Intensity Interferometry at Calern – and beyond!

William Guerin for the I2C consortium

Institut de Physique de Nice (INPHYNI)

Université Côte d'Azur & CNRS

https://inphyni.univ-cotedazur.eu/sites/cold-atoms

The I2C consortium

INPHYNI, cold-atom team

Robin Kaiser, William Guerin, Mathilde Hugbart, Guillaume Labeyrie

Lagrange

Farrokh Vakili, Jean-Pierre Rivet, Olivier Lai, Armando Domiciano

Former members:

Antoine Dussaux
(Post-doc, 2015-2016)
Antonin Siciak
(PhD student, 2018-2021)
Nolan Matthews
(Post-doc, 2021-2023)

Géoazur, MéO team

Clément Courde, Julien Chabé

The basics of intensity correlations

Field correlation function:

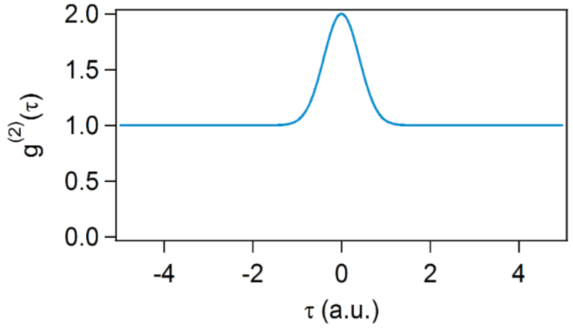
$$g^{(1)}(\Delta r,\tau)=\frac{\langle E^\star(r,t)E(r+\Delta r,t+\tau)\rangle}{\langle I(r,t)\rangle^2}$$

→ "Visibility" of direct interferometry

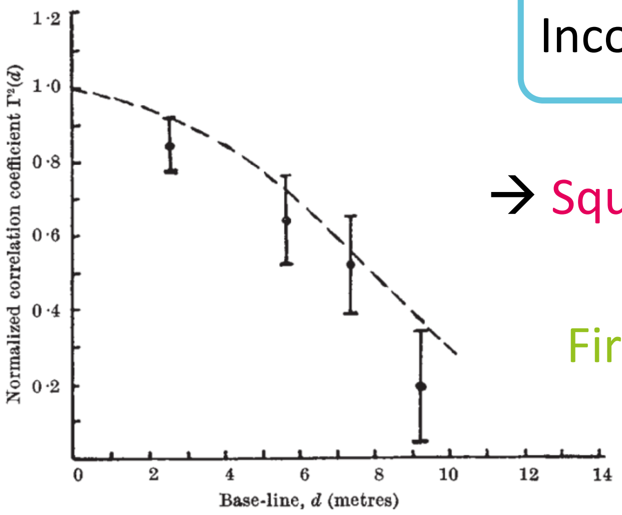
Intensity correlation function:

$$g^{(2)}(\Delta \boldsymbol{r},\tau)=\frac{\langle I(\boldsymbol{r},t)I(\boldsymbol{r}+\Delta \boldsymbol{r},t+\tau)\rangle}{\langle I(\boldsymbol{r},t)\rangle^2}$$

→ "Bunching" of photons (or "HBT effect")



Incoherent light: $g^{(2)}(\Delta r,\tau)=1+\left|g^{(1)}(\Delta r,\tau)\right|^2$



→ Squared visibility : same information as the fringe contrast without interference!

First SII on Sirius, 1956

Hanbury Brown & Twiss, *Nature* **177**, 27 (1956).
Hanbury Brown & Twiss, *Nature* **178**, 1046 (1956).
Twiss, Little & Hanbury Brown, *Nature* **180**, 324 (1957).

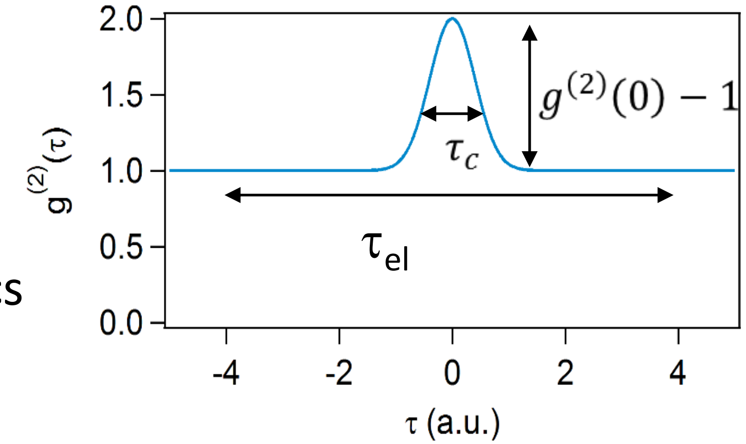
Amplitude vs Intensity interferometry

Amplitude interferometry:

Efficient because optics does the job well (interference): narrow filtering not needed, full contrast → very high sensitivity.
Very demanding because optics sets the required precision: λ → adaptive optics, active delay lines, fringe tracking, etc.

Intensity interferometry:

Not efficient because electronics does the job poorly (detect correlations).
"Easy" because electronics sets the required precision: τ_{el} = 100 ps → 3 cm.



- → Insensitive to turbulence, no need of good optical quality or adaptive optics
- → Scalable to many telescopes and long baselines
- → Electronics allows other things, like post-processing…

$$1/\Delta\omega \sim \tau_c << \tau_{el}$$

Recent revival of intensity interferometry, mainly triggered by CTA (Cherenkov Telescope Array)

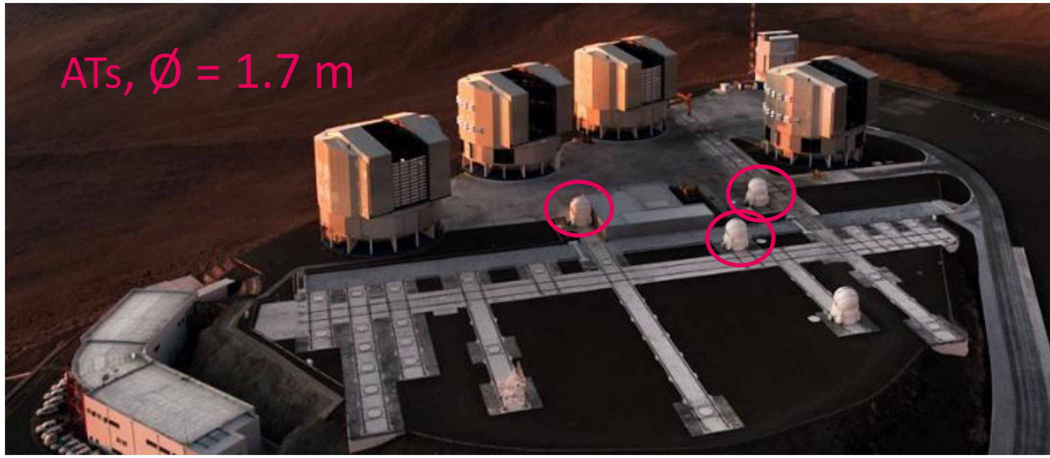
Many papers…

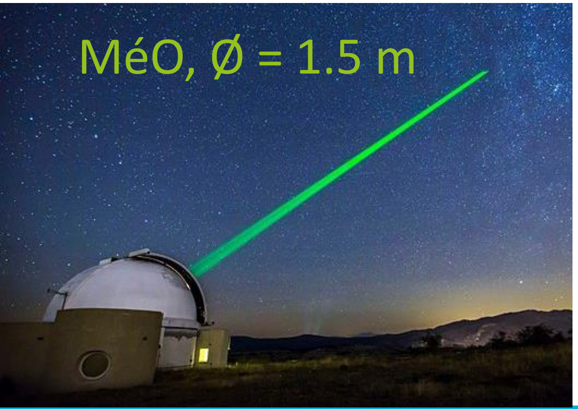
Our approach: SII with optical telescopes

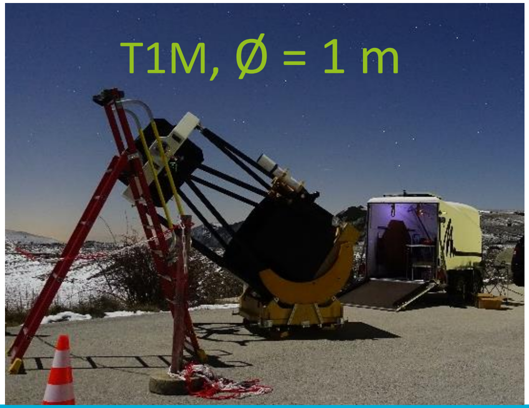
Drawback: - Large arrays of large optical telescopes will never be available

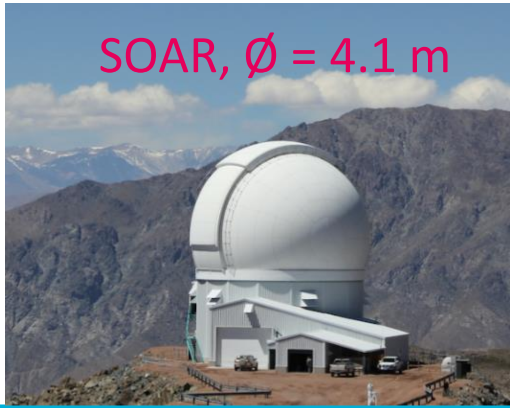
Advantages:
- The small PSF allows using the best detectors and other photonic technologies (fibers, narrow filters, etc.)
- The instrument can be adapted to any existing facility
- No big issue with the sky background

Methodology:
- Step-by-step progress
- Tests and calibrations in the lab (at INPHYNI)
- On-sky demonstrations at Calern
- Go to bigger facilities…

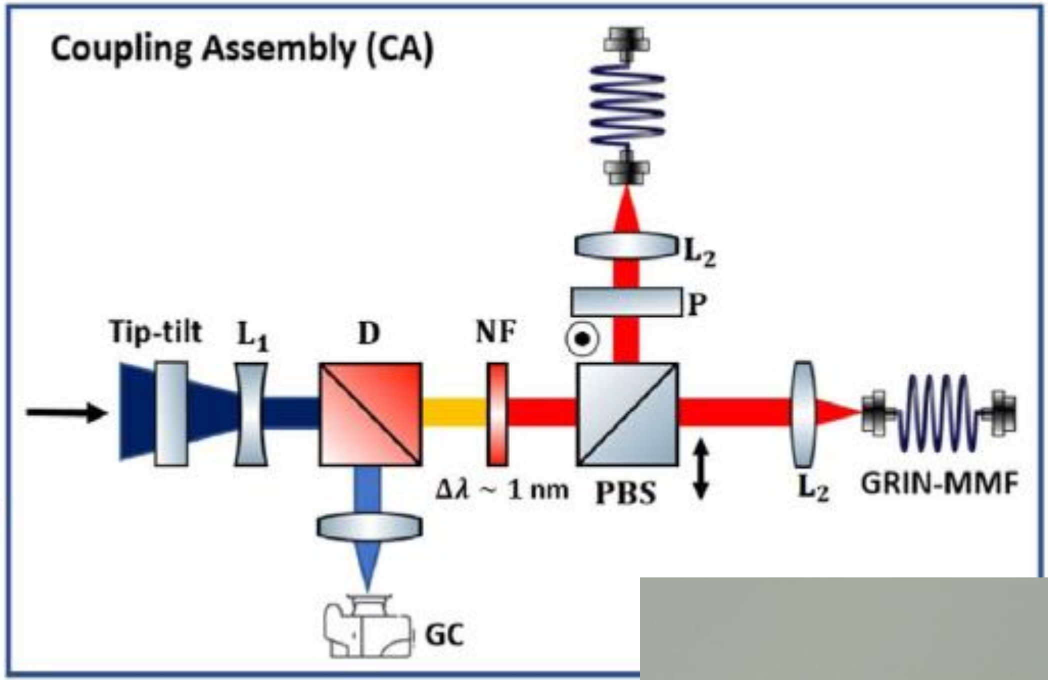






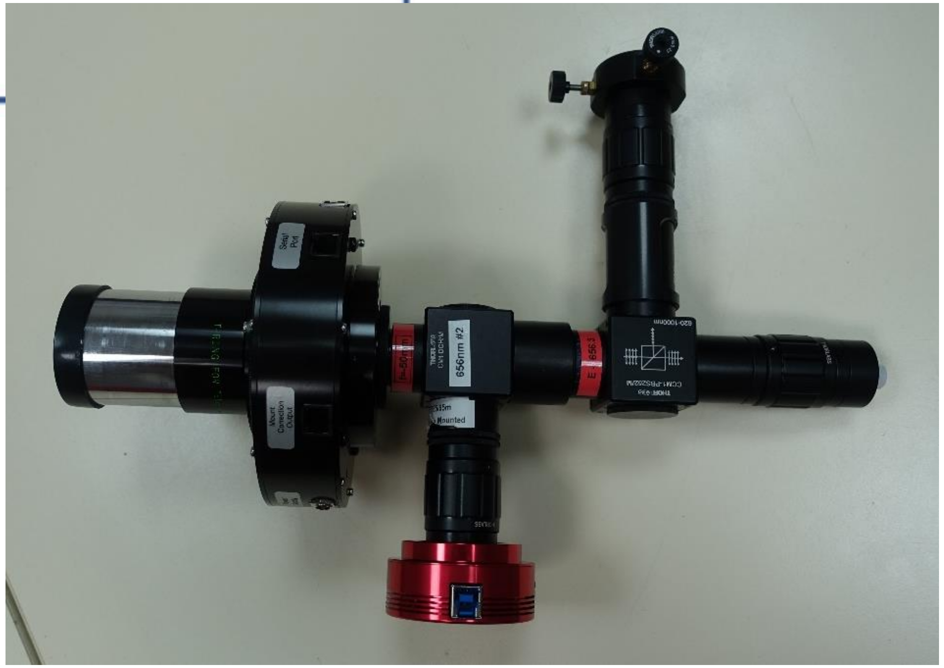


Optical setup



Compact and transportable setup

- Only off-the-shelf components
- Collimated beam at the filter position
- Filter width $\Delta\lambda$ = 1 nm (τ_c ~ 1 ps)
- Two polarization channels
- Light injected in MMF (Ø = 100 µm)

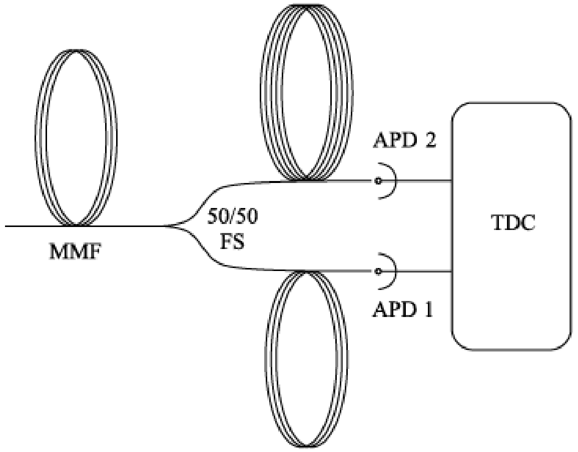


So far:
λ = 780 nm or 656 nm (Hα)

Detection setup

50/50 Multimode fiber beamsplitter

To measure the zero-baseline visibility and overcome the APD dead time



SPAD: Single photon avalanche detector

Quantum efficiency	$\eta \sim 70$ % (650 nm)
Max count rate	~ 20 MHz
Active surface	Ø = 180 µm
Jitter	$\tau_{el} \sim 500$ ps

Excelitas

TDC: Time to Digital Convertor

Cross-channel rms jitter = 12 ps
Max data transfer rate = 1 Gtags/s

Swabian Instruments

Data acquisition

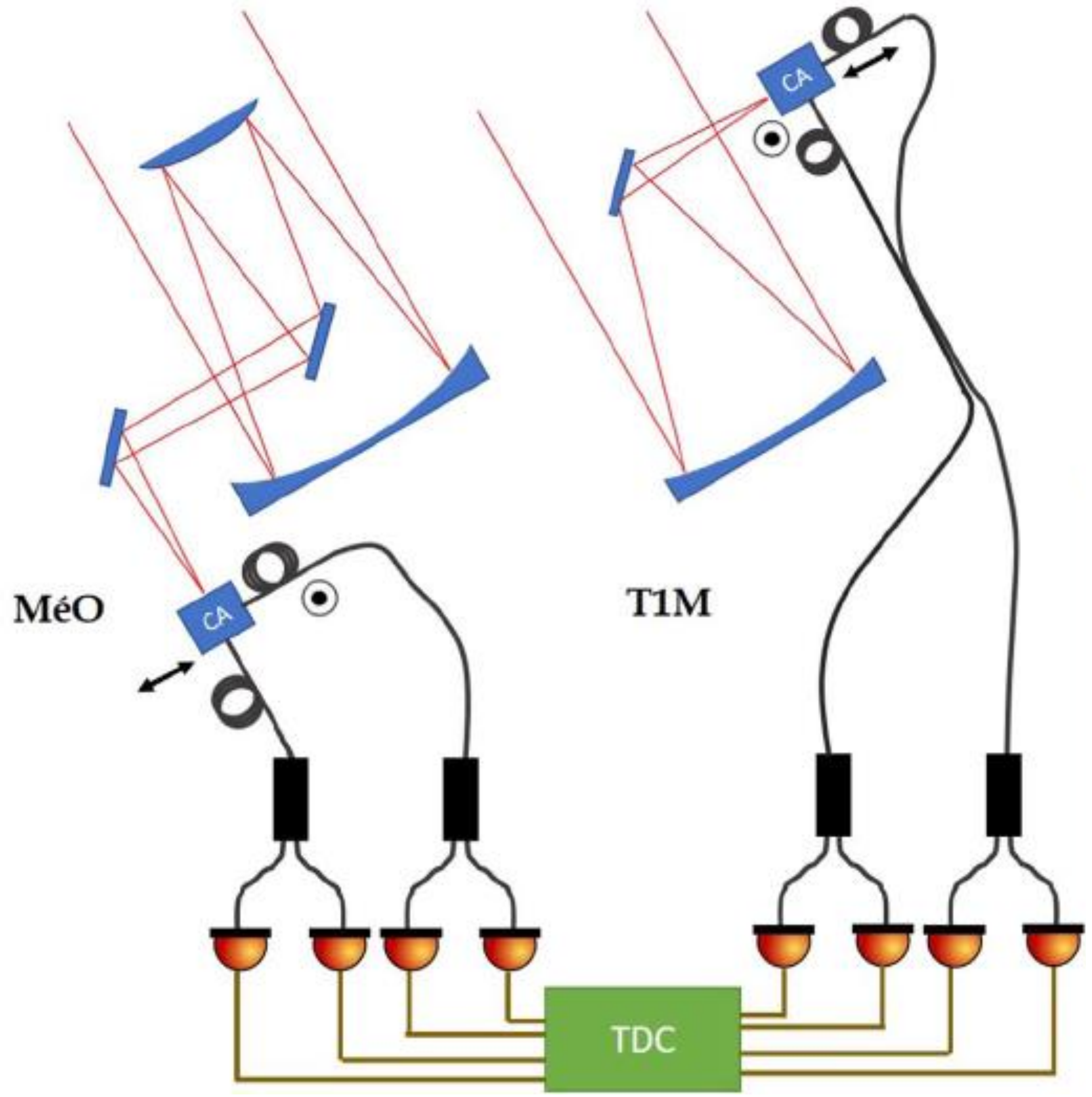
Example with:

- 2 telescopes
- 2 polarization channels
- zero-baseline correlations on all channels

→ 4 correlation functions at zero baseline

→ 4 correlation functions x 2 polarizations

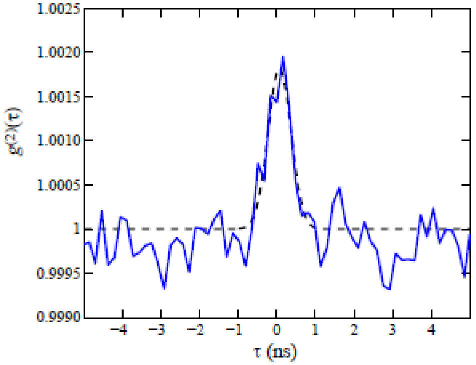
→ 12 correlation functions on the fly



- They're all added up for the analysis (no polarization effect expected)
- They're all saved every 10 s, then shifted in time to compensate for the time-varying optical-path difference, then added up.
- We don't record (so far) all photons!

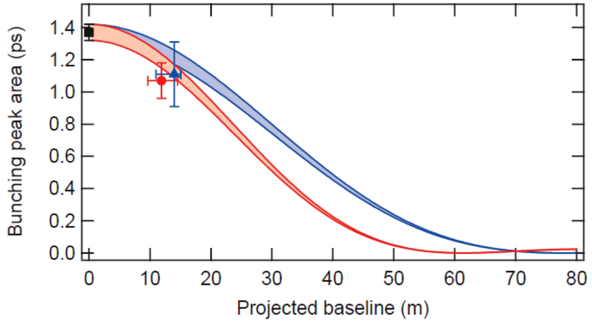
Brief summary of what we've done so far

2015
Learning how to measure sub-nanosecond intensity correlation, test on light scattered by a hot vapor
Dussaux *et al.*, *PRA* **93**, 043826 (2016)



2016
Feasibility study + design + lab test of a telescope instrument

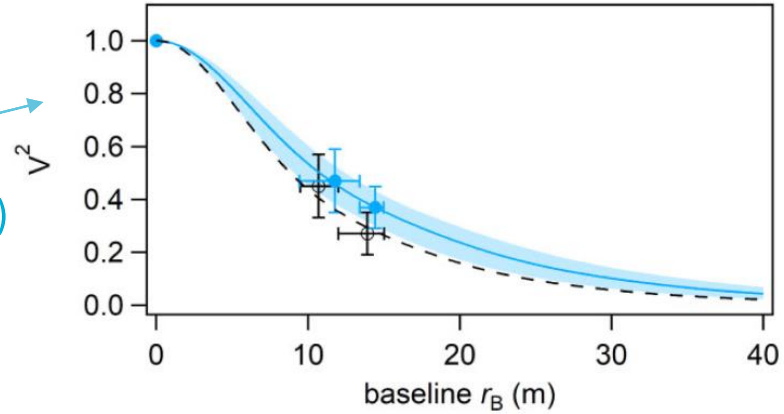
2017
Feb.: Bunching with star light (one telescope)
Oct.: Intensity interferometry with two telescopes
Guerin *et al.*, *MNRAS* **472**, 4126 (2017); *MNRAS* **480**, 245 (2018)



2018
Aug.: SII at Hα on P Cygni, refinement of the star's distance
Rivet *et al.*, *MNRAS* **494**, 218 (2020)

2019
Apr.: Bunching at SOAR in one night (η Car)
Jun.: Successful lab test of a nontrivial synchronization procedure for long-baseline SII

2020
Feb. SII at Hα on Rigel
de Almeida *et al.*, *MNRAS* **115**, 1 (2022)
Aug.: SII at Hα on P Cygni (again)
Proposal for SII with segmented mirrors
Gori *et al.*, *MNRAS* **505**, 2328 (2021)



Brief summary of what we've done so far

2021

ANR project starts (€€€)

Aug.: Lab test of SNSPDs (at TU Delft)

2022

Matthews *et al.*, *Astron. J.* **167**, 117 (2023)

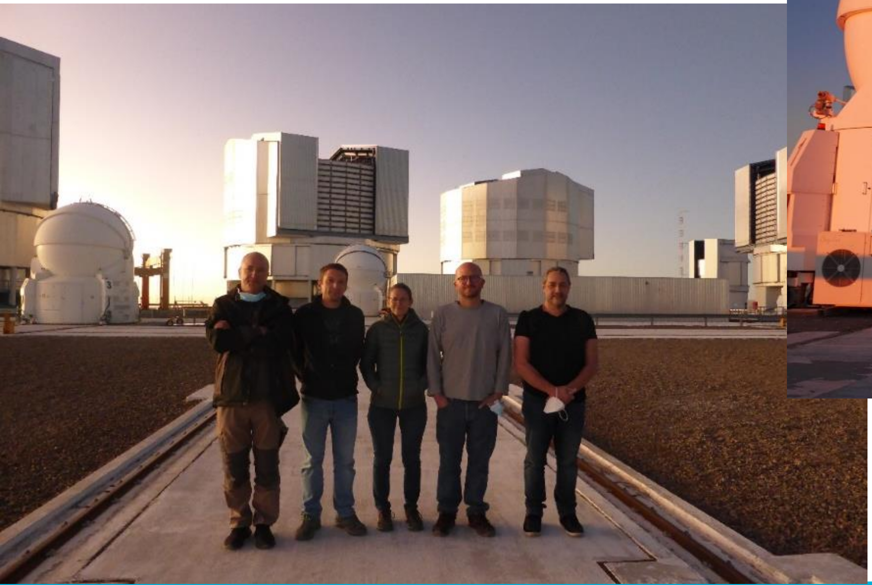
Jan.: SII on γ Cas between the laser ranging telescope and a 1 m mobile telescope

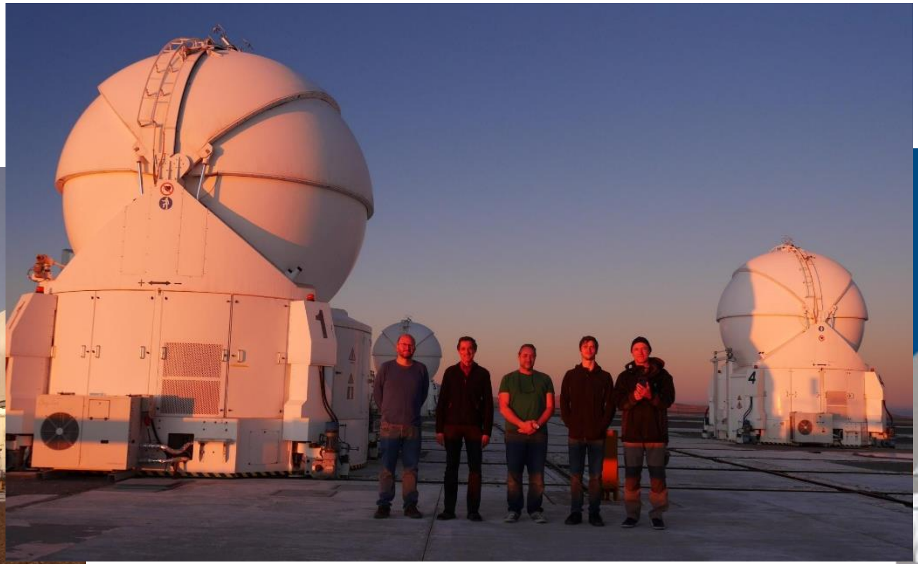
March: Technical run (6 nights) at Paranal on two ATs at their maintenance station (separation 49 m)

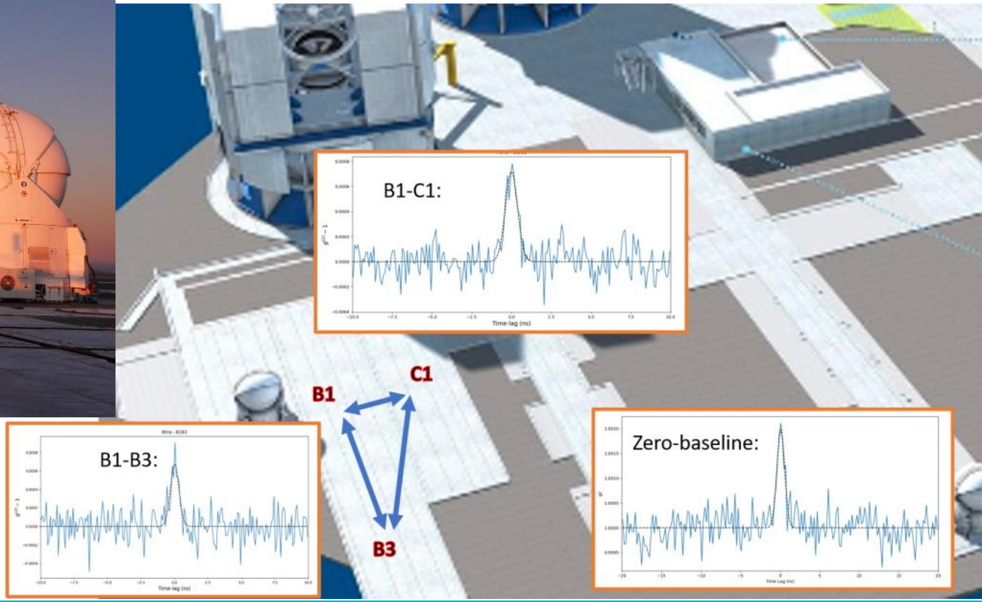
Matthews *et al.*, *Proc. SPIE* **12183**, 121830 (2022)

2023

May: Technical run (5 nights) at Paranal on three ATs at standard stations







What’s next ?

Increase the sensitivity!

$$SNR = \sqrt{N_{channels}}\, A\, \eta\, F(\nu)\, |V(r)|^2 \sqrt{\frac{T_{obs}}{2\pi\tau_{el}}}$$

Short term:

- Demonstration of SII with **SNSPDs**: 500 ps → 20 ps → SNR ×5
- Implementation of a nontrivial **synchronization procedure between distant sites**
- 3-telescope experiment at Calern (MéO + C2PU, 150 m separation)

Middle term:

- **Wavelength multiplexing**: 100 channels → SNR ×10

Link with this workshop!

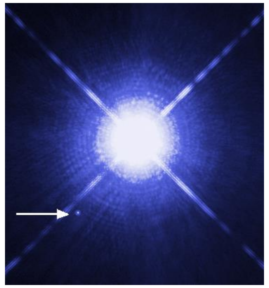
- Two time taggers with a common clock distributed over telecom fibers (jitter/drift < 1ps)
- All photons recorded
- Correlations computed off line

Long-term goals

1) A visitor instrument at Paranal

- The 4 ATs (movable telescopes) are not used ~1 week/month!
- Currently, interferometry (VLTI) only works in the IR
  → Intensity interferometry could do the visible

2) Resolution of Sirius B at Hawaii



- The closest and brightest white dwarf
- Maximum baseline = 630 m: Keck (10 m) – CFHT (3.6 m)
- Partial resolution with λ = 420 nm.
- With N_{channel} = 16, τ_{el} = 20 ps, QE = 90%, throughput = 20%:

SNR = 6 in 1h ☺

Thank you !

https://inphyni.univ-cotedazur.eu/sites/cold-atoms/research/i2c

(Picture by Serge Brunier)