SYNCHRONISATION ENTRE SITES DISTANTS POUR MESURES DE CORRÉLATIONS D’INTENSITÉ EN ASTROPHYSIQUE

FIRST TF

OBSERVATOIRE DE LA CÔTE D’AZUR
UNIVERSITÉ CÔTE D’AZUR

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INVESTISSEMENTS D’AVENIR

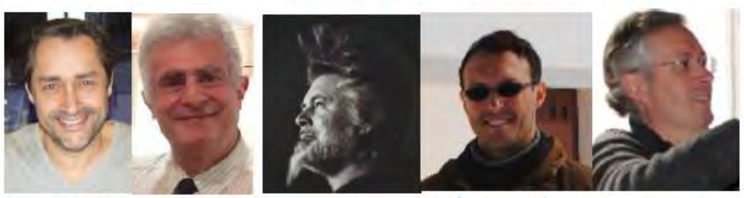
People involved

INPHYNI "Cold Atom" Team

Robin Kaiser | William Guerin | Mathilde Hugbart | Guillaume Labeyrie | Nolan Matthews

Former members:
Antoine Dussaux
(Post-doc UNS, 2015-2016)
Antonin Siciak
(PhD student UCA, 2018-2021)

Lagrange (OCA)



Jean-Pierre Rivet | Farrokh Vakili | Olivier Lai | Armando Domiciano de Souza | David Vernet

Géoazur, MéO team

Clément Courde | Julien Chabé

- First discussion in 2017
- Labex First TF financial support in 2018
- In 2020 we obtained a research grant from the French national research agency (ANR) to support our effort (Grant ANR-20-CE31-0003, 409 k€ for 4 years: 2021-2024).

What is intensity interferometry in astronomy ?

- Hanbury Brown and Twiss experiment :
- "Light from a star is received on two separated photoelectric detectors, D_1 D_2 and produces output currents I_1 I_2.
- These currents fluctuate and an intensity interferometer relies on the fact that the fluctuations are *partially correlated*.
- The principal component of the fluctuations is the classical *shot noise* associated with any current but, in addition, there is a smaller component called *wave noise* which corresponds to the fluctuations in the intensity of the light wave."

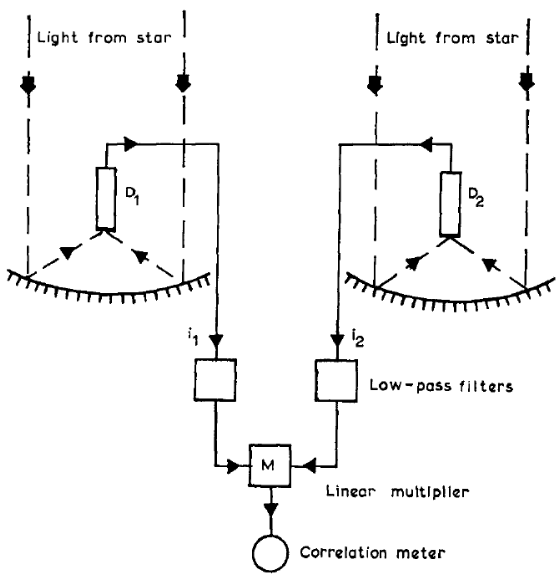


Fig. 2.4. Simplified outline of an intensity interferometer.

$$g^{(2)}(r,\tau) = \frac{\langle I_1(t) I_2(r, t+\tau) \rangle}{\langle I_1 \rangle \langle I_2 \rangle}$$

THE INTENSITY INTERFEROMETER
its Application to Astronomy (1974)

R. HANBURY BROWN, F.R.S.
Professor of Physics {Astronomy)
University of Sydney

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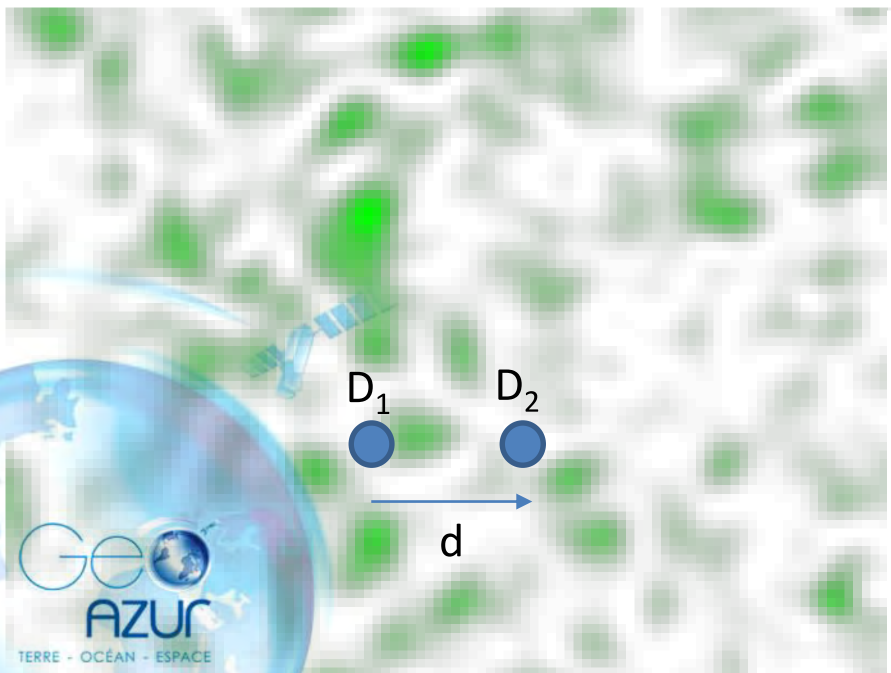
What is intensity interferometry in astronomy ?

- The intensity (speckle) pattern in the observing plane from a star:
  - Speckle size = correlation radius $L_{coh} = \lambda/\theta$
  - Coherence time $\tau_c = 1/\Delta\omega$



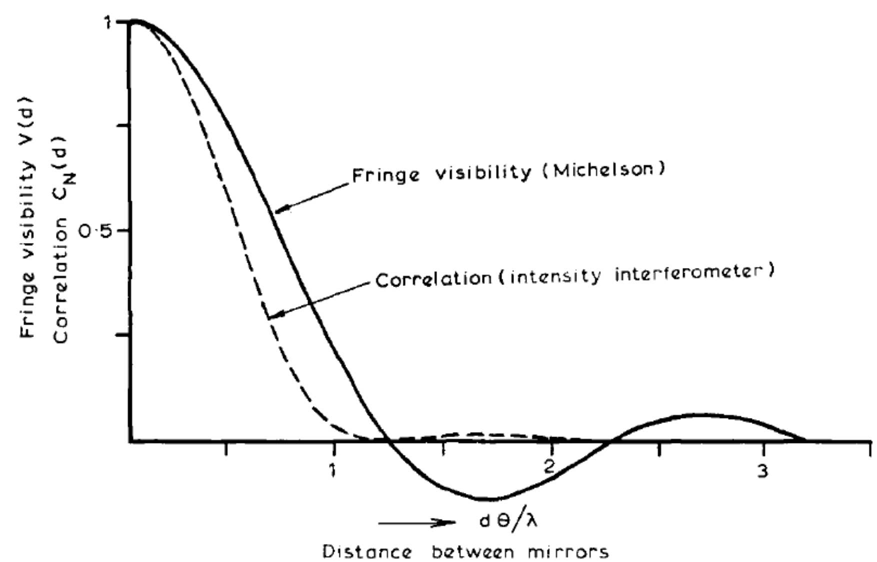


Fig. 2.3. Variation of fringe visibility with separation of mirrors for a Michelson interferometer (full line), an intensity interferometer (broken line). The source is a uniform circular disc.

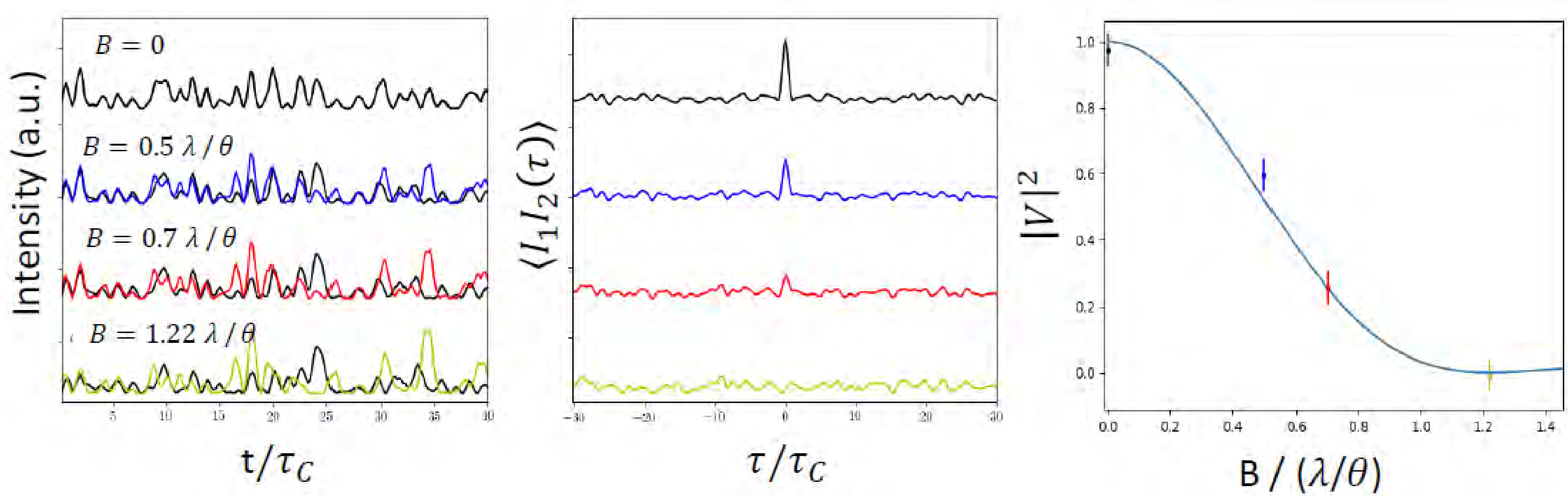
A bit of theory…

- The $g^{(2)}(r)$ function is related to $g^{(1)}$ so to the square modulus of the visibility of the Michelson interferometer:

$$g^{(2)}(r,\tau) = 1 + |g^{(1)}(r,\tau)|^2$$

$$g^{(1)}(r,\tau) = V(r)g^{(1)}(\tau)$$

$$|V(r)|^2 = \frac{g^{(2)}(r,\tau=0)-1}{g^{(2)}(r=0,\tau=0)-1}$$



A bit of history…

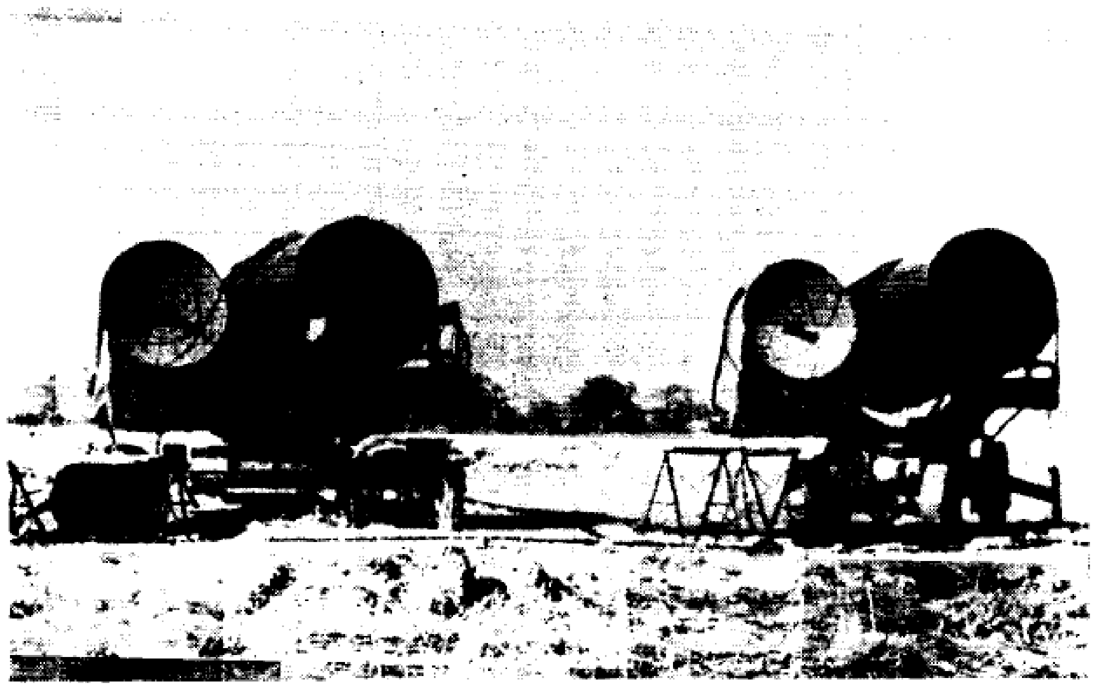
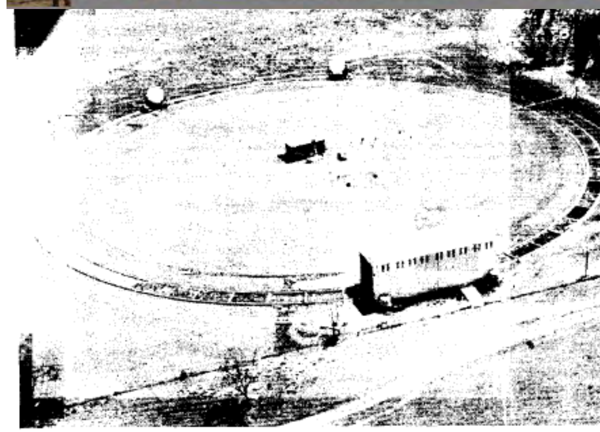


Fig. 7.5. The first stellar intensity interferometer at Jodrell Bank (University of Manchester) in 1956.

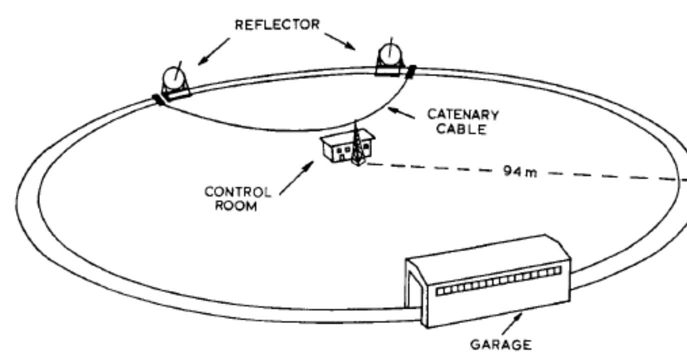
1956 : They measured the diameter of the star Sirius with a prototype intensity interferometer involving two 1.56 m searchlight projectors used as photons collectors !

A bit of history…

- HB & T built an interferometer at Narabi Observatory in Australia
- Bucket detector with phototubes
- They collected data over 10 years on 32 stars



(a)



(b)

Fig. 8.1. (a) An aerial view of the stellar interferometer at Narrabri Observatory. (b) The general layout of the interferometer.

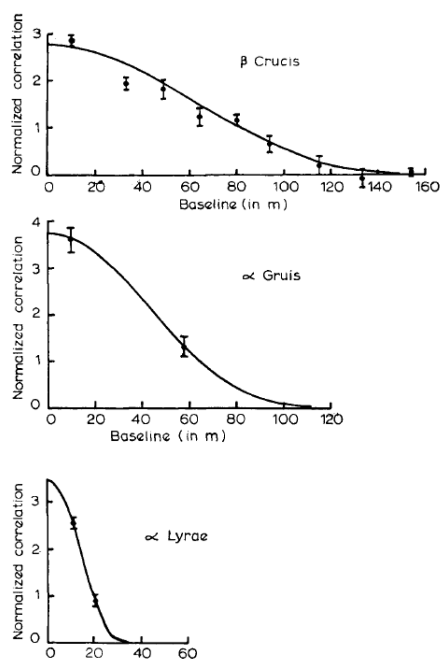


Fig. 10.2. Correlation versus baseline measured for three stars of different angular size. The full lines were fitted to the points as described in the text. From Hanbury Brown, Davis, Allen and Rome (1967).

A bit of modernity…we don't collect light anymore we count photons !

telescope area

light collection efficiency

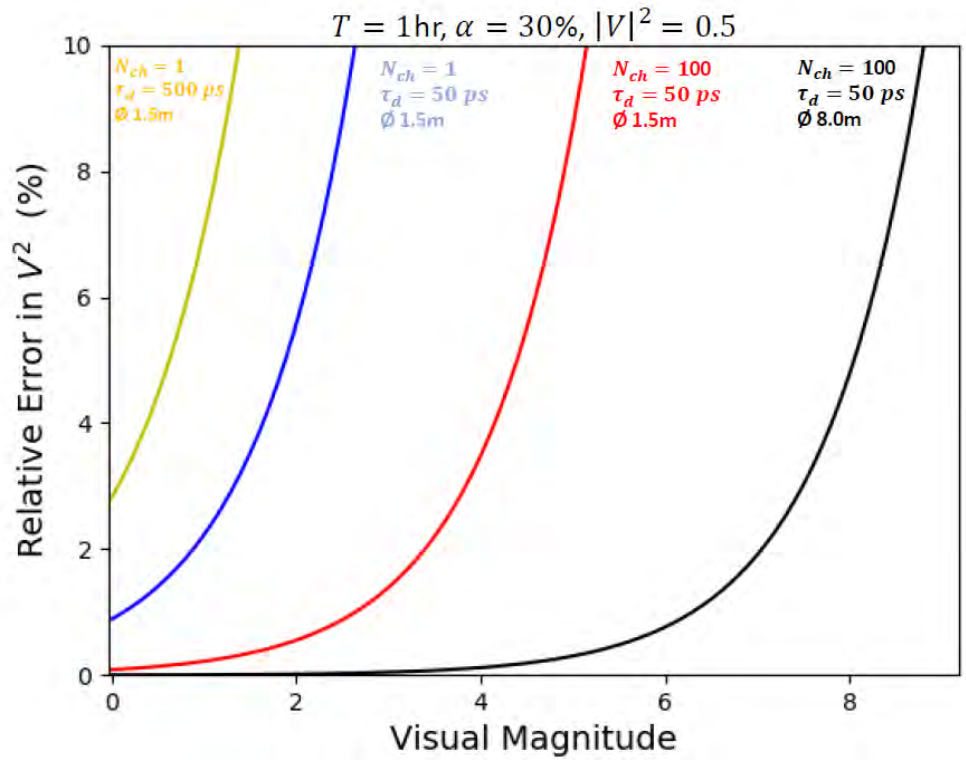
Observing time

$$S/N = \frac{A\alpha}{\sqrt{\tau_d}} \times \sqrt{N_{ch}} \times \eta |V(d)|^2 \times \sqrt{T}$$

time resolution

spectral flux density

# of spectral/polarization channels

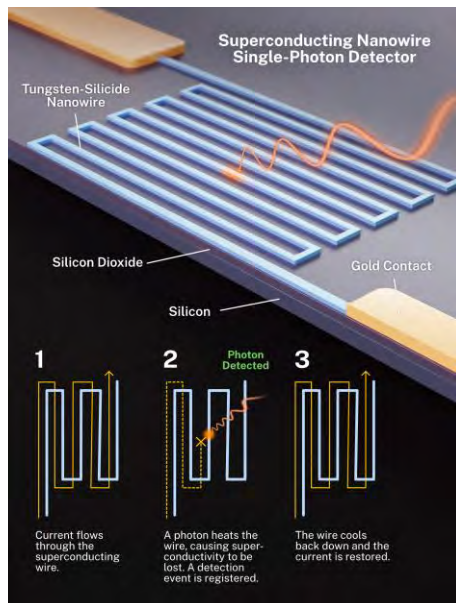


- Photon counters timing resolution -> large band pass
- Timing jitter of the signal processing system (TDC, cables, clocks,…)

Timing resolution needed

- Coherence time : $\tau_c = \lambda^2/c\Delta\lambda$ ~ ps
- Detector Timing jitter: 15ps to 500 ps
- « Timing system » : < 15ps

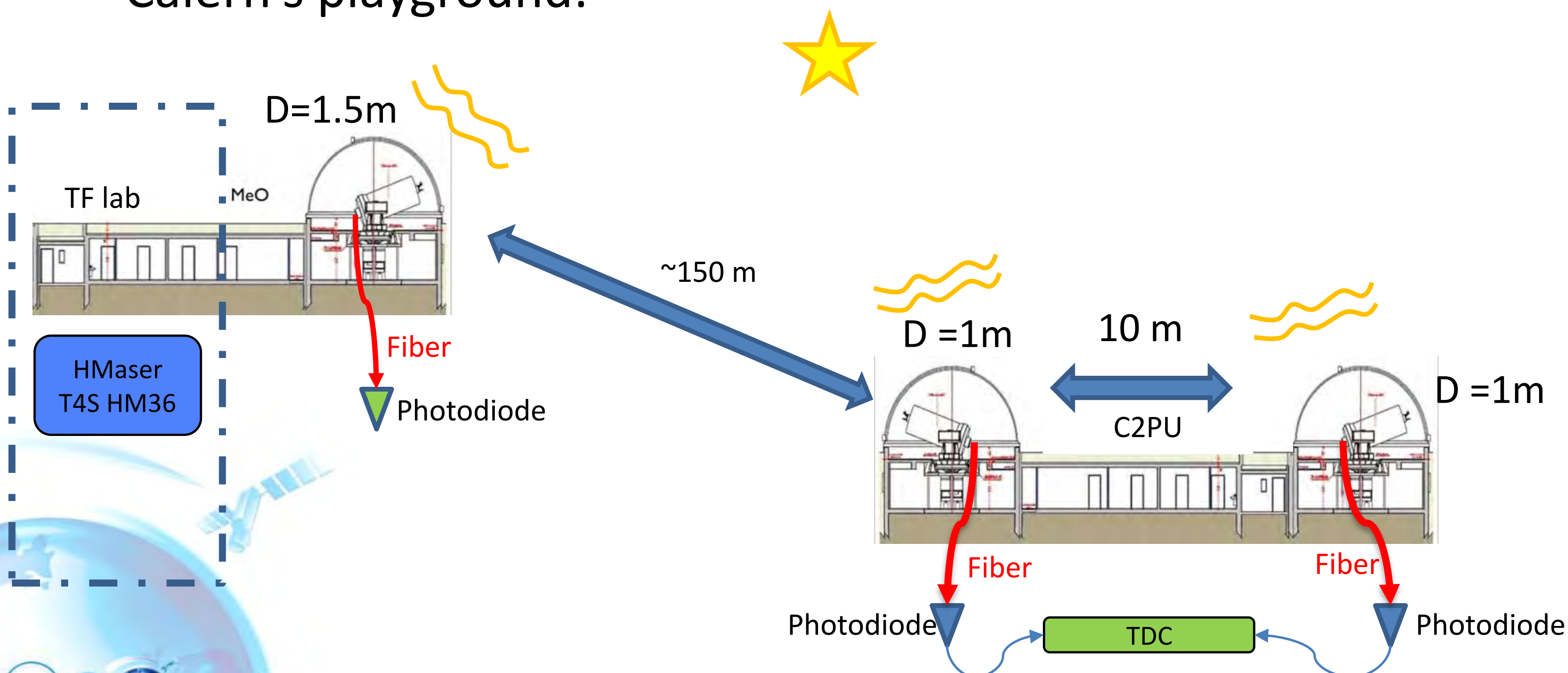
Excelitas SPAD



SNSPD (Single Quantum)

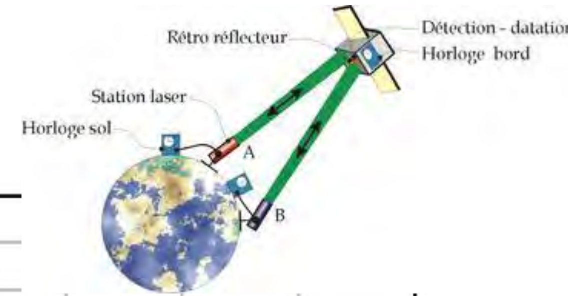
What timing system for 2 or more telescope ?

- What is the baseline :
  - From tens of meter up to 1km !
- Calern's playground:



A good clock for each telescope ?

Lessons from T2L2 mission era



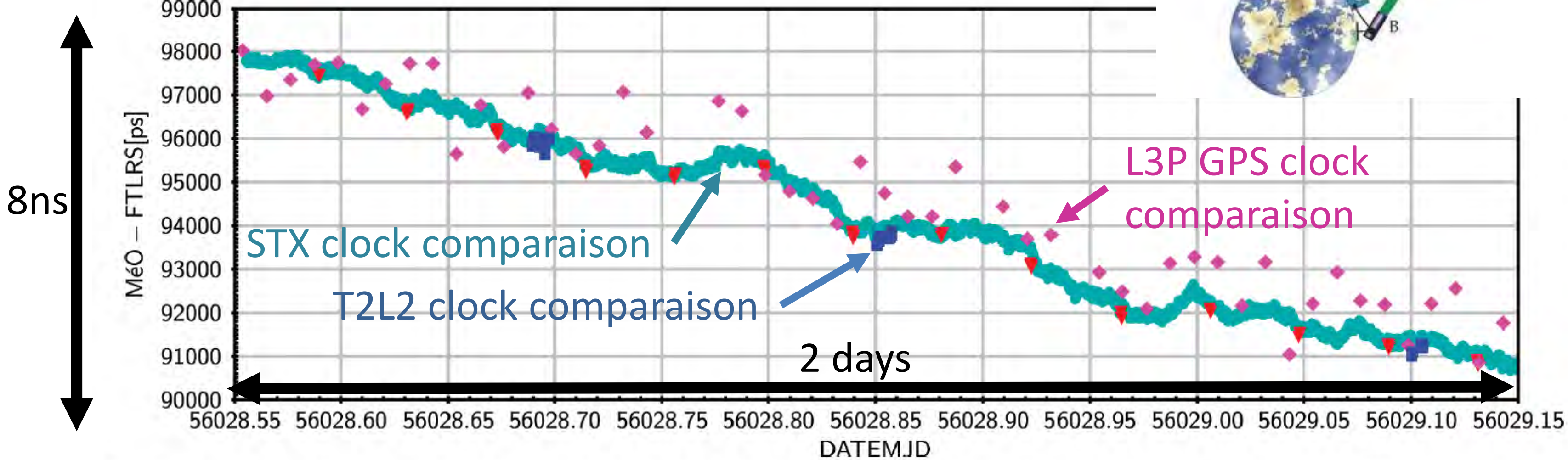


Fig. 5. Comparison of time transfer techniques during 2 d: April 11 and 12, 2012 (56028 and 56029). Cyan circles represent STX301 measurements, red triangles those of SR620, pink diamonds those of L3P GPS, and blue squares those of T2L2. All are time differences between the two reference points of the laboratory.

- It is difficult to rely on independant clocks and GPS time comparison for our purpose

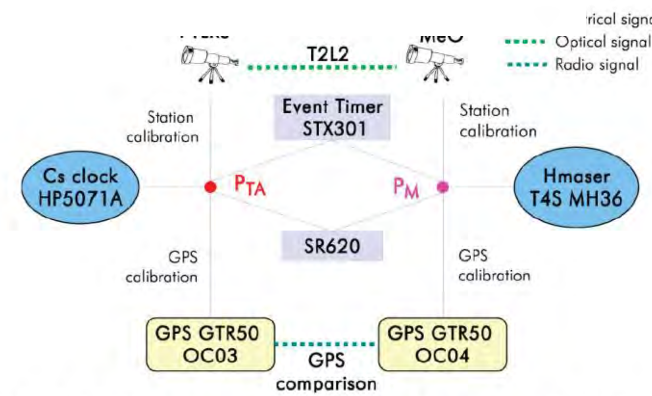


Fig. 3. Simplified diagram of equipment and links during the April 2012 T2L2 accuracy campaign in Calern. We used two ground links, STX301 and SR620, and two space links, T2L2 and GPS. The FTLRS laser station was connected to the cesium clock and MéO to the hydrogen maser. Two reference points, P_{TA} and P_M, were defined.

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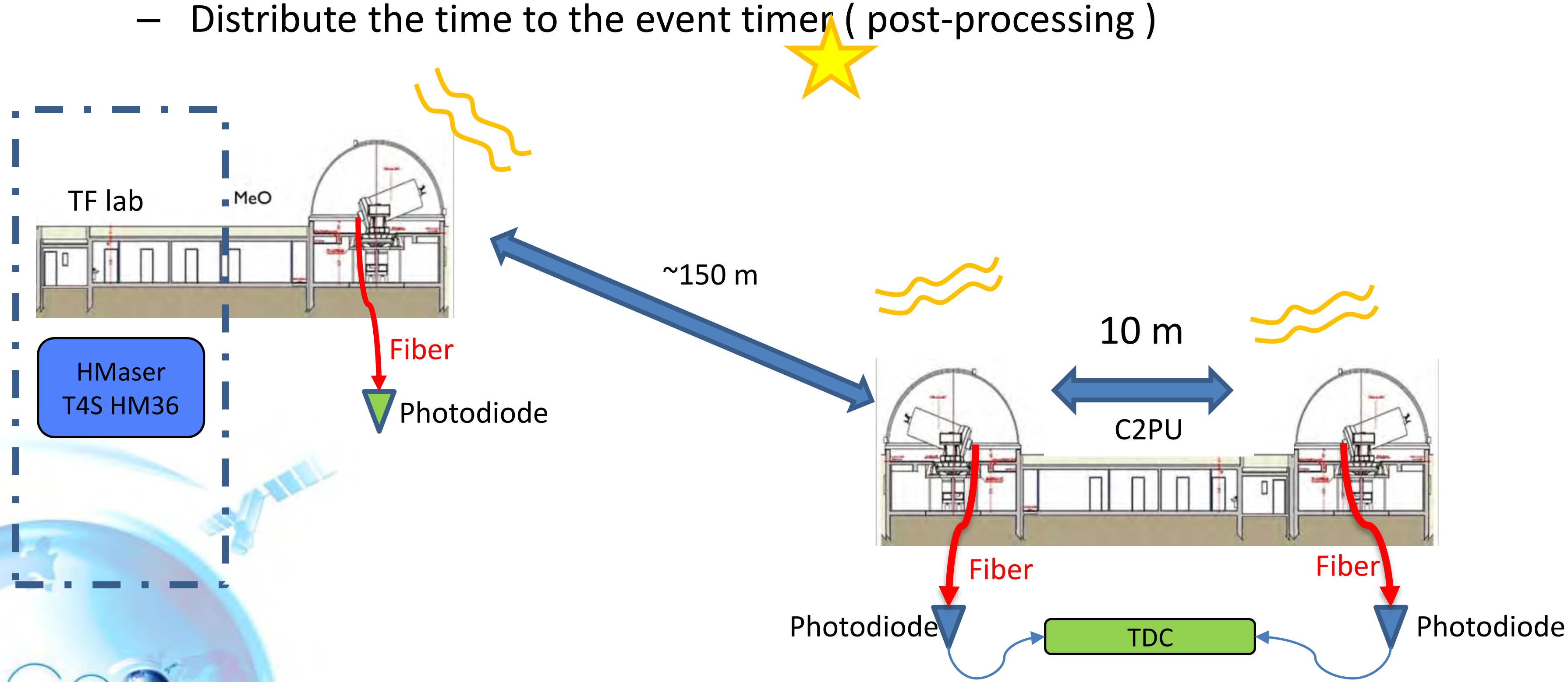
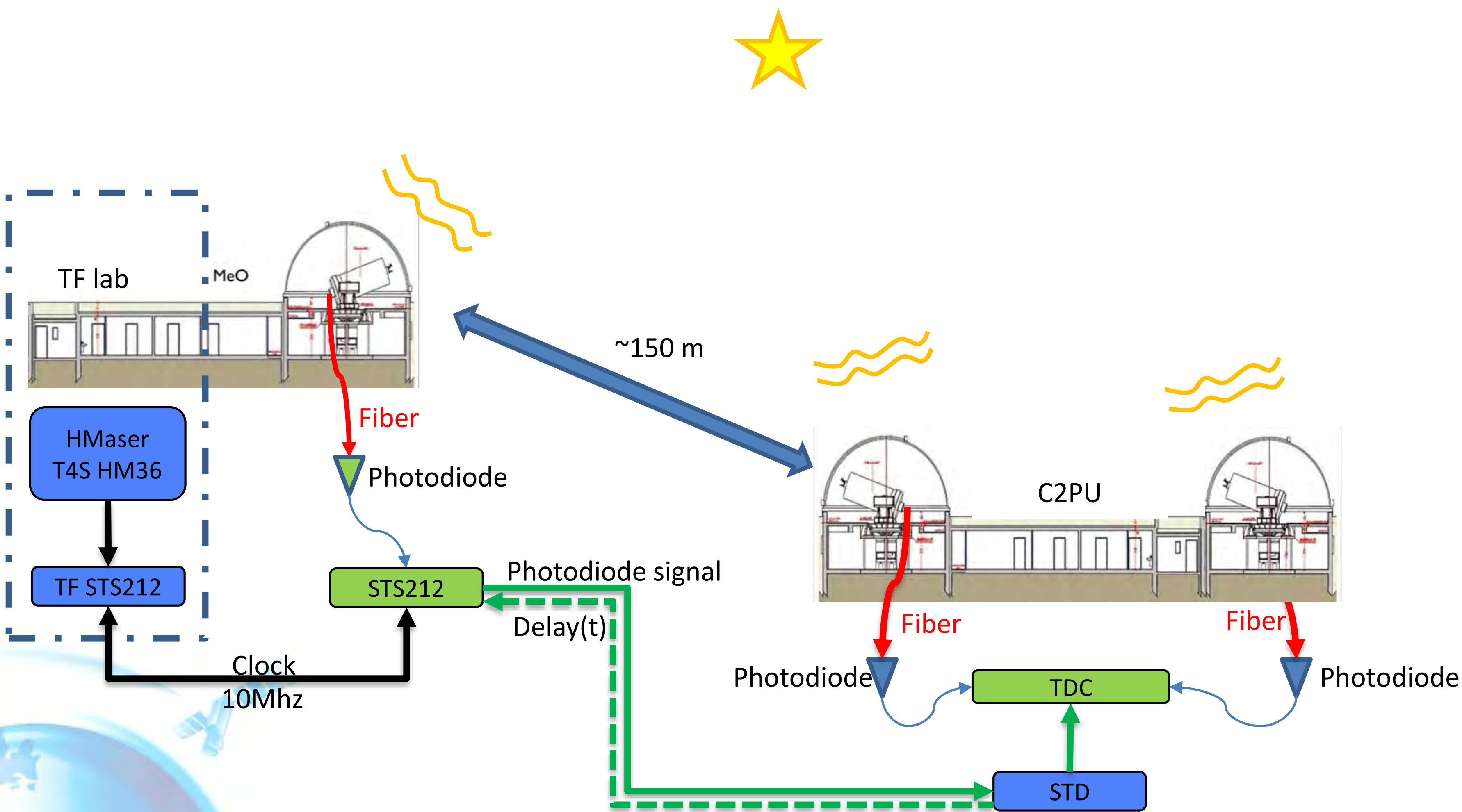
What timing system for 2 or more telescope ?

- We want to:
  - Distribute the photons events to the correlator (real time correlation averaging)
  - Distribute the time to the event timer (post-processing)



What timing system for 2 or more telescope ?



ST212 – STD system (Labex First-TF funded)

- Picosecond Event Timer from T2L2 era modified to:
  - Accept analog signal from exelitas photodiode
  - Generate a P/N pair signals to propagate toward STD
- STD transmits :
  - an analog signal to the TDC
  - Reproduce the P/N pairs for the STS212 for the measurement of the propagation time

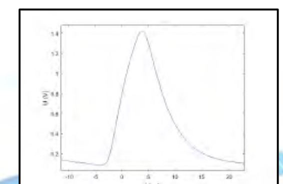
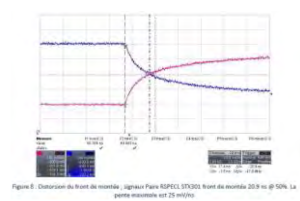
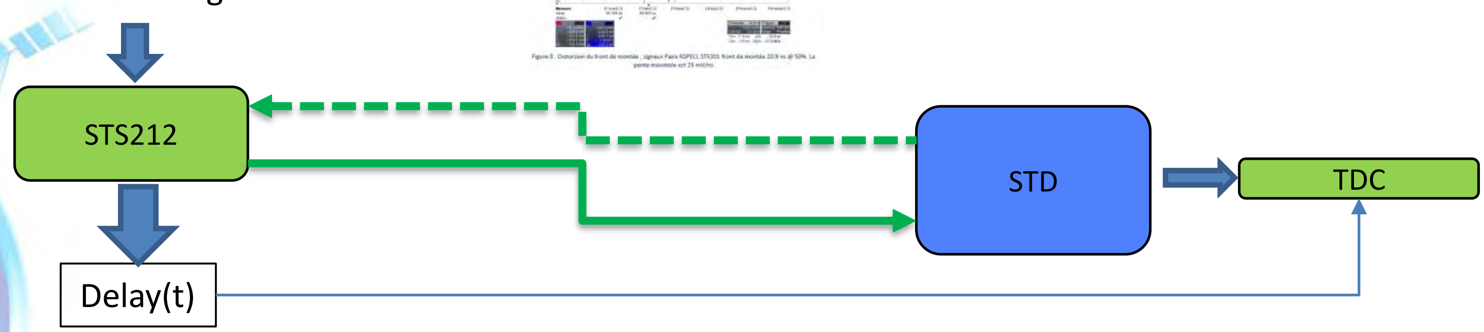


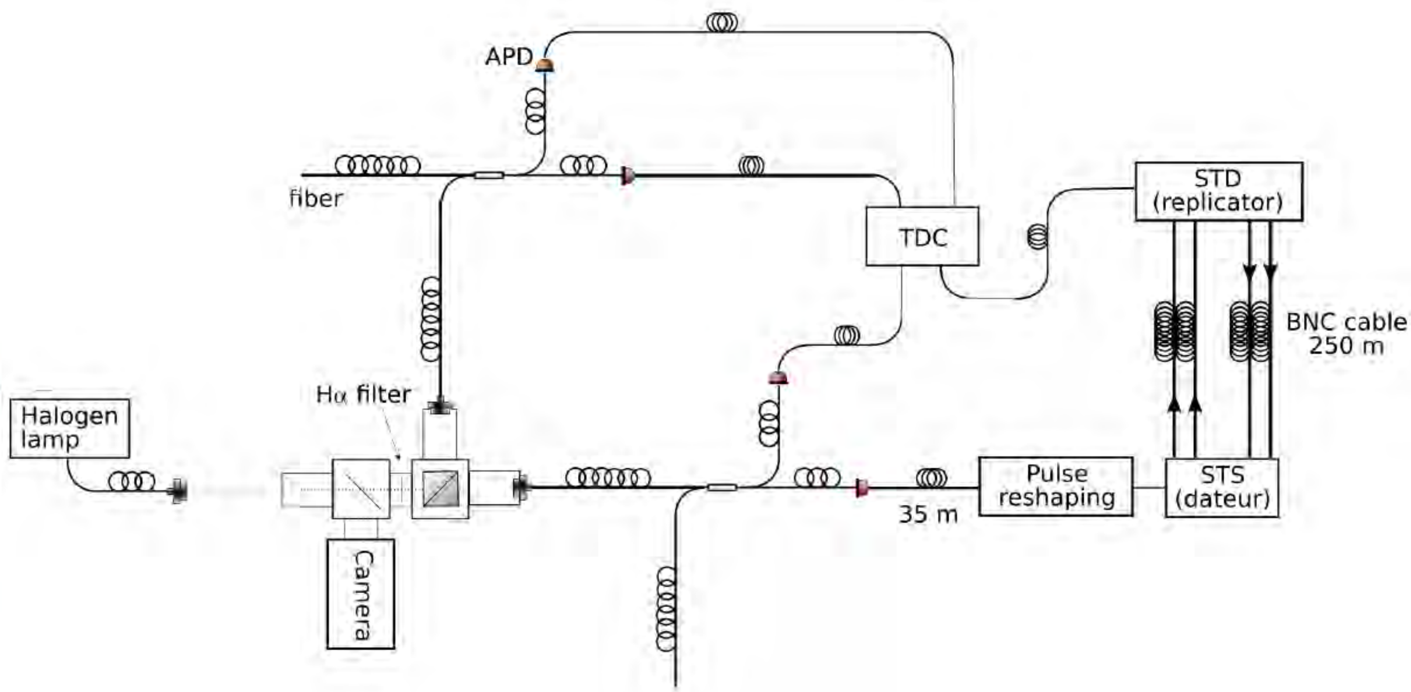
Figure 1 : Signal analogique issu de l'APD





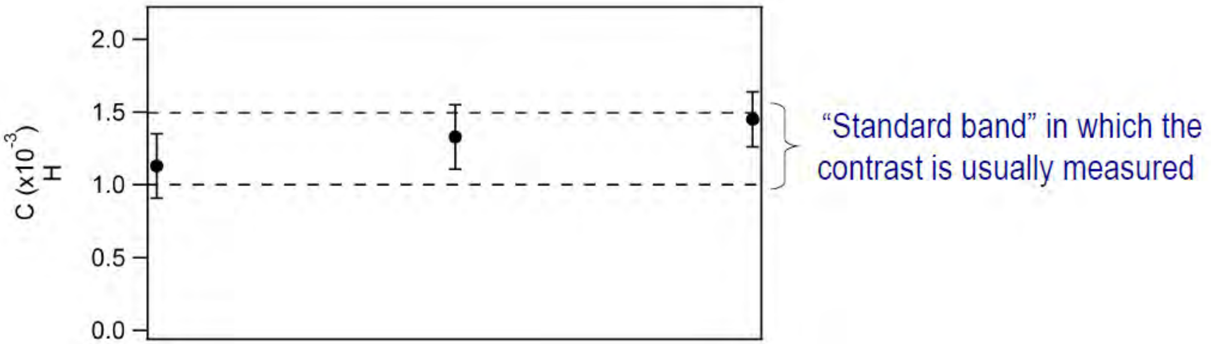
Performances of the wired system (Labex First-TF funded)

- Nominal Rate: DC - 1 MHz, Propagation Timing jitter over 250m : 1.6ps
- Delay measurement timing jitter de 2.2 ps RMS.
- Over 1 MHz : drift of 20 ps of the propagation @ 5MHz.
- Laboratory experiment:



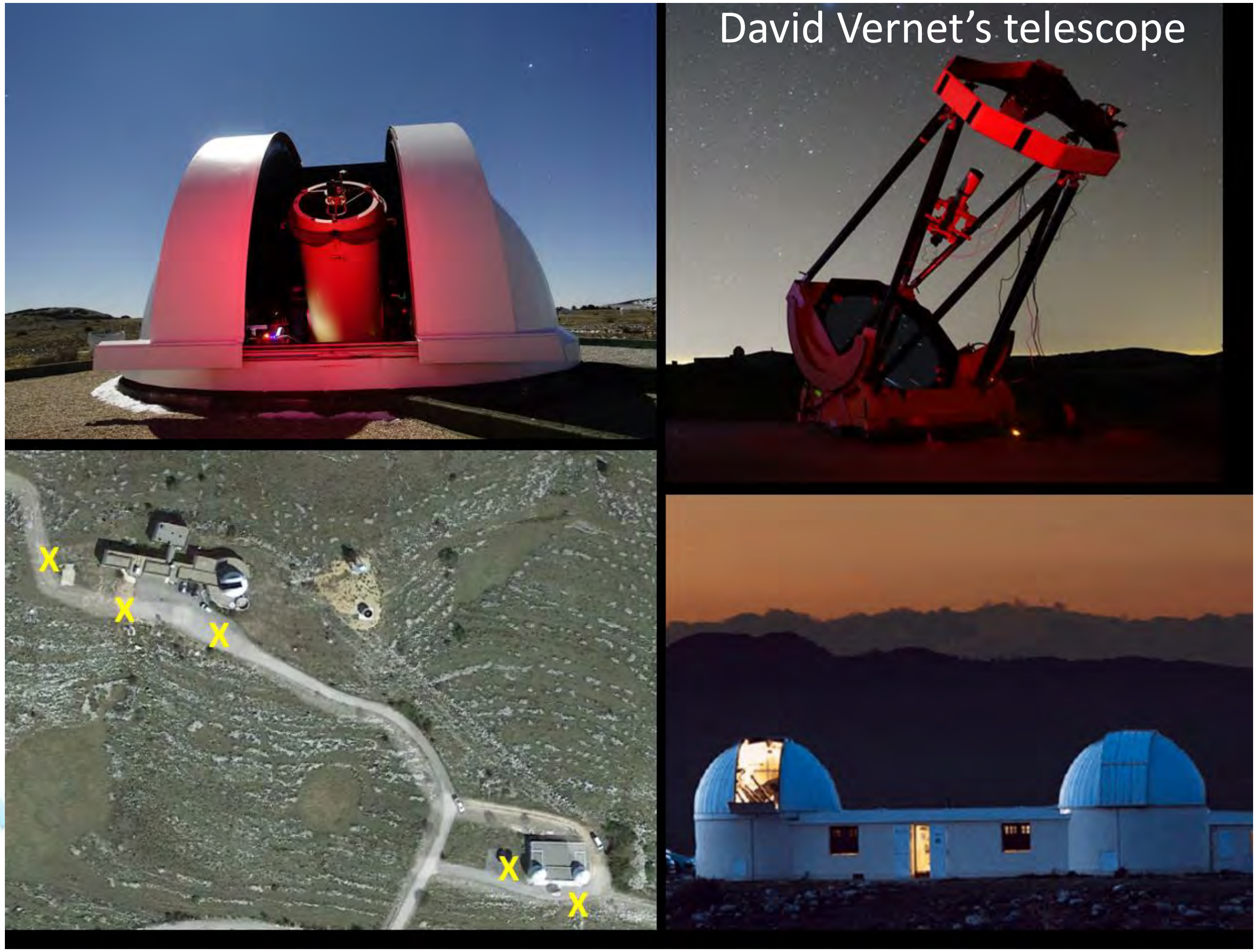
Performance of the wired system on $g^2(\tau)$

	H			V		
	C x 10^3	FWHM (ps)	Area (ps)	C x 10^3	FWHM (ps)	Area (ps)
No STS	1.13 +/- 0.22	772 +/- 73	0.926 +/- 0.18	1.22 +/- 0.14	804 +/- 45	1.05 +/- 0.12
STS+ STD 1 Mcounts/s	1.33 +/- 0.22	854 +/- 68	1.21 +/- 0.2	1.92 +/- 0.24	567 +/- 35	1.16 +/- 0.15
STS+ STD 4 Mcounts/s	1.45 +/- 0.19	660 +/- 43	1.02 +/- 0.14	1.23 +/- 0.14	793 +/- 44	1.04 +/- 0.12



- No degradation of $g^2(\tau)$ signal

Let's play on the sky : Calern extended playground



- IGN has mesured 5 new geodetic points for the mobile telescope
- Several configurations are usable to sample the visibility curve

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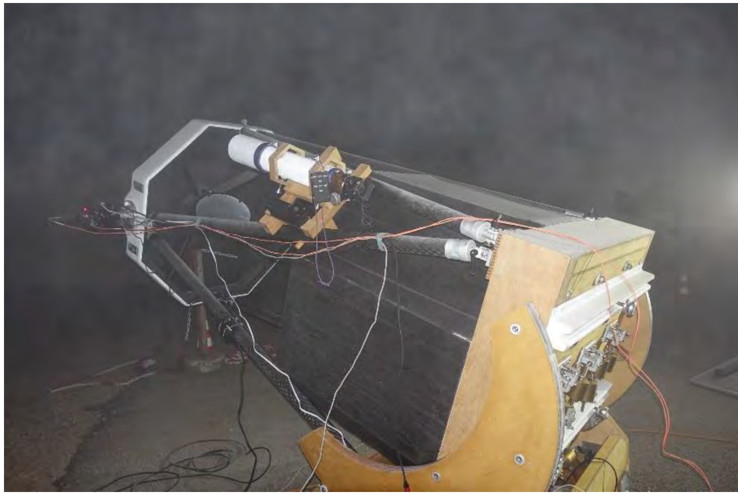
Observation Campaign (January 2022)

Quiet night



Freezing night

Smoky night

Pictures by David Vernet

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Observation Campaign (January 2022)

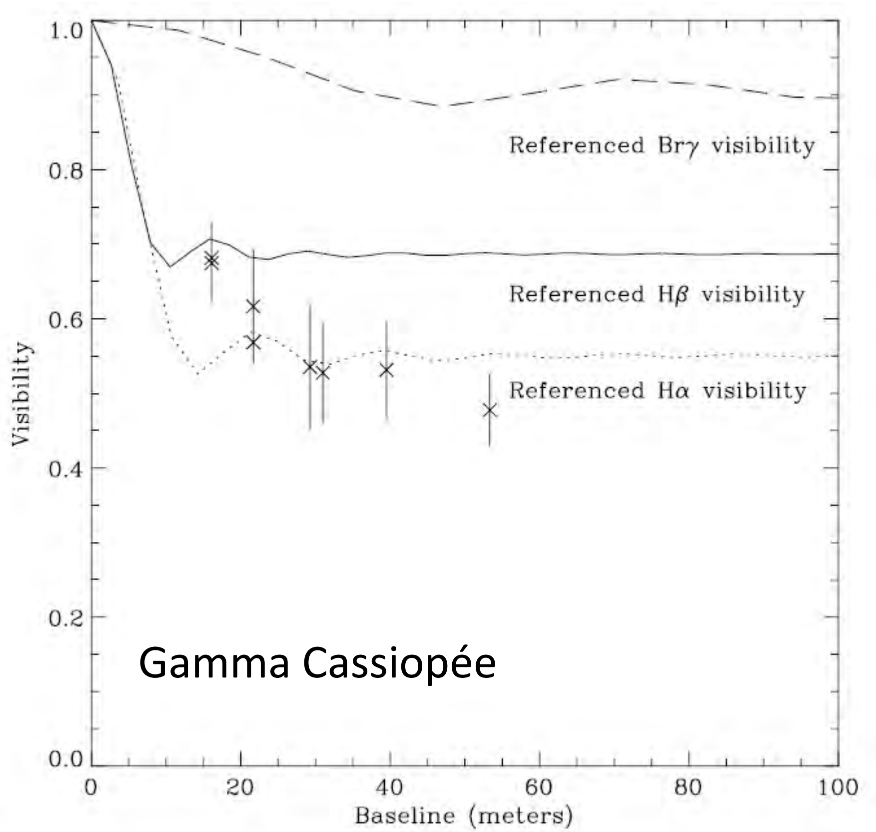
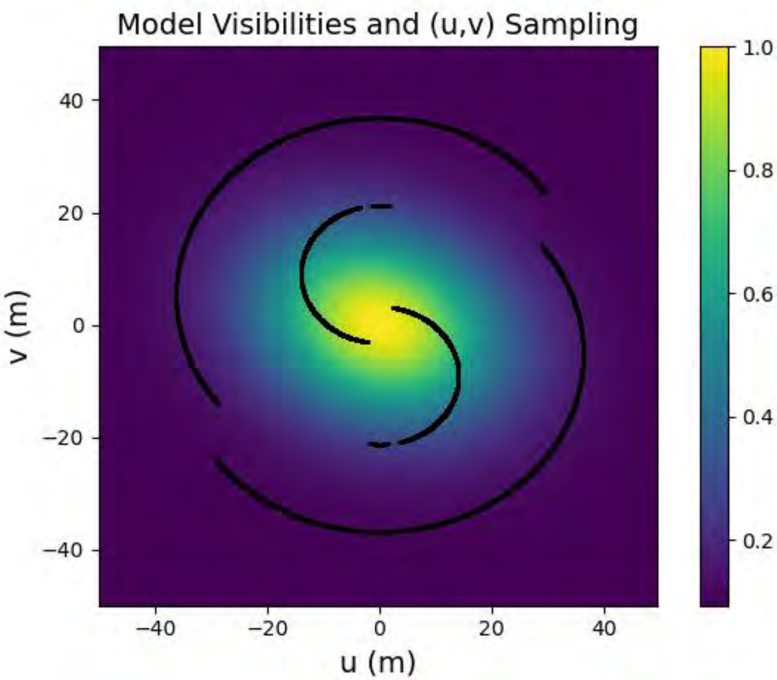


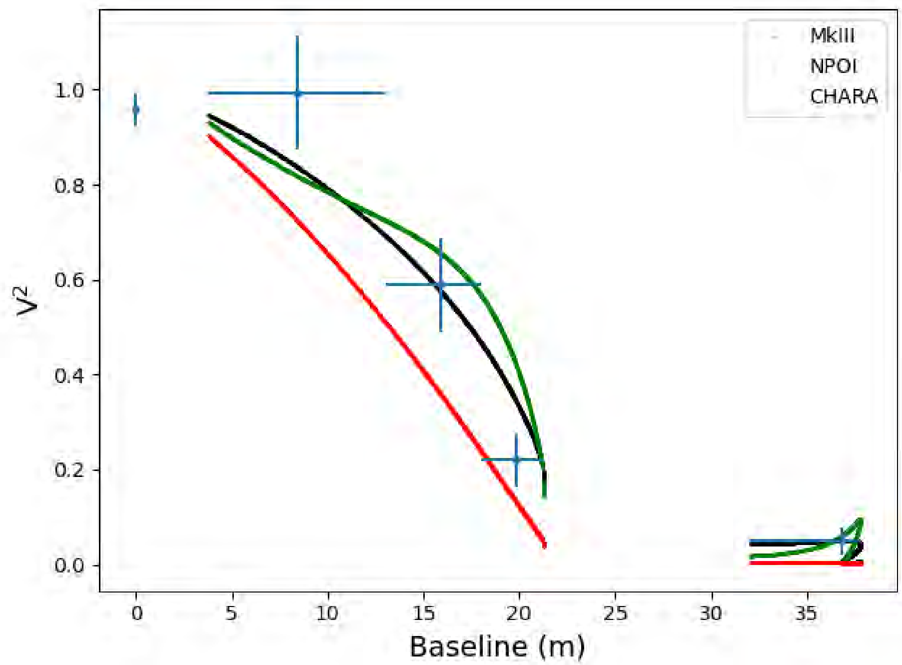
Fig. 4. Referenced visibilities as a function of baseline (in meters) in the North-South direction for the Be Star γ Cas. Respectively in the Hβ (solid line), Hα (dotted line) and Brγ (dashed line) line profiles. The crosses are data in the Hα line obtained from the GI2T during the 1993 campaign (see Paper I for more details)

Stee et al. A&A 367, 532 548 (2001)

Observation Campaign (January 2022)



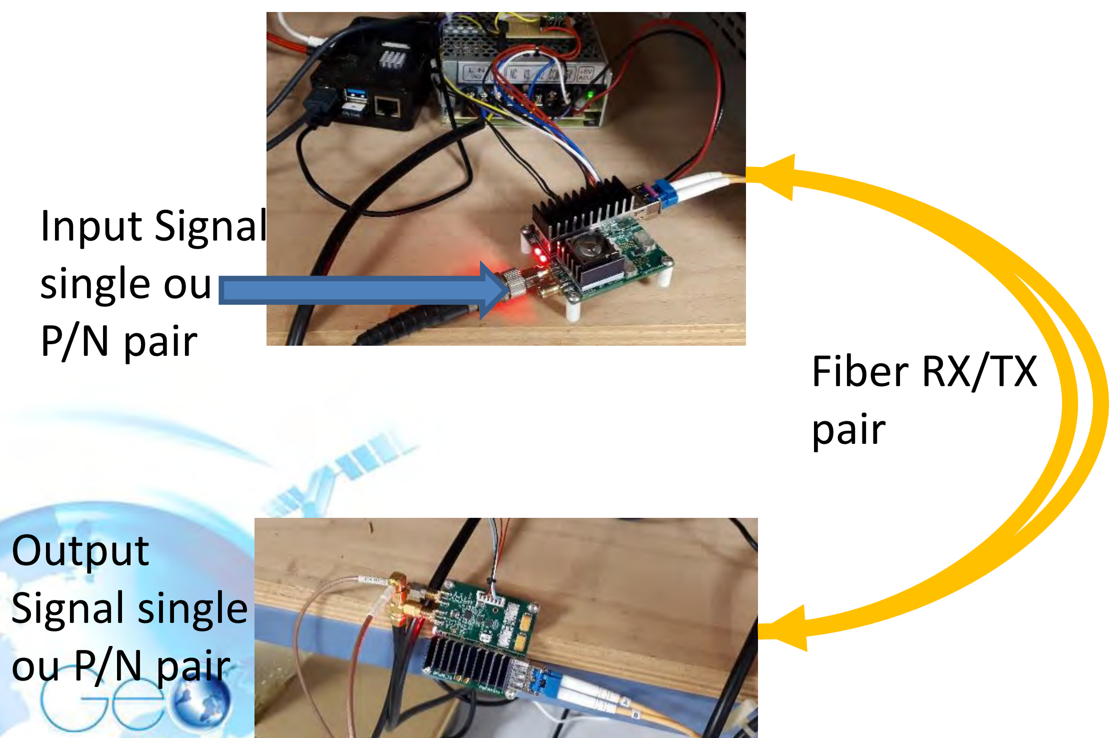
UV-plane sampling, on top of a Gaussian disk model of Gam Cas using parameters from Stee et al. (2012)



Squared visibilities from our data, along with the points one would sample in the uv-plane for the Gaussian disk model from three different observations (Quirrenbach et al. 1997 / MkIII, Tycner et al. 2018 / NPOI, and Stee et al. 2012 / CHARA)

Fibered System (funded by ANR) : STS 416

- Convert the photonic event to a telecom signal using SFP modules (no loss) : scalable at any size, multichannel
- Bring the detector as close as possible of telescope focal plane to limit fiber loss of stellar photons (in the visible)



SigmaWorks
etienne.samain@sigmaworks.fr

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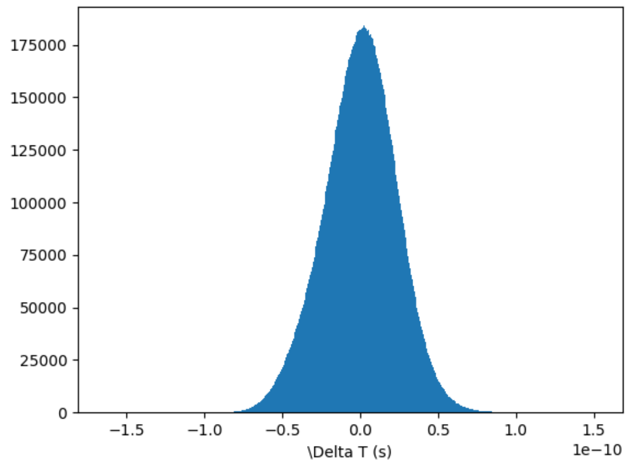
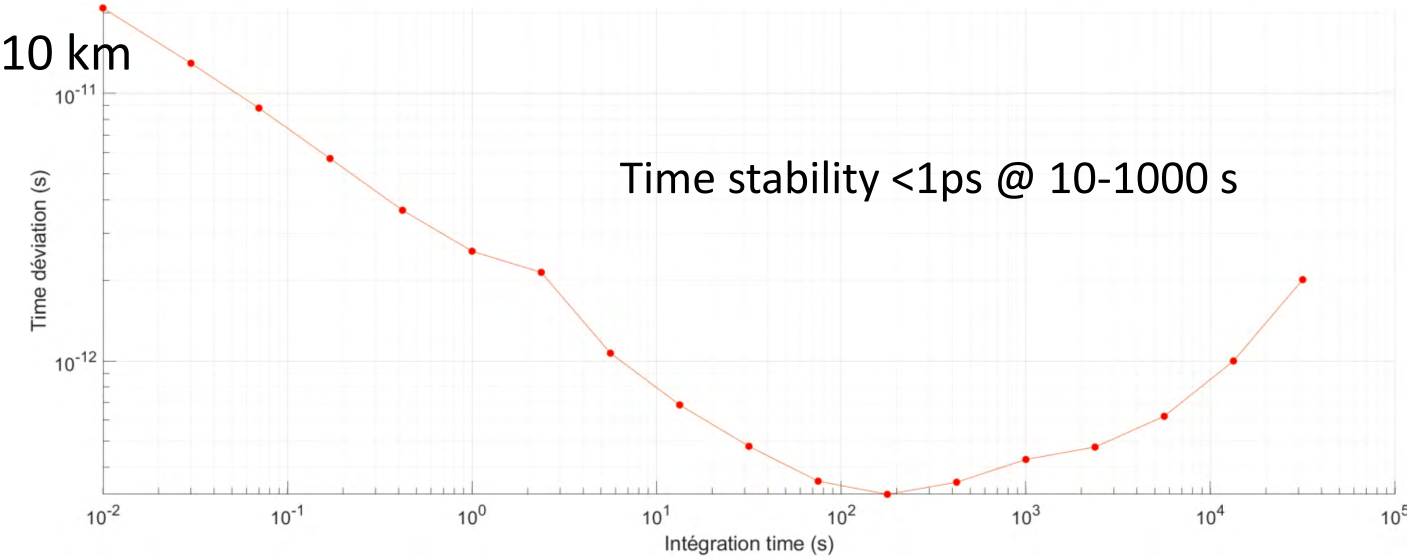
Performances of the fibered system

- Cadence des signaux max : 5 MHz
- Incertitude : < 5 ps RMS
- Stabilité : < 10 ps @ 1000 s
- Déclenchement sur front de monté
- Durée des pulses : quelques dizaines de ns
- Nombre de canal : 1
- Distance min : 1 m
- Distance max : < 10 km

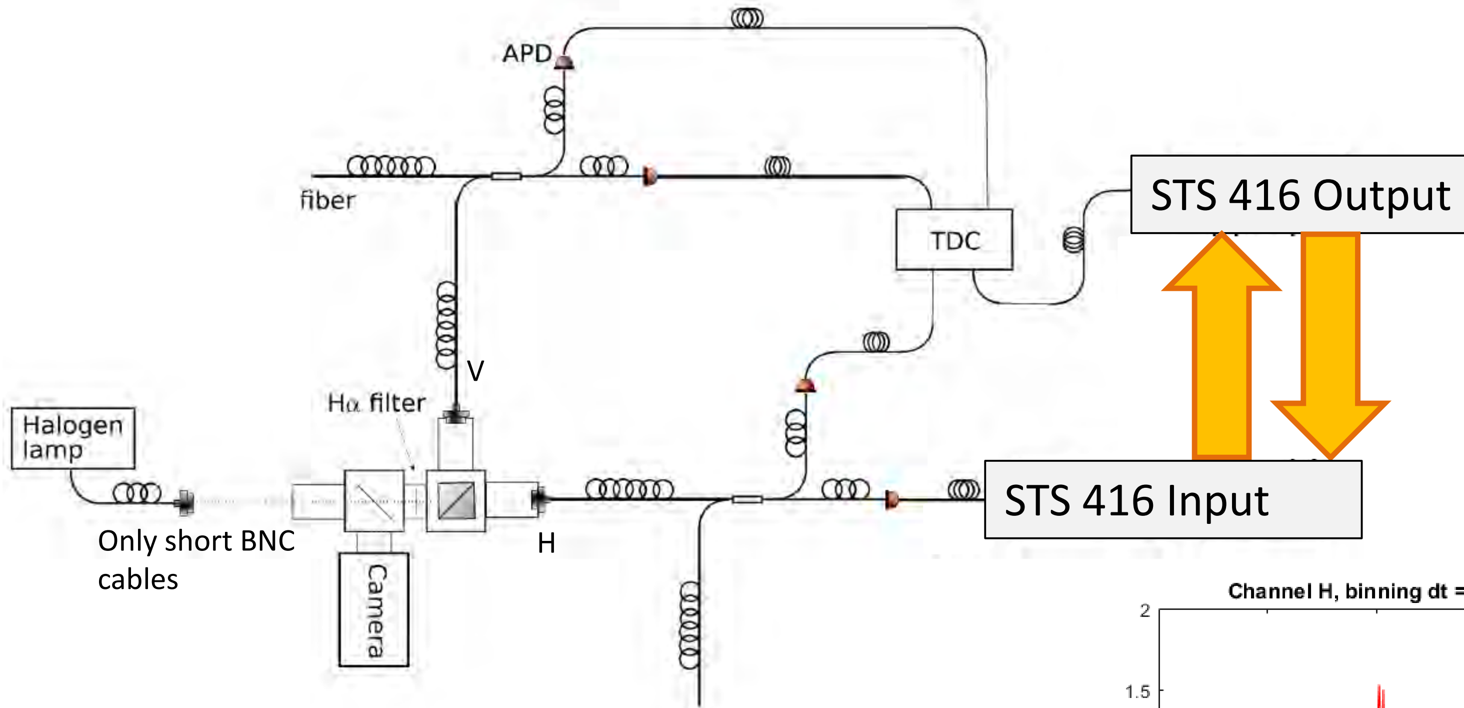
Standart deviation ~23ps RMS

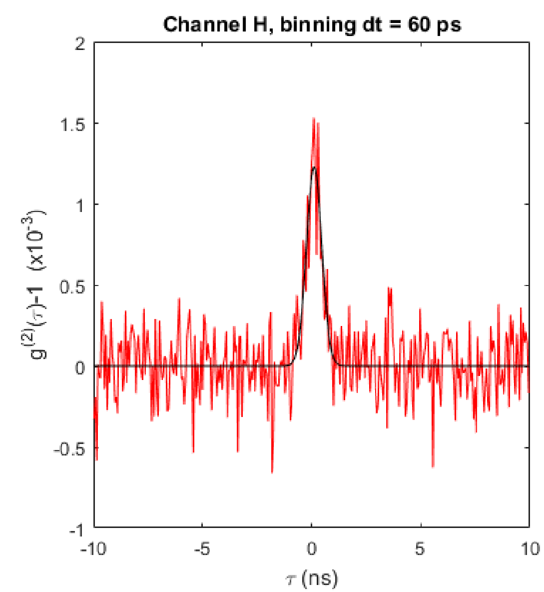




Time stability <1ps @ 10-1000 s

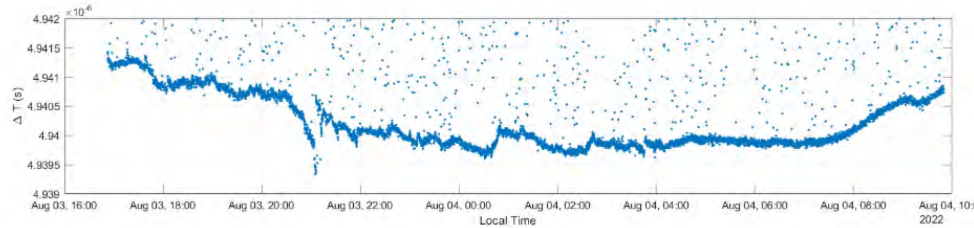
Lab test with 1km fiber



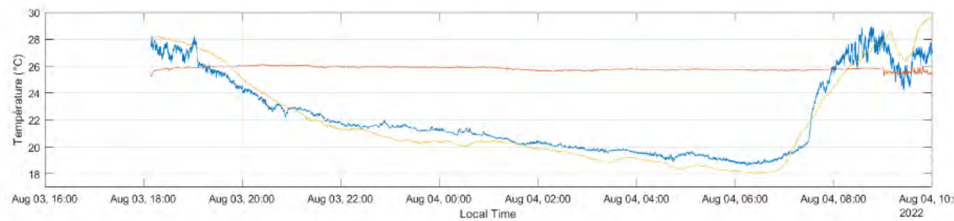


- The TDC computes the bunching peak over 10s

Lab test with 1km fiber in « real » conditions

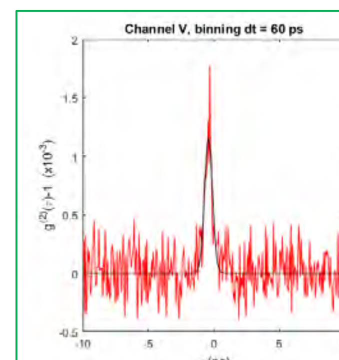


$\Delta\tau \sim 1.5$ ns



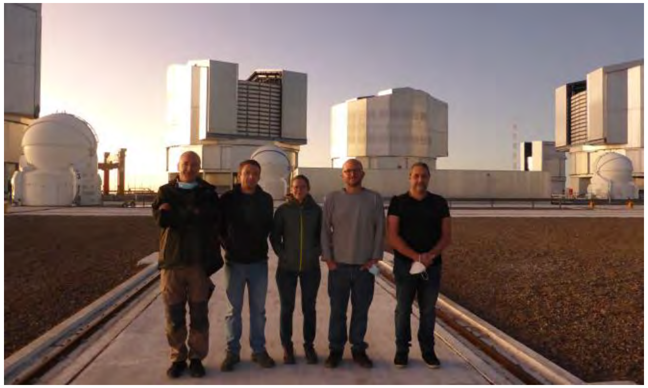
$\Delta T \sim 10$ °C

Fiber	Short Cable Channel (witness)	Fibered STS 416 Channel	Count Rate (Mcp)
10 cm	FWHM H: 1030 ± 1 ps	FWHM V: 969 ± 1 ps	1 – 1.6
1km lab	FWHM H: 1040 ± 1 ps	FWHM V: 970 ± 1 ps	1 – 1.6
1 km outdoor uncompensated	FWHM H: 827 ± 25 ps	FWHM V: 1510 ± 61 ps	2.4 – 2.8
1 km outdoor compensated	FWHM H: 827 ± 25 ps	FWHM V: 714 ± 23 ps	2.4 – 2.8



What's Next ?

- First campaign on the auxillary telescope at VLTI in march 2022:
  - 2m telescope
  - with adaptive optics



- A collaboration has started with Single Quantum for custom SNSPD detector
- STS 416 will be upgraded to a modular 16 channels system for :
  - Single spectral channel up to 4 telescopes
  - 4 spectral channels for 2 telescopes
- Gamma cassiopae paper to be submitted soon
- Timing system paper on preparation
- 4 telescopes + SNSPD + long base @ Calern ?

What science ?

- Same as amplitude interferometer do:
  - star angular diameter, stellar rotation, stellar surface and circumstellar structure,…
  - Easier to implement than an amplitude interferometer (OPD < wavelength)
- « Quantum » astrophysics:
  - Cosmic laser sources: η Carinae

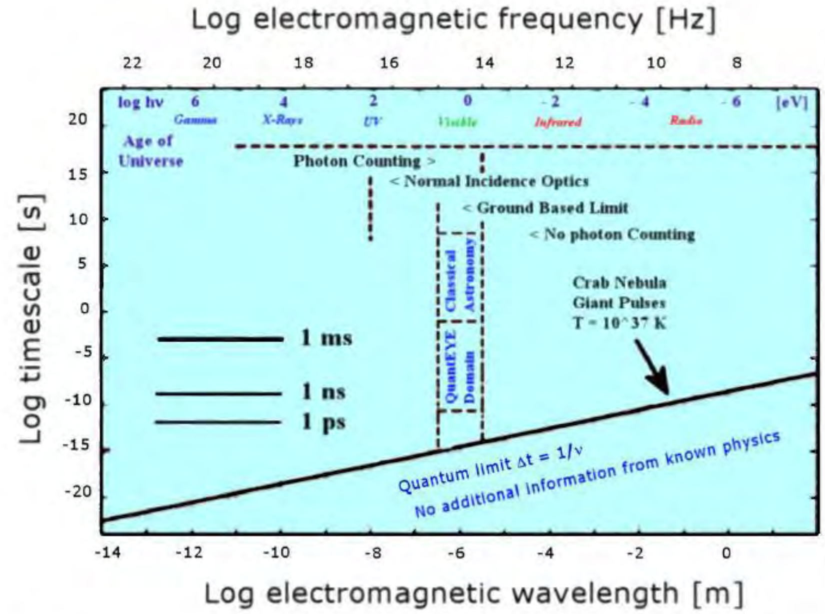


Fig.1.1. All of astronomy on the log(timescale)-log(frequency) diagram (adapted from Dravins 1994)

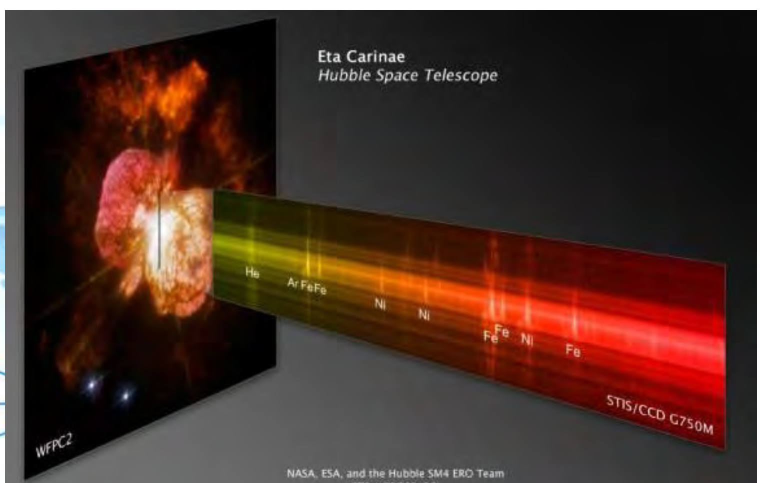


Table 6.1 Properties of the second-order correlation function $g^{(2)}(\tau)$ for classical light.

Light source	Property	Comment
All classical light	$g^{(2)}(0) \geq 1$ $g^{(2)}(0) \geq g^{(2)}(\tau)$	$g^{(2)}(0) = 1$ when $I(t)$ = constant
Perfectly coherent light	$g^{(2)}(\tau) = 1$	Applies for all τ
Gaussian chaotic light	$g^{(2)}(\tau) = 1 + \exp\left[-\pi(\tau/\tau_c)^2\right]$	τ_c = coherence time
Lorentzian chaotic light	$g^{(2)}(\tau) = 1 + \exp\left(-2\vert\tau\vert/\tau_0\right)$	τ_0 = lifetime

Thank you for listening

To get the best SNR

light collection efficiency

telescope area

Observing time

$$S/N = \frac{A\alpha}{\sqrt{\tau_d}} \times \sqrt{N_{ch}} \times \eta |V(d)|^2 \times \sqrt{T}$$

spectral flux density

time resolution

# of spectral/polarization channels

- Large telescope
- Large spectral flux density
- Several spectral channel
- Long observing time
- Good timing resolution