Challenges in infrared long baseline heterodyne astronomical interferometry & radial velocity spectroscopy

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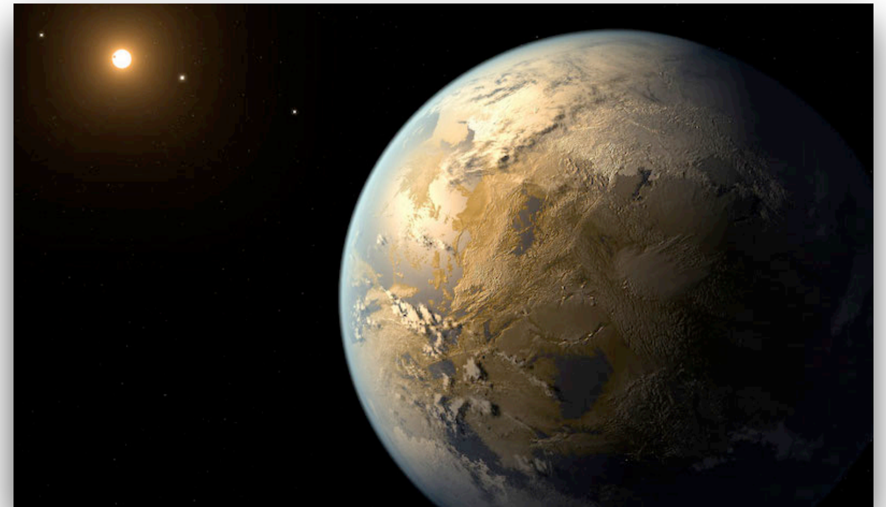
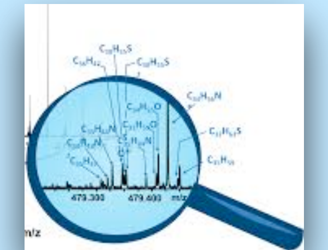


Funding FOCUS Focal Plane Array for Universe Sensing INSU

Strong potential of REFIMEVE-related technologies for astronomy

- Progresses in astronomy are often related to advances in instrumentation technologies (Nobel prize in physics 2019, 2020)
- There are numerous "potential" applications of laser frequency combs in astronomy

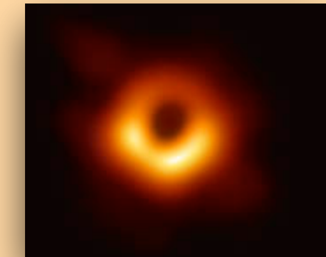
Constantes physiques fondamentales/ astro chimie



Recherche matière noire/test RG Einstein

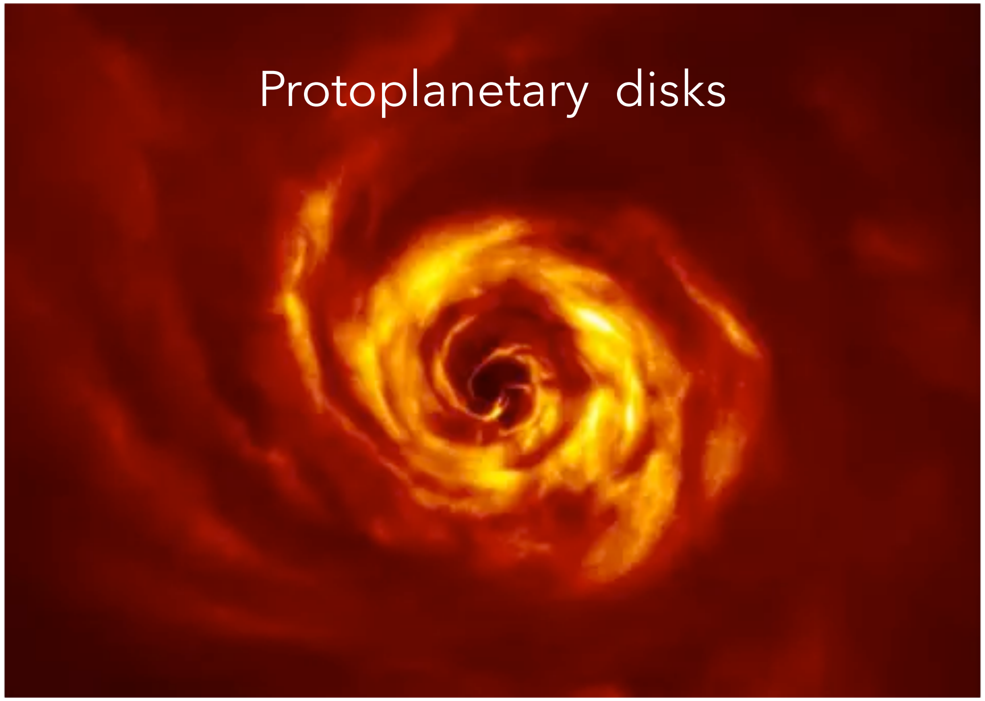
Recherche exo-terres

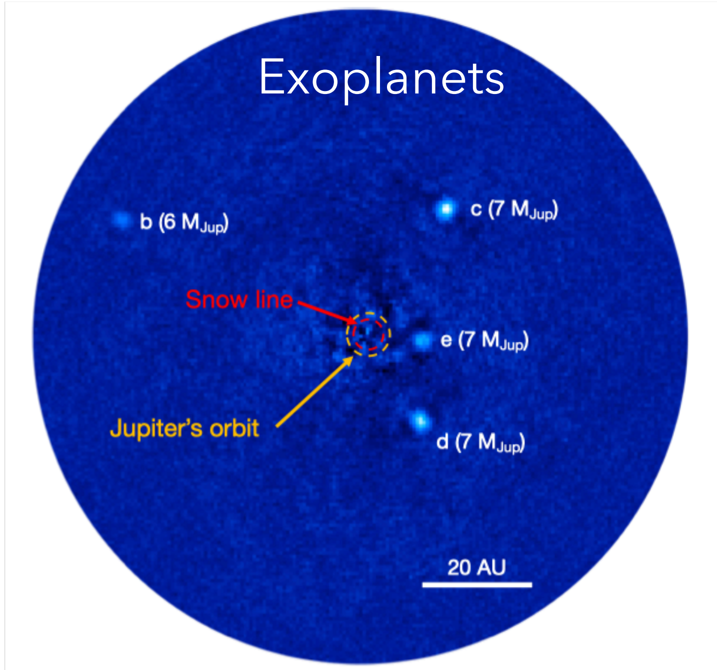
Synthèse d'ouverture



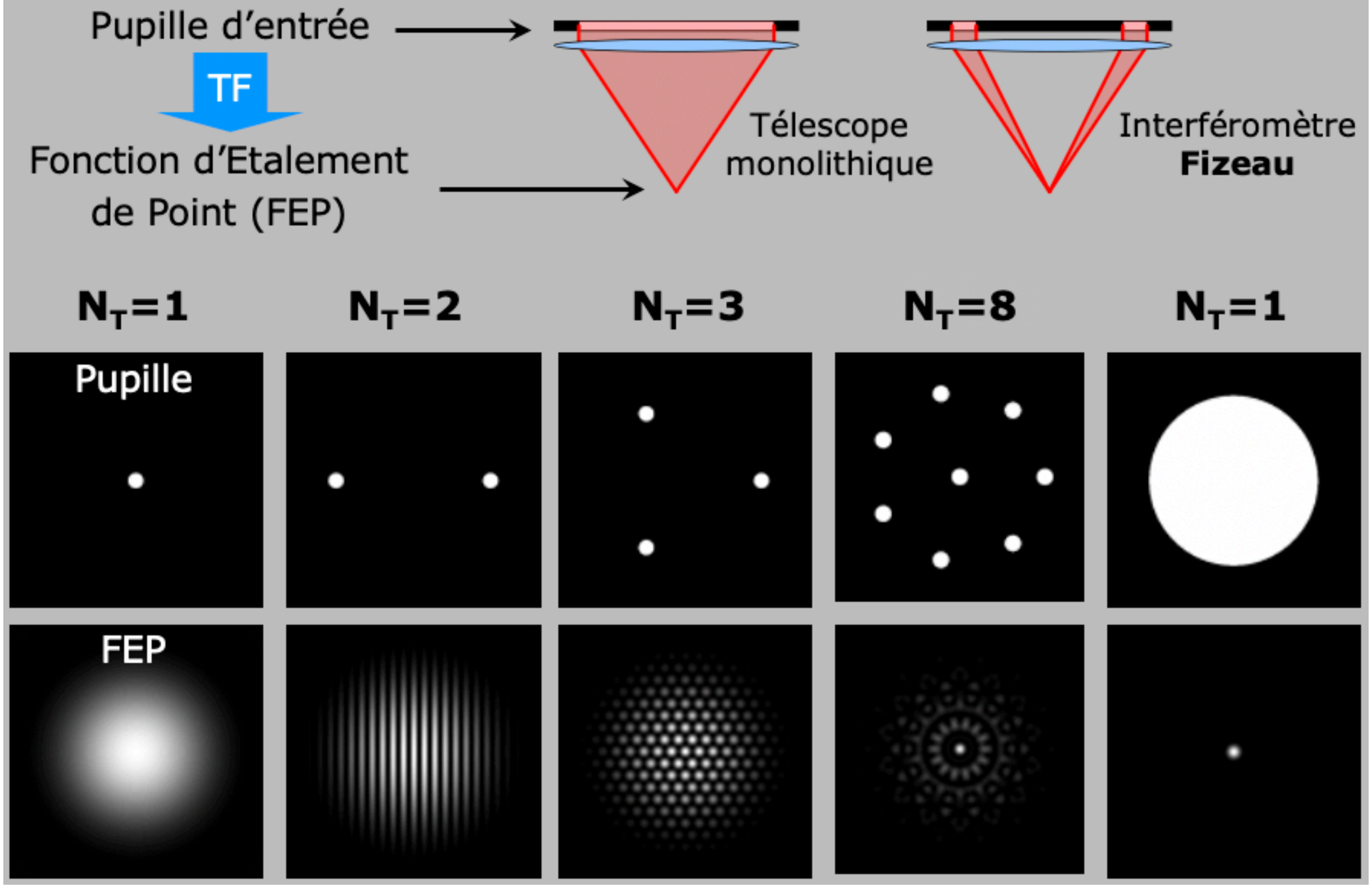
Aperture synthesis imaging

Scientific motivation @ IPAG

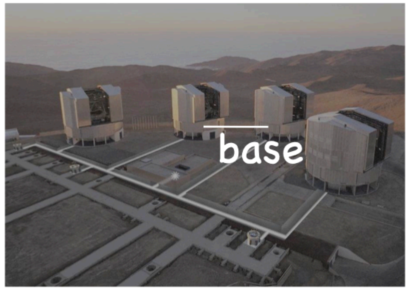


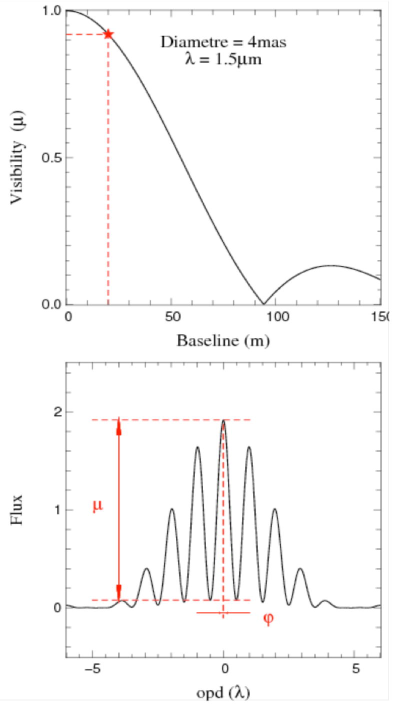


De la pupille à l'image

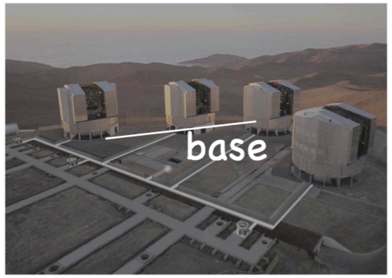


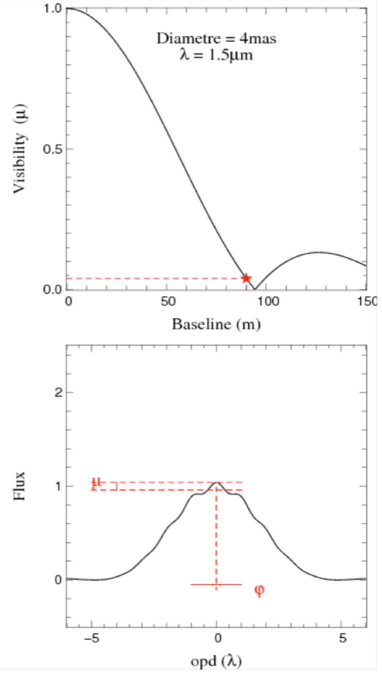
Principles of a long baseline interferometer





$$V(\vec{B}\lambda) = F(I(\vec{\theta}))$$





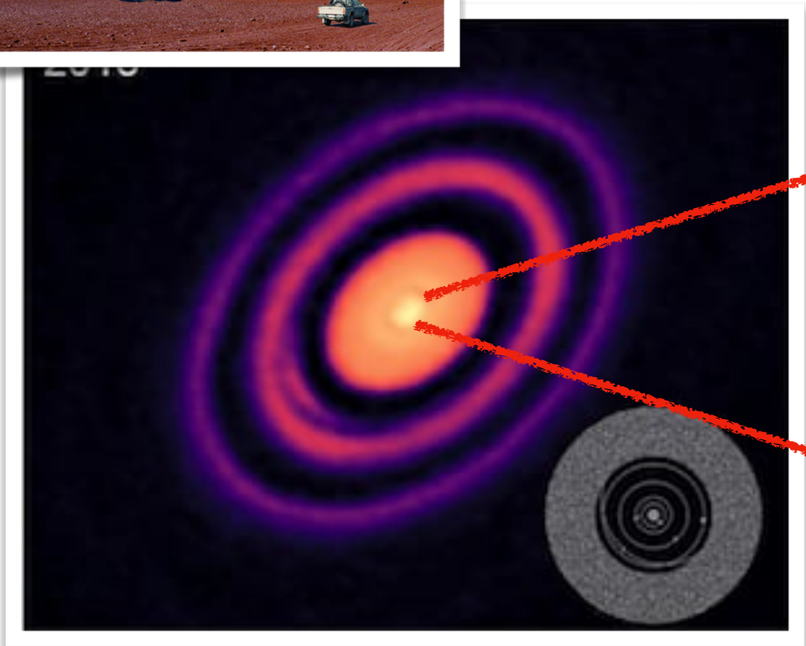
$$V(\vec{B}\lambda) = F(I(\vec{\theta}))$$

The van Cittert - Zernike theorem

$$\mathcal{F}(I_s(\vec{\theta})) = \hat{I}_s\left(\vec{f} = \frac{\vec{B}}{\lambda}\right) = \hat{I}_s(u,v) = \Gamma_{12}(\vec{f})$$

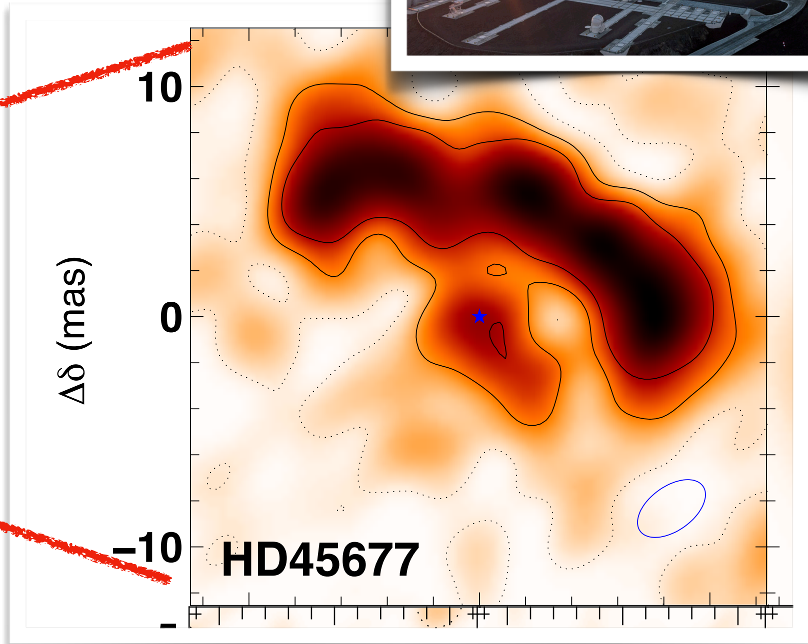
Infrared interferometry image complexity is limited by the number of telescopes

ALMA

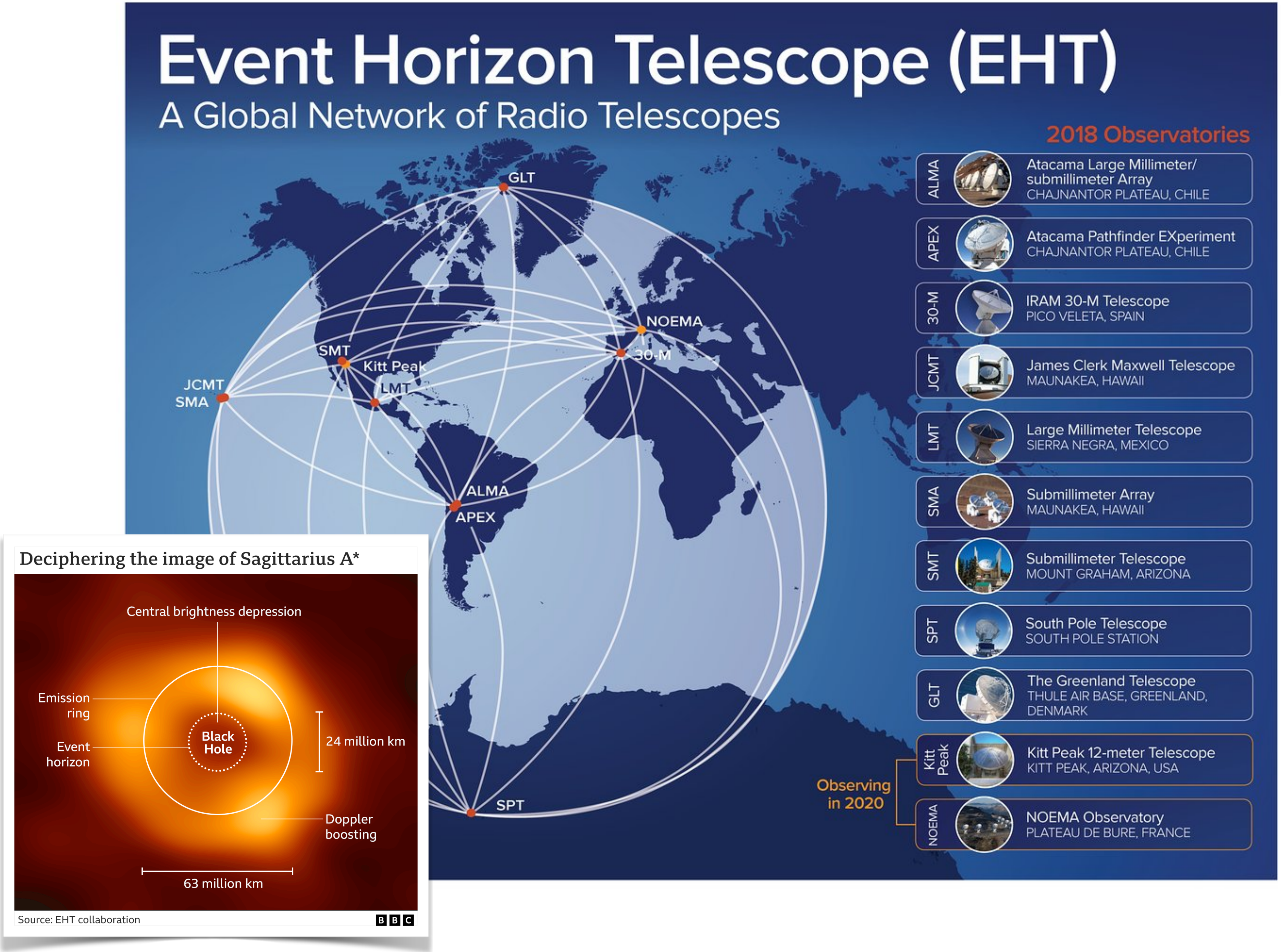


Isella et al. 2018

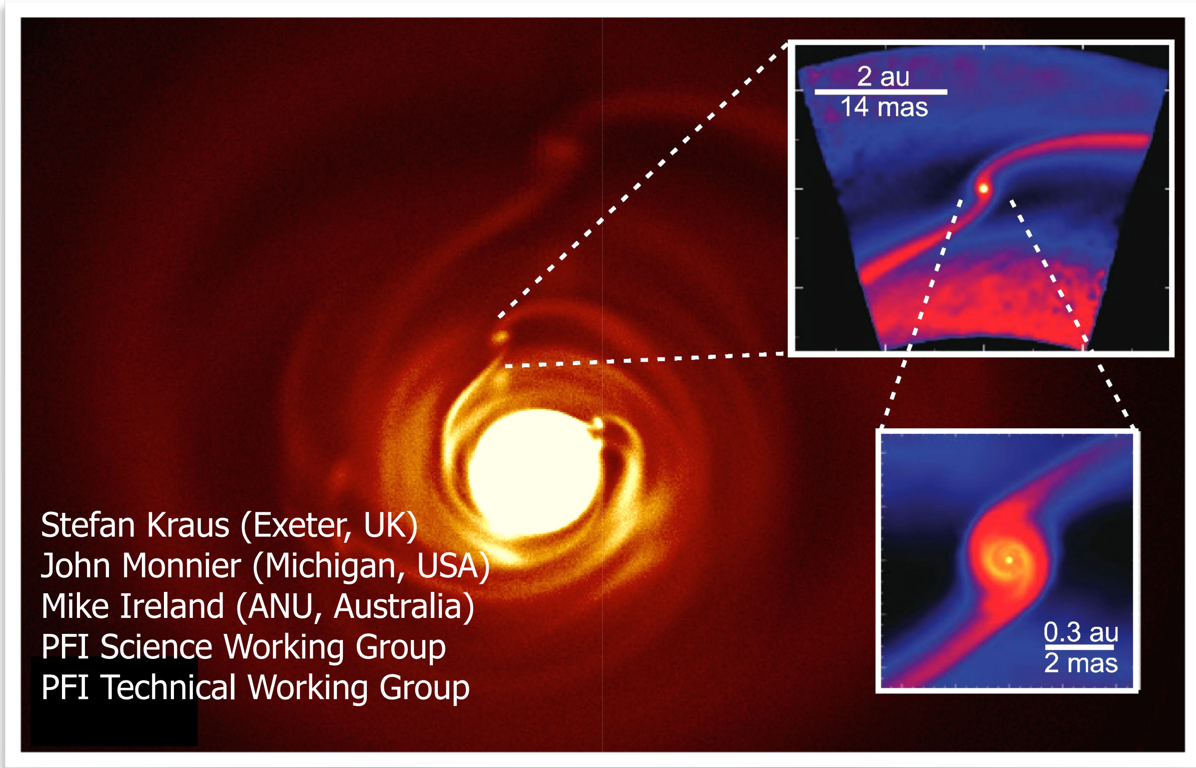
VLTI-PIONIER



Kluska et al. 2020


Event Horizon Telescope (EHT)
A Global Network of Radio Telescopes
2018 Observatories
GLT
NOEMA
30-M
SMT
Kitt Peak
LMT
JCMT
SMA
ALMA
APEX
SPT
ALMA Atacama Large Millimeter/submillimeter Array CHAJNANTOR PLATEAU, CHILE
APEX Atacama Pathfinder EXperiment CHAJNANTOR PLATEAU, CHILE
30-M IRAM 30-M Telescope PICO VELETA, SPAIN
JCMT James Clerk Maxwell Telescope MAUNAKEA, HAWAII
LMT Large Millimeter Telescope SIERRA NEGRA, MEXICO
SMA Submillimeter Array MAUNAKEA, HAWAII
SMT Submillimeter Telescope MOUNT GRAHAM, ARIZONA
SPT South Pole Telescope SOUTH POLE STATION
GLT The Greenland Telescope THULE AIR BASE, GREENLAND, DENMARK
Observing in 2020
Kitt Peak Kitt Peak 12-meter Telescope KITT PEAK, ARIZONA, USA
NOEMA NOEMA Observatory PLATEAU DE BURE, FRANCE
Deciphering the image of Sagittarius A*
Central brightness depression
Emission ring
Event horizon
Black Hole
24 million km
Doppler boosting
63 million km
Source: EHT collaboration
BBC

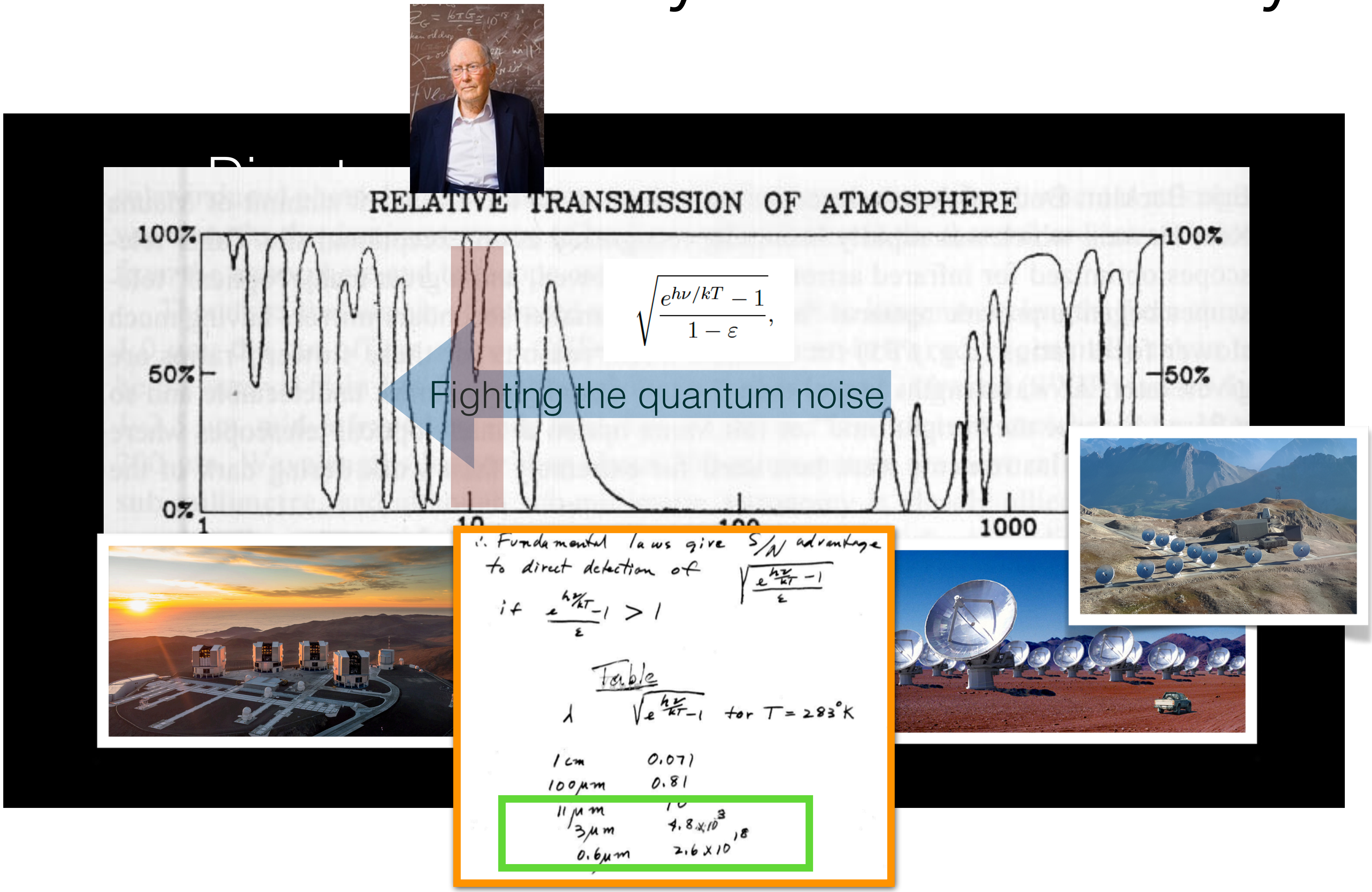
Exo - **Planet Formation Imager:** a facility designed to image the key stages of planet formation



Top level science requirements

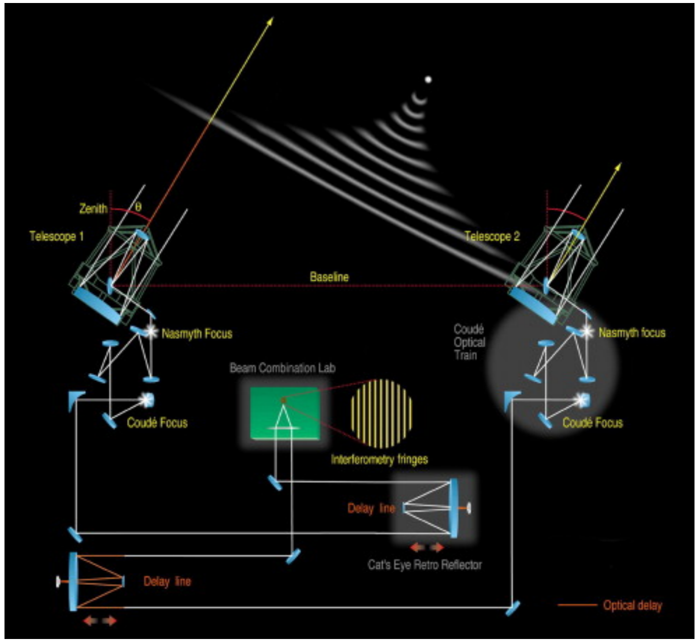
- Caracterising young exoplanets up to Taurus
- Resolving circumplanetary disks spatially and kinematically
- Mappping dust distribution and kinematics

Direct vs. Heterodyne interferometry

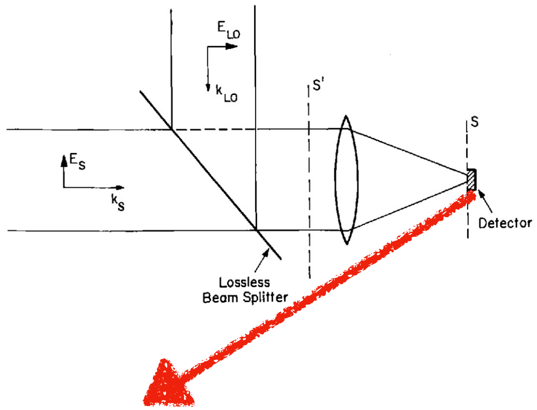


Two ways to do interferometry

Direct interferometry



Two ways to do interferometry



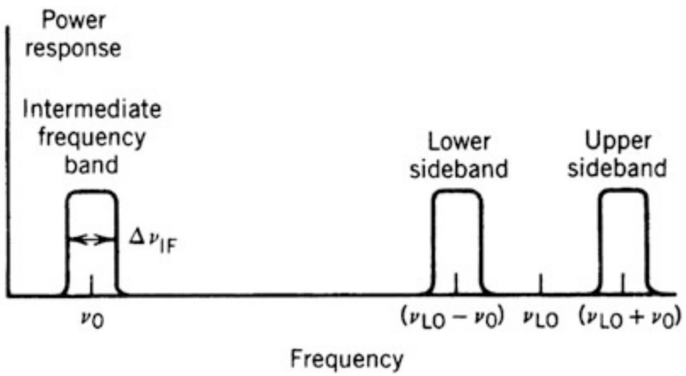
$$E(t) = E_L e^{-i\omega_L t} + E_S e^{-i\omega_S t}$$

Phase

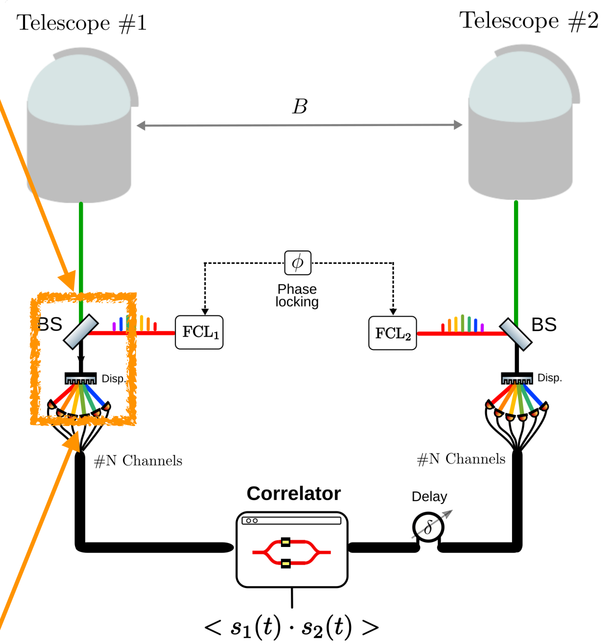
$$i(t) \propto \frac{\eta e}{h\nu}|E(t)|^2 = i_L(t) + i_S + 2\sqrt{i_L i_S} cos((\omega_S - \omega_L)t + \phi)$$

Noise and Signal

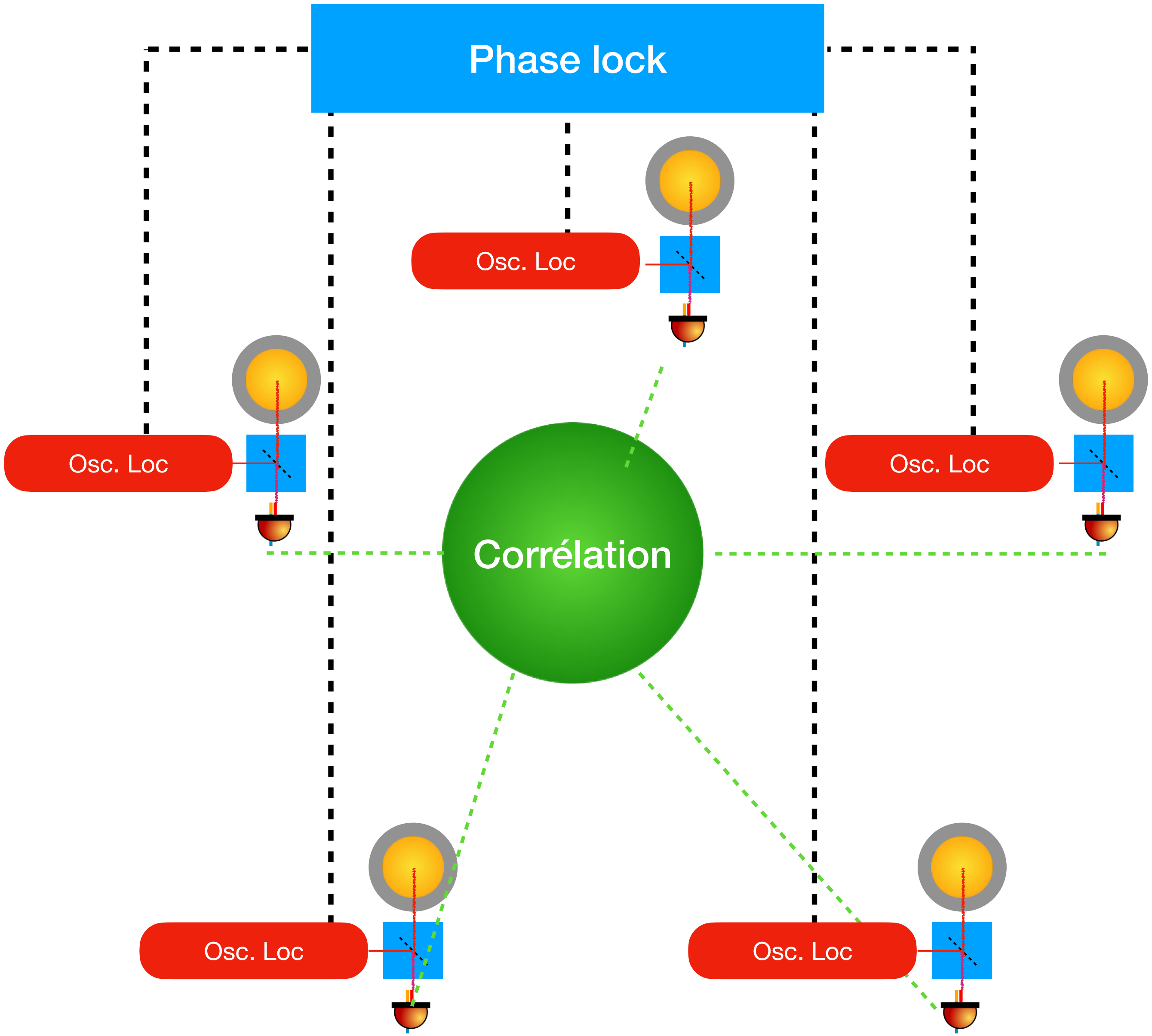
Noise and



Heterodyne interferometry

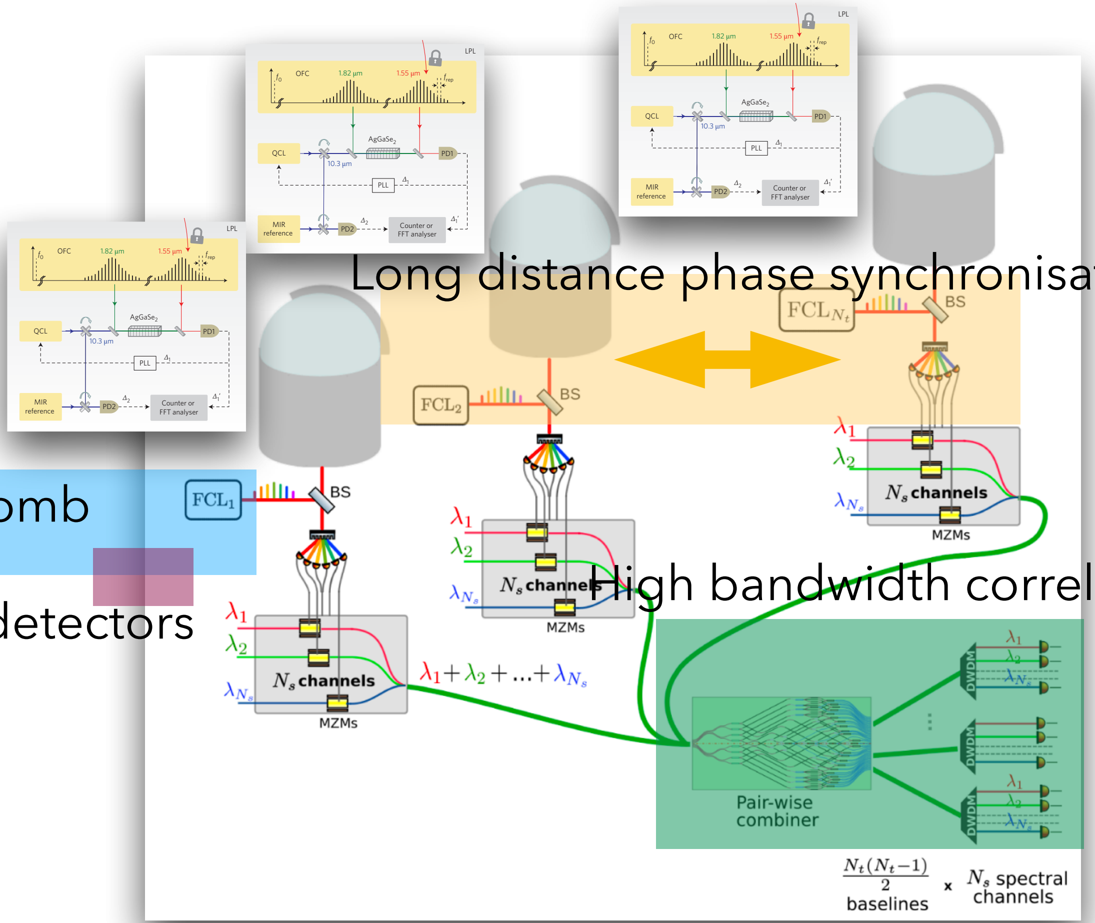


Can we expand the scheme for N > 10 telescopes over kilometric baselines ?



Technological vision: no free space propagationlimited “relay” infrastructure

Several major technological challenges



Long distance phase synchronisation

Mir-IR comb

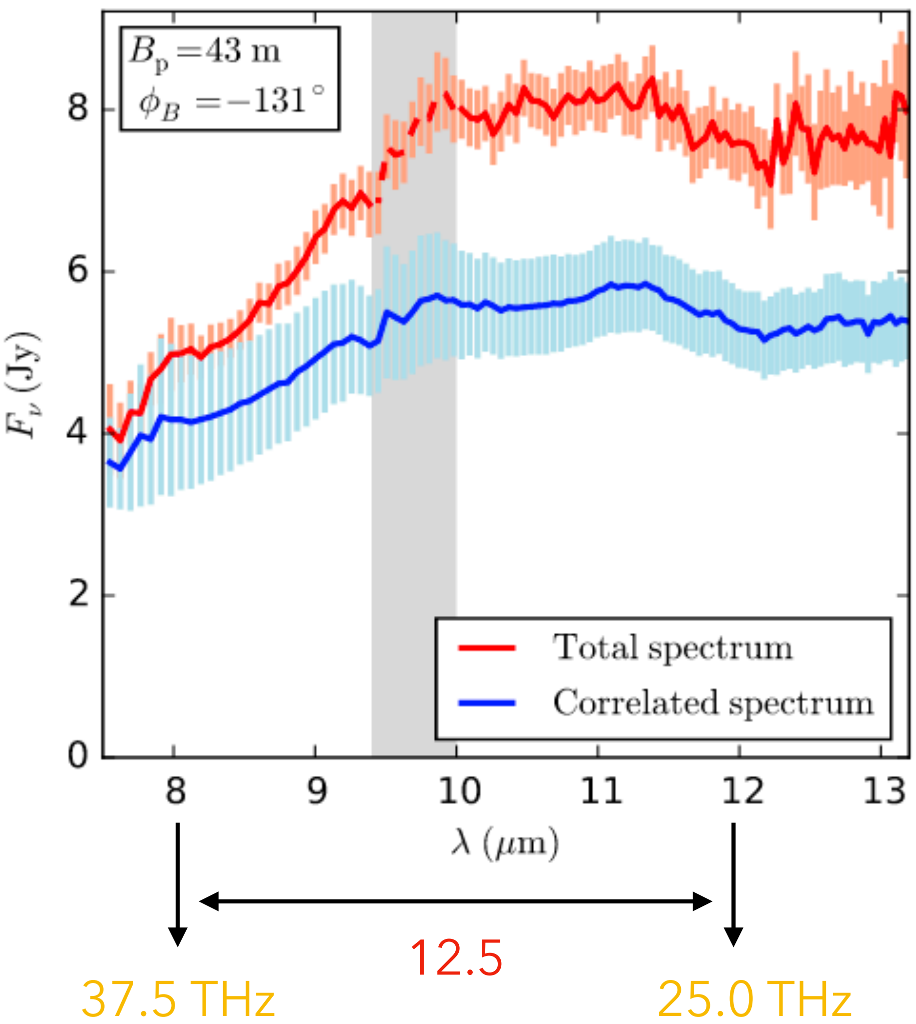
High bandwidth correlation

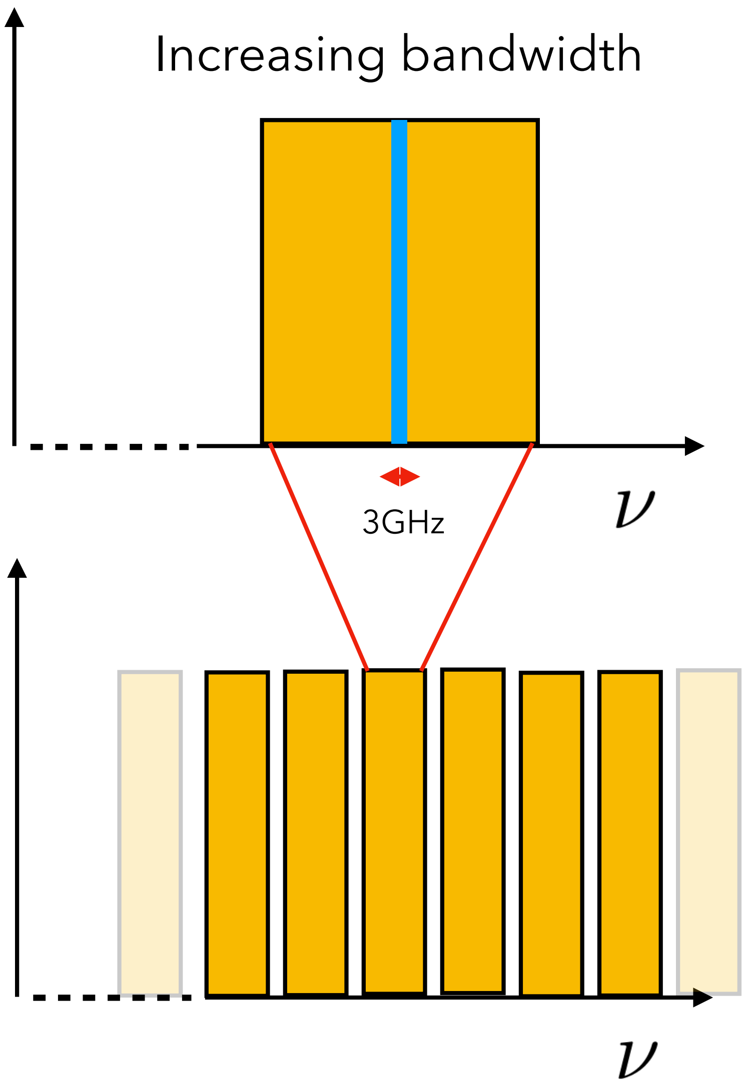
Broadband detectors

Local oscillators: mid IR combs (10-30 GHz)

The need for spectral coverage

MIDI instrument at VLTI



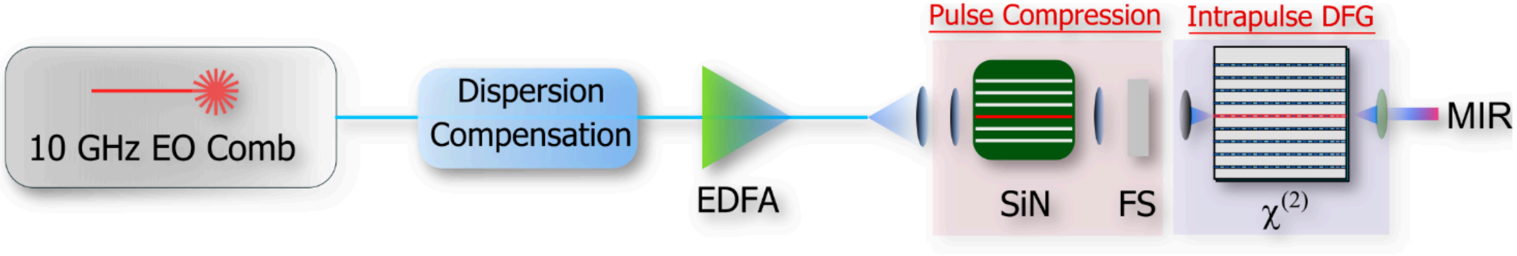


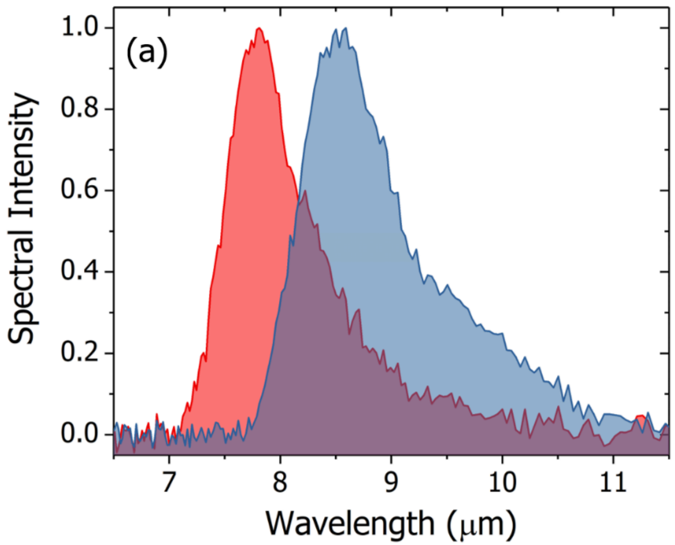
Using frequency combs

Need:

- high bandwidth (>20GHz) high responsivity mid-IR detectors
- Frequency combs with tooth separations of ~ 20GHz

Challenge 1: broadband mid-IR comb





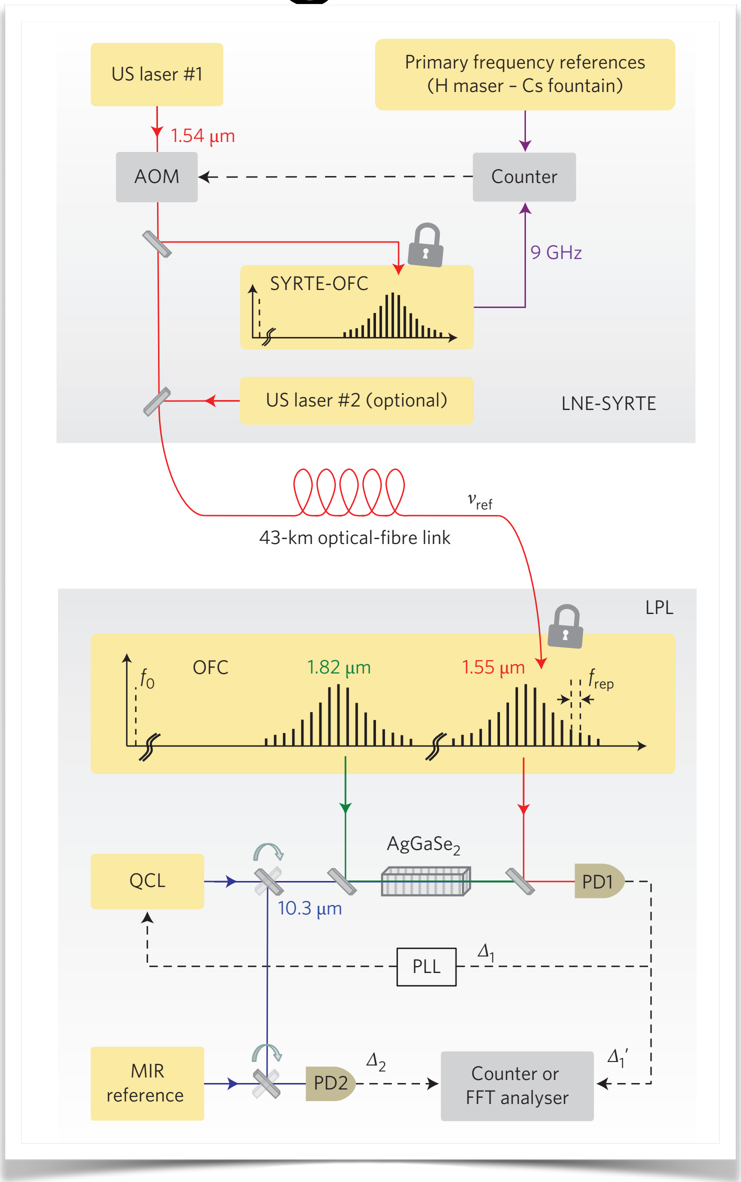
Abstract: We demonstrate mid-infrared (MIR) frequency combs at 10 GHz repetition rate via intra-pulse difference-frequency generation (DFG) in quasi-phase-matched nonlinear media. Few-cycle pump pulses (≲15 fs, 100 pJ) from a near-infrared (NIR) electro-optic frequency comb are provided via nonlinear soliton-like compression in photonic-chip silicon-nitride waveguides. Subsequent intra-pulse DFG in periodically-poled lithium niobate waveguides yields MIR frequency combs in the 3.1–4.8 μm region, while orientation-patterned gallium phosphide provides coverage across 7–11 μm. Cascaded second-order nonlinearities simultaneously provide access to the carrier-envelope-offset frequency of the pump source via in-line *f*-2*f* nonlinear interferometry. The high-repetition rate MIR frequency combs introduced here can be used for condensed phase spectroscopy and applications such as laser heterodyne radiometry.

Fig. 4. 10 GHz frequency combs in the long-wave infrared. (a) LWIR spectra from OP-GaP pumped by few-cycle pulses from 1280 nm (red) and 1620 nm (blue) width Si_3N_4 waveguides. (b) The reference and transmission spectra for the measurement of $C_2H_4F_2$. Inset: measured absorption spectrum compared with the NIST WebBook database [50].

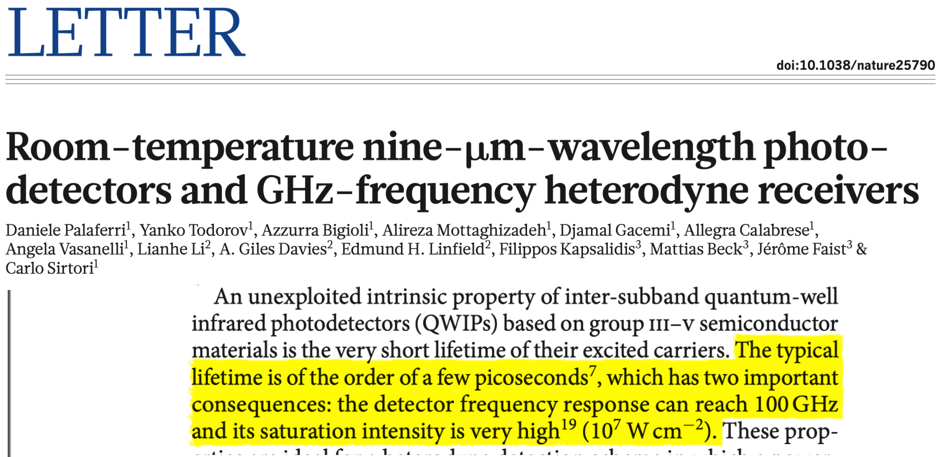
Kowligy et al. 2020

Challenge 2: locking local oscillators together

Argence et al. 2015



High bandwidth detection

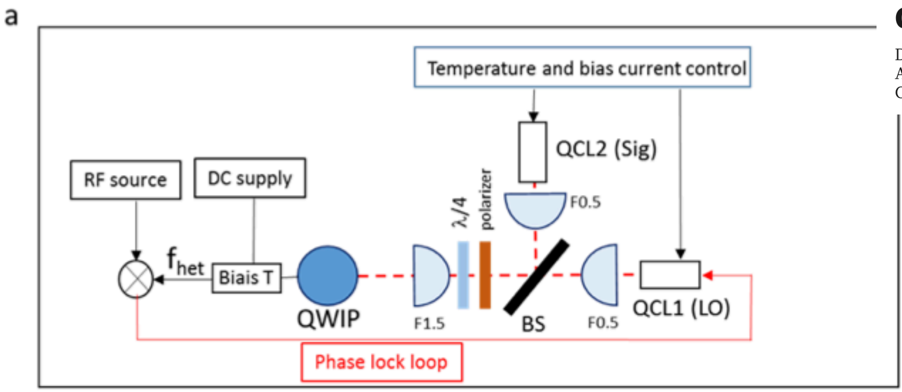

LETTER
doi:10.1038/nature25790

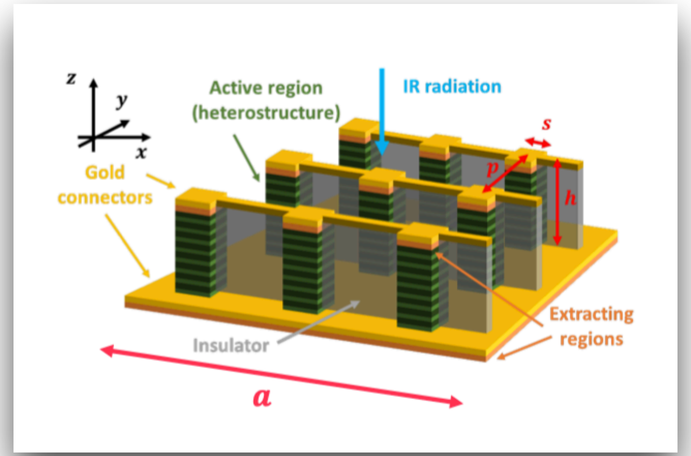
Room-temperature nine-µm-wavelength photodetectors and GHz-frequency heterodyne receivers

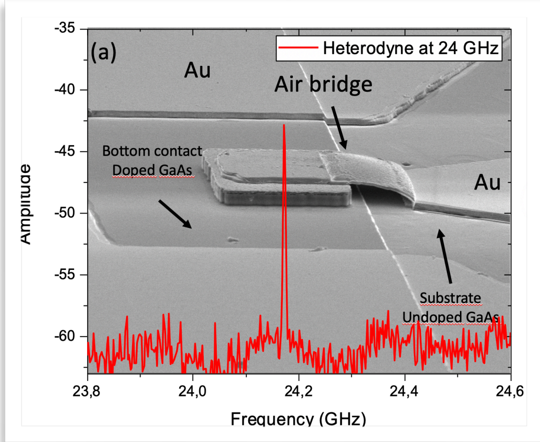
Daniele Palaferri[1], Yanko Todorov[1], Azzurra Bigioli[1], Alireza Mottaghizadeh[1], Djamal Gacemi[1], Allegra Calabrese[1], Angela Vasanelli[1], Lianhe Li[2], A. Giles Davies[2], Edmund H. Linfield[2], Filippos Kapsalidis[3], Mattias Beck[3], Jérôme Faist[3] & Carlo Sirtori[1]

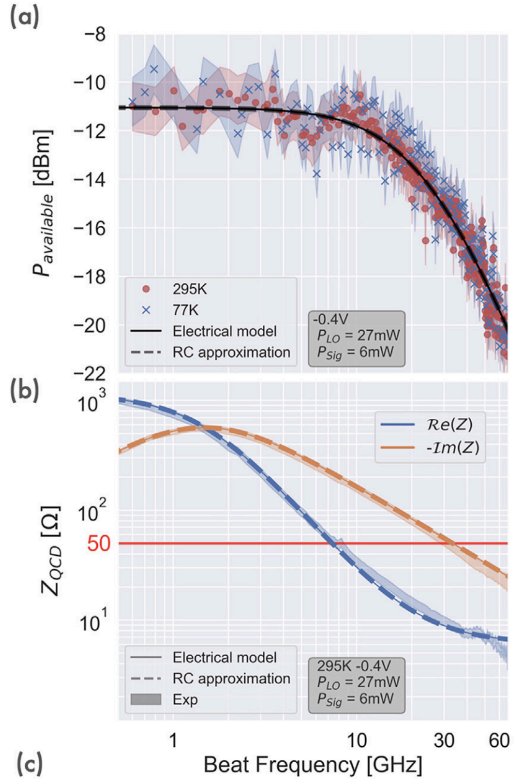
An unexploited intrinsic property of inter-subband quantum-well infrared photodetectors (QWIPs) based on group III–V semiconductor materials is the very short lifetime of their excited carriers. The typical lifetime is of the order of a few picoseconds[7], which has two important consequences: the detector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

a









C. Sirtori (LPENS) group, Palaferri et al. 2018, Gacemi et al. 2018, Bigioli et al. 2020
IEMN: Quinchard 2019, 2022

Challenge 4: high bandwidth correlation

Thèse: T. Allain (2024)

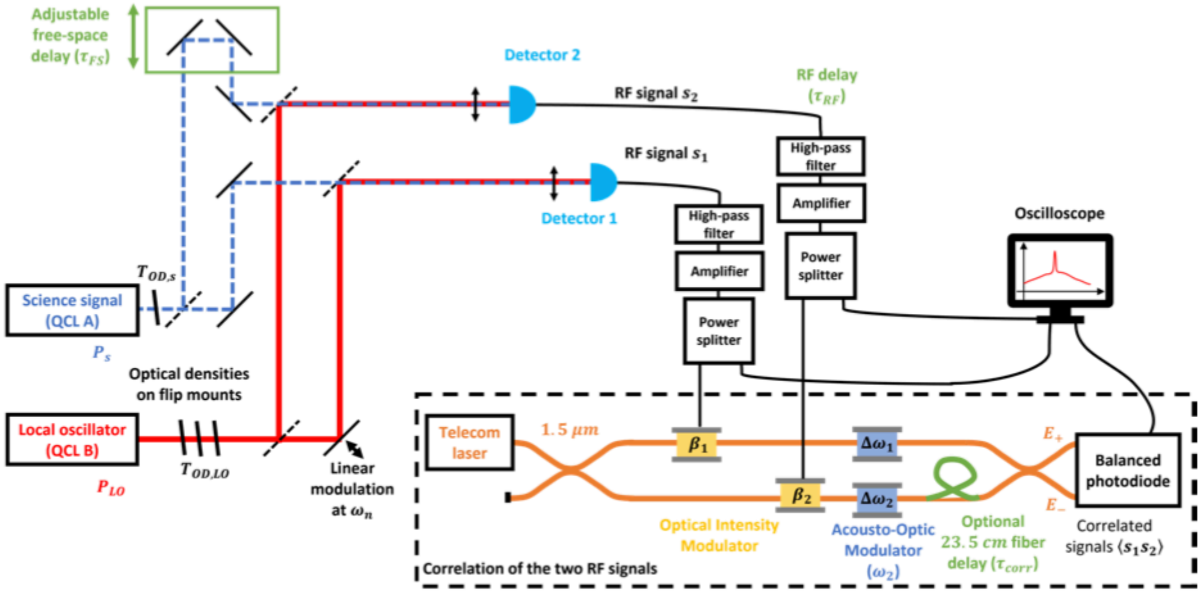
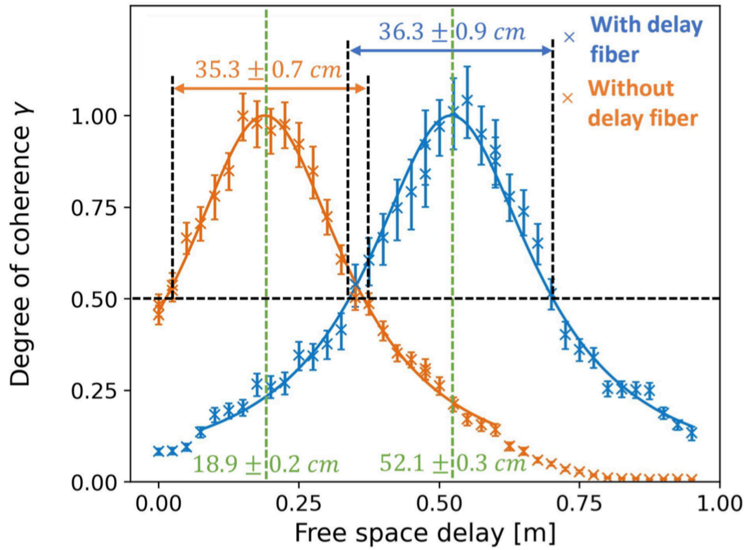


Fig. 3: Representation of the current state of the demonstration bench.



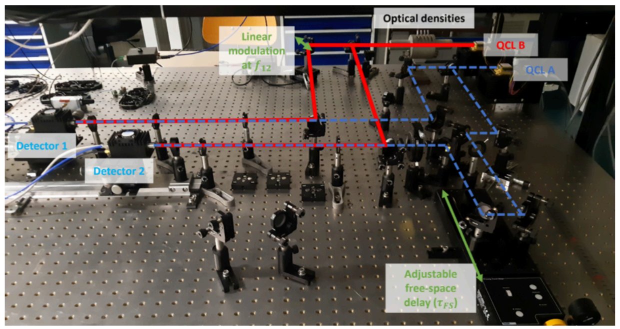


Fig. 4: Photograph of the IR heterodyne detection stage of the bench with annotations highlighting the main elements.

HIKE bench

Demonstrating mid-infrared coherence propagation and measurement over kilometric distances

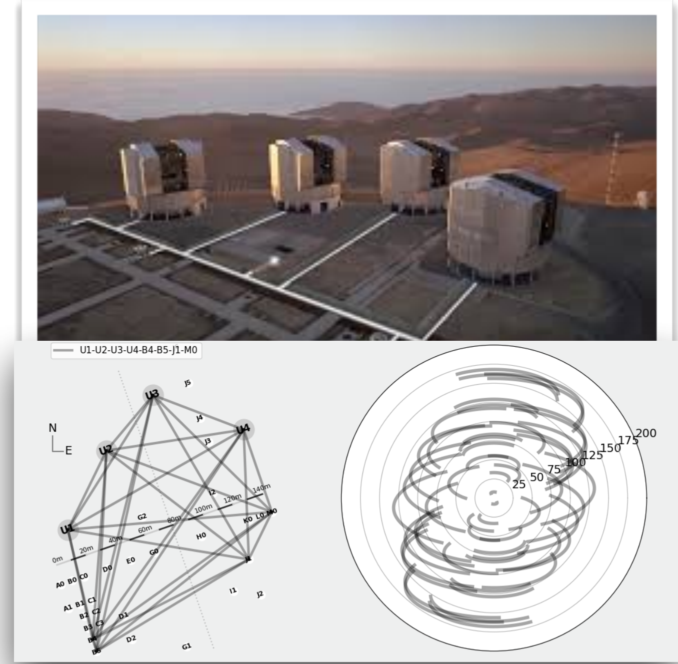
Next steps

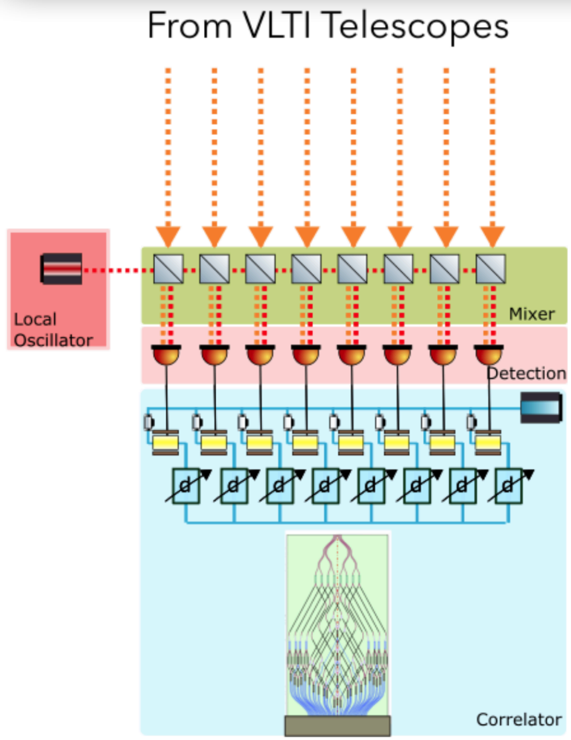
- Integration of (active) long delays (km) in the bench

- System study: turning prototype into instrument

- Exploration of Q band detectors (18-22 microns)

- On-sky demonstration centered on prominent astrophysical mid-IR lines



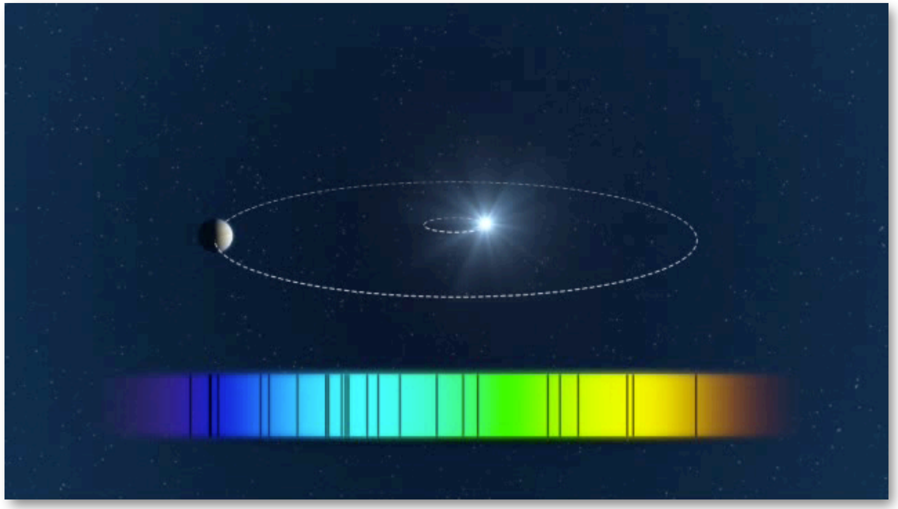


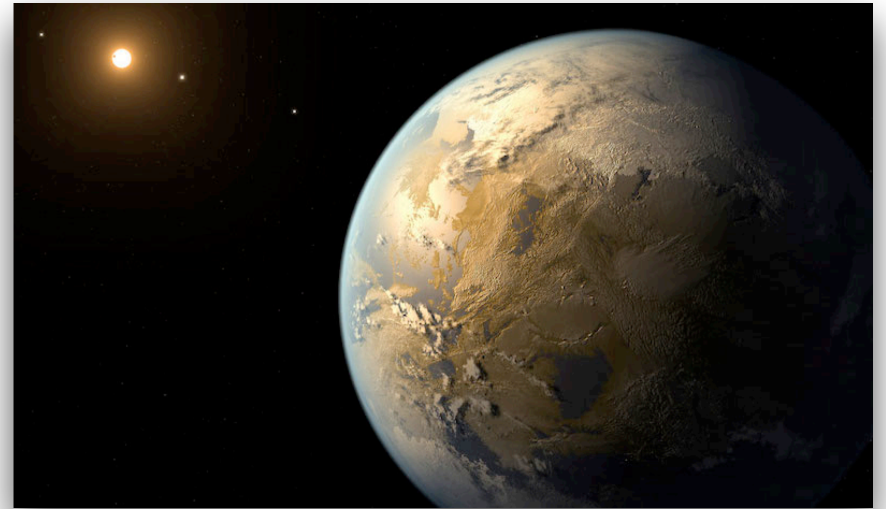
Precision radial velocity

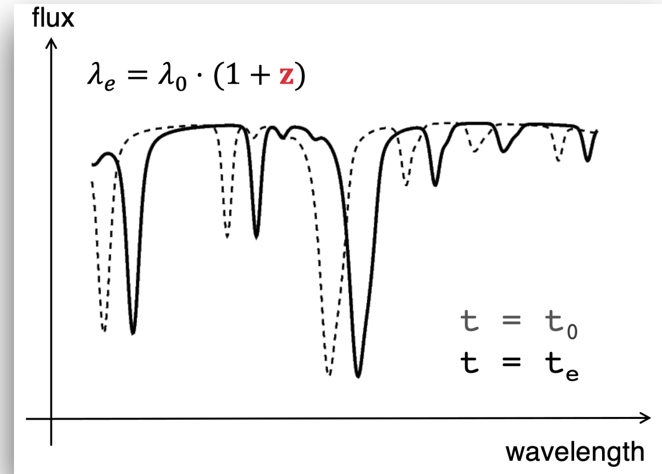

Habitable Worlds
OBSERVATORY

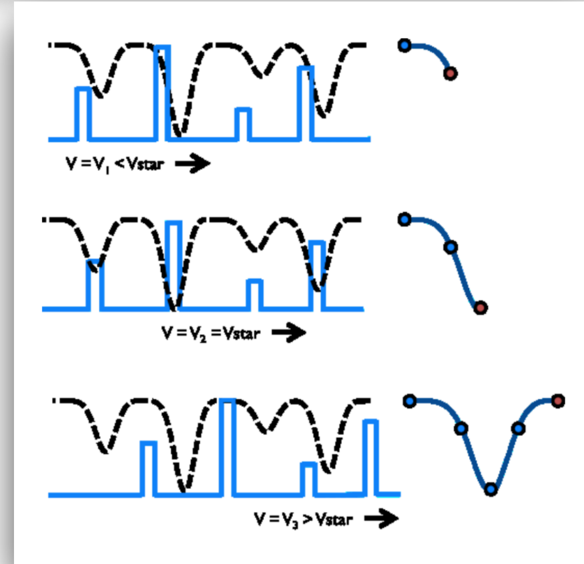
High precision radial velocity measurement

Sun-like stars (0.5-2.2 microns)



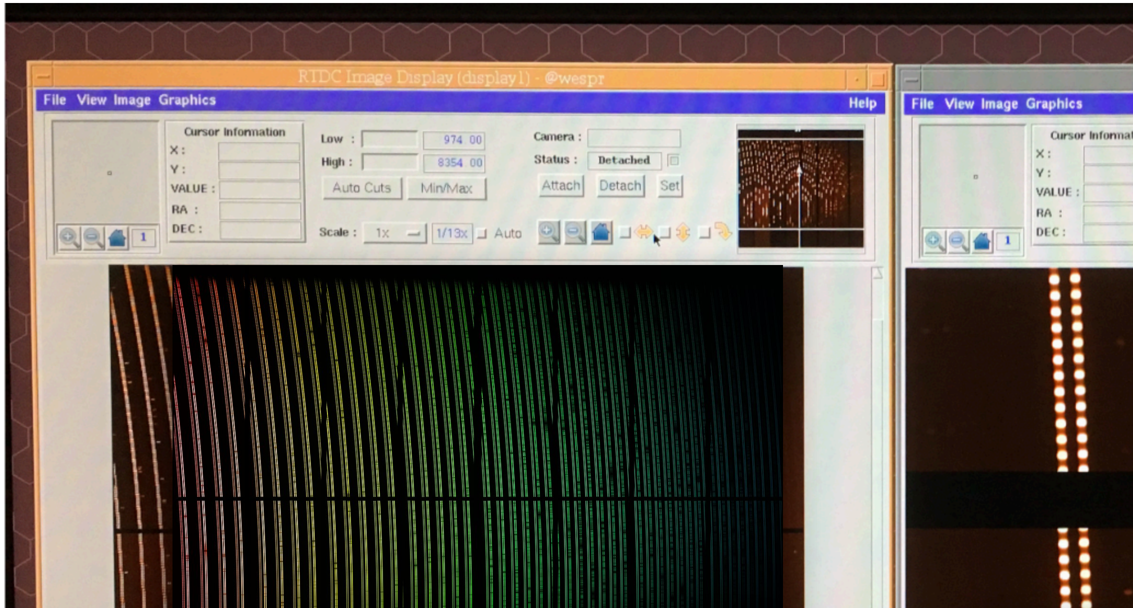


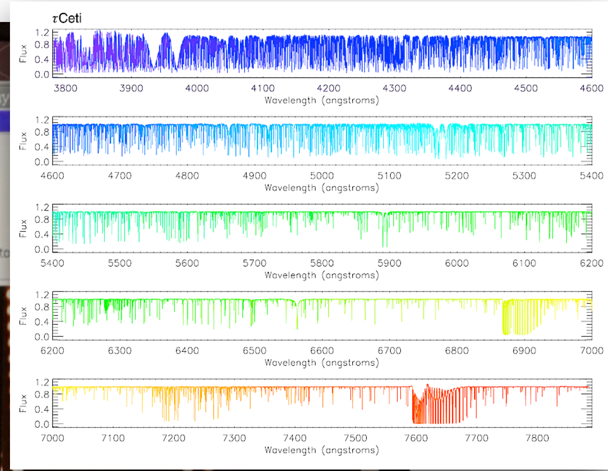


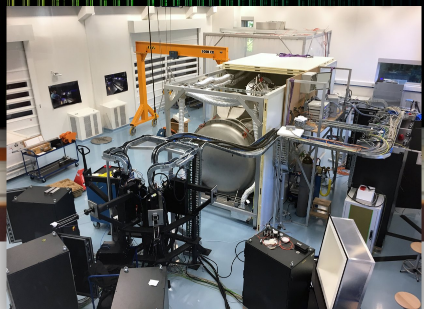


- Measuring a radial velocity of 10cm/s => wavelength shift of 1/10000 of pixel

Need for high precision calibration







ANR Traces: 2026-2029
Building a robust broadband LFC for exoplanet radial velocity exploration
PI (N. Forget)
co-I: IPAG & U. Bordeaux

- LFC are potentially the best calibration sources (12 instruments currently in use) but
  - Spectral coverage limited (ideally 0.4 - 0.8 mic, 1 - 2.2 microns)
  - 10-30 GHz line spacing
  - Spectral flatness, temporal variability, coupling to multi-mode spectrographs, remote operatibility, high frequency stability
  - Overall complexity, size, weight, stability, stability of long periods (~10 years), cost

Ex: Obrzud et al. 2019

Wrap up

- Observing and characterizing exo-planets young and mature is a major astrophysical endeavour that requires new instrumentation.
- Frequency stabilized laser frequency combs have tremendous potential for astronomical applications but specific characteristics are needed.
- High precision radial velocity measurements are key to finding earth-like planets. First application of LFC are very promising but a significant work is needed for widespread application (robustness wavelength coverage)
- Infrared aperture synthesis could be the next big field of application of LFC but requires increase in TRL level for many functions (projects ongoing)

Fin