

Stellar interferometry at long baseline and short wavelength (but on bright objects): recent progress in *intensity* interferometry

William Guerin for the I2C consortium
(*Intensity Interferometry at Calern*)

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



Federico Izraelevitch Andreas Zmija Tolila Sarah Ilian Ellafi

Former members:

Antoine Dussaux
(Post-doc, 2015-2016)

Antonin Siciak
(PhD student, 2018-2021)

Nolan Matthews
(Post-doc, 2021-2023)

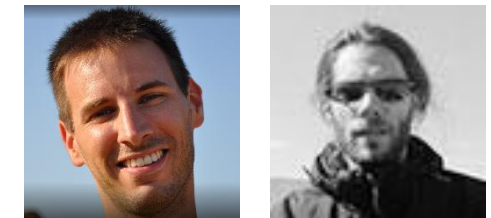
Farrokh Vakili
(Senior astronomer, retired)

Lagrange (OCA)



Jean-Pierre Rivet Olivier Lai

Géoazur, MéO team (OCA)



Clément Courde Julien Chabé

The basics of intensity correlations

Field correlation function:

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

→ “Visibility” of direct interferometry



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

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

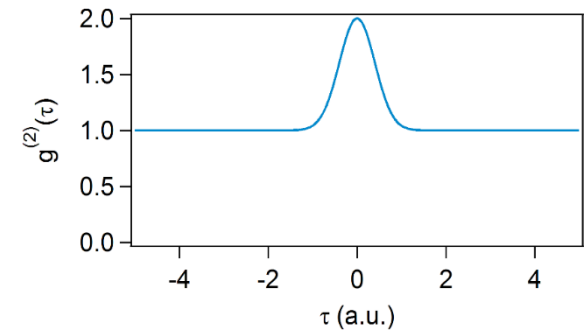
Very efficient 😊
Very demanding ☹️

Invented in the 50s, successfully used in the 60s-70s (Narrabri), then abandoned.

Intensity correlation function:

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

→ “Bunching” of photons (or “HBT effect”)



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

Much less demanding 😊
Much less efficient ☹️



Revival of stellar intensity interferometry (SII)

1. Detectors made a lot of progress since the 1970s (QE, jitter) + other technologies
2. Use of existing facilities without new heavy infrastructure
→ Use them during idle times (bright moon, twilight, bad seeing...)!
3. Reach 0.1 mas resolution with kilometric baselines & short wavelengths

Ideal targets: Hot and compact objects

A growing community (annual workshop with ~50-60 people):





Revival of intensity interferometry

Different approaches:

1. Use of Imaging Air Cherenkov Telescopes
2. Use existing (possibly large) optical telescopes
3. Build a dedicated array of small telescopes
4. Pedagogical projects

A growing community (annual workshop with ~50-60 people):





Intensity Interferometry with IACTs

Imaging Atmospheric Cherenkov Telescopes can be used as intensity interferometer during bright moon periods!

- Main trigger for the revival of intensity interferometry: CTAO (under construction)

South site (Chile):

37 “small-size telescopes” (4.3 m)

14 “medium-sized telescopes” (11.5 m)

North site (La Palma):

9 “medium-sized telescopes” (11.5 m)

4 “large-sized telescopes” (23 m)

Maximum baseline ~3 km

- **White paper** on science cases for SII with CTAO to be published by the end of the year.

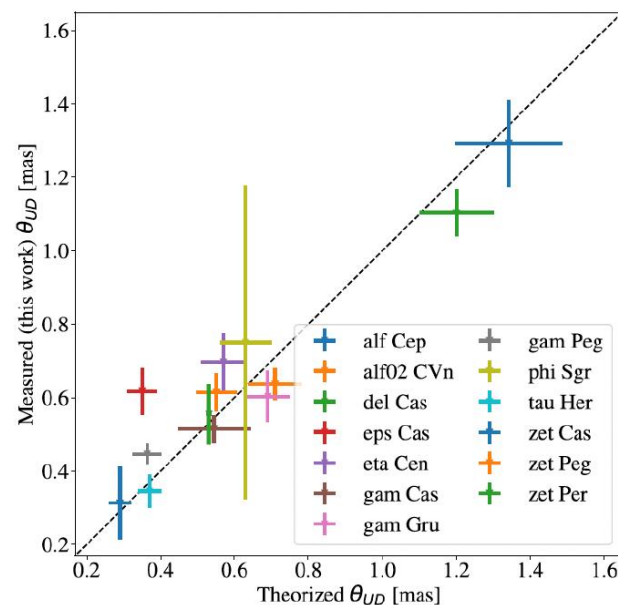
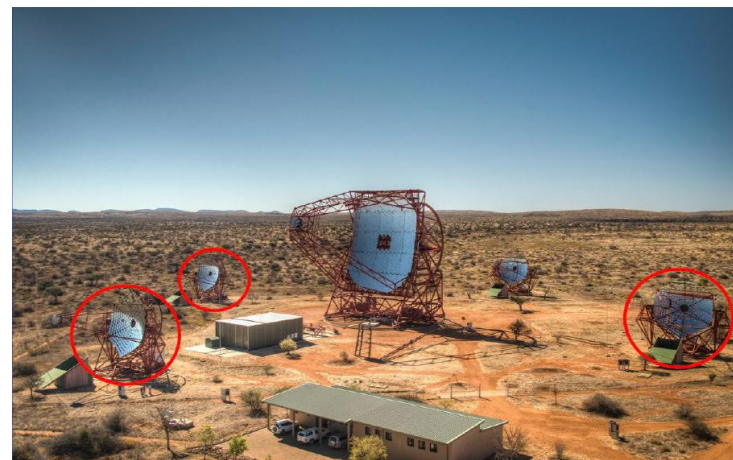


LeBohec & Holder, ApJ **649**, 399 (2006) ; Dravins & LeBohec, Proc. SPIE (2008)

Recent results with Cherenkov telescopes

Intensity interferometry has been implemented on all operating Cherenkov observatories:

- **VERITAS** (4 telescopes, $\varnothing = 12$ m, $B = 40 - 150$ m): routinely takes data, recent results on γ Cas and β UMa
- **MAGIC** (2 telescopes, $\varnothing = 17$ m, $B = 85$ m) + **LST** ($\varnothing = 23$ m, $B = 150$ m): routinely takes data
- **HESS** (3 telescopes, $\varnothing = 12$ m, $B = 120 - 170$ m)



Our work in Nice

We have pioneered the revival of intensity interferometry with optical telescopes.

2017 – 2018: First SII since Narrabri, first ever in the photon-counting regime

2018 – 2020: Used SII to determine P Cygni's distance

2019 – 2023: Demonstrate adaptability and transportability (SOAR, VLTI, ...)

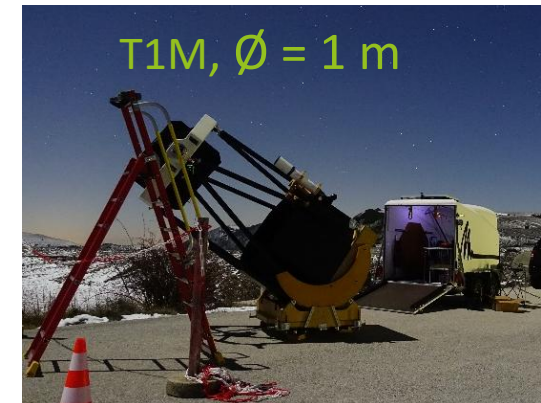
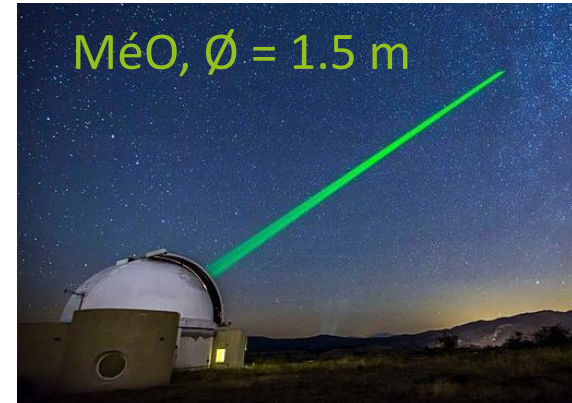
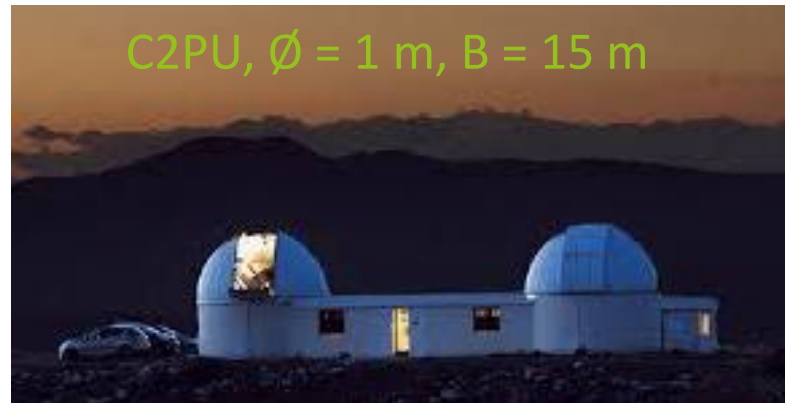
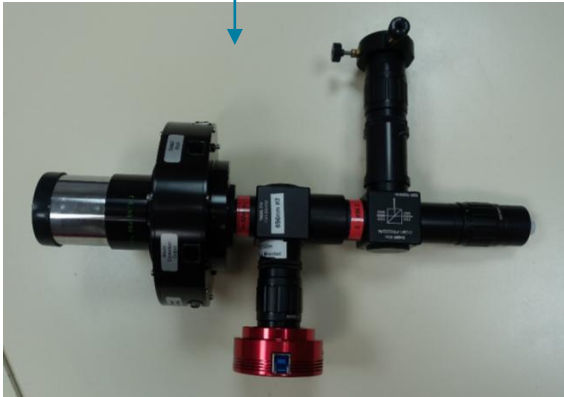
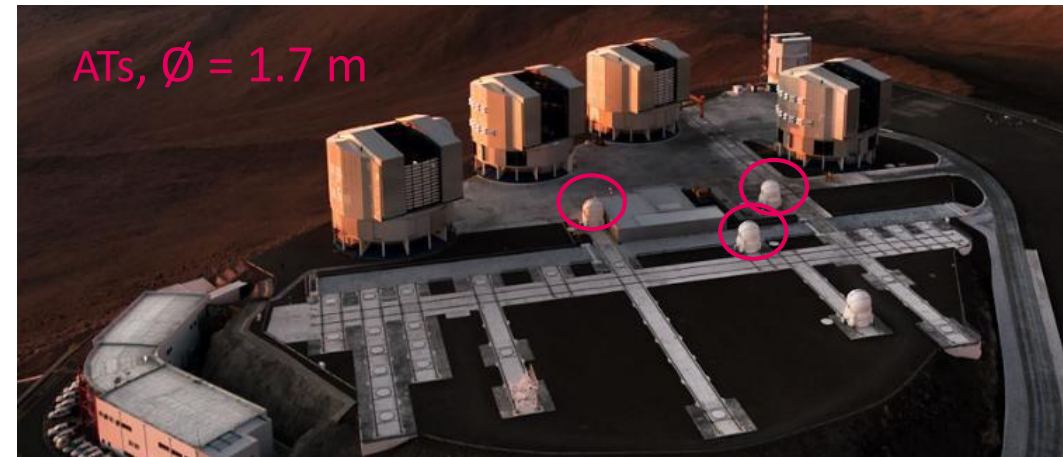
2024: Got an ERC funding (€€€, 2025 – 2029)

Methodology:

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

Instrument:

- Photon-counting regime (shot-noise limited)
- Compact and transportable
- Real-time computation of the $g^{(2)}$.



Towards a second-generation instrument

Improving the sensitivity...



European Research Council
Established by the European Commission

What we want:

- Better detectors: lower timing jitter & good quantum efficiency
- Wavelength multiplexing
- Adaptable to large telescopes and long baselines
- Excellent throughput

$$SNR = \frac{1}{2} \alpha N_{\text{ph}}(\lambda) A |V(r)|^2 \sqrt{\frac{T_{\text{obs}}}{2\sqrt{\pi}\tau_{\text{el}}}} \times \sqrt{N_{\text{ch}}}$$

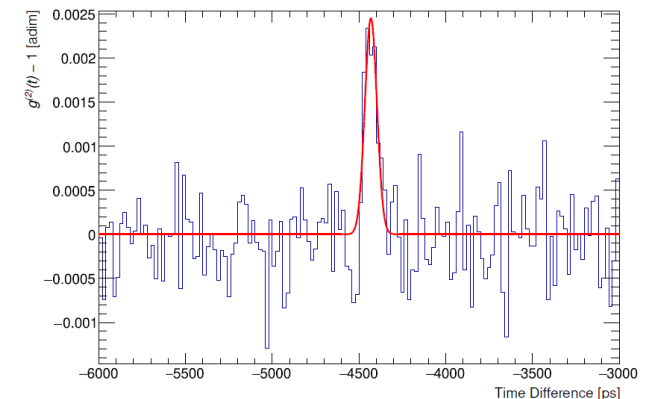
What we chose: LINPinx from Photonscore



- QE ~ 33% @ 420 nm
- Jitter ~ 30 – 35 ps (FWHM)
- Diameter = 8 mm !!!

✓ Tested on sky at Calern (April 2026)

+ White Rabbit
+ time tags



Leopold *et al.*, JATIS **11**, 035005 (2025)

Izraelevitch-Patitucci *et al.*, Proc. SPIE, in press (2026)

Wavelength multiplexing with 16 channels

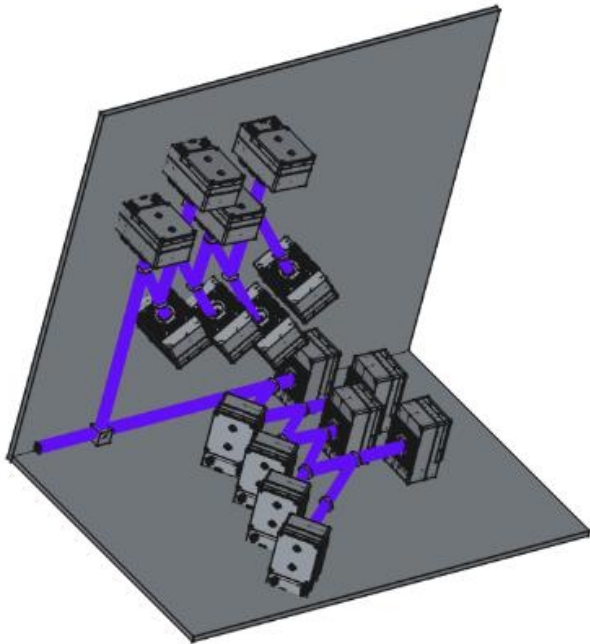
Preliminary design of the instrument:

16 channels \times 2 telescopes

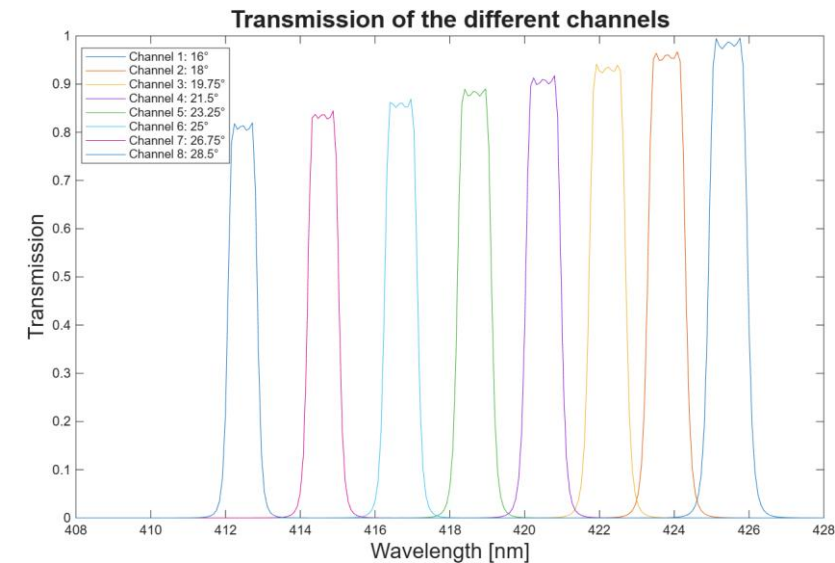
8 spectral \times 2 polarizations = 16 channels

Design using cascaded tilted narrow filters

→ Expected average throughput $\sim 90\%$



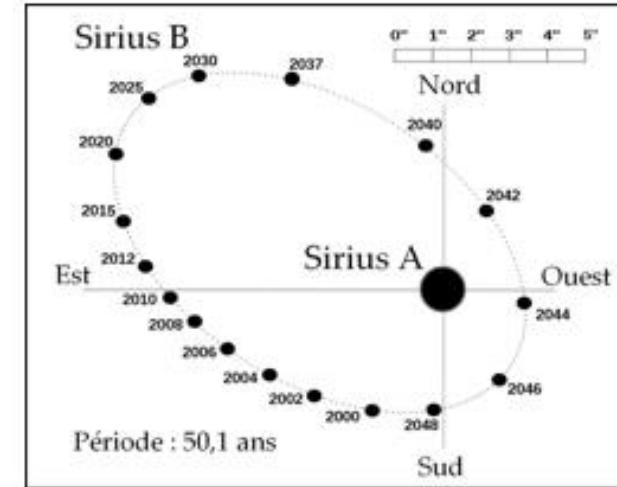
→ 32 detectors !



Goal: Partial resolution of Sirius B at Hawaii

$$SNR \approx 0.436 \frac{1}{2} \alpha N_{\text{ph}}(\lambda) A |V(r)|^2 \sqrt{\frac{T_{\text{obs}}}{\tau_{\text{el}}}} \times N_{\text{ch}}$$

- $\alpha \approx 0.33$ (QE) $\times 0.8$ (atm.) $\times 0.8$ (telescope) $\times 0.9$ (instrument) $\times 0.86$ (spectral shape factor) ≈ 0.16
- $N_{\text{ph}}(\lambda = 420 \text{ nm}) = 4.6 \times 10^{-8}$ photons/m²/s/Hz (from HST calibrated spectrum)
- $A = \sqrt{A_1 A_2}$ with $A_i = 76 \text{ m}^2$ (Keck), 8.4 m^2 (CFHT), 48.4 m^2 (Gemini), 51.3 m^2 (Subaru)
- $|V^2| \approx 0.9$
- $\tau_{\text{el}} \approx 35 \text{ ps rms}$ (2 detectors + TDC + WR)
- $N_{\text{ch}} = 16$



Separation $\sim 11''$ (2025 – 2030)

$SNR = 10$ reached in ...

$T_{\text{obs}} = 46 \text{ h}$ for Keck – CFHT (630 m)

$T_{\text{obs}} = 8 \text{ h}$ for Keck – Gemini (630 m)

$T_{\text{obs}} = 12 \text{ h}$ for Subaru – Gemini (790 m)

CONCLUSION: Challenging but possible!

Thank you !

- Guerin *et al.*, MNRAS **472**, 4126 (2017)
- Guerin *et al.*, MNRAS **480**, 245 (2018)
- Rivet *et al.*, Exp. Astron. **46**, 531 (2018)
- Lai *et al.*, Proc. SPIE **10701**, 1070121 (2018)
- Rivet *et al.*, MNRAS **494**, 218 (2020)
- Gori *et al.*, MNRAS **505**, 2328 (2021)
- Guerin *et al.*, Proc. SF2A, 331 (2021)
- de Almeida *et al.*, MNRAS **515**, 1 (2022)
- Matthews *et al.*, Proc. SPIE **12183**, 121830G (2022)
- Matthews *et al.*, Astron. J. **167**, 117 (2023)
- Tolila *et al.*, Proc. SF2A, p.197 (2024)
- Matthews *et al.*, MNRAS **538**, 867 (2025)
- Guerin *et al.*, Comptes Rendus. Physique **26**, 659 (2025)
- Izraelevitch-Patitucci *et al.*, Proc. SPIE, in press (2026)

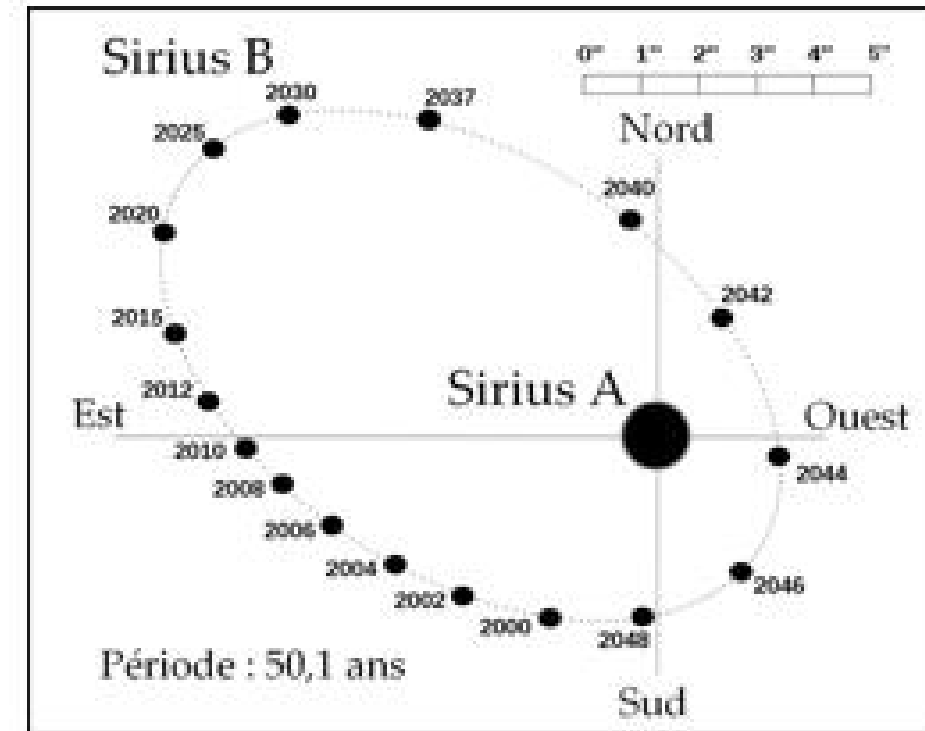


(Picture by Serge Brunier)

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

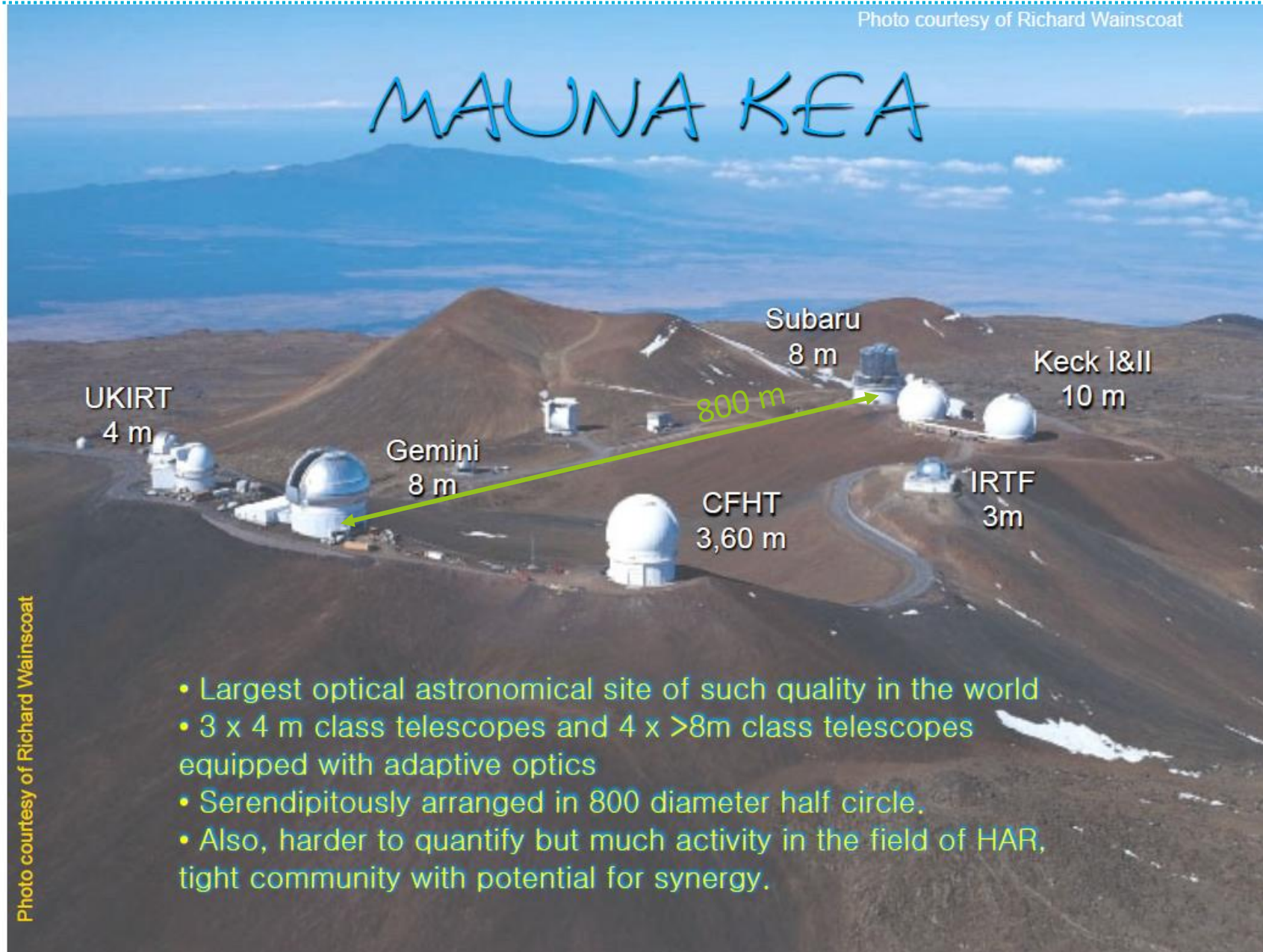
Goal: partial resolution of Sirius B

- Sirius B: the closest and brightest **white dwarf**, $m_B = 8.4$
- No angular diameter of a white dwarf has even been measured directly (evaluated from photometry)
- Why ? Needs baseline ~ 1 km !
- Right time to do it (separation $\sim 11''$) !



Where to do it ?

Photo courtesy of Richard Wainscoat



- Largest optical astronomical site of such quality in the world
- 3 x 4 m class telescopes and 4 x >8m class telescopes equipped with adaptive optics
- Serendipitously arranged in 800 diameter half circle.
- Also, harder to quantify but much activity in the field of HAR, tight community with potential for synergy.

Olivier Lai is well introduced there...



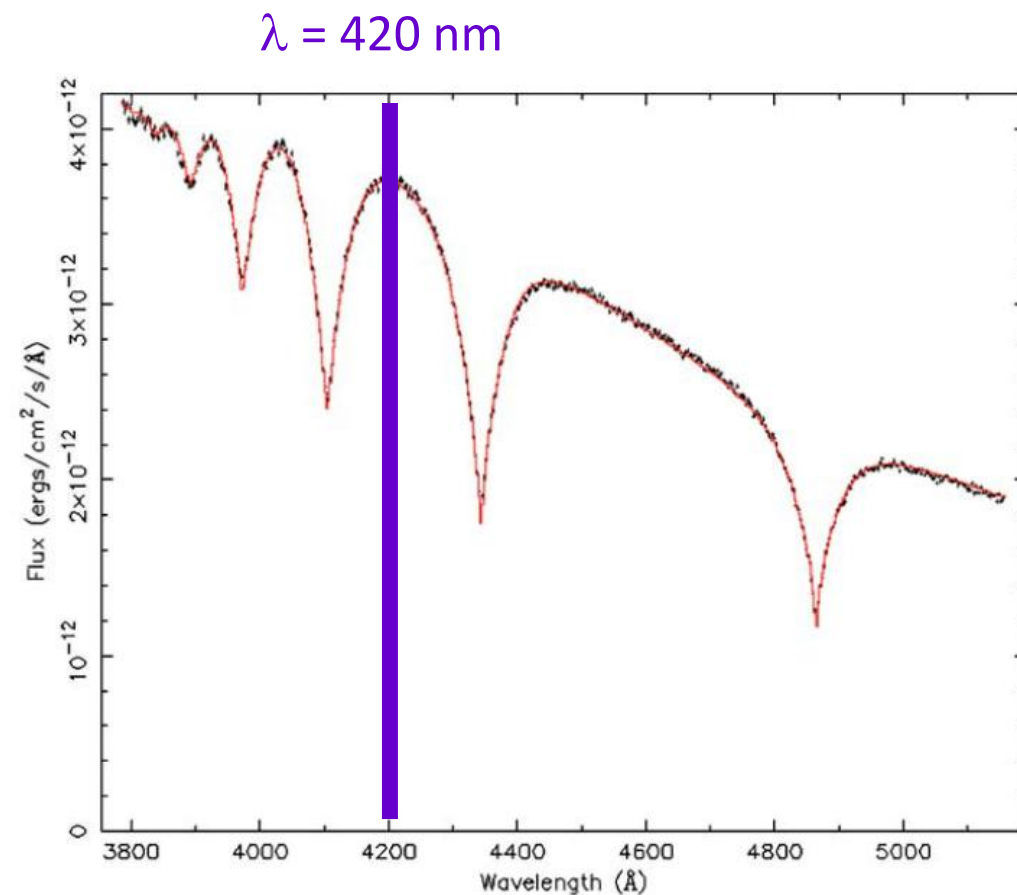
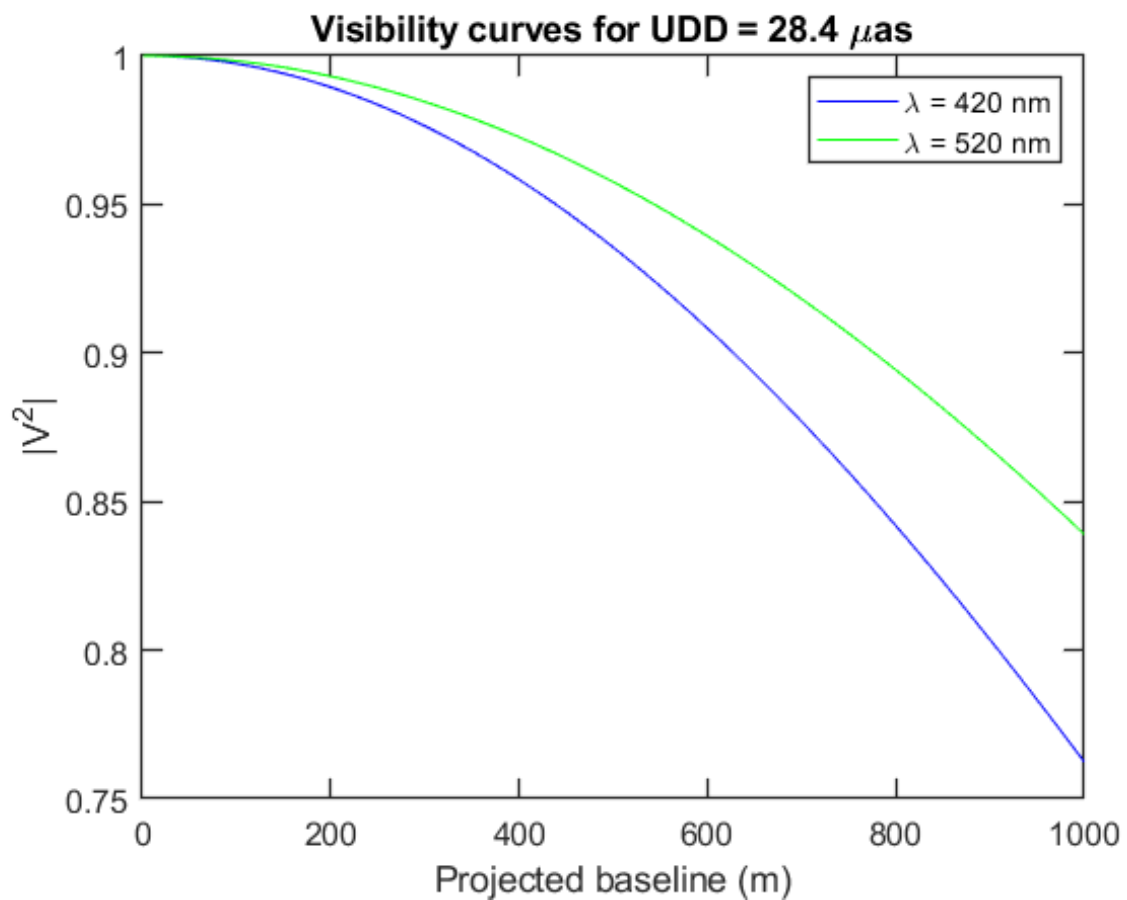
Larger baselines:

- Subaru – Gemini: 790 m
- Keck I – Gemini: 630 m
- Keck I – CFHT: 630 m

(Another possibility could be at Paranal: UTs – Vista : ~1.5 km, but more complicated access...)

At which wavelength ?

Even 800 m is not enough: the shorter the better !



With which detectors ?

Inspired by the Erlangen group (J. von Zanthier): LINPinx from Photonscore

Leopold *et al.*, *JATIS* **11**, 035005 (2025)



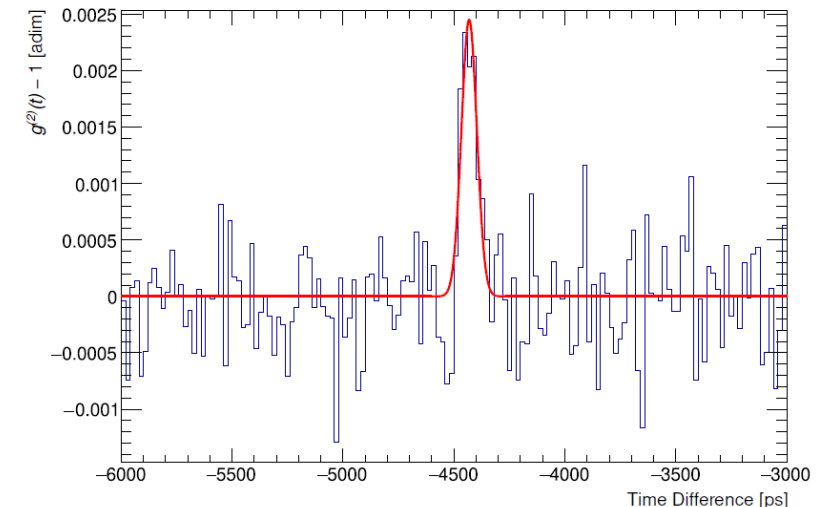
- QE ~ 33% @ 420 nm
- Jitter ~ 30 – 35 ps (FWHM)
- Negligible dark count, low dead time (max count rate ~ 100 MHz)
- Diameter = 8 mm !!!

✓ Tested on sky at Calern (April 2026)

+ long-distance synchronization (White Rabbit)

+ writing all time tags on disk

→ $\tau_{el} = 35$ ps (rms) including everything



Izraelevitch-Patitucci *et al.*, *Proc. SPIE*, in press (2026)



Why not use SPAD arrays ?

- Big telescopes, either:
- with AO: low throughput ☹ (and in the blue anyway...)
 - without AO: VERY hard to focus on small-area detectors

Conservation of étendue (or “optical extent”): $A \Omega = \text{cst}$

Seeing = 0.65” = 3.2 μrad (median seeing on Mauna Kea)

$$A = (8 \text{ m})^2$$

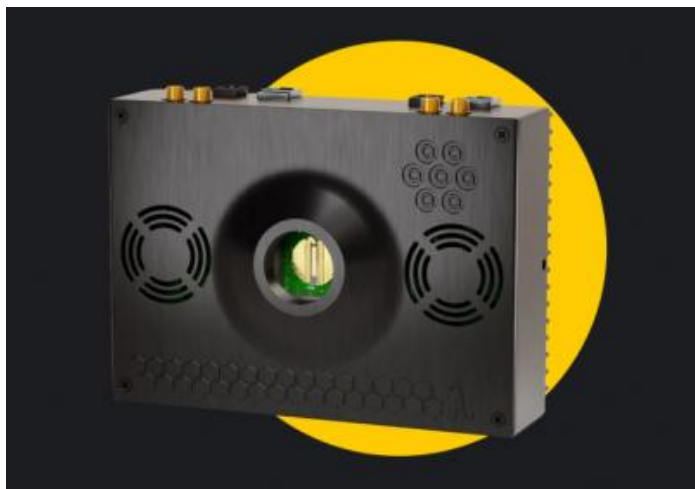
If you want to focus on, say, $A' = (20 \mu\text{m})^2$, you need $NA = 0.98$!!!

If you focus with a large NA , say $NA = 0.5$ (i.e. 30°) (without aberration!), you'll get $A' = (50 \mu\text{m})^2$.

In the future: SNSPD array with large pixels ?

SPAD arrays with small telescopes

SPAD λ from Plimaging

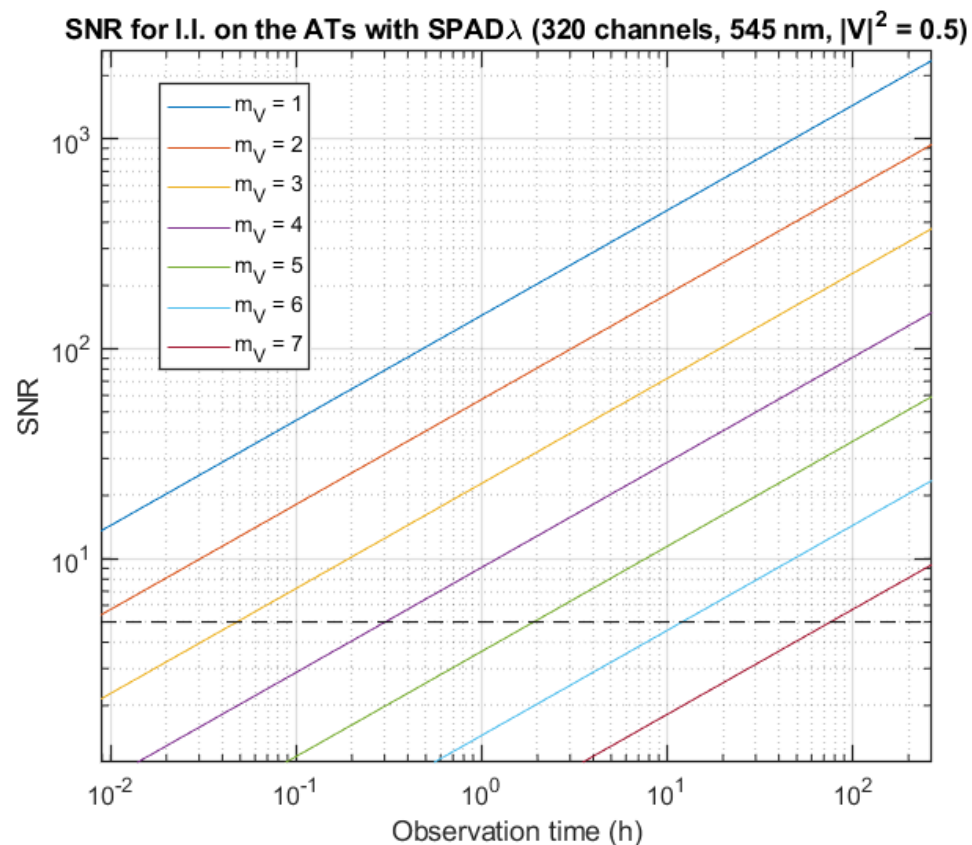


- Linear array of 320 pixels
- Pixel size = 18 μm , pitch = 28 μm , 80% fill factor with microlenses (limited NA)
- Jitter 90 ps (FWHM), QE = 50% @ 500 nm

Expected SNR using the ATs at Paranal:

(free one week /month !!!)

→ mag. 6 in one night, 7 in one week

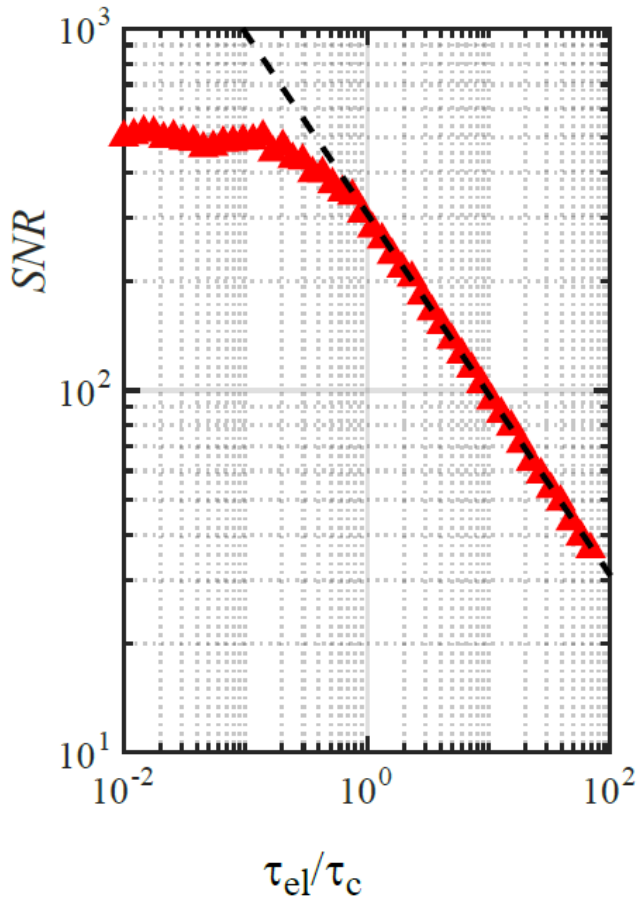


Limitations to the SNR

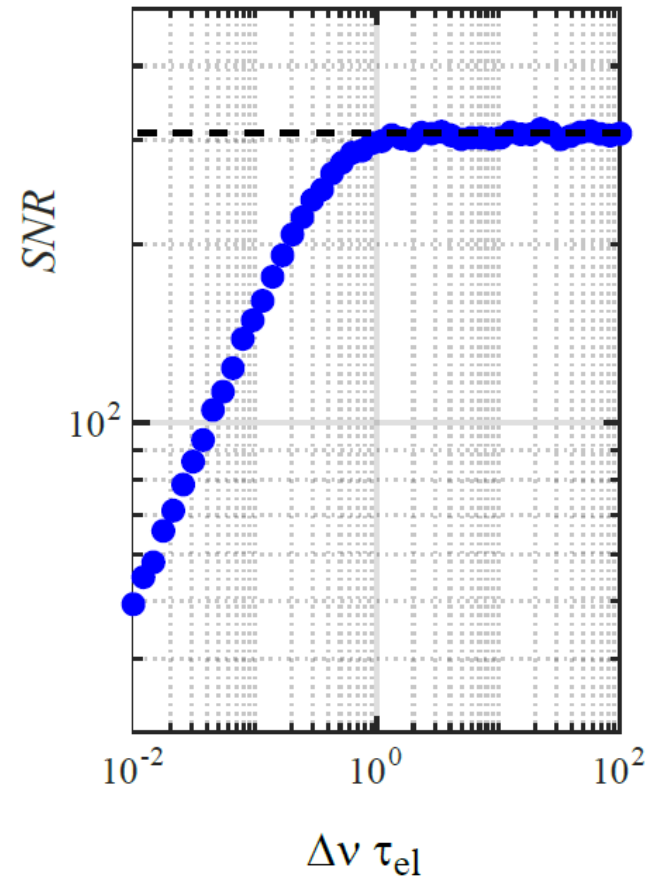
Not useful to improve the detectors' jitter τ_{el} beyond the coherence time τ_c .

For a given spectral range, increasing the number of channels increases $\tau_c \rightarrow$ the SNR saturates.

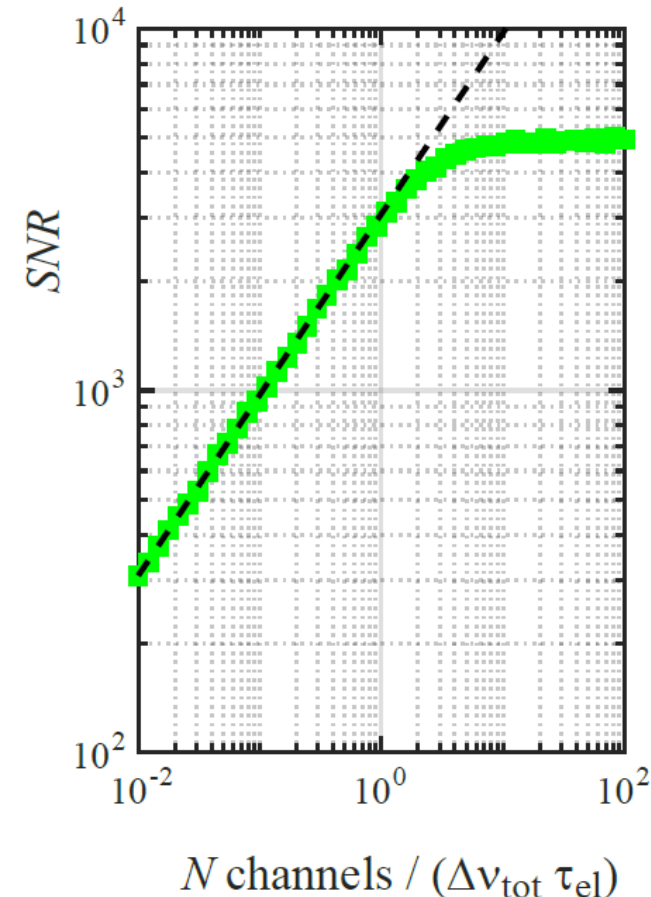
(a) τ_c fixed



(b) τ_{el} fixed



(c) τ_{el} & $\Delta\nu_{tot}$ fixed



Example:

$$\tau_{el} = 10 \text{ ps}$$

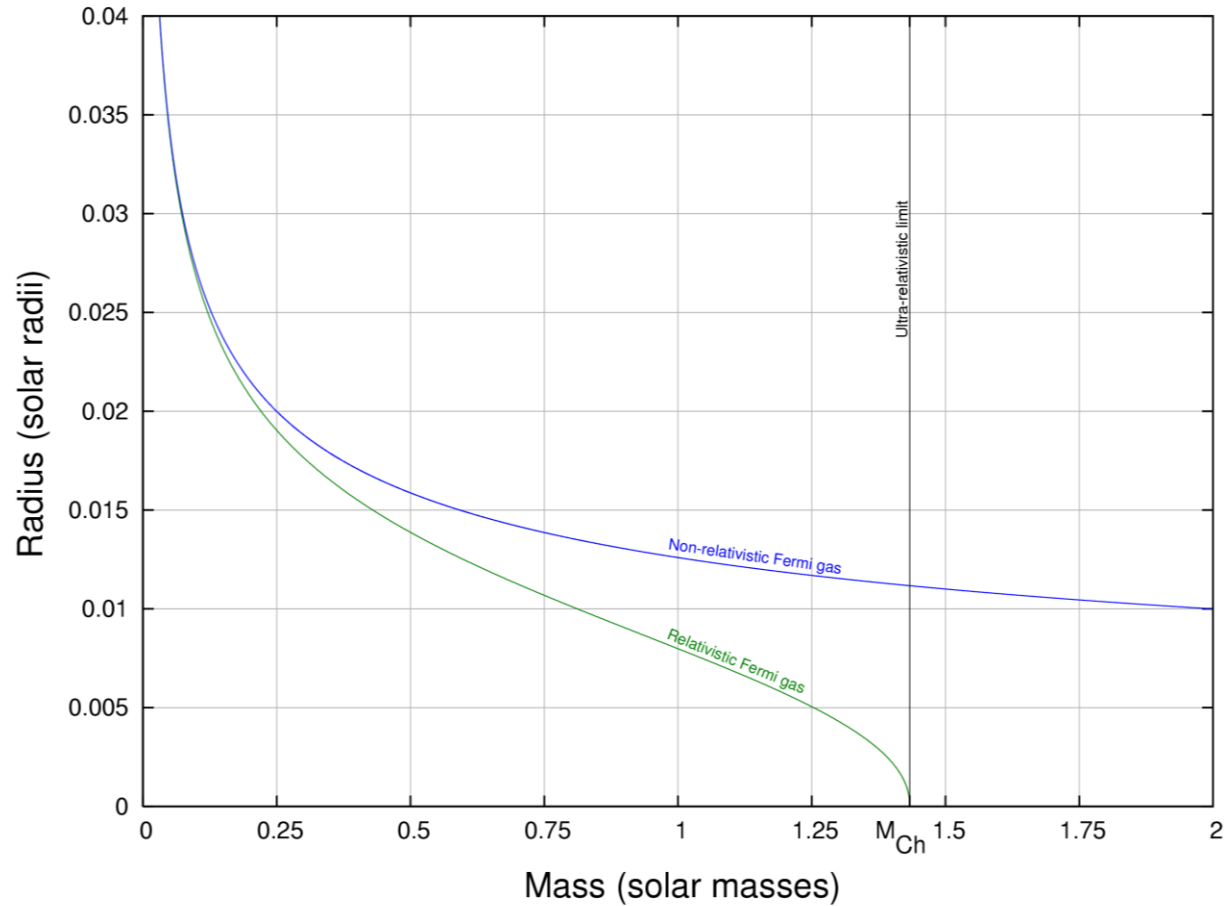
$$\Delta\lambda = 0.1 \text{ nm @ } 500 \text{ nm}$$

$$\rightarrow \tau_c = 8 \text{ ps} < \tau_{el} \text{ OK}$$

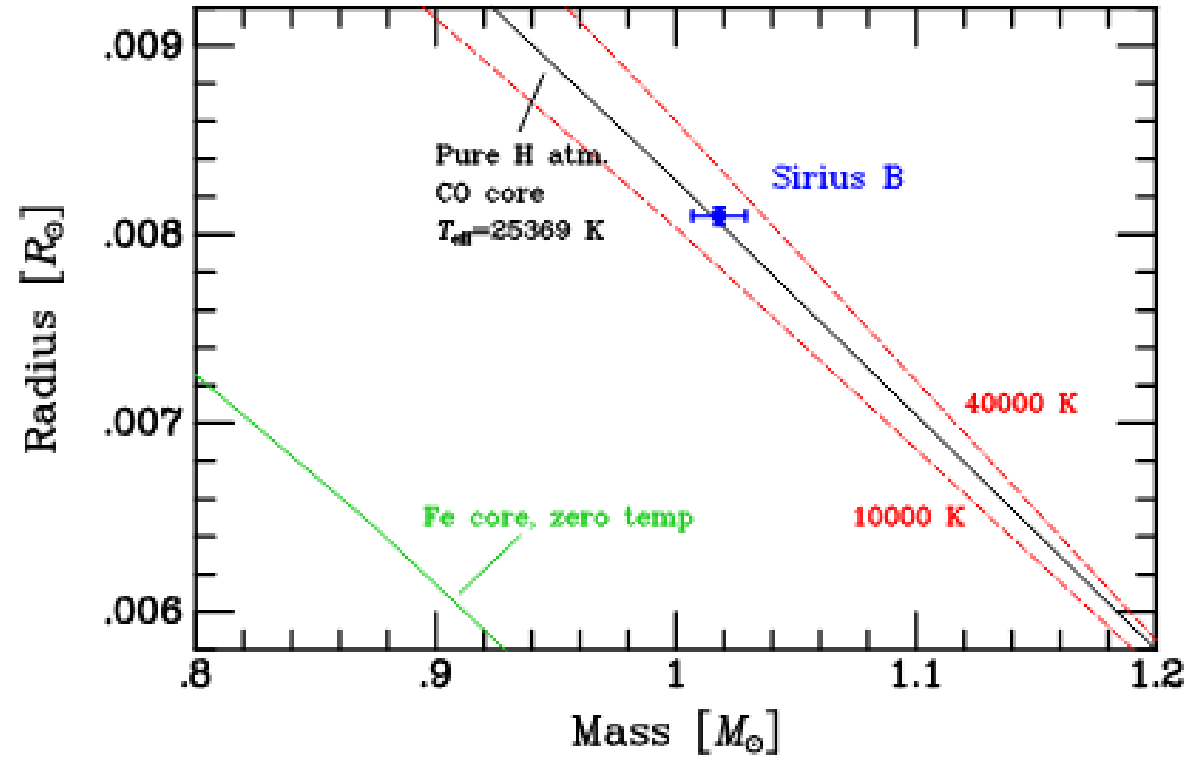
$$\text{Then if } N_{ch} = 2000$$

$$\rightarrow \Delta\lambda_{tot} = 200 \text{ nm !}$$

Sirius B

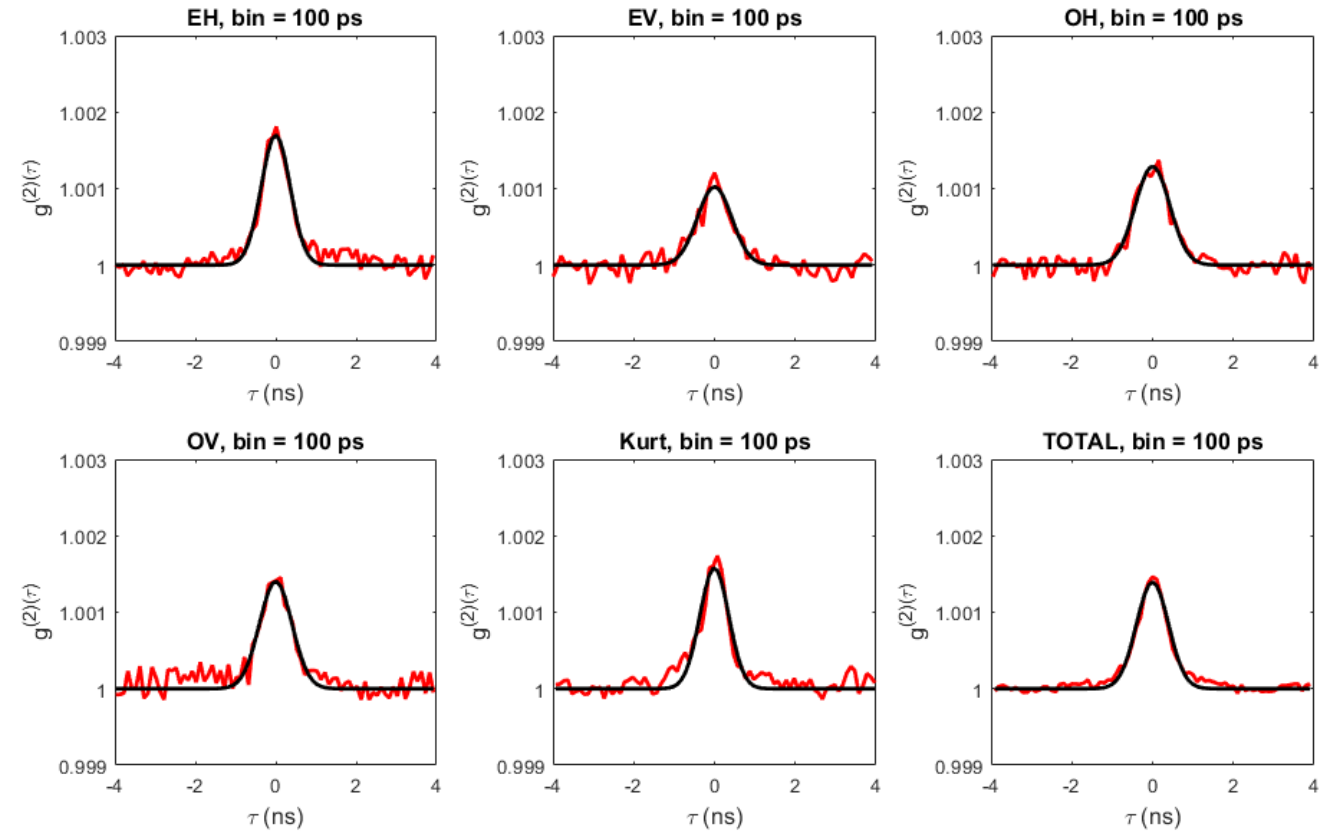
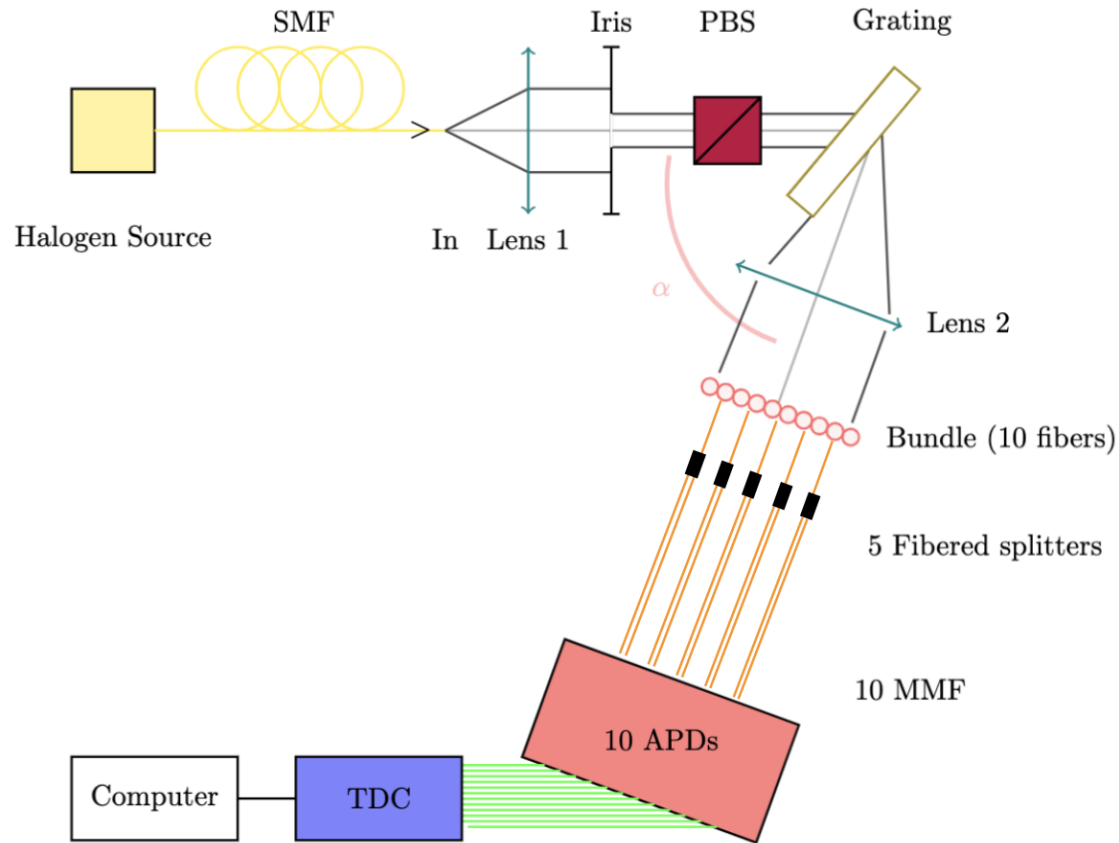


Chandrasekhar, MNRAS **95**, 207 (1935)



Bond et al., ApJ **840**, 70 (2017)

First lab tests of wavelength multiplexing



Single SNRs between 21 and 32 $\rightarrow \Sigma(\text{SNR}^2) = 59$

Measured SNR on the total curve: 51. Not bad, but averaging not optimum!

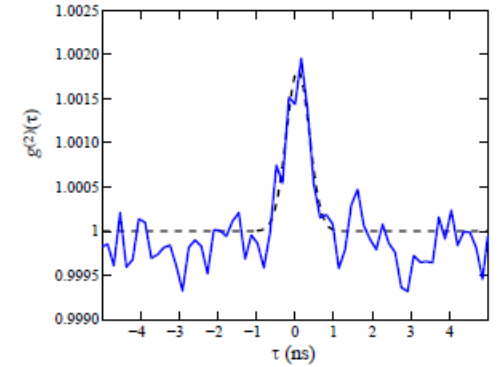
Brief summary of what we've done so far



2015
2016
2017
2018
2019
2020

Learning how to measure sub-nanosecond intensity correlation, test on light scattered by a hot vapor

Dussaux et al., PRA 93, 043826 (2016)

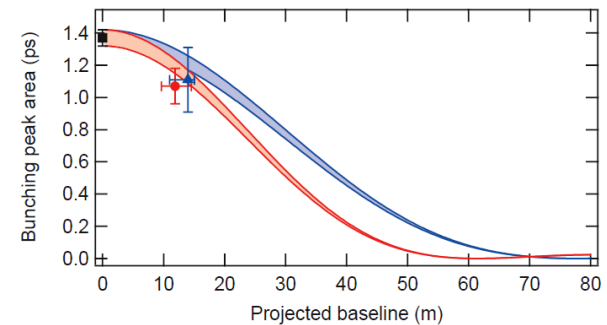


Feasibility study + design + lab test of a telescope instrument

Guerin et al., MNRAS 472, 4126 (2017); MNRAS 480, 245 (2018)

Feb.: Bunching with star light (one telescope)

Oct.: Intensity interferometry with two telescopes



Aug.: SII at H α on P Cygni, refinement of the star's distance

Rivet et al., MNRAS 494, 218 (2020)

Apr.: Bunching at SOAR in one night (η Car)

Guerin et al., Proc. SF2A 2021, p. 331

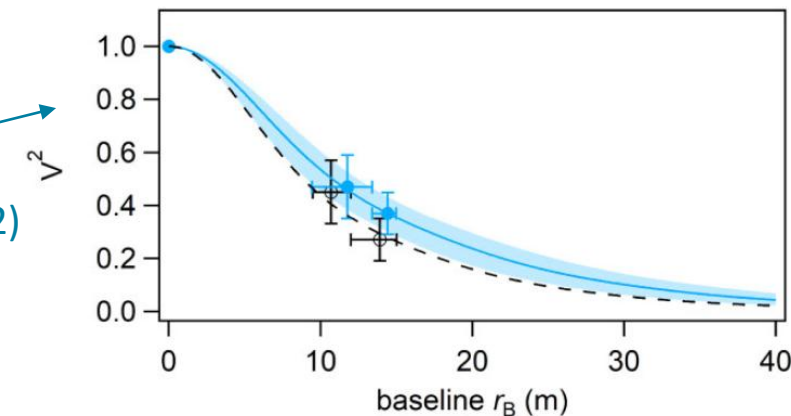
Feb.: SII at H α on Rigel

de Almeida et al., MNRAS 115, 1 (2022)

Aug.: SII at H α on P Cygni (again)

Proposal for SII with segmented mirrors (I3T concept)

Gori et al., MNRAS 505, 2328 (2021)



Brief summary of what we've done so far

2021 ANR project starts (€€)

Adding tip-tilt correction...

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

2022 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

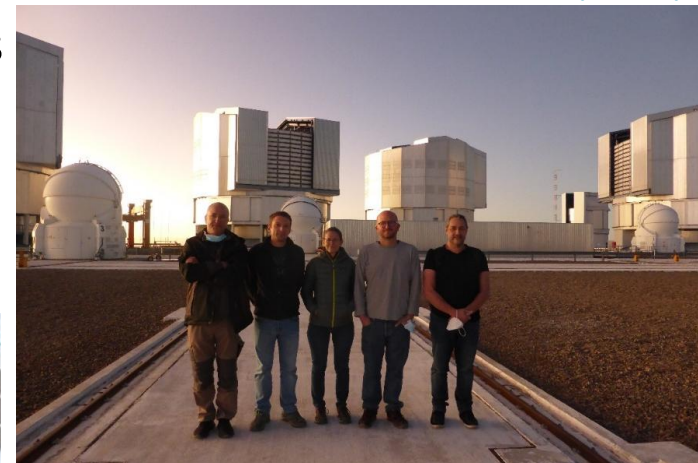
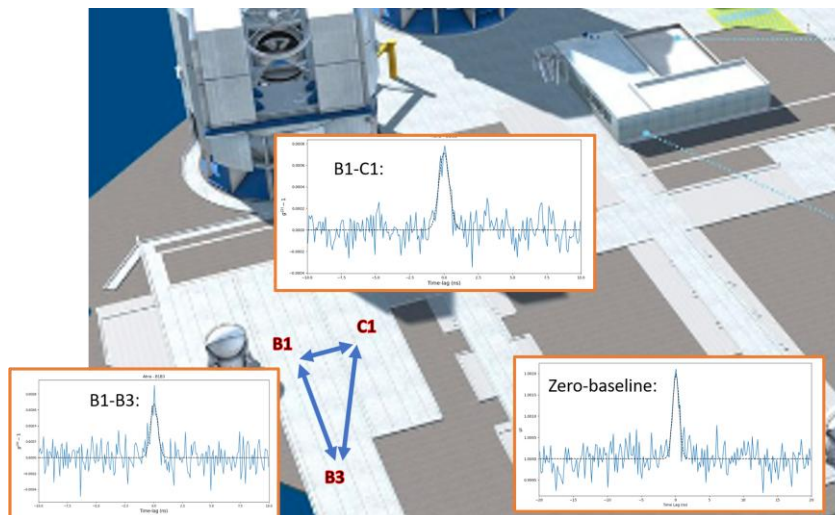
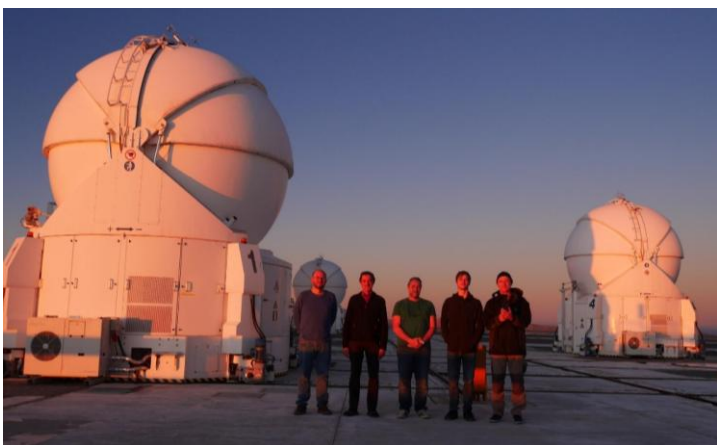
2024 June: First lab test of multiplexing $N_{\text{ch}} = 5$

Tolila et al., Proc. SF2A 2024, p. 197

Extension of I3T

Matthews et al., MNRAS 538, 867 (2025)

2025 ERC project starts (€€€€€)



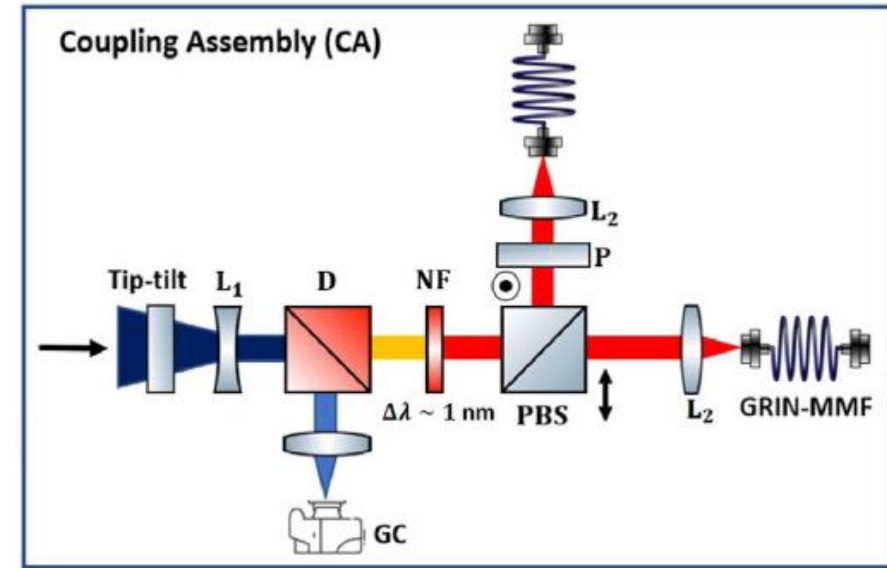
First generation instrument

Main features:

- Photon-counting regime (shot-noise limited)
- Compact and transportable
- Real-time computation of the $g^{(2)}$
- Two polarization channels
- Tip-tilt correction

Technical details:

- Filter width $\Delta\lambda = 1 \text{ nm}$ ($\tau_c \sim 1 \text{ ps}$)
- $\lambda = 780 \text{ nm}$ or 656 nm ($H\alpha$)
- Light injected in MMF ($\varnothing = 100 \mu\text{m}$)
- Detectors $\tau_{el} \sim 500 \text{ ps}$ (FWHM)
- Time tagger from Swabian Instrument

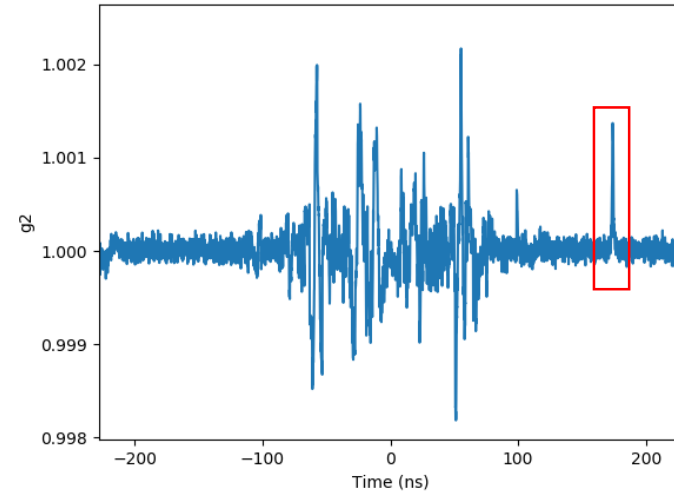
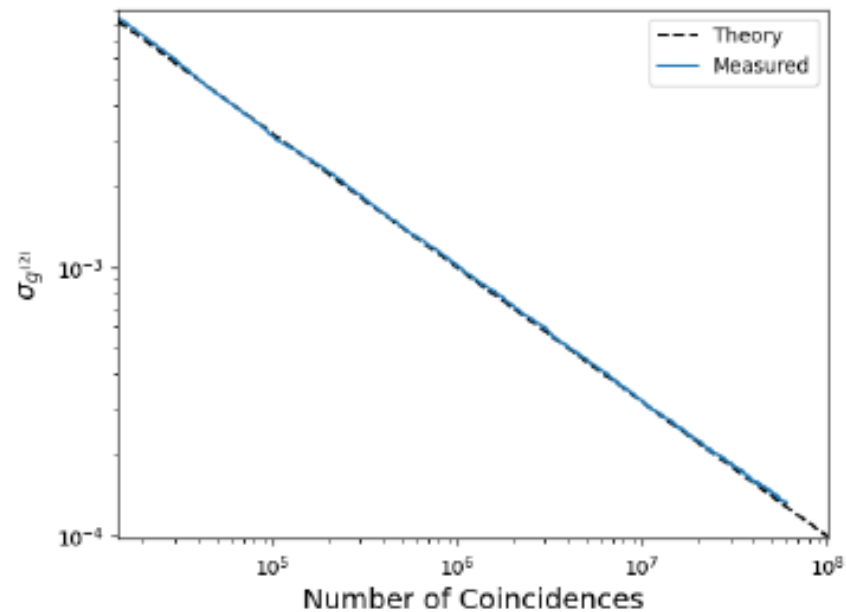
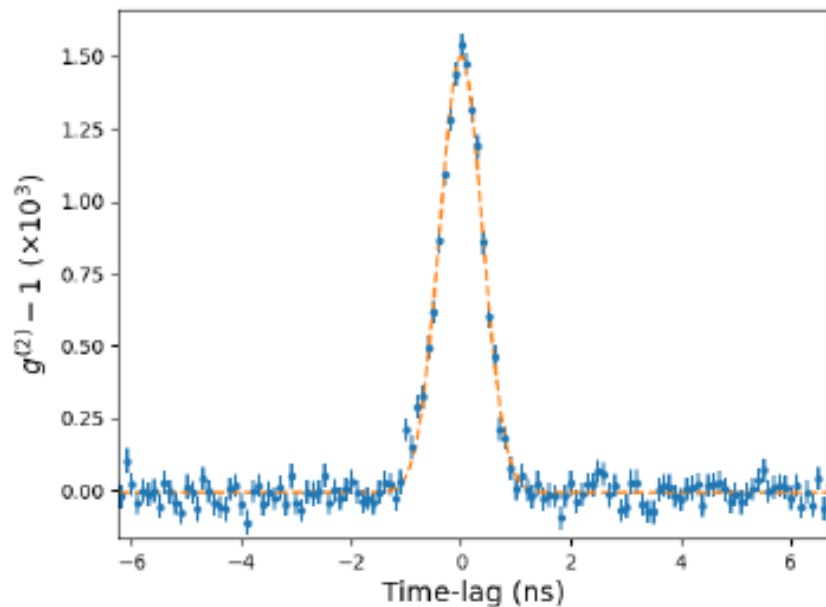


How to transport a stellar interferometer:



Noise

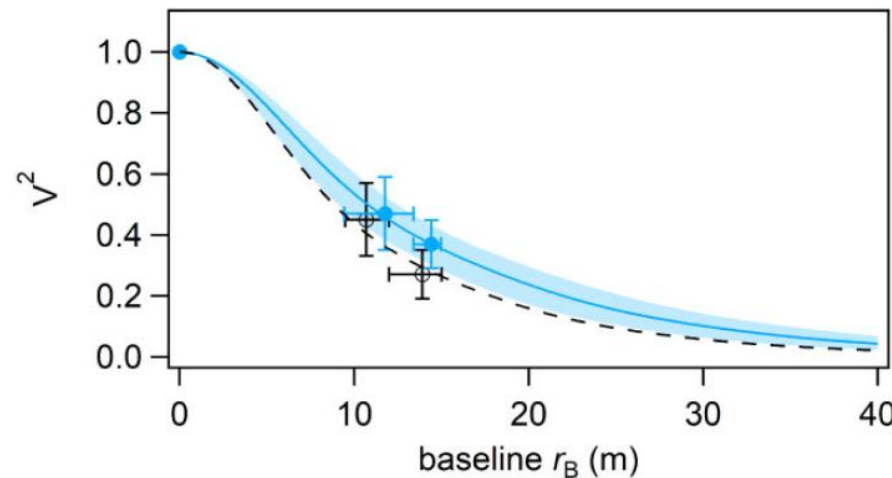
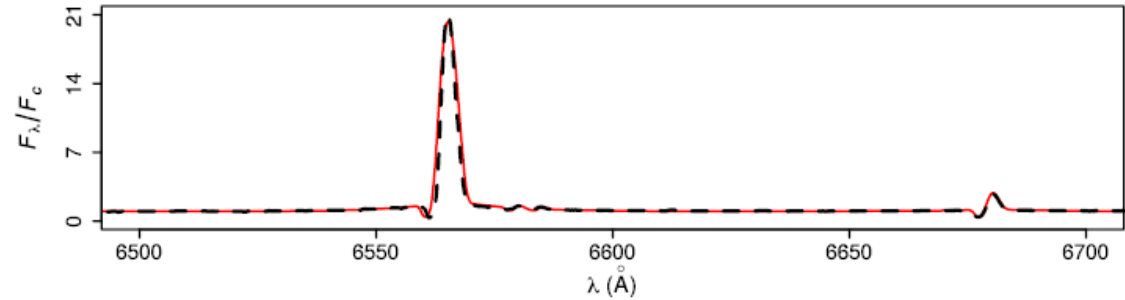
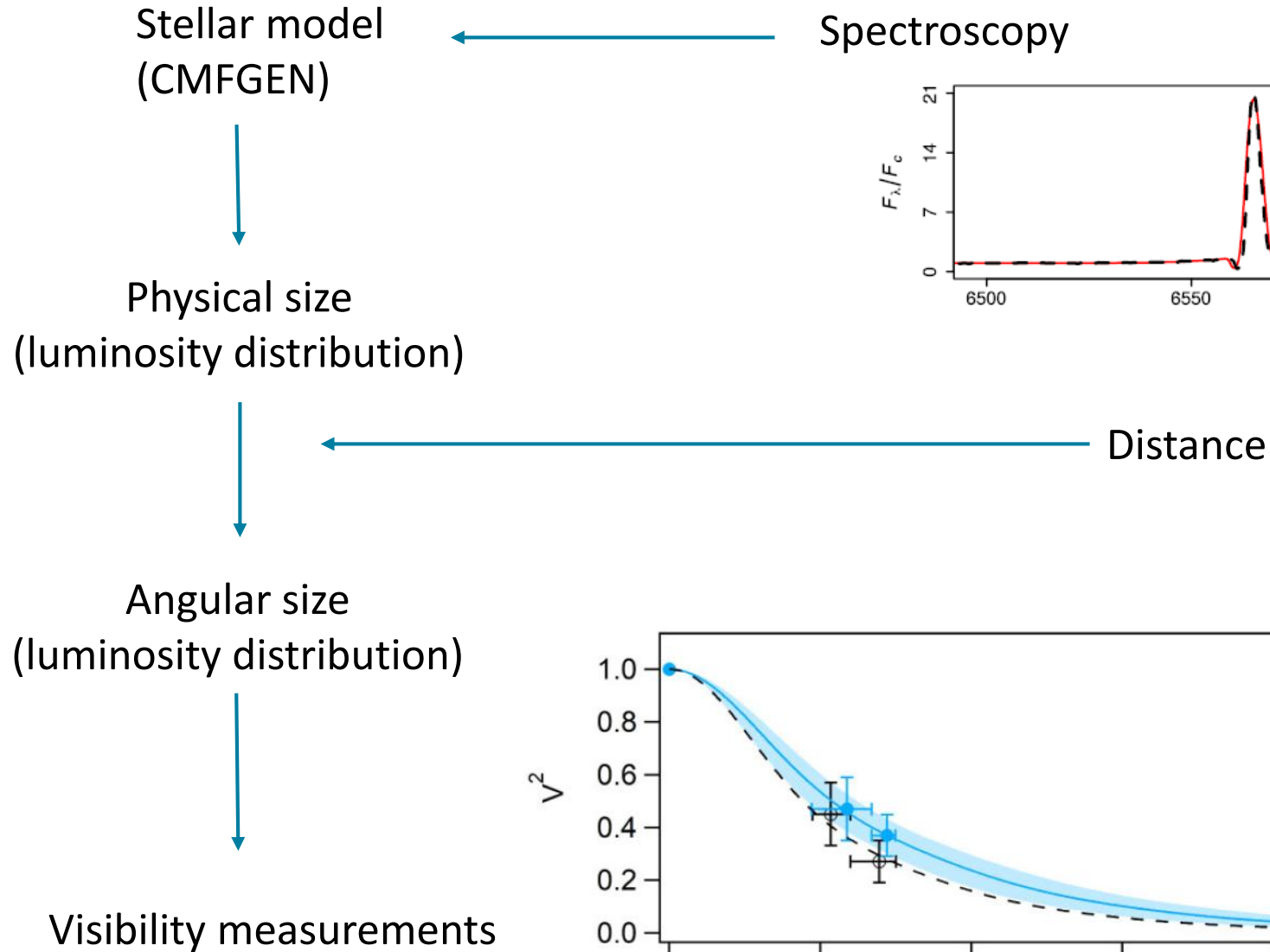
Spurious correlations (induced by the TDC and/or by cross talk between APDs)
→ avoided using cable (electronic or optical) delays.



Measurement limited by photon statistics down to 1% (at least).
Coherence time agrees with the measured spectral filter.

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

P Cygni's distance



$$d_{\text{PCyg}, 2018} = 1.56 \pm 0.25 \text{ kpc}$$

$$d_{\text{PCyg}, 2020} = 1.67 \pm 0.26 \text{ kpc}$$

$$d_{\text{PCyg}, \text{averaged}} = 1.61 \pm 0.18 \text{ kpc}$$

$$d_{\text{PCyg}, \text{eDR3}} = 1.60^{+0.21}_{-0.17} \text{ kpc}$$

Rivet *et al.*, *MNRAS* **494**, 218 (2020)
Almeida *et al.*, *MNRAS* **515**, 1 (2022)

Story of intensity interferometry in short

1956: - Discovery of the “Hanbury Brown & Twiss effect” (controversy with some physicists)

- SII demonstration on Sirius

Hanbury Brown & Twiss, *Nature* **177**, 27 (1956).

Hanbury Brown & Twiss, *Nature* **178**, 1046 (1956).

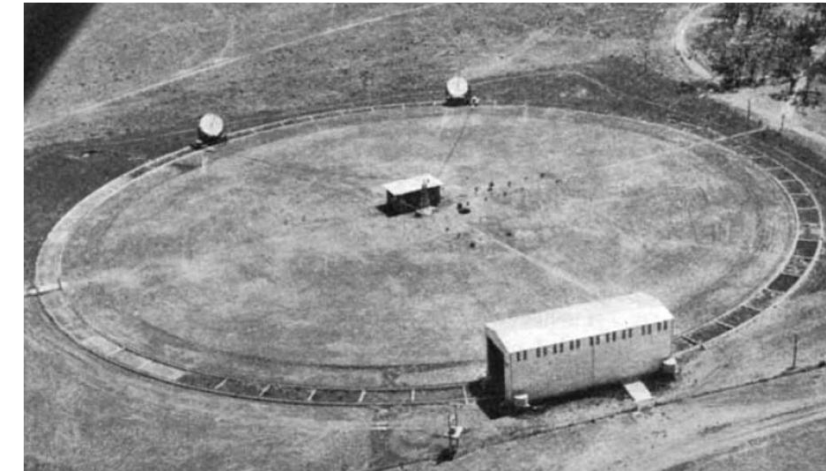
Twiss, Little & Hanbury Brown, *Nature* **180**, 324 (1957).

Early 1960s: Construction of a dedicated **observatory at Narrabri**, Australia

Two huge collectors ($\varnothing = 6.7$ m) on a circular trail ($\varnothing = 188$ m)

→ adjustable baseline size and orientation

1963 – 1972: Angular diameters of **32 bright stars** + study of 2 binary systems (Spica and γ^2 Vel)



Hanbury Brown, Davis & Allen, *MNRAS* **137**, 375 (1967).

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