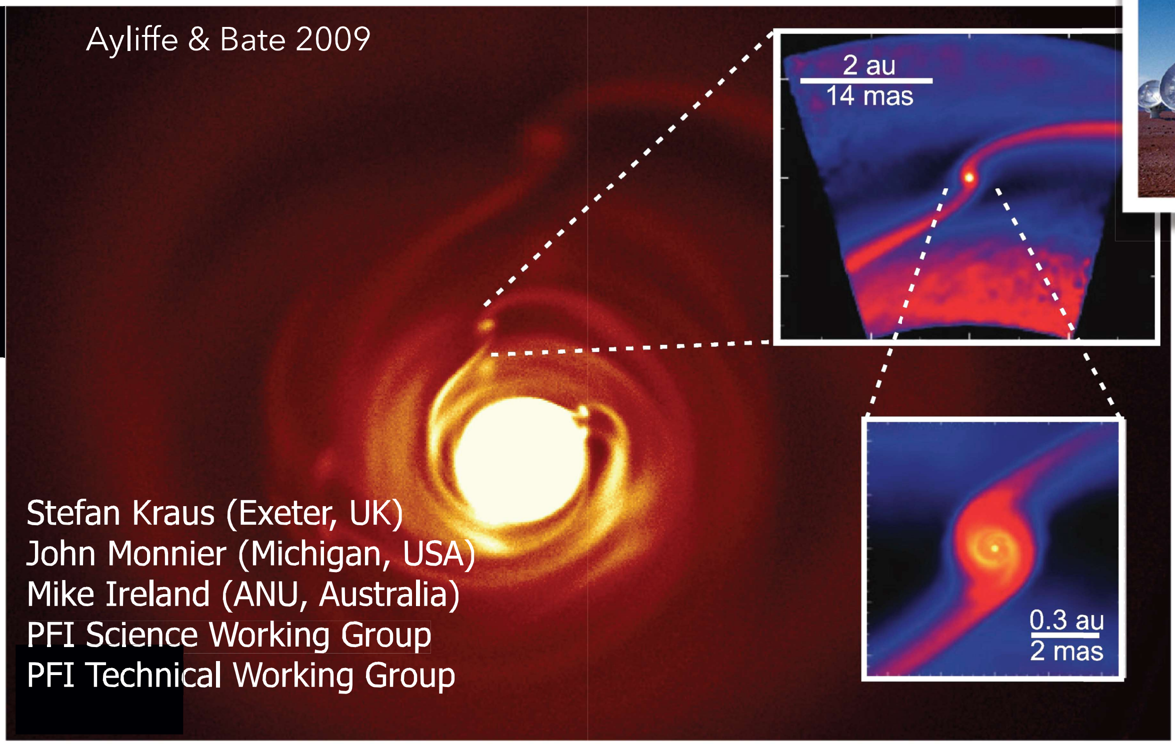
CHARA-MIRC/VLTI_PIONIER

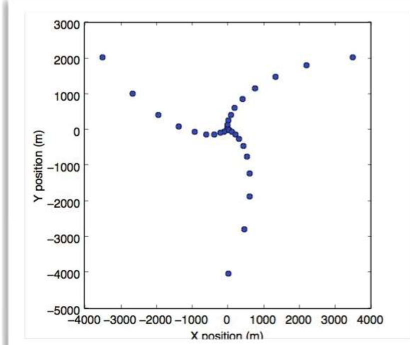




Planet Formation Imager: a facility designed to image the key stages of planet formation

- PI: J. Monnier
- PS: S. Kraus
- IS: M. Ireland
- SW Group
- TW Group

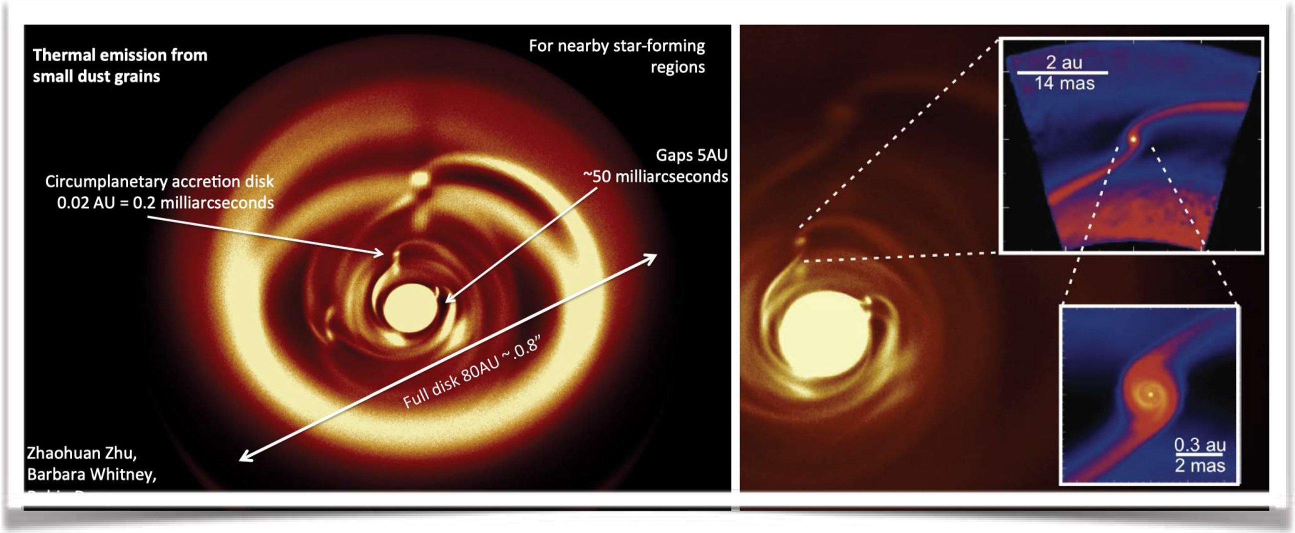




Top level science requirements

- Caracterising young exoplanets up to Taurus
- Resolving circumplanetary disks spatially and kinematically
- Mappping dust distribution and kinematics

PFI specifications: a starting point



Parameter	Value
Number of telescopes	12 to 21
Maximum baseline	1.2km
Science wavelengths	N band (possible ext. to Q band)
Sensitivity (point source, $5\,\sigma$)	$m_N \sim 12.5$ (0.36 mJy) in $t = 10^4\,s$
Surface brightness	$150\,K$ in $t = 10^4\,s$
Spectral resolution	$R = 100$ (300 GHz) to $R = 1 \times 10^5$ (300 MHz)
Number of spectral channel	50 to 10 000
Fringe tracking wavelengths	H and K band
Fringe tracking limits	$m_H < 13$ (point source)
Field of view	0.7" in N band

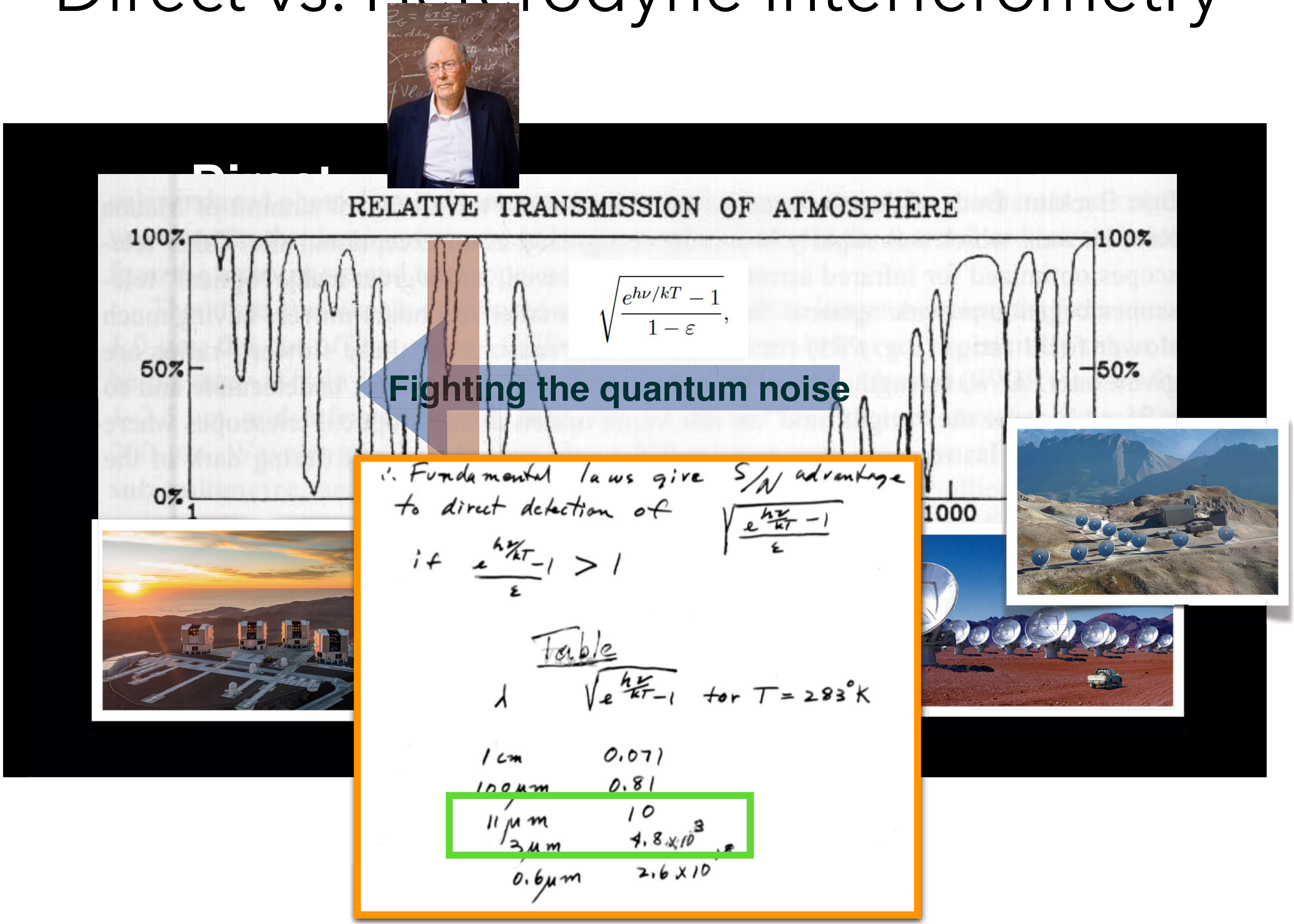
Monnier et al. 2016, 2018, Ireland et al. 2016

Direct vs. Heterodyne interferometry

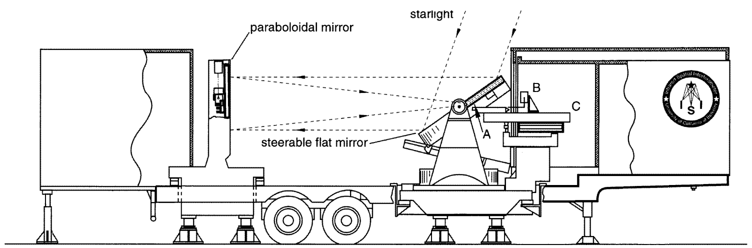
- Intrinsically more sensitive BUT …
- Simpler instrumentation
- Broad band
- Complex and expensive infrastructure
- Loss of sensitivity with the number of telescopes

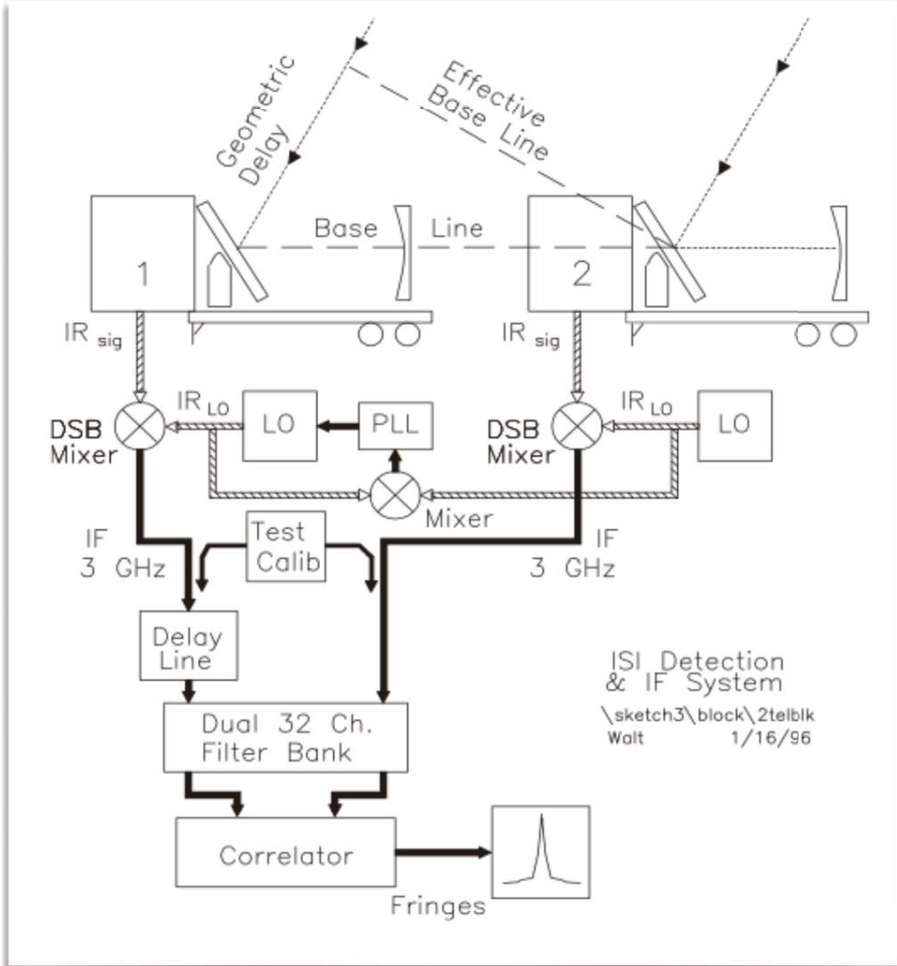
- Less sensisitive (quantum noise)BUT … Narrowband
- More complex instrumentation
- Simpler infrastructure
- Better adapted to a high number of telescope (can be amplified)

Direct vs. Heterodyne interferometry



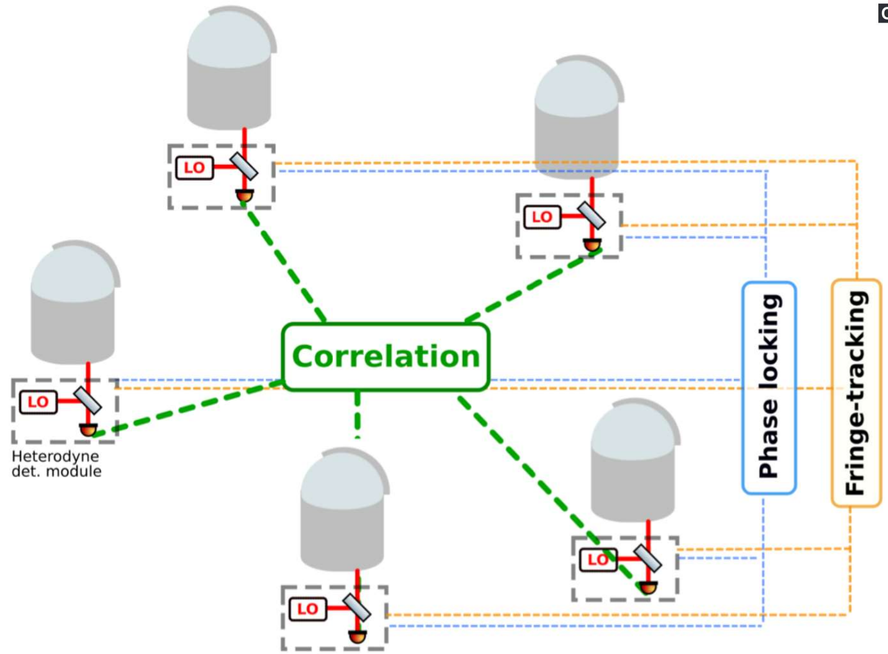
The Berkeley ISI precursor





Townes, 1984, Johnson et al. 1974, Johnston and Townes, 2000, Hale et al. 2000, Danchi et al. 2003, Wishnow

Long-term technology vision



The Astrophysical Journal, 875:134 (21pp), 2019 April 20 https://doi.org/10.3847/1538-4357/ab11c4
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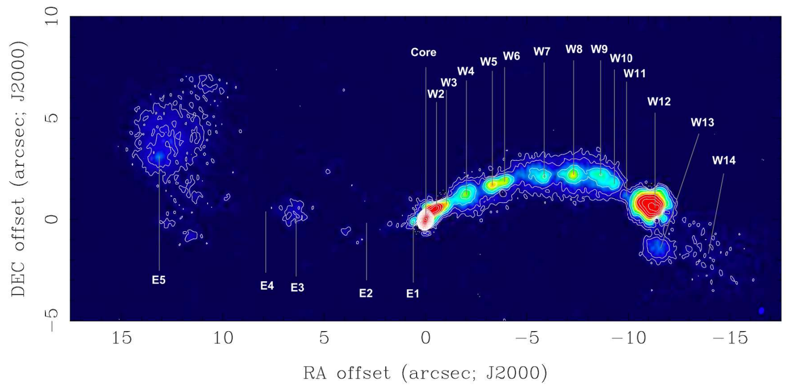
A Procedure for Making High Dynamic-range Radio Images: Deep Imaging of the Kiloparsec-scale Radio Structures of a Distant Blazar, NRAO 530, with JVLA Data

Jun-Hui Zhao[1], Mark R. Morris[2], and W. M. Goss[3]



9, and 33 GHz during the period between 2012 and 2015, we developed a procedure for the reduction of wideband data at high angular resolution. We have demonstrated that, correcting for residual interferometer errors, such as antenna-based errors caused by residual delays as well as baseline-based closure errors, radio astronomers can now achieve high-fidelity radio images with a dynamic range (peak:rms) exceeding 1,000,000:1. We outline the procedure in detail, noting that it can have broad application in the analysis of broadband continuum observations.

Dynamic ranges goes with number of telescopes (and quality of calibration)
=> need simplified infrastructure

Can we conceive a complete phased stabilised fiber-link capable of propagating mid-coherence ?

See alternative approaches by E. Michael 2018, 2019

10 Gbit s^{-1} Free Space Data Transmission at 9 µm Wavelength With Unipolar Quantum Optoelectronics

*Hamza Dely, Thomas Bonazzi, Olivier Spitz, Etienne Rodriguez, Djamal Gacemi, Yanko Todorov, Konstantinos Pantzas, Grégoire Beaudoin, Isabelle Sagnes, Lianhe Li, Alexander Giles Davies, Edmund H. Linfield, Frédéric Grillot, Angela Vasanelli, and Carlo Sirtori**

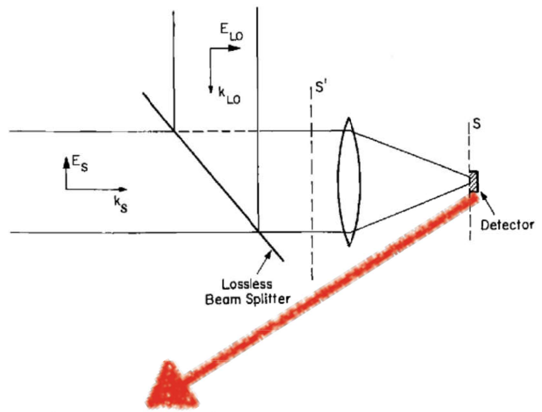
Free space optics data transmission with bitrate in excess of 10 Gbit s^{-1} is demonstrated at 9 µm wavelength by using a unipolar quantum

1. Introduction

Unipolar quantum optoelectronic

Industry is pushing mid-IR photonics technologies

Heterodyne in a nutshell



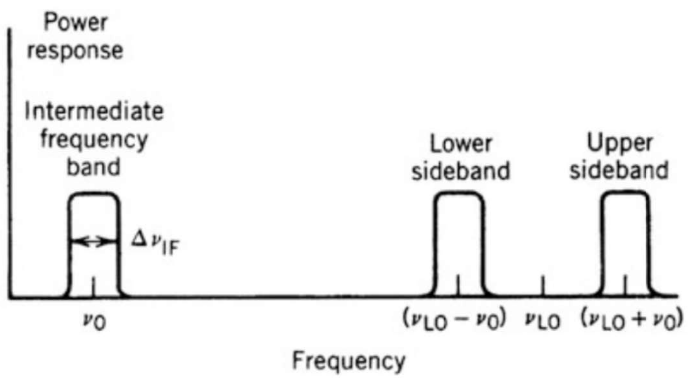
$$E(t) = E_L e^{-i\omega_L t} + E_S e^{-i\omega_S t}$$

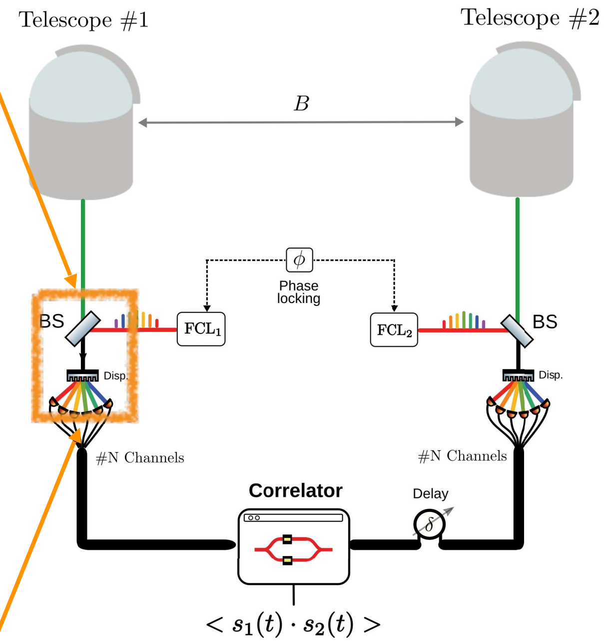
Phase detection

$$i(t) \propto \frac{\eta e}{h\nu}|E(t)|^2 = i_L(t) + i_S + 2\sqrt{i_L i_S} cos((\omega_S - \omega_L)t + \phi)$$

Noise and Signal

Noise and Signal

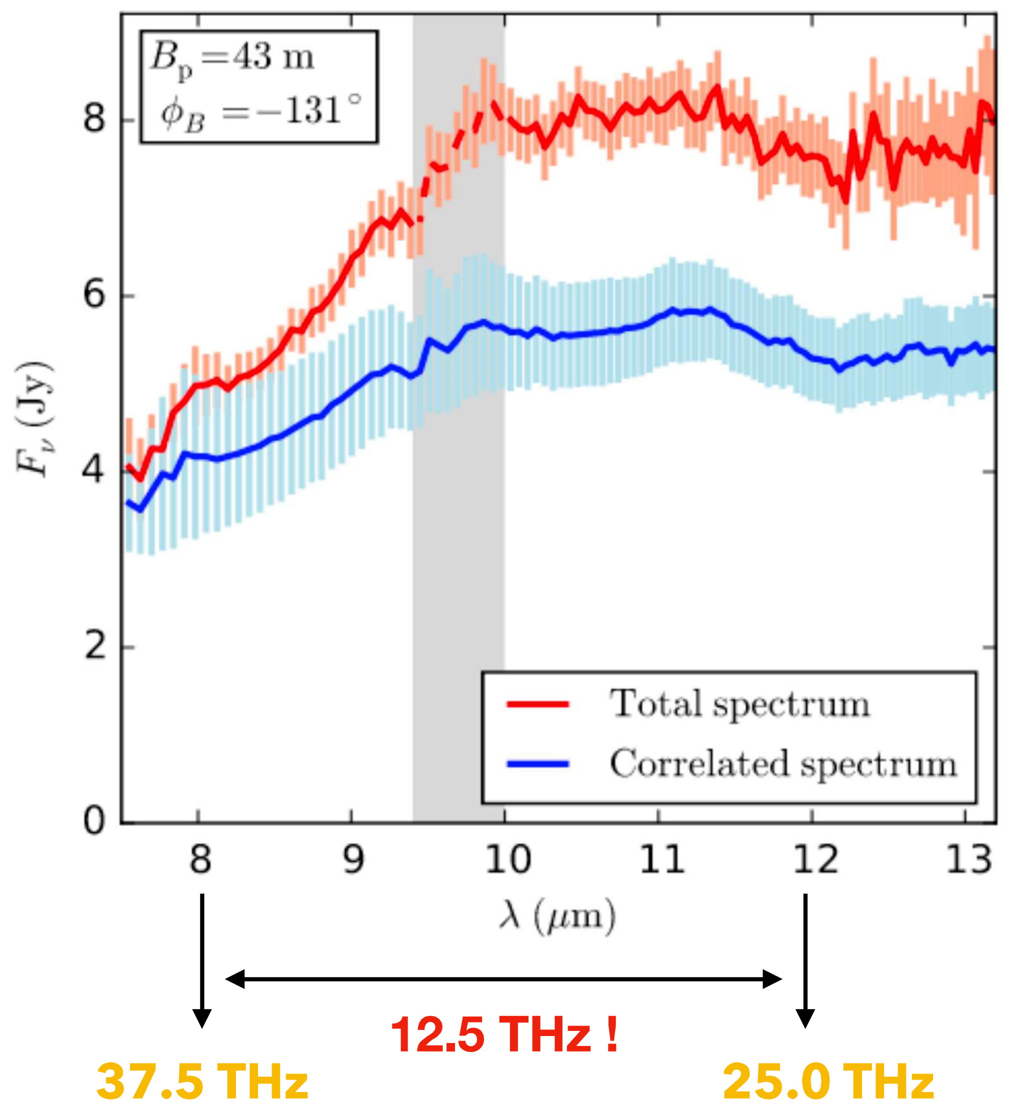




The sensitivity issue

Direct interferometry correlated spectrum

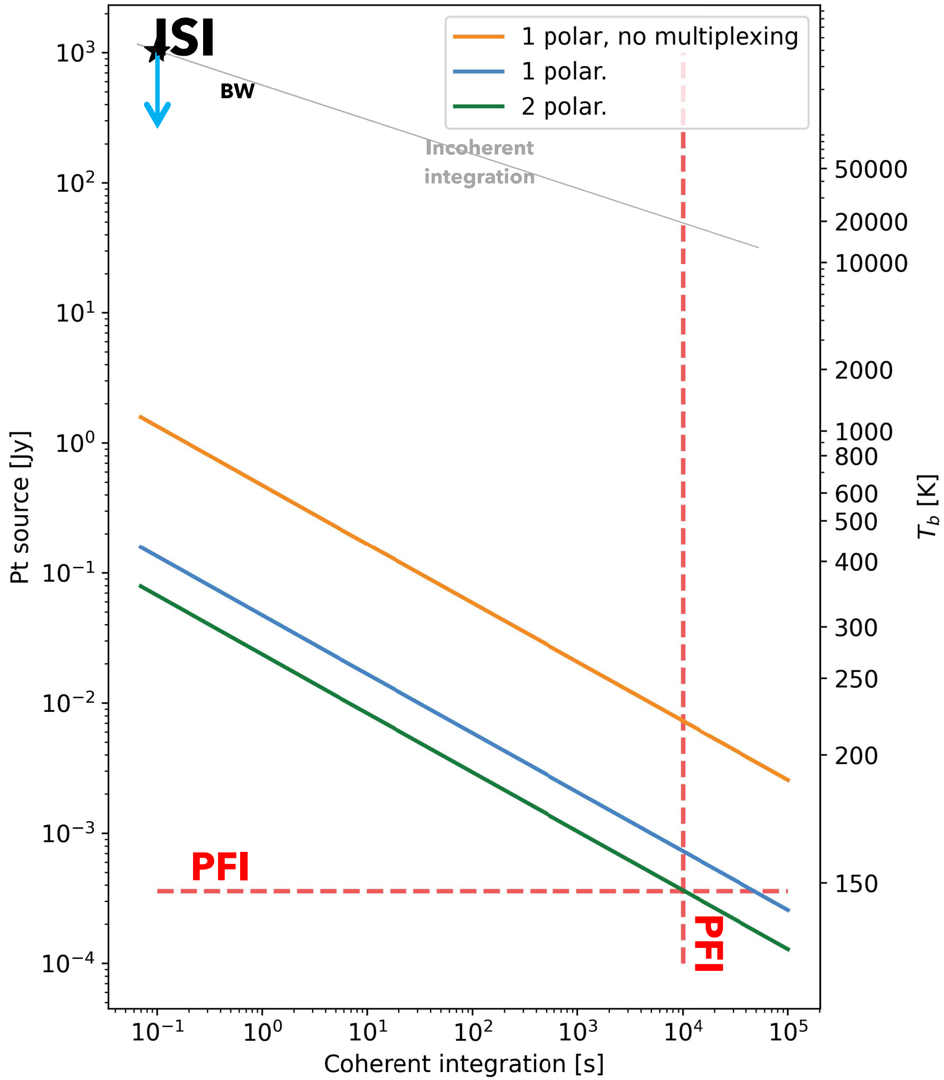
MIDI instrument at VLTI



Sensitivity budget

Item	Parameter	Gain

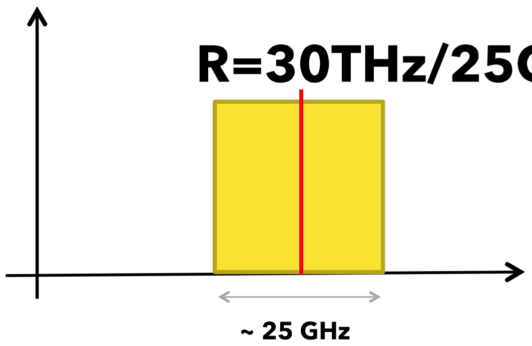
- ISI: (2.5GHz , QE=50%)
  R=30THz/2GHz=15,000

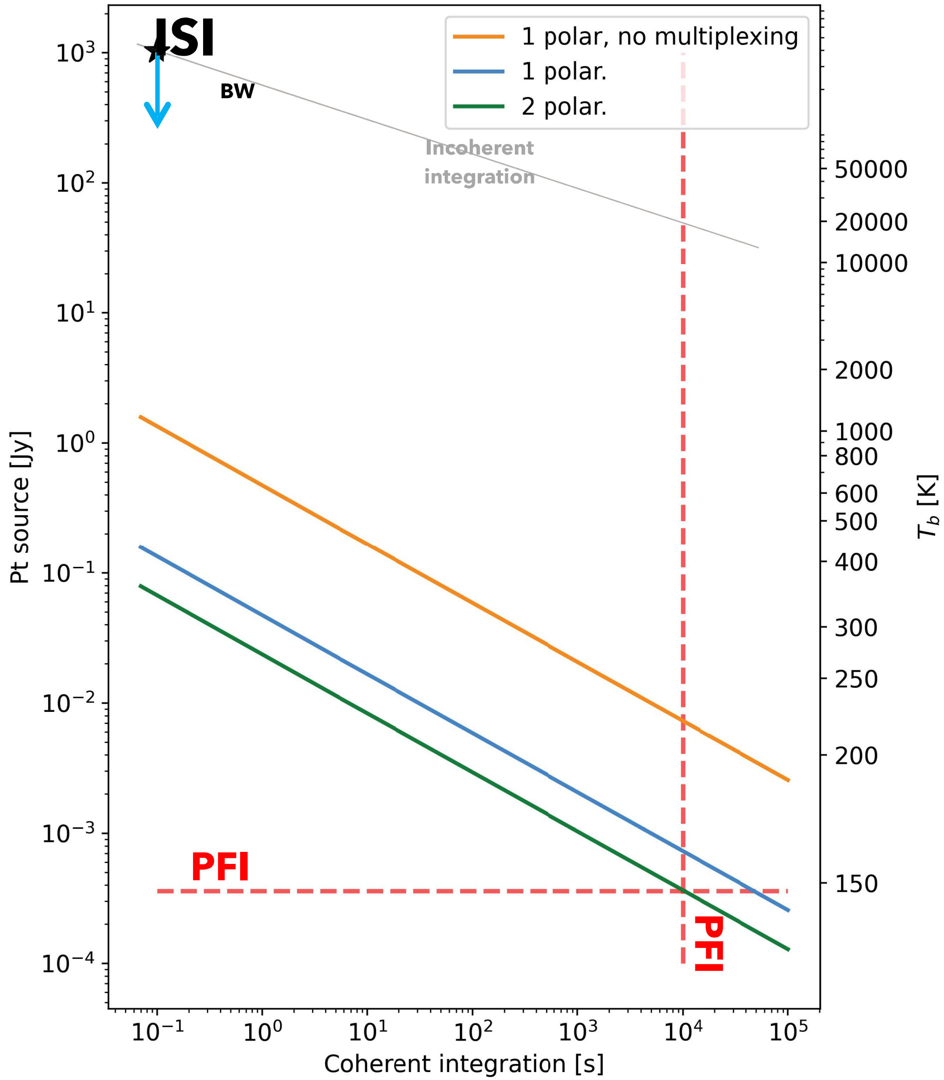


Sensitivity budget

Item	Parameter	Gain
Detector bandwidth	$\Delta\nu$	$\sqrt{10} = \times 3$

- High bandwidth detectors (25GHz , QE=50%)

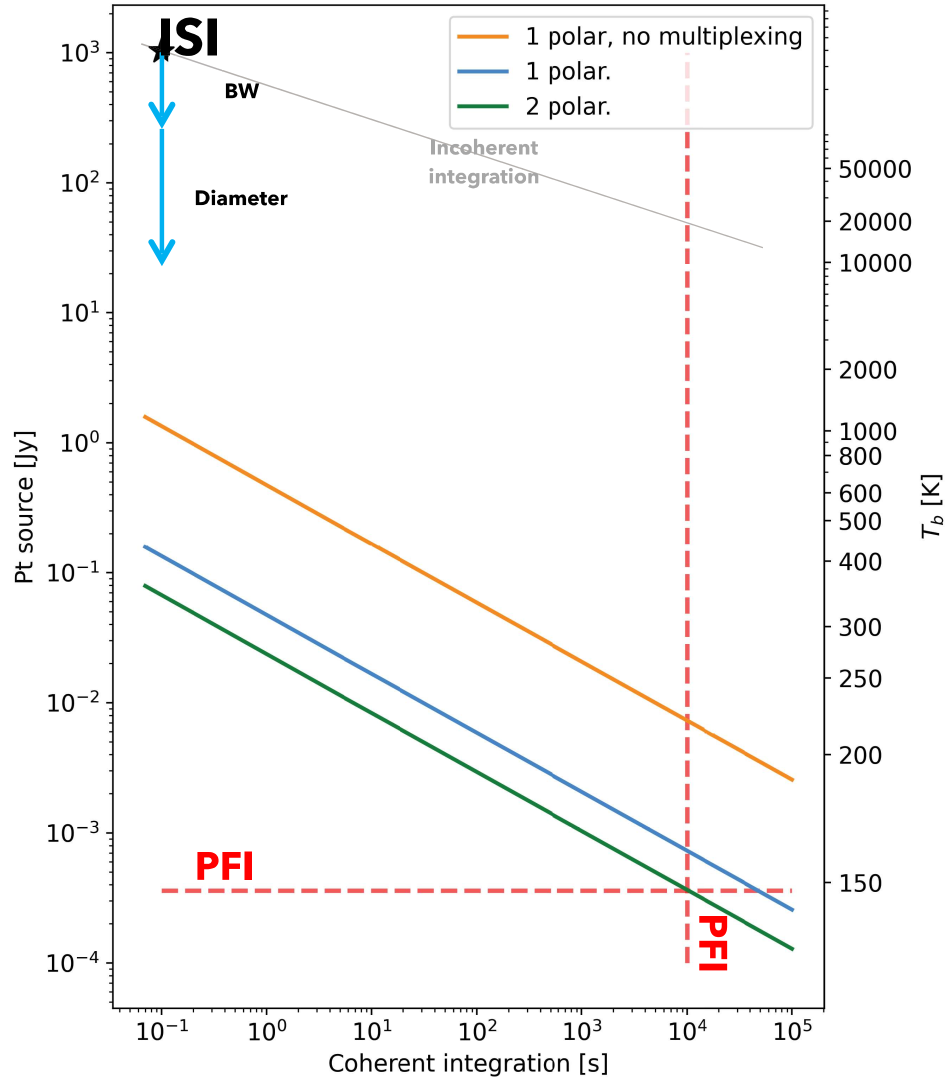




Sensitivity budget

Item	Parameter	Gain
Detector bandwidth	$\Delta\nu$	$\sqrt{10} = \times 3$
Telescope diameter	D	$\times 1$ to $\left(\frac{4.5}{1.6}\right)^2 = \times 7.9$

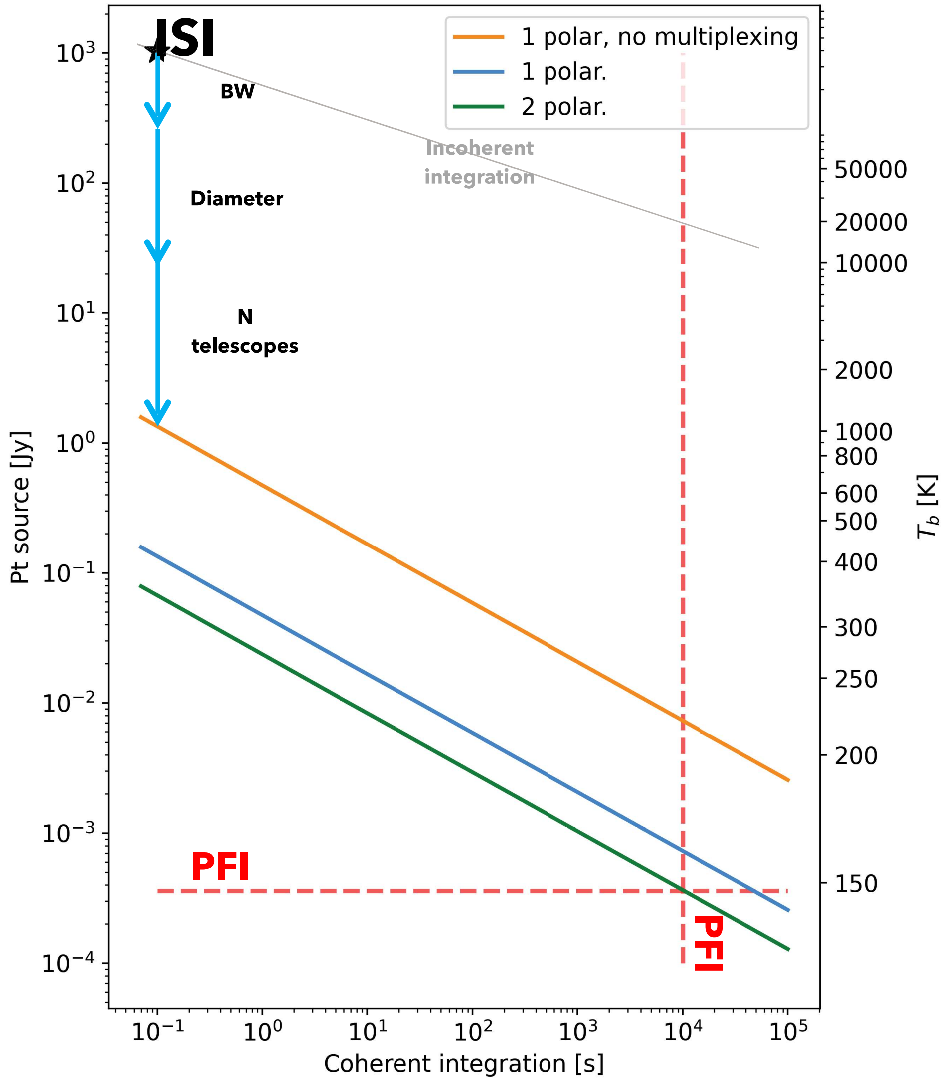
- Large diameter telescopes (4.5m)



Sensitivity budget

Item	Parameter	Gain
Detector bandwidth	$\Delta\nu$	$\sqrt{10} = \times 3$
Telescope diameter	D	$\times 1$ to $\left(\frac{4.5}{1.6}\right)^2 = \times 7.9$
Number of telescopes	N_t	$\times 1$ to $\sqrt{\frac{N_t(N_t-1)}{2}} = \times 8.1/\times 15$

- Large number of telescopes (12<N<25)



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Item	Parameter	Gain
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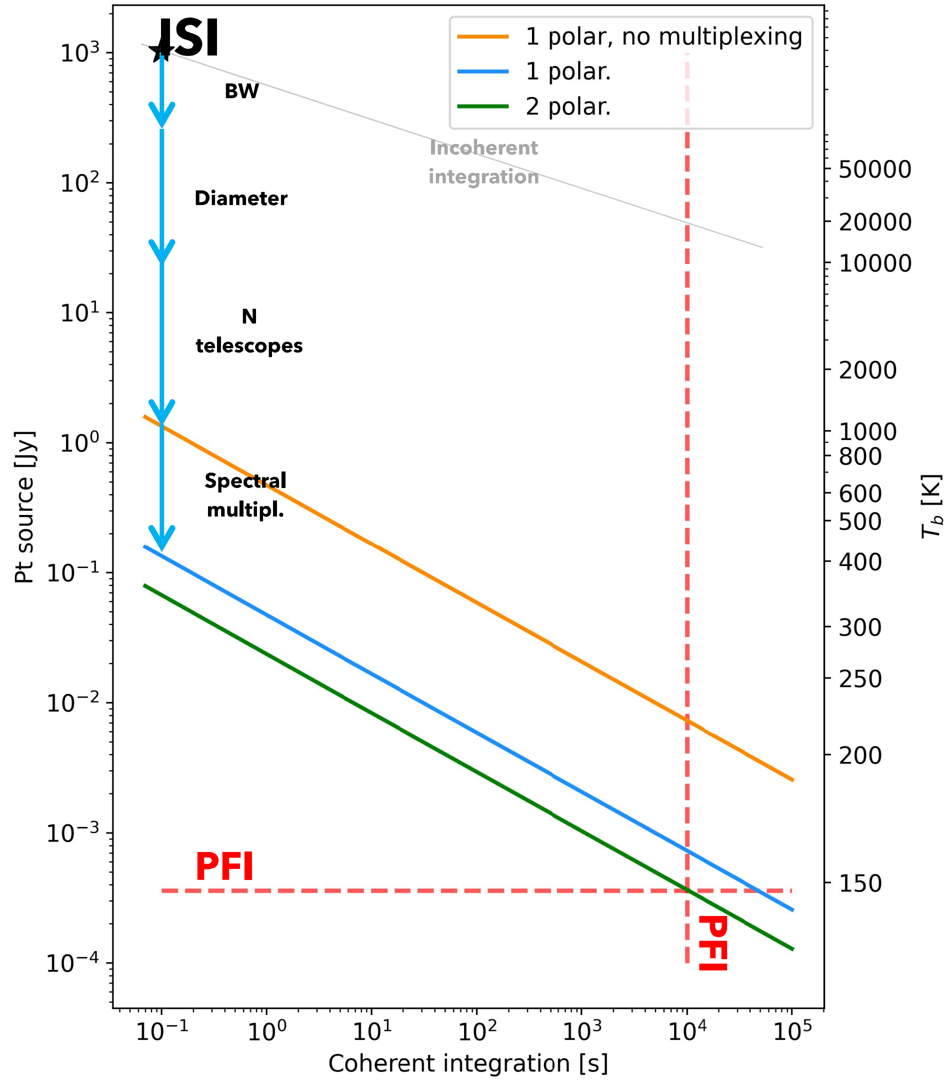
Number of telescopes	N_t	$\times 1$ to $\sqrt{\frac{N_t(N_t-1)}{2}} = \times 8.1/\times 15$
Spectral channels	N_{SD}	$\times 1$ to $\sqrt{100} = \times 10$

- QCLs and Frequency combs lasers (FCLs) in mid-IR
- Efficient HR disperser in the mid-IR



Sensitivity budget

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Detector bandwidth	$\Delta\nu$	$\sqrt{10} = \times 3$
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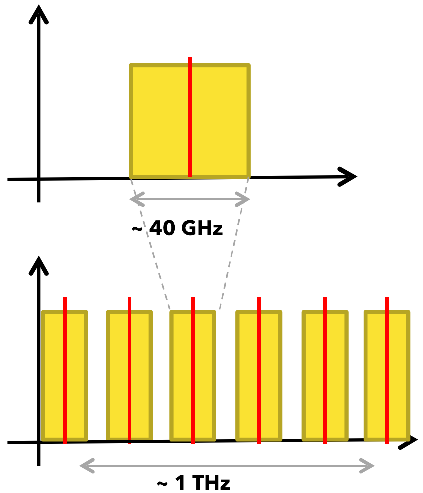
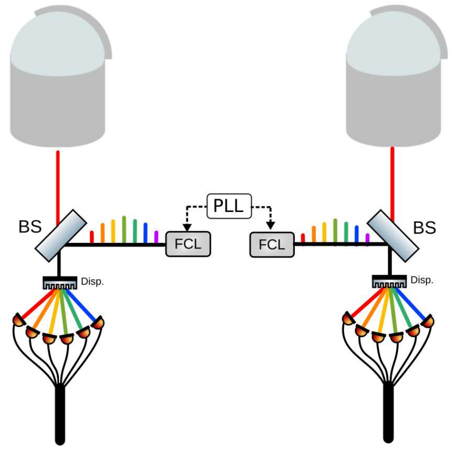


Swenson, 1986
Ireland & Monnier, 2014



Sensitivity budget

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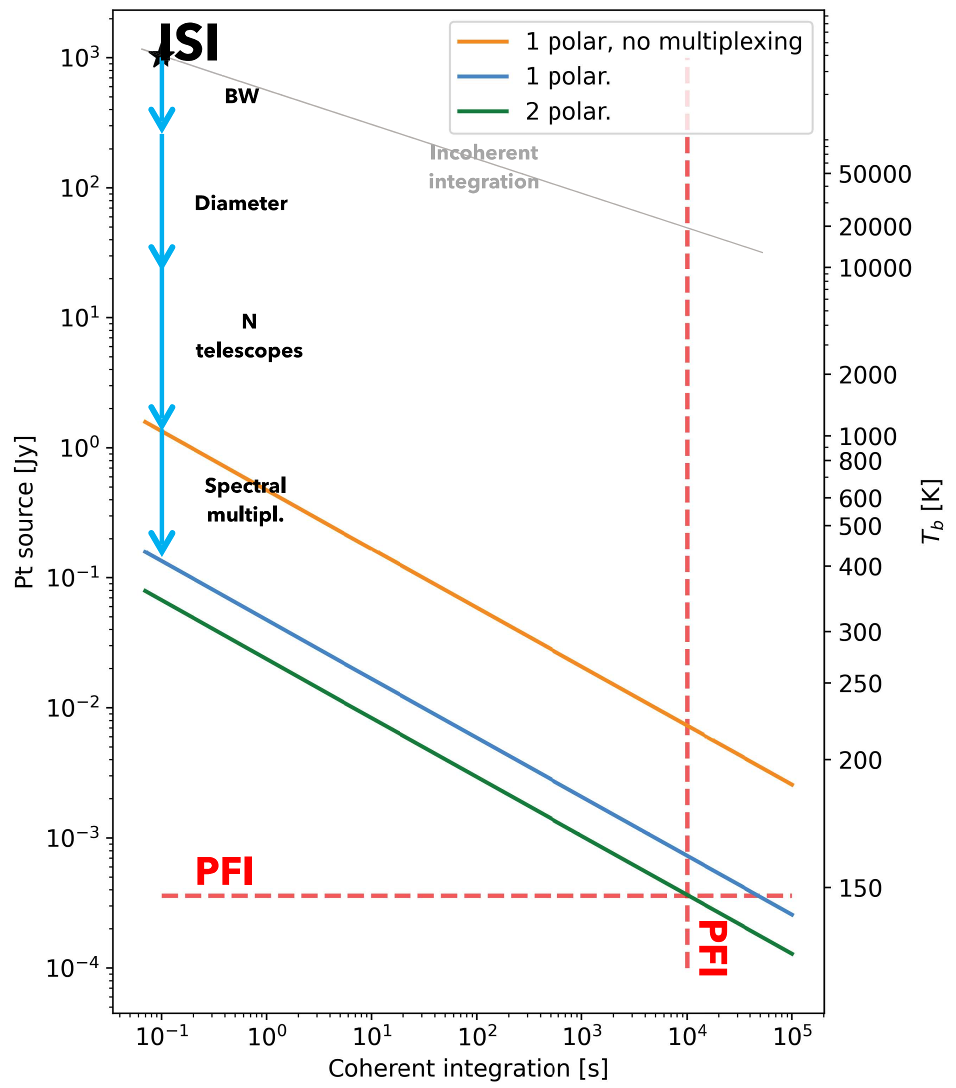
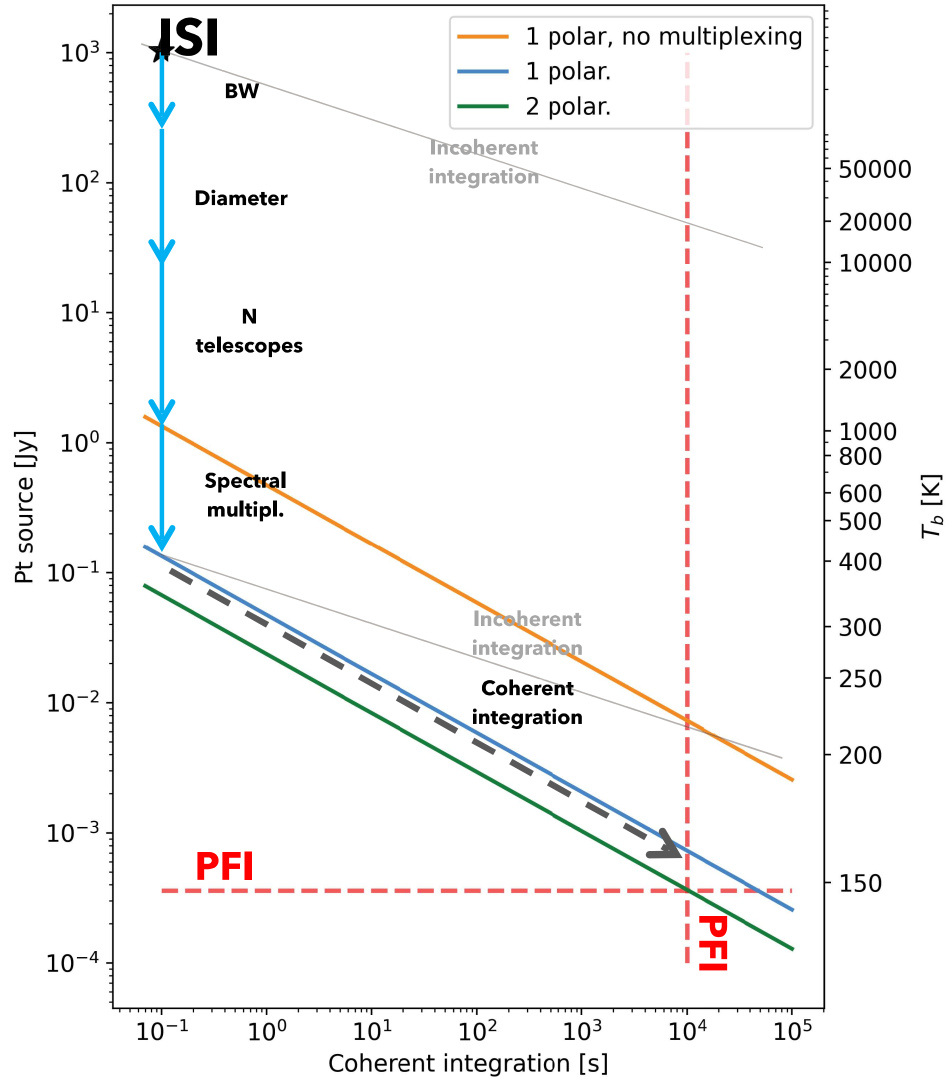


Sensitivity budget

Item	Parameter	Gain
Detector bandwidth	$\Delta\nu$	$\sqrt{10} = \times 3$
Telescope diameter	D	$\times 1$ to $\left(\frac{4.5}{1.6}\right)^2 = \times 7.9$
Number of telescopes	N_t	$\times 1$ to $\sqrt{\frac{N_t(N_t-1)}{2}} = \times 8.1/\times 15$
Spectral channels	N_{sp}	$\times 1$ to $\sqrt{100} = \times 10$
Coherent integration	t_c	$(60 \times 10)^{1/4} = \times 4.9$ and $(3600 \times 10)^{1/4} = \times 14$

- External fringe-tracker (NIR)



Exploring photonics technologies building blocks

- Mid-infrared detection
- High bandwidth correlation
- Local oscillator distribution
- Mid-infrared combs

High bandwidth detection

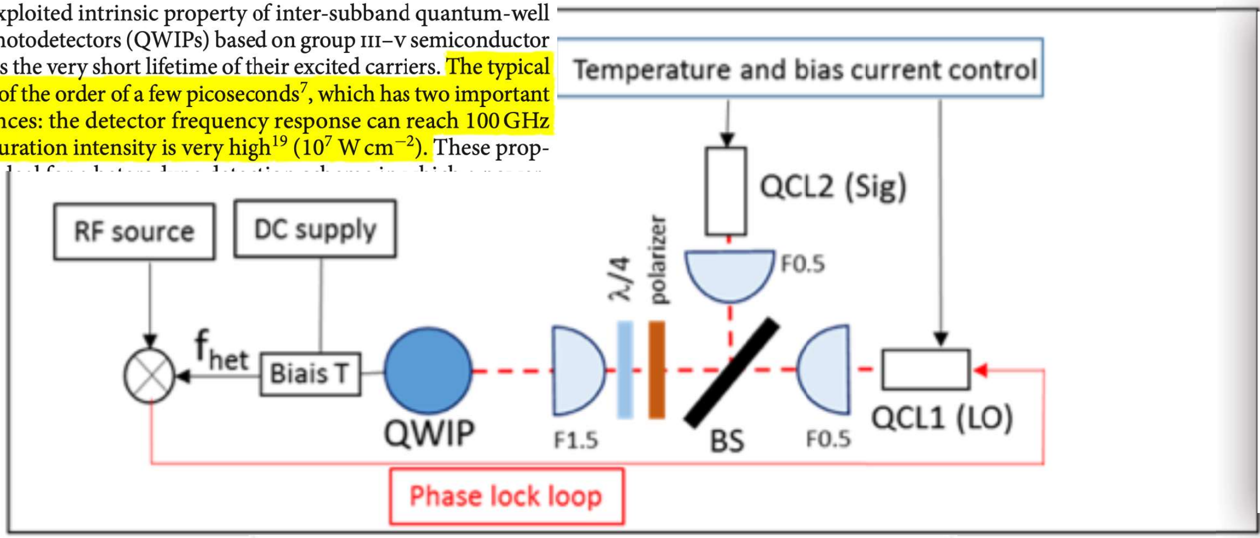
LETTER

doi:10.1038/nature25790

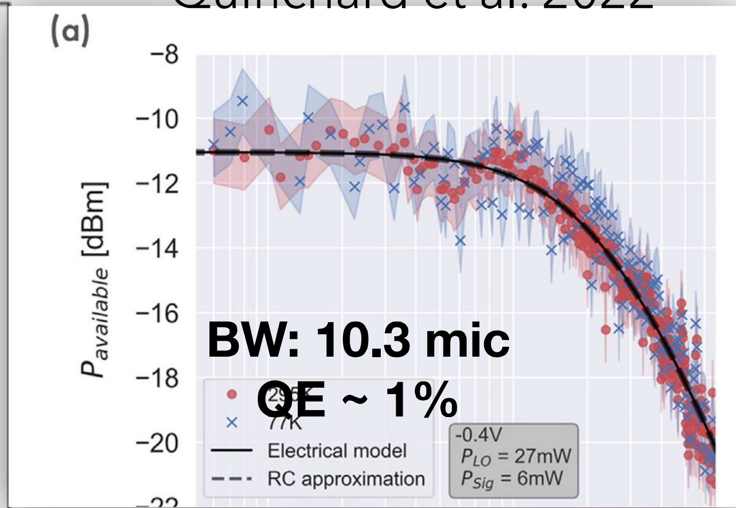
Room-temperature nine-µm-wavelength photodetectors and GHz-frequency heterodyne receivers

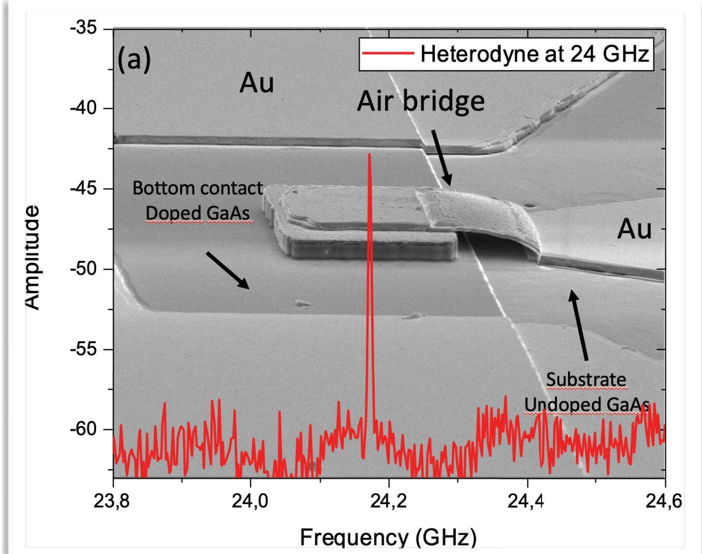
Daniele Palaferri[1], Yanko Todorov[1], Azzurra Bigioli[1], Alireza Mottaghizadeh[1], Djamal Gacemi[1], Allegra Calabrese[1], Angela Vasanelli[1], Lianhe Li[2], A. Giles Davies[2], Edmund H. Linfield[2], Filippos Kapsalidis[3], Mattias Beck[3], Jérôme Faist[3] & Carlo Sirtori[1]

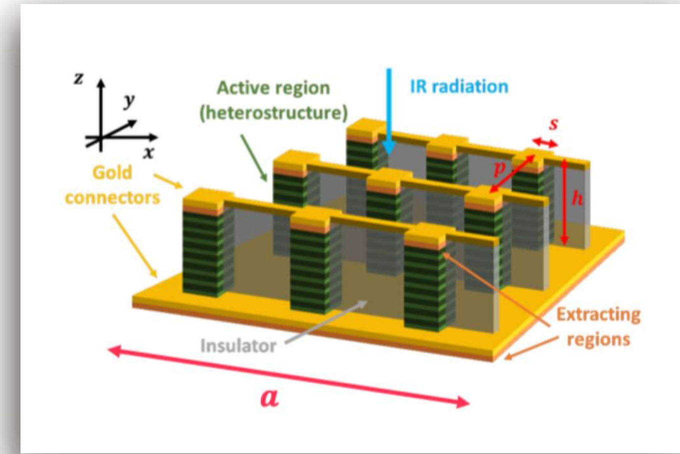
An unexploited intrinsic property of inter-subband quantum-well infrared photodetectors (QWIPs) based on group III–V semiconductor materials is the very short lifetime of their excited carriers. The typical lifetime is of the order of a few picoseconds[7], which has two important consequences: the detector frequency response can reach 100 GHz and its saturation intensity is very high[19] (10^7 W cm^{-2}). These prop-



Quinchard et al. 2022



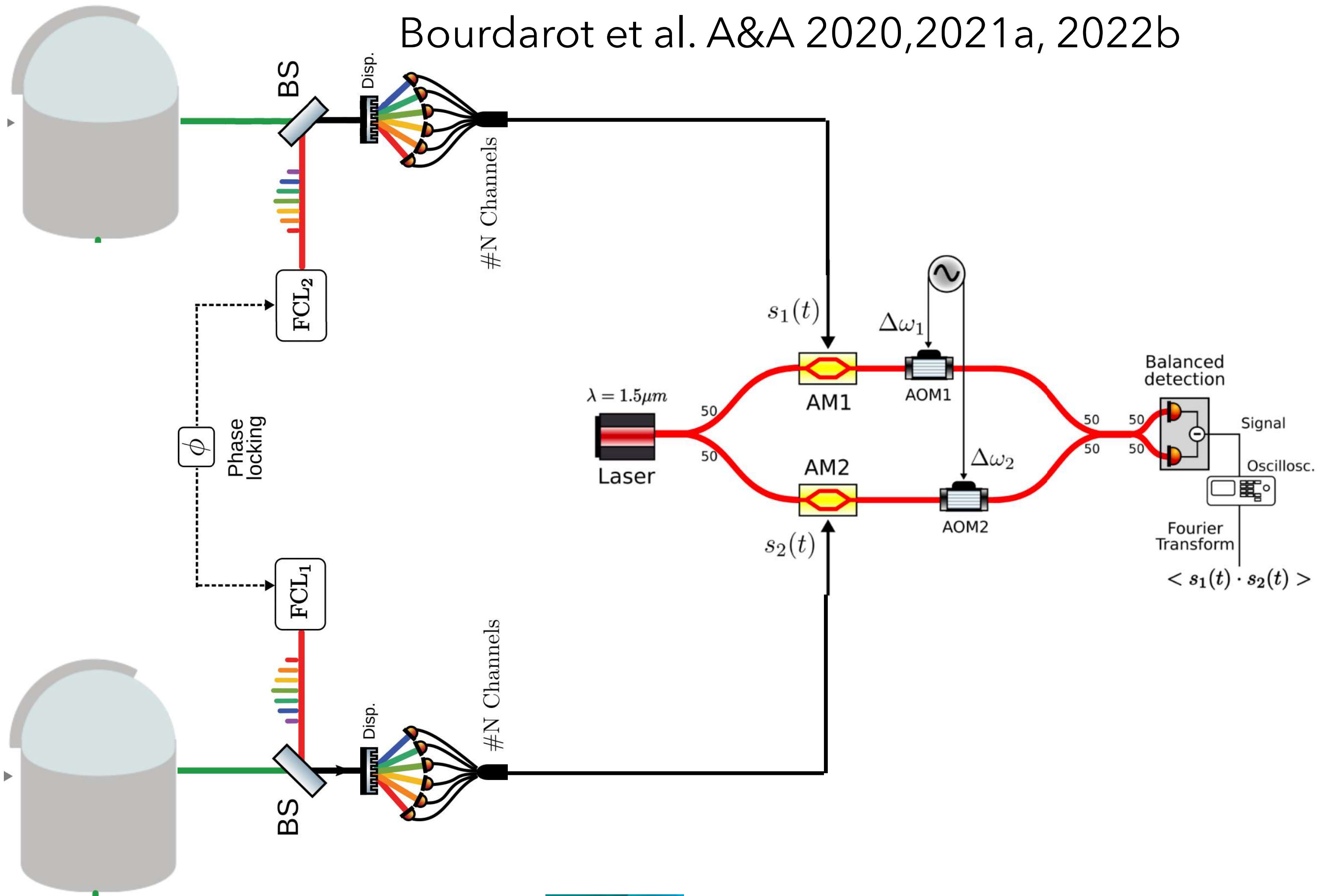




C. Sirtori (LPENS) group, Palaferri et al. 2018, Gacemi et al. 2018

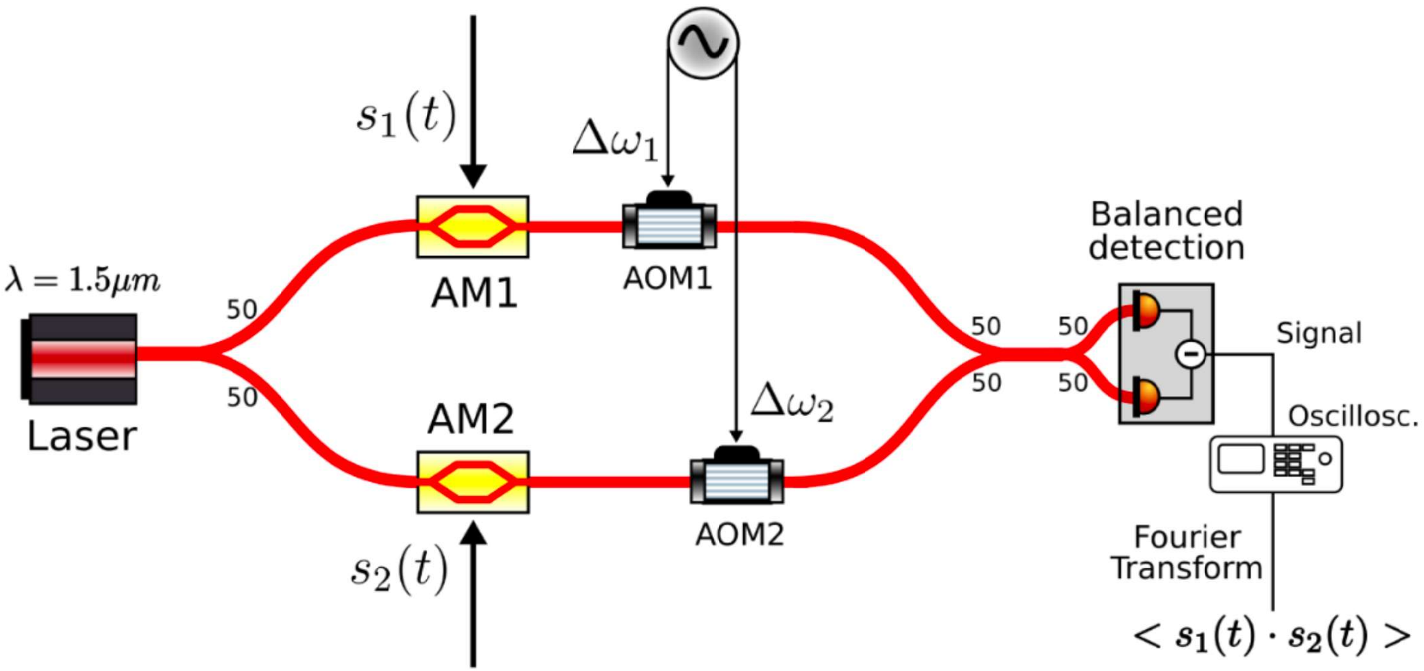
A photonics based 2 telescope all analog photonics demonstrator

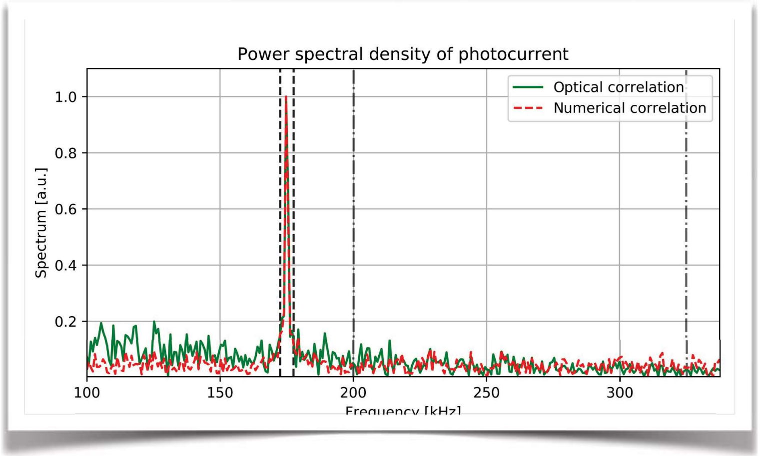
Bourdarot et al. A&A 2020,2021a, 2022b

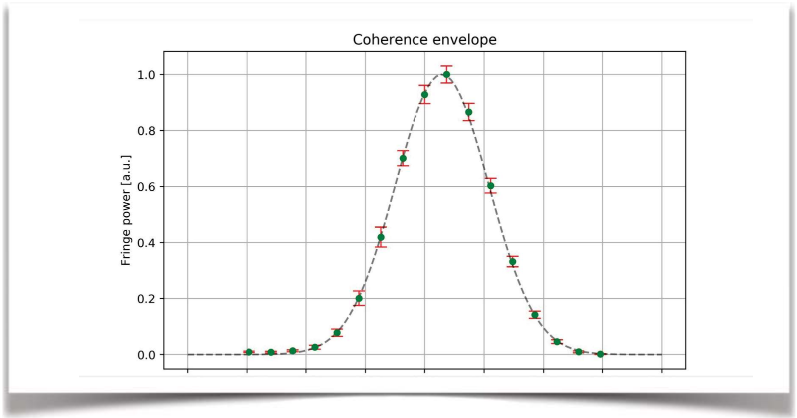


Coll: H. Guillet de Chatellus

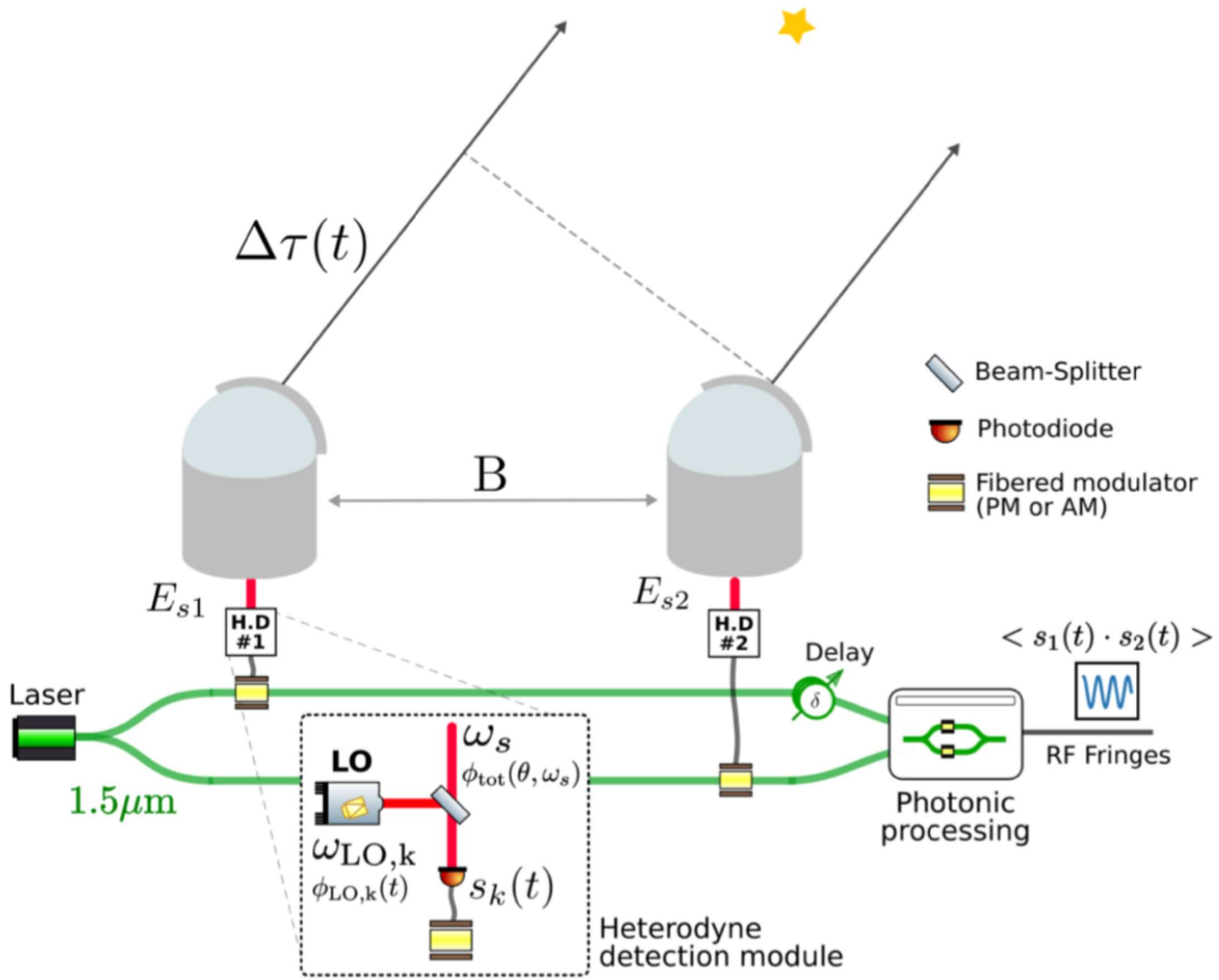
Photonics correlation: the core trick







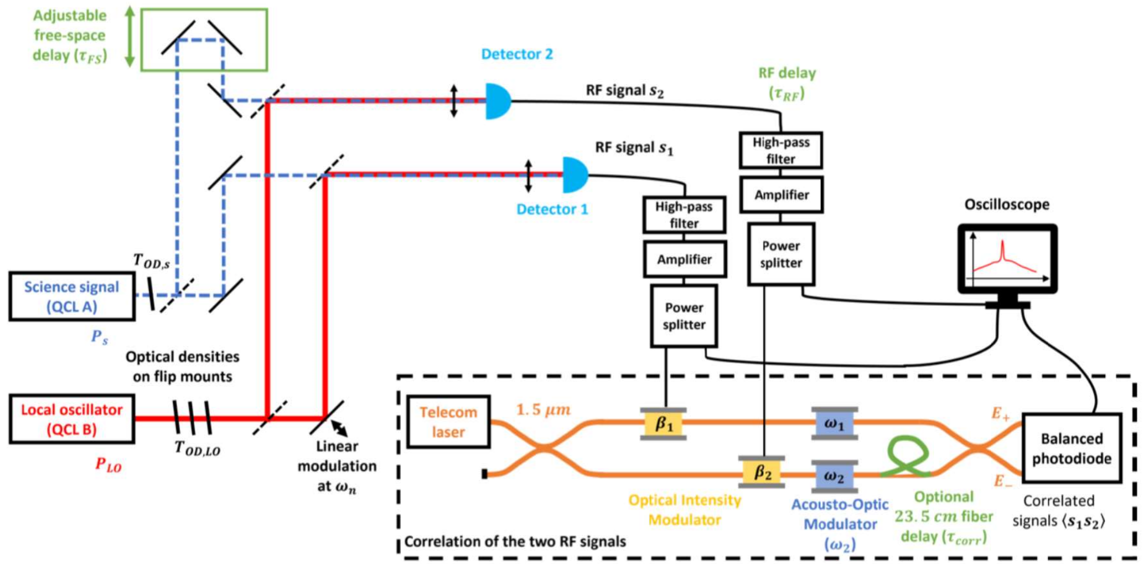
The concept:

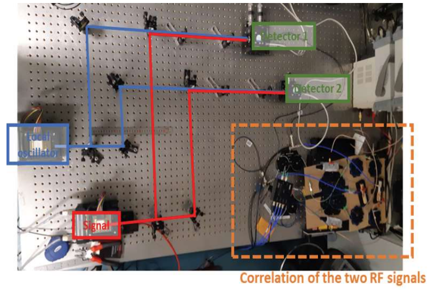


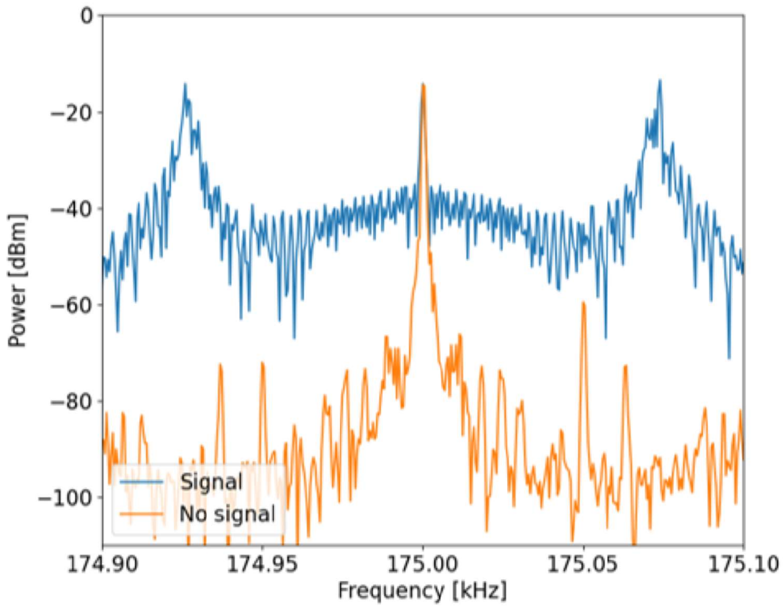
$\Delta\tau(t)$
B
Beam-Splitter
Photodiode
Fibered modulator
(PM or AM)
E_{s1}
E_{s2}
H.D
#1
H.D
#2
Laser
$1.5\mu m$
LO
ω_s
$\phi_{tot}(\theta, \omega_s)$
$\omega_{LO,k}$
$\phi_{LO,k}(t)$
$s_k(t)$
Heterodyne
detection module
Delay
δ
$< s_1(t) \cdot s_2(t) >$
RF Fringes
Photonic
processing

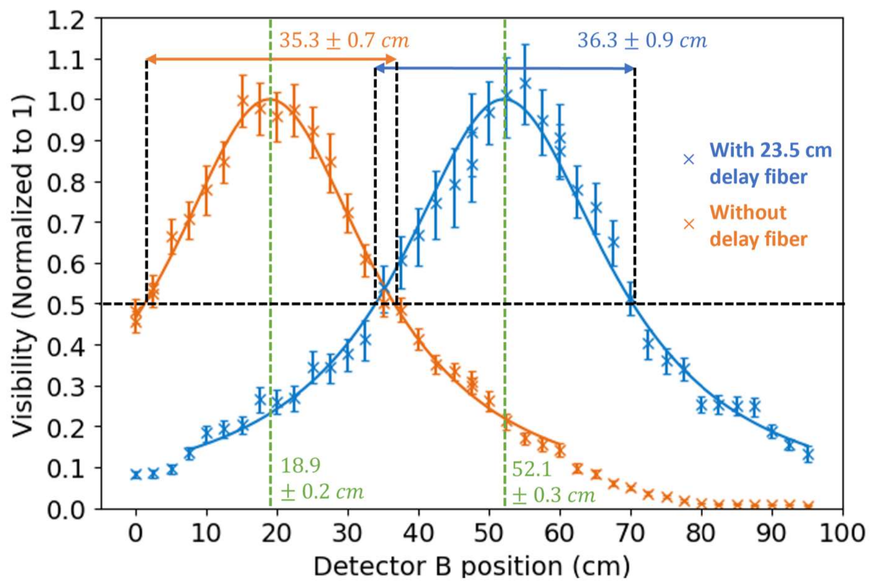
A proof of concept

Tituan Allain









Can we do spectroscopy ?
Principle of analog correlation

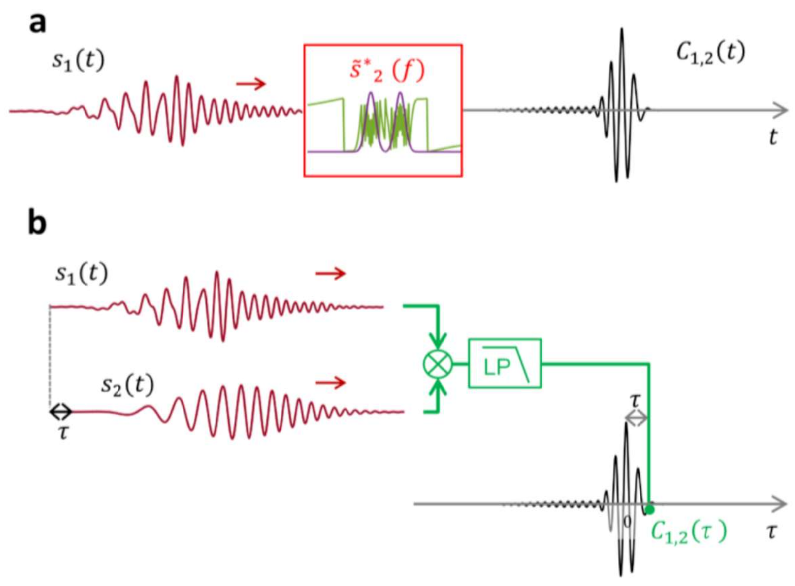


FIG. 1: a: Analog cross-correlation of two signals $s_1(t)$ and $s_2(t)$ in the frequency domain. $s_1(t)$ passes through a filter, whose transfer function is the complex conjugate of $\tilde{s}_2(f)$ (magenta: amplitude, green: phase). The output signal is $C_{1,2}(t)$. When $s_1 = s_2$, the process corresponds to auto-correlation (AC), or matched filtering. b: Time domain analog cross-correlation (CC). Analog multiplication of the signals time-shifted by τ followed by low-pass filtering calculates the CC coefficient $C_{1,2}(\tau)$. The measurement is repeated while varying the delay, to reconstruct the whole CC function $C_{1,2}(\tau)$.

Wideband multi-delay analog photonic correlator for RF signal processing

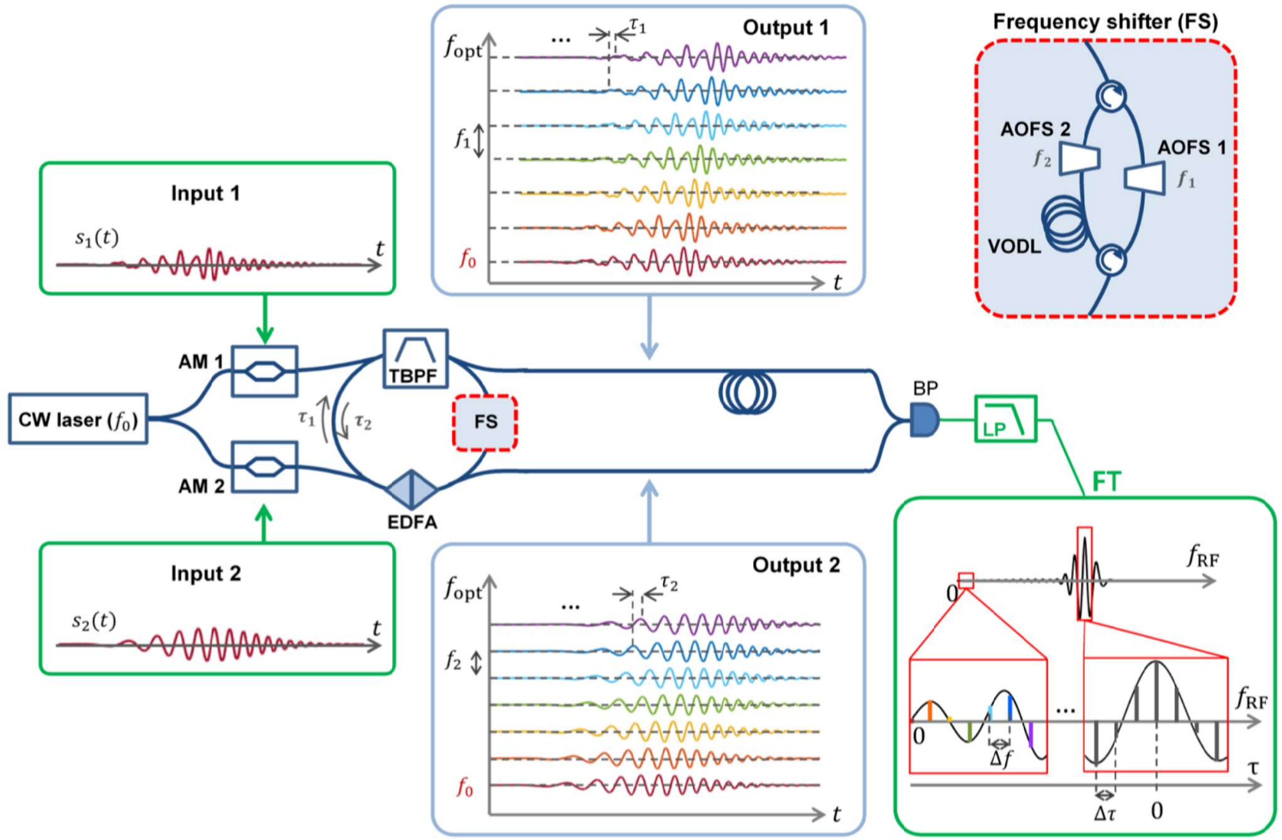


FIG. 2: Sketch of the analog photonic-based correlator. A bidirectional fiber frequency shifting loop is seeded in both ways, by a CW laser at 1550 nm, modulated in amplitude (AM) by two signals $s_1(t)$ and $s_2(t)$. Two variable optical attenuators (not shown) enable to control the light power injected in the loop. The non-reciprocal frequency shifter (FS) is sketched in the inset (top right). A variable optical delay line (VODL) enables to control the time delay $\Delta\tau = \tau_2 - \tau_1$. The loop contains an amplifier (EDFA) and a tunable bandpass filter (TBPF), both bidirectional. The loop produces replicas of the input signals, shifted both in time and in frequency. Photodetection by the balanced detector (BP) produces multi-heterodyne beatings. After low-pass filtering (LP), the Fourier transform (FT) of the photocurrent (i.e. the RF spectrum) sampled at multiples of $\Delta f = f_1 - f_2$ provides the CC coefficients for values of the relative delay multiples of $\Delta\tau$ (see text). A fiber delay line is inserted in path #1 in order to bring the position of the null delay (i.e. $\tau = 0$) to the center of the RF spectrum.

G. Bourdarot, J.P. Berger, H. Guillet de Chatellus, Optica 2021

Wideband multi-delay analog photonic correlator for RF signal processing

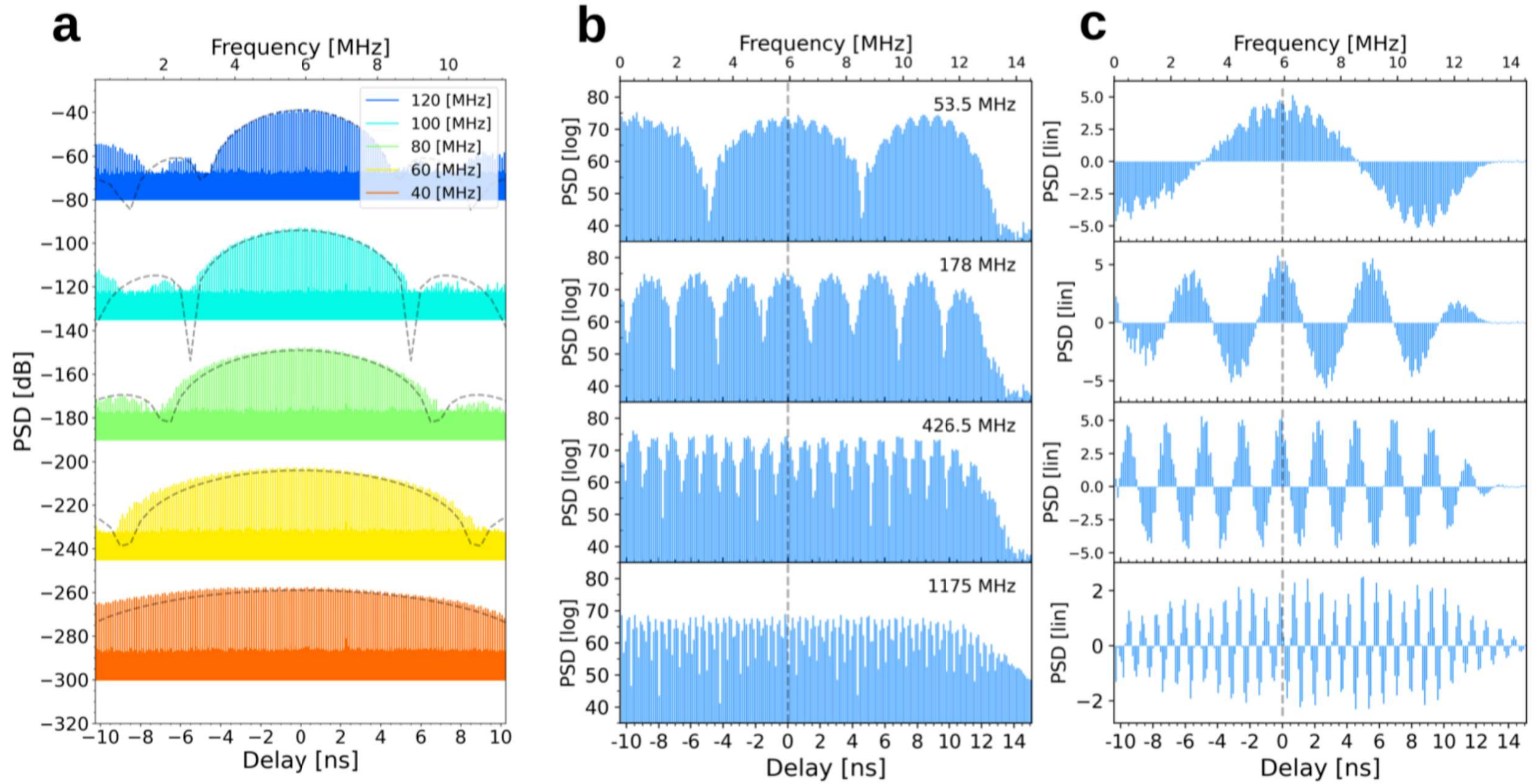
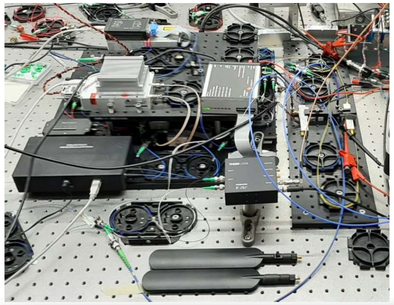
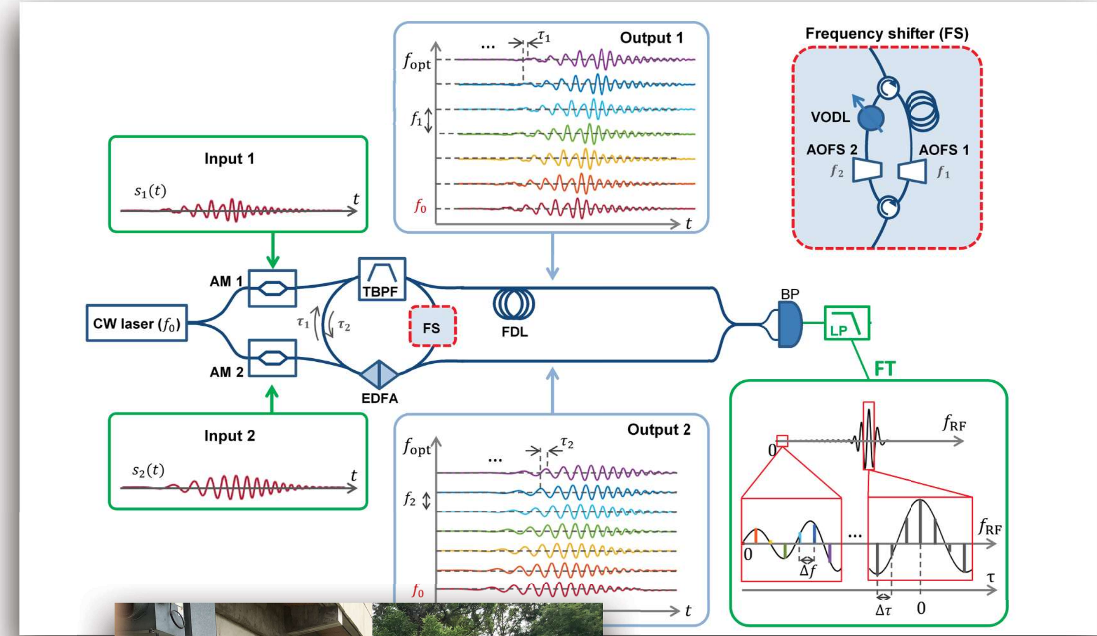
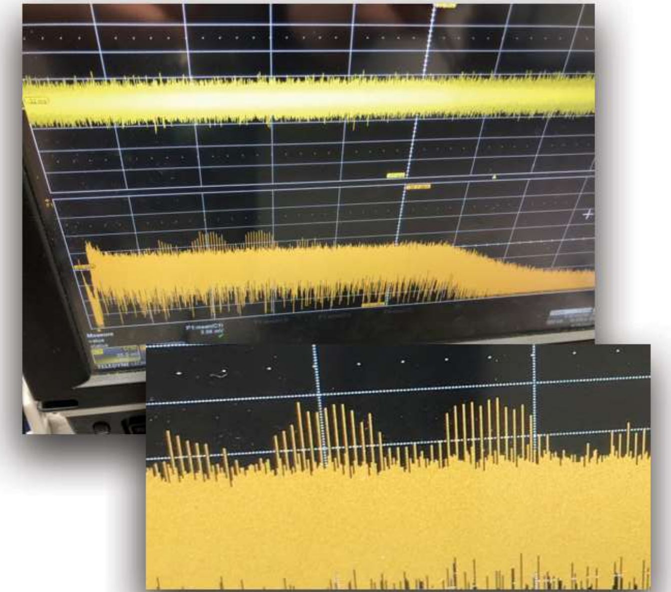


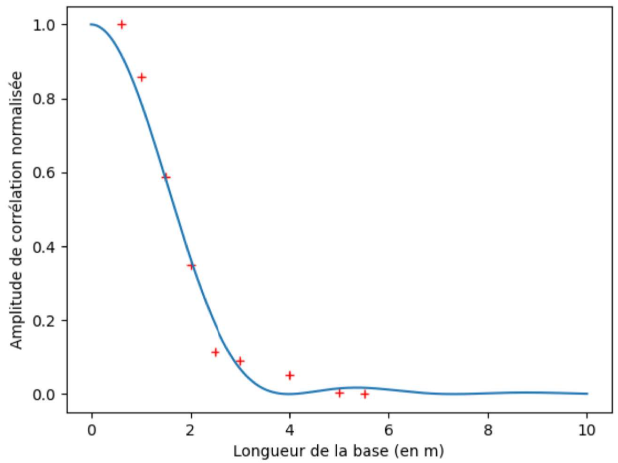
FIG. 3: a: Square modulus of the auto-correlation (AC) of a white noise waveform, with different bandwidths (120 MHz to 40 MHz) (acq. time: 200 ms). The dashed line is the expected (numerical) AC trace. b: Square modulus of the AC of sine waves with different frequencies (log. scale, acq. time: 100 ms). The noise background in the AC traces has been numerically filtered

I3CM experiment on the sun

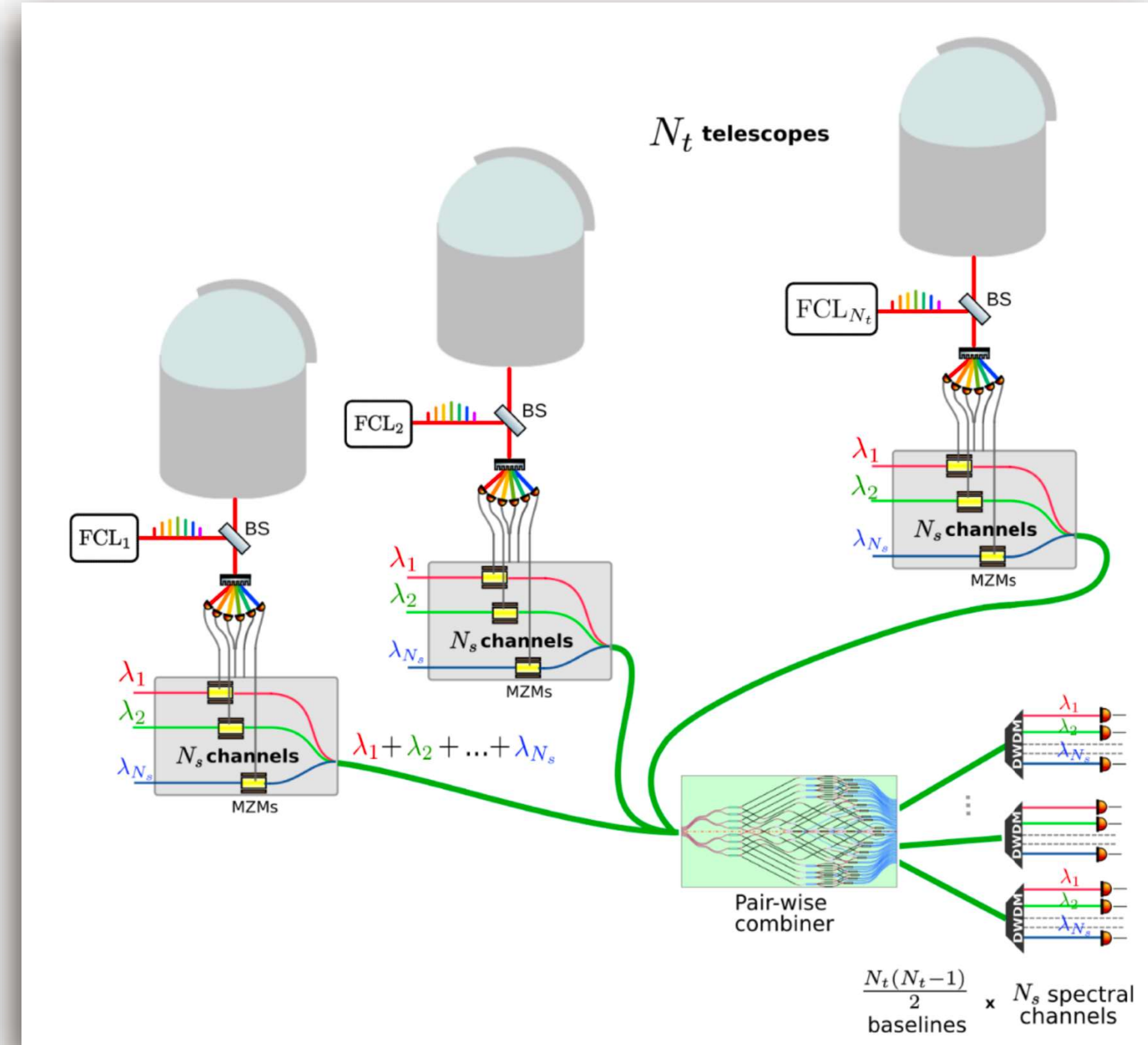




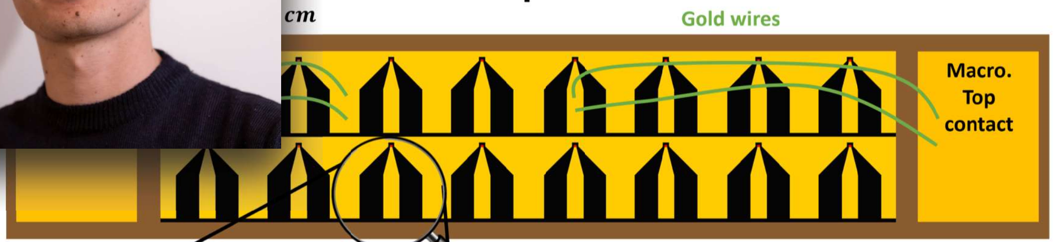


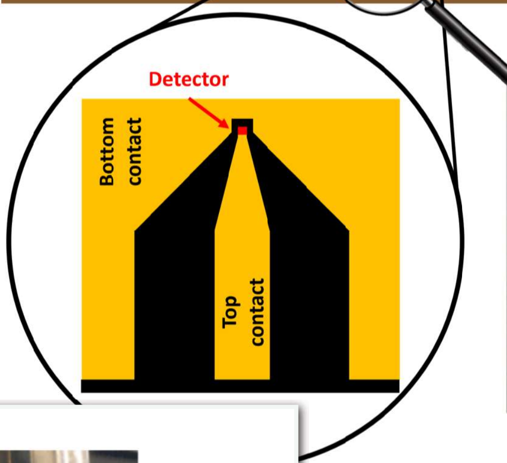


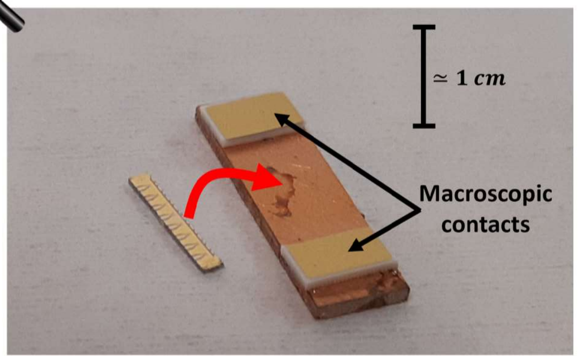
A very high bandwidth analog correlator ?



First attempts







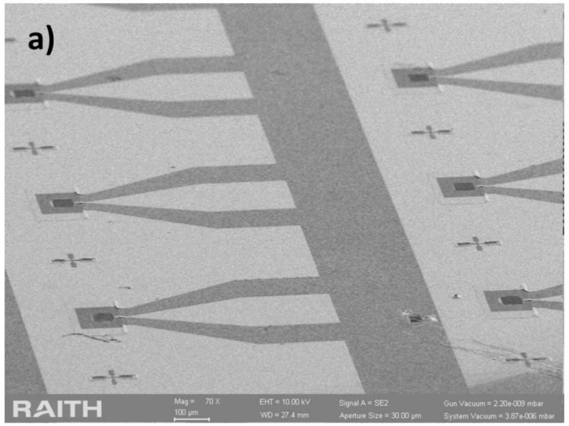
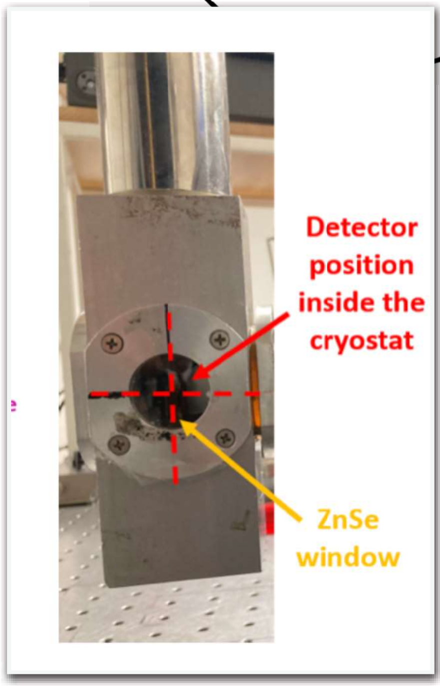
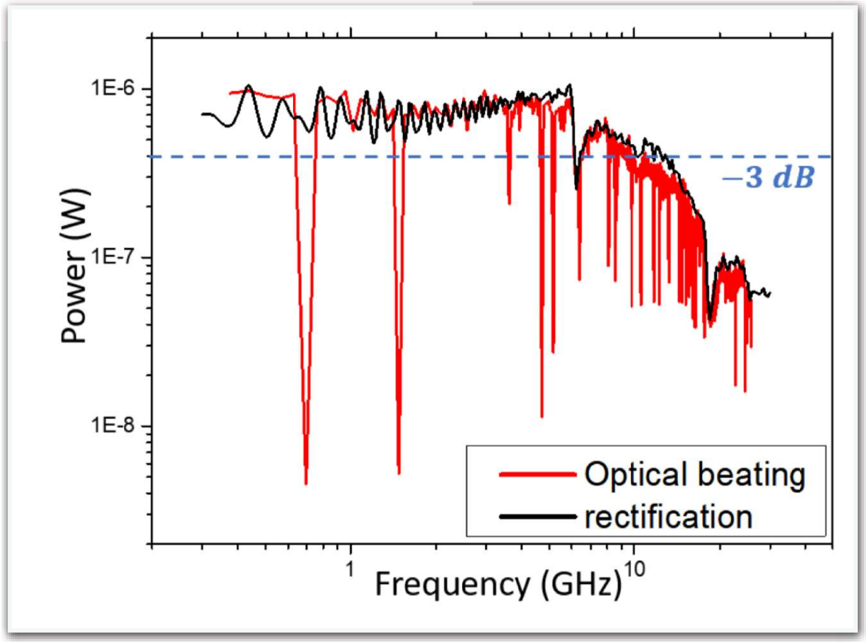
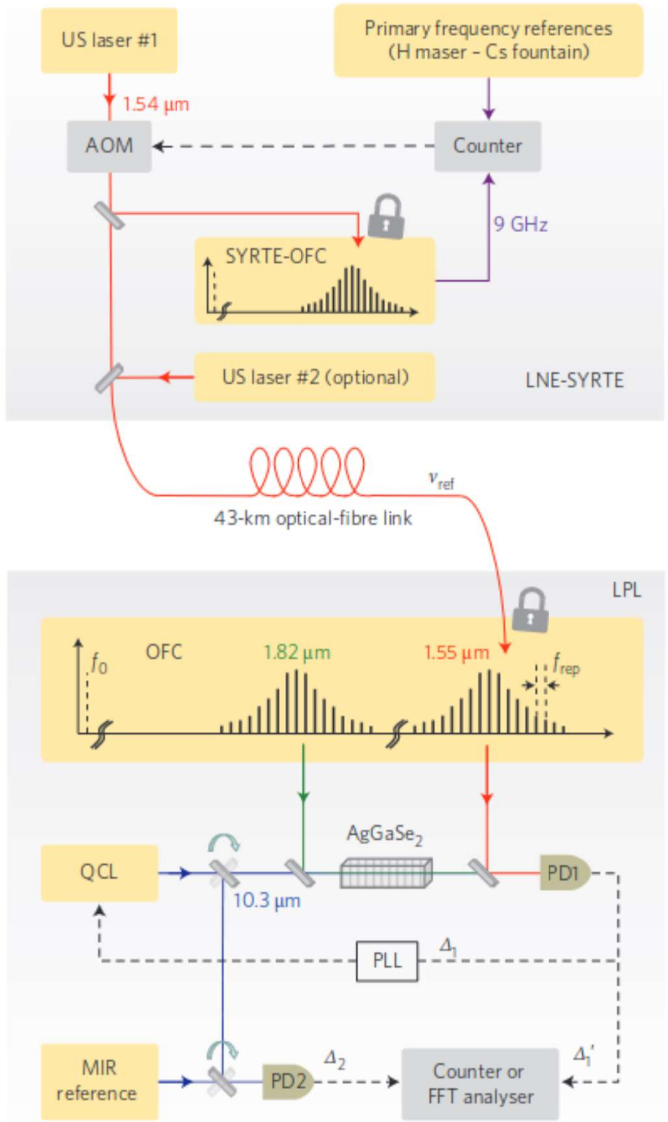


Figure 1.2: SEM image of a few stripe QWIPs.



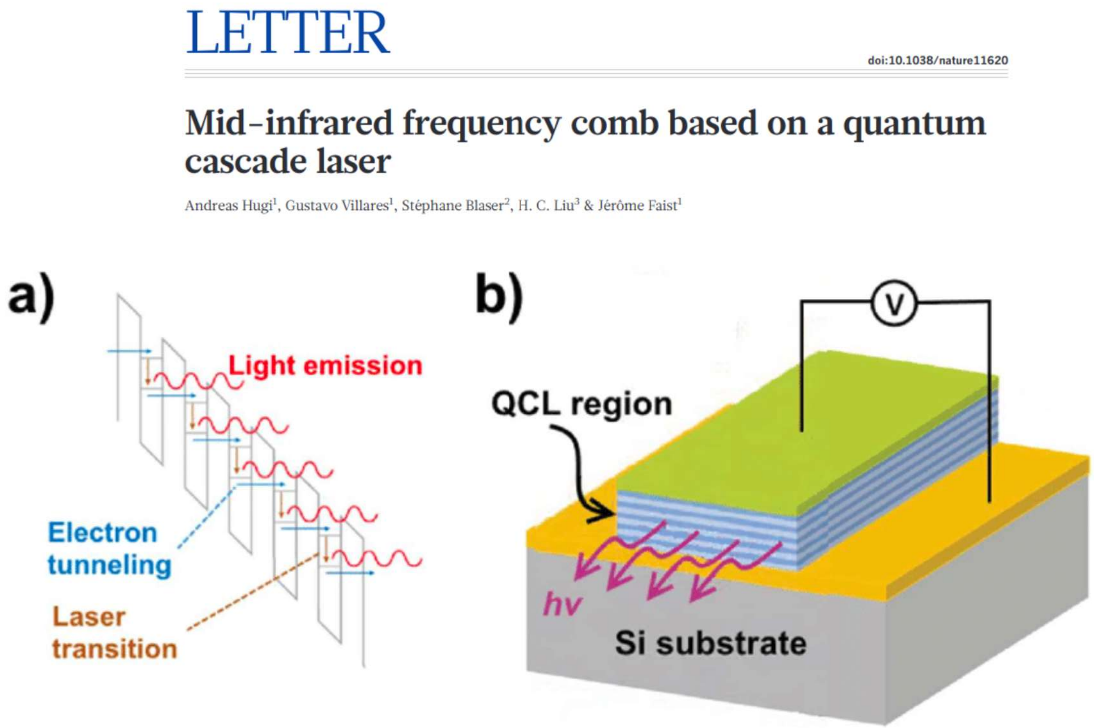


Progresses in local oscillators

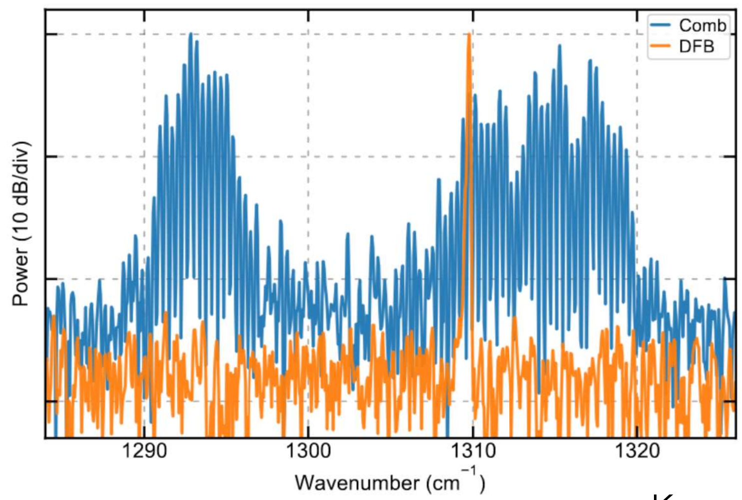


Chanteau et al, NJP (2013)

Argence et al, Nature Photonics (2015)



Hugi et al. 2012



80 lines

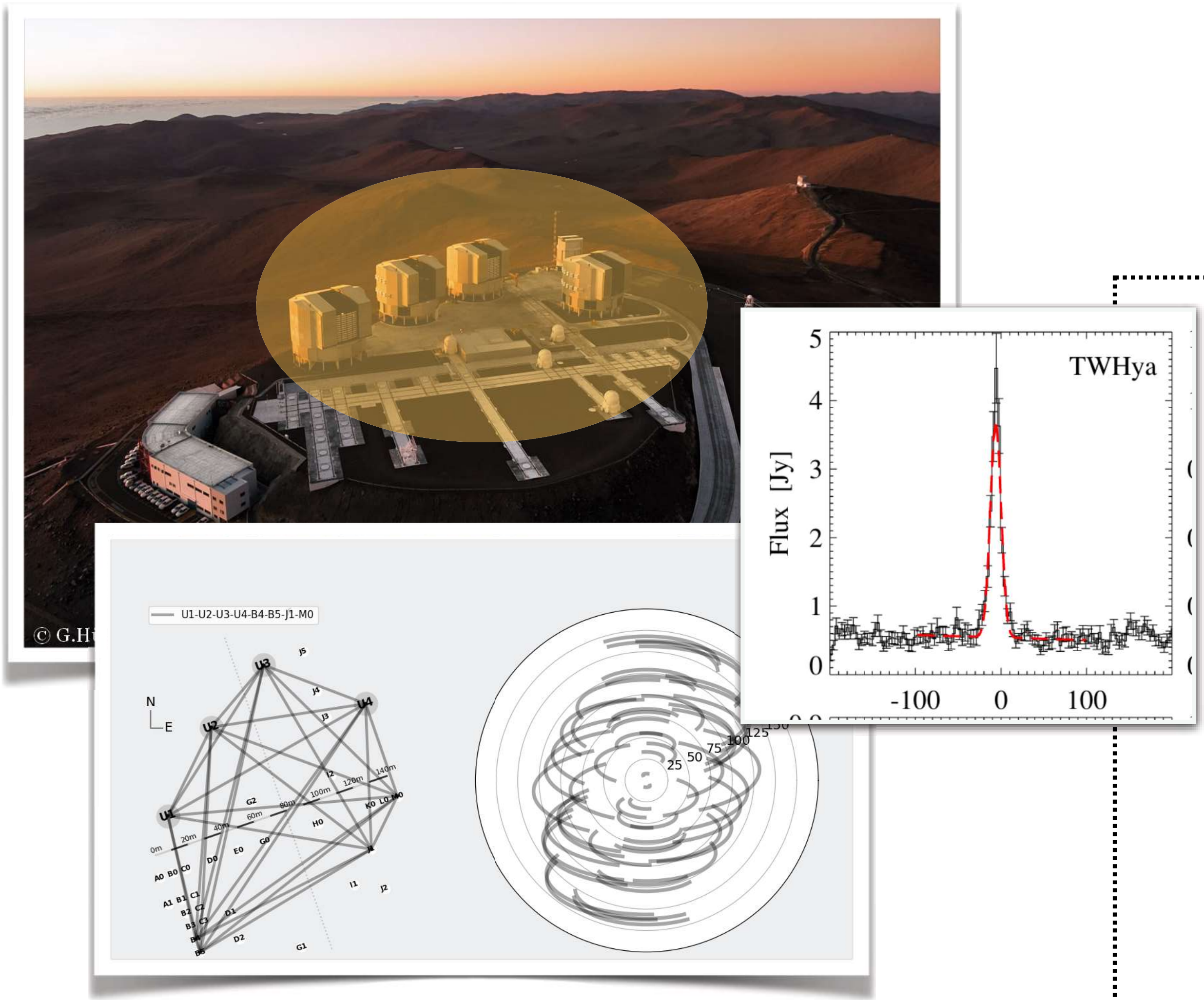
10 GHz separation

Komagata et al. 2023

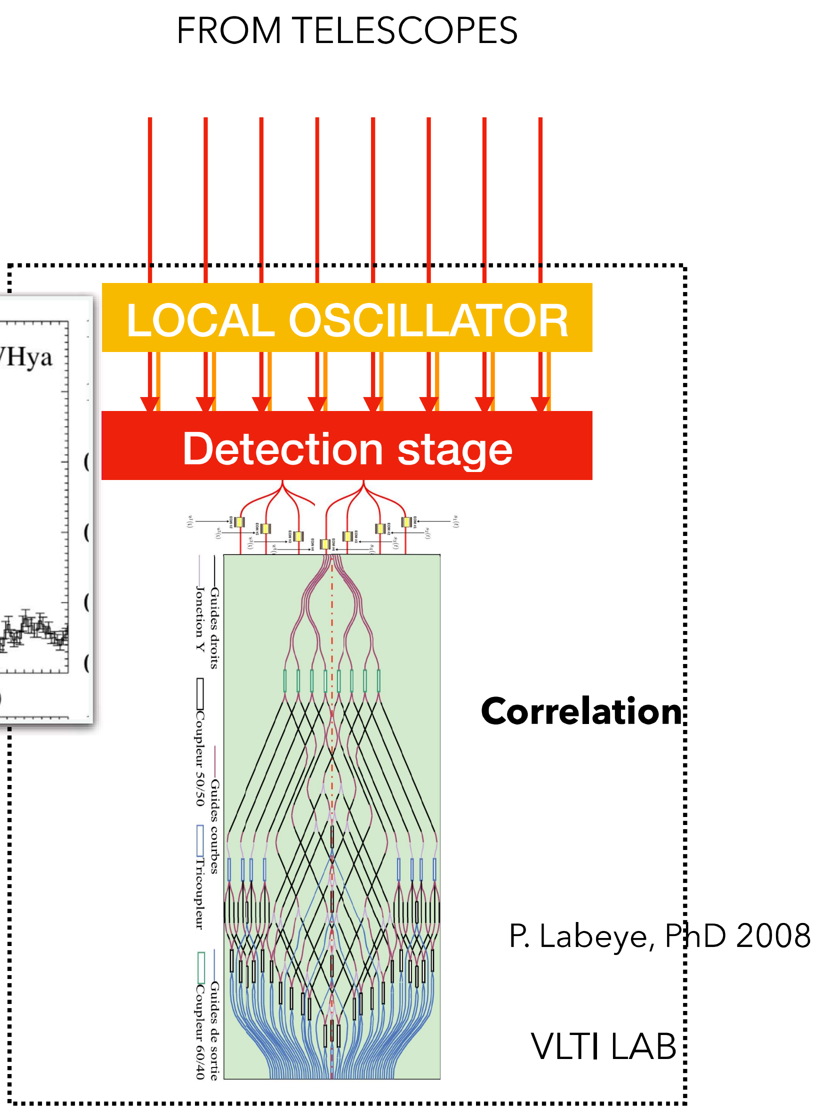
A precursor

V4/V8

An heterodyne instrument dedicated to the study of the Ne II Lines in YSOs



No delay lines full sky coverage



Wrap-up

Wrap up

- Infrared long baseline interferometry is a powerful astronomical technique but …
- It's observing capability is limited by the number of telescopes and baseline length
- Mid-IR heterodyne interferometry likely competitive (sensitive & cost) in N and Q bands for # telescopes> 10 but this requires technological developments
- global physics/industry R&D pushing in the right direction (detection, combs, phase locking, computing power). **But still we are at at paper concept/TRL 1.5 level**
- We have demonstrated that the coherence of "broad-band" mid-infrared source could be carried onto a telecom fiber and that commercial fiber delay lines could be used.
- Technological challenges that remain:
    - High quantum efficiency detectors
    - Demonstrating the local oscillator synchronisation
    - Mid-IR laser combs
    - Near-infrared phase tracking