Intensity correlations: imaging and quantum optics in astrophysics

Robin Kaiser

Institut de Physique de Nice
CNRS / Université de la Côte d'Azur

May 12th 2025
LNPHE, Paris, France

Outline

1) **Optical astrophysical imaging**
   and Hanbury Brown and Twiss experiments

2) **80' : Intensity correlations for quantum physics**

3) **Renewal of intensity correlations for astrophysics**

4) **HBT revival @ Nice (2015-2024):**
   Laboratory intensity correlation experiments (2015/2016)
   On-sky intensity correlations from 2017-2023

5) **State of the art of intensity interferometry in 2024**

6) **IC4Star project in Nice**

2

Intensity Correlation team in Nice

INPHYNI
INSTITUT DE PHYSIQUE DE NICE


R.K.

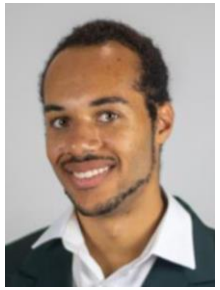

W. Guerin


M. Hugbart


G. Labeyrie


S. Tolila


I. Ellafi


R. Roudeix

Lagrange

LAGRANGE


F.Vakili


J.P. Rivet


O. Lai

Geo AZUR
TERRE - OCÉAN - ESPACE


C. Courde


J. Chabé

Outline

1) **Optical astrophysical imaging and Hanbury Brown and Twiss experiments**

2) **80' : Intensity correlations for quantum physics**

3) **Renewal of intensity correlations for astrophysics**

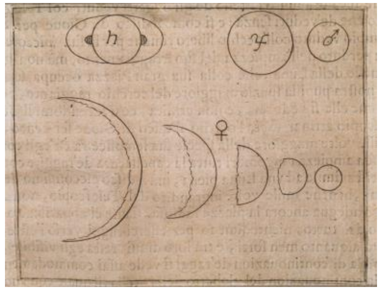
4) **HBT revival @ Nice (2015-2024):**
   Laboratory intensity correlation experiments (2015/2016)
   On-sky intensity correlations from 2017-2023

5) **State of the art of intensity interferometry in 2024**

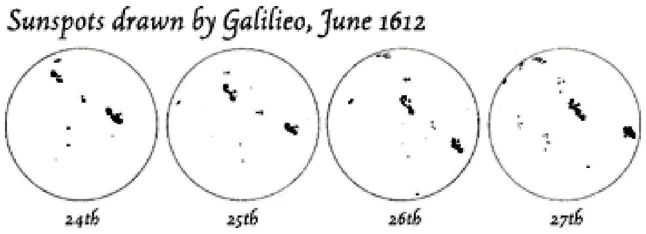
6) **IC4Star project in Nice**

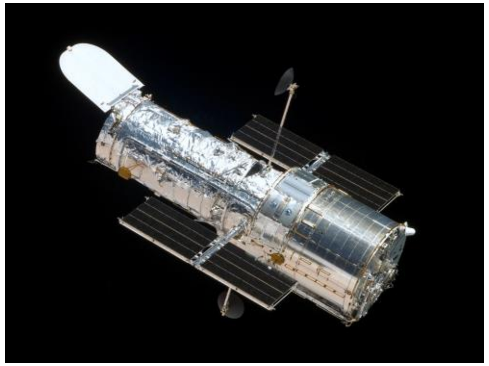
From Galileo (1564-1642) to Hubble Telescope (1990-2026?) & JWST

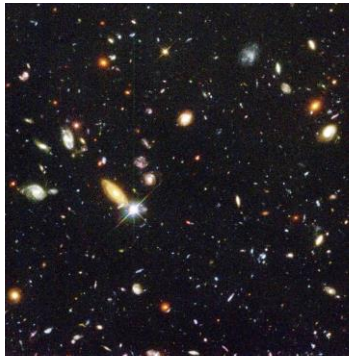
Direct imaging : large telescopes

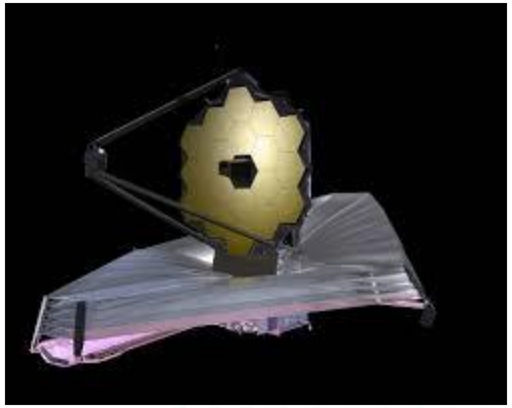


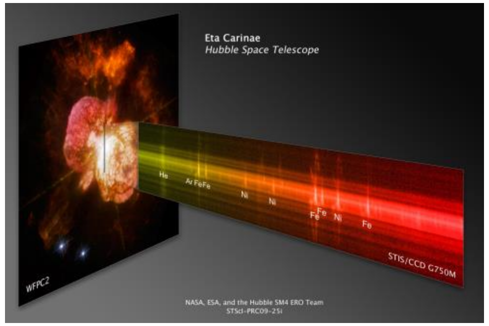
Phases of Venus



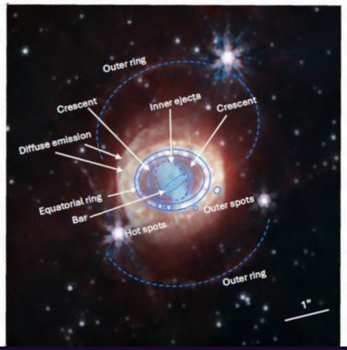


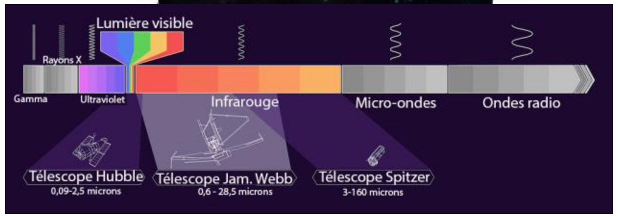






Eta Carinae

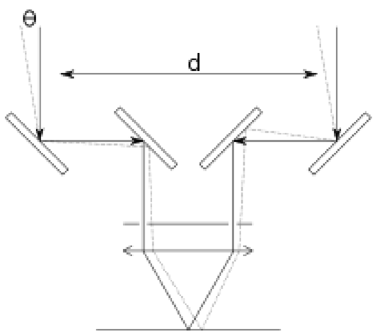


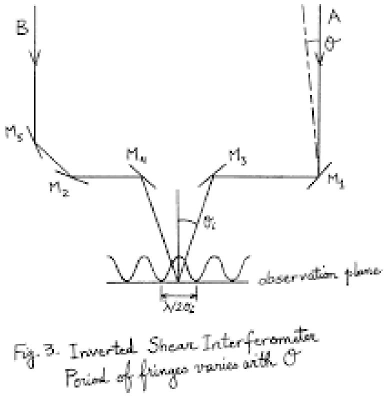


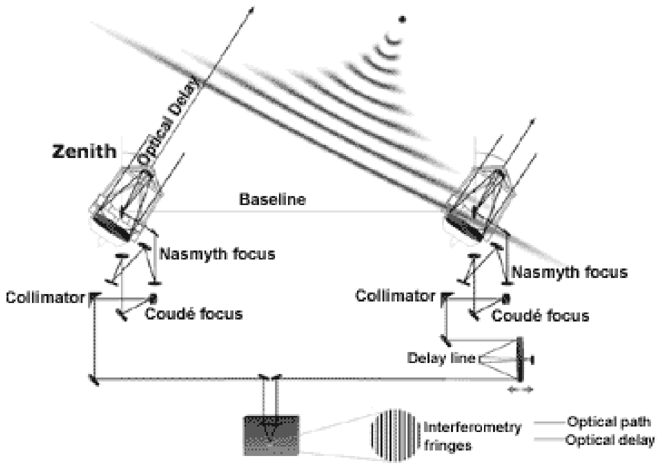
Black holes, dark matter,

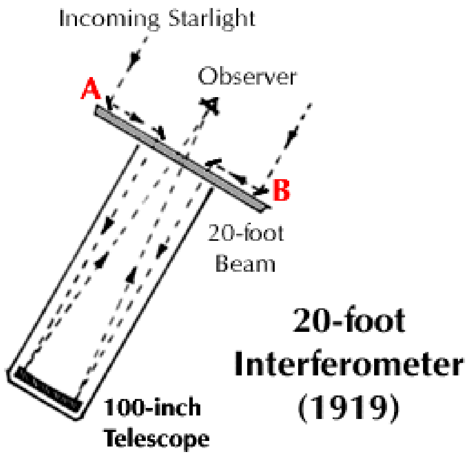
universe expansion…

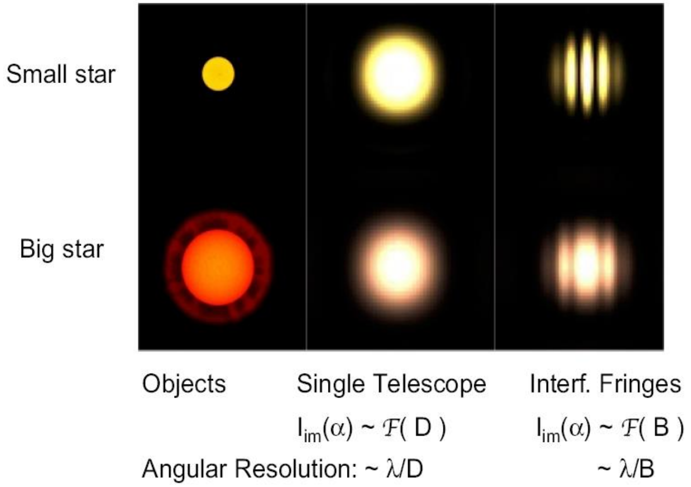
Interferometric imaging: large separation





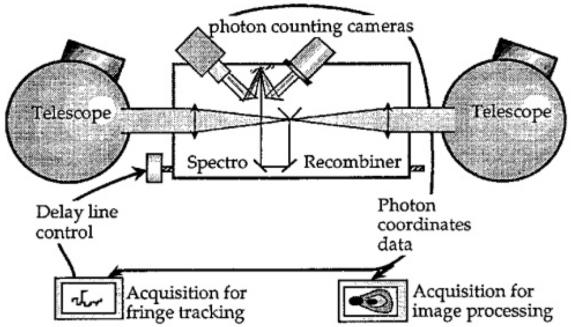


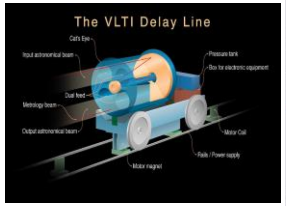


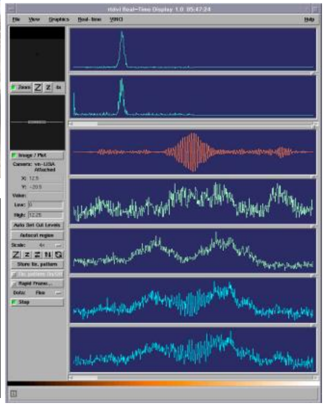


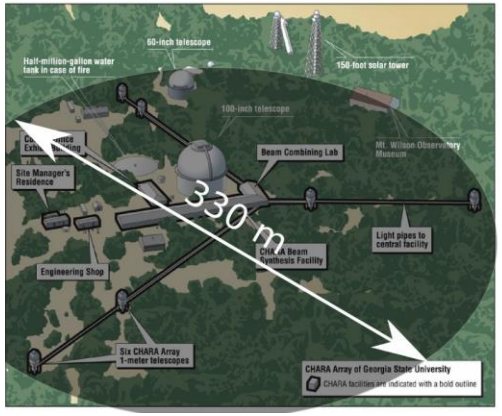
Interferometric imaging: large separation

From A. Labeyrie (12m) to VLTI (130-200m) and CHARA (330m)



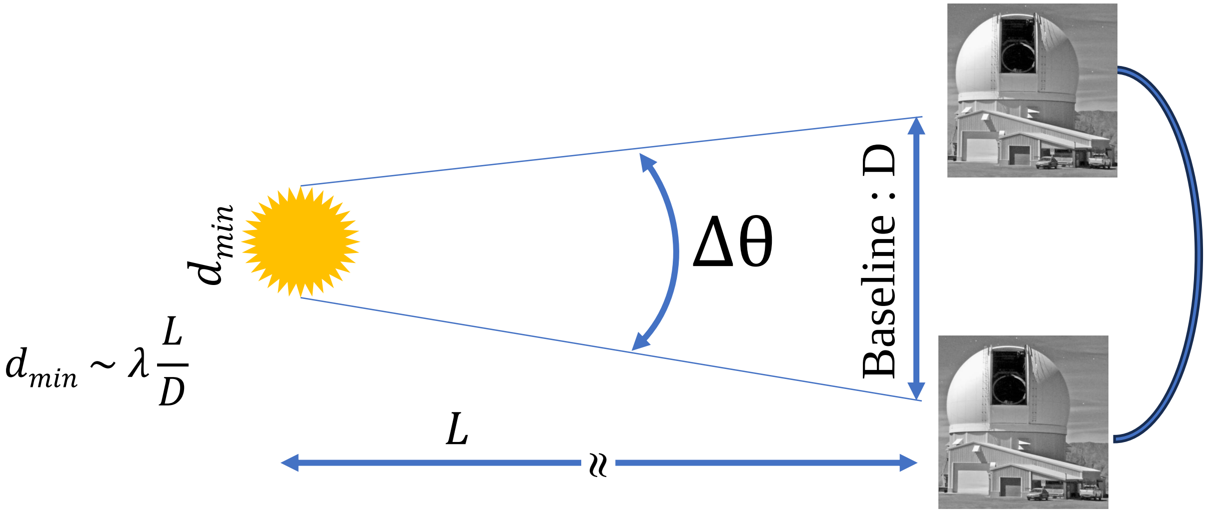






Calern (France) **Paranal (Chili)** **Mt Wilson (USA)**

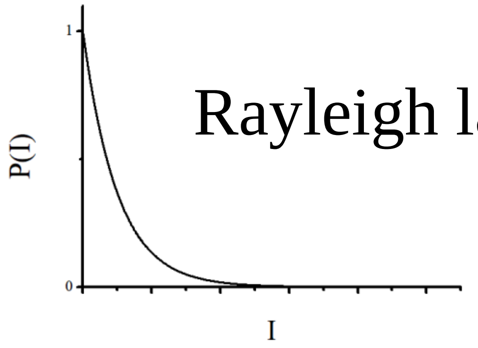
High angular resolution for stars : $\Delta\theta \sim \frac{\lambda}{D}$



i. interferometric recombination
(VLTI, Chara, NPOI < 300m)

ii. intensity correlations $g^2(r)$
Hanbury Brown & Twiss

Speckle statistics

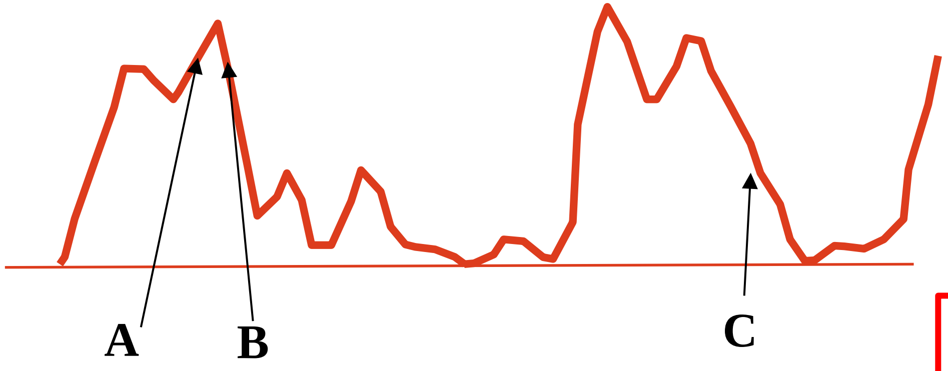


Rayleigh law

$P(I) \propto e^{-I}$

$\langle I^2 \rangle = 2\langle I \rangle^2$

$\mathrm{var}(I) = \langle I^2 \rangle - \langle I \rangle^2 = \langle I \rangle^2$



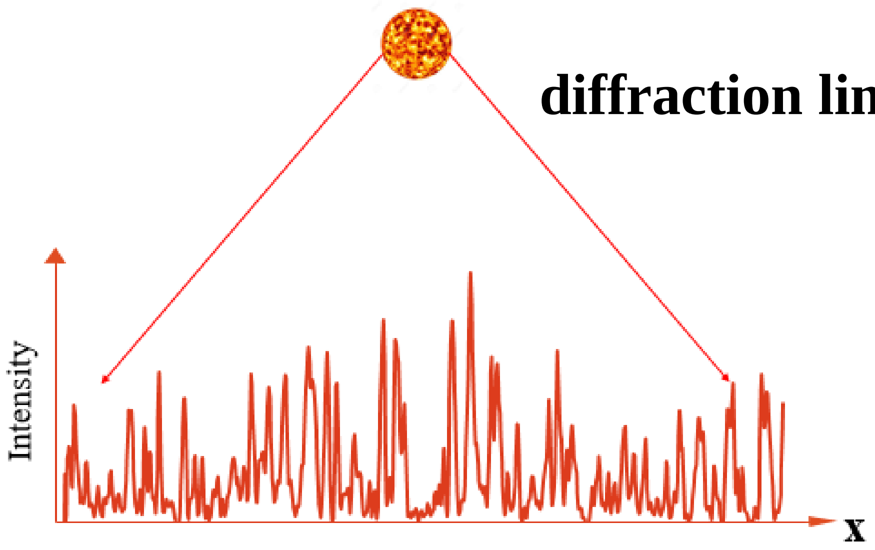
$I_A \sim I_B \neq I_C$

$$\begin{cases} \langle I_A I_B \rangle = \langle I_A^2 \rangle = 2\langle I \rangle^2 \\ \langle I_A I_C \rangle = \langle I_A \rangle \langle I_C \rangle = \langle I \rangle^2 \end{cases}$$

$$g_{AB}(2) = \langle I_A I_B \rangle / \langle I_A \rangle \langle I_B \rangle = 2$$

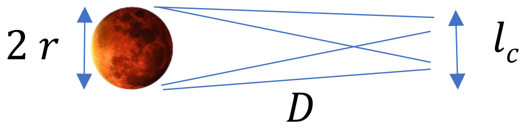
$$g_{AC}(2) = \langle I_A I_C \rangle / \langle I_A \rangle \langle I_C \rangle = 1$$

Time and spatial scales



diffraction limit $\theta = \lambda / D$

$$l_c = \frac{\lambda D}{\pi r}$$



Speckle grain size : $l_c = \theta L \sim \lambda L / D$

Coherence time : $\tau_c = 1 / \Delta\omega$

Robert Hanbury Brown
radio-astronomer

Richard Q. Twiss
applied mathematician

1952: First application of this idea to **radio astronomy**

[Hanbury Brown, Jennison & Das Gupta, *Nature* **170**, 1061 (1952)].

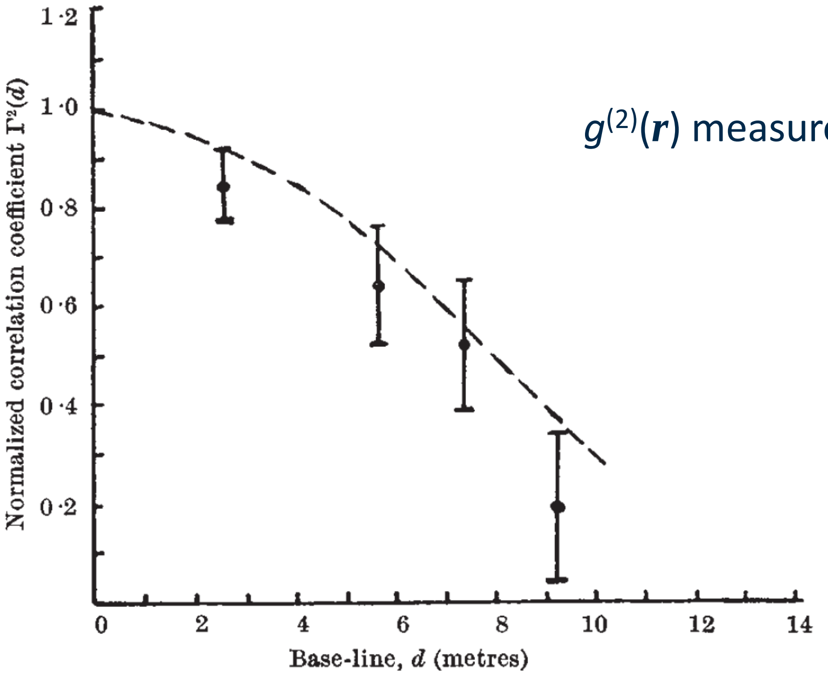
1954: The theory behind it [Hanbury Brown & Twiss, *Phil. Mag*. **45**, 663 (1954)].

1956: Lab experiment with **light** [Hanbury Brown & Twiss, *Nature* **177**, 27 (Jan. 1956)].

1956: Measurements on a **star** [Hanbury Brown & Twiss, *Nature* **178**, 1046 (Nov. 1956)].

A TEST OF A NEW TYPE OF STELLAR INTERFEROMETER ON SIRIUS

By R. HANBURY BROWN
Jodrell Bank Experimental Station, University of Manchester
AND
DR. R. Q. TWISS
Services Electronics Research Laboratory, Baldock



$g^{(2)}(\boldsymbol{r})$ measured on **Sirius**, the brightest star in the visible.

Two telescopes of 1.56 m diameter
Separation up to 9 m

→ First direct measurement of the angular diameter: 6.8 ±0.5 mas

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

1956-1957: Some **controversy** on the Hanbury Brown & Twiss effect: **a two particle interference effect !**

- Brannen & Ferguson, *Nature* (Sept. 1956): unsuccessful experiment in the photon counting regime, claim that the HBT effect contradicts quantum mechanics !
- HBT, *Nature* (Dec. 1956): the other experiments were not sensitive enough !
- Purcell, *Nature* (Dec. 1956): no conflict with QM (“clumping” of bosons).

1961: Interpretation in term of interference between paths of indistinguishable particles

[Fano, Am. J. Phys. **29**, 539 (1961)].

1963: Theory of quantum coherence, based on correlation functions

[Glauber, *Phys. Rev. Lett*. **10**, 84 (1963); *Phys. Rev.* **130**, 2529 (1963)].

Quantum theory : R. Glauber (1963 => Nobel 2005  **)**

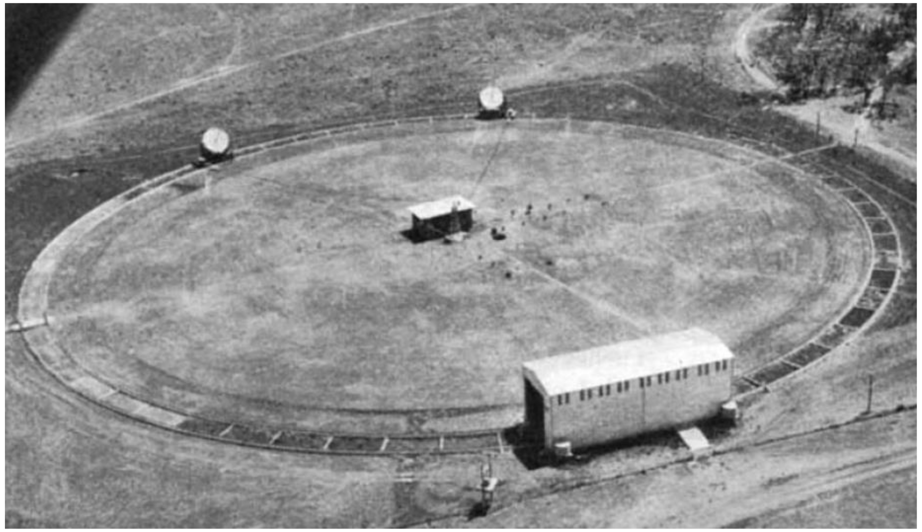
HBT experiment : milestone in the development of quantum optics
&
photon correlations are still the daily bread of quantum opticians

The Narrabri stellar intensity interferometer

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

1963 – 1972: Angular diameters of **32 bright stars**
+ study of several binaries

Two huge collectors (Ø = 6.7 m)
on a circular trail (Ø = 188 m)
→ adjustable baseline size and orientation



Hanbury Brown, Davis & Allen, *MNRAS* **137**, 375 (1967).
Hanbury Brown, Davis, Allen & Rome, *MNRAS* **137**, 396 (1967).
Hanbury Brown, *Nature* **218**, 637 (1968).
Hanbury Brown, Hazard, Davis & Allen, *MNRAS* **148**, 103 (1970).
Herbison-Evans, Hanbury Brown, Davis & Allen, *MNRAS* **151**, 161 (1971).
Hanbury Brown, Davis & Allen, *MNRAS* **167**, 121 (1974).

70' : Intensity interferometry stopped !

The big issue of intensity interferometry:

the signal-to-noise ratio (SNR) is poor ☹

→ very long integration time

→ limited to brightest stars

Thus, although we can see how the limitations of the existing instrument might be removed, we have no plans at the moment to extend the programme. Until the data on single stars have been analysed and discussed by astronomers and astrophysicists at large, it will be too early to judge whether it would be worthwhile to extend the work. In the meantime, our programmes on peculiar objects have started and we are interested to see what they reveal.

Hanbury Brown, Nature, 1968

Antoine Labeyrie, Calern

After 1975: Competition of direct "amplitude" interferometry

→ much better SNR ☺

Outline

1) Optical astrophysical imaging
   and Hanbury Brown and Twiss experiments

2) 80' : Intensity correlations for quantum physics

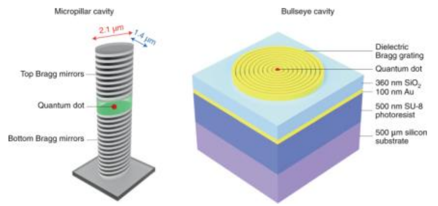
3) Renewal of intensity correlations for astrophysics

4) HBT revival @ Nice (2015-2024):
   Laboratory intensity correlation experiments (2015/2016)
   On-sky intensity correlations from 2017-2023

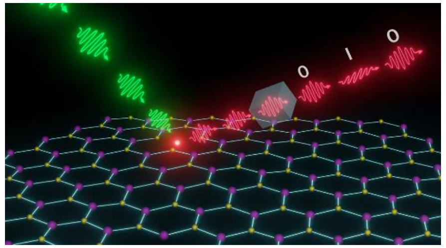
5) State of the art of intensity interferometry in 2024

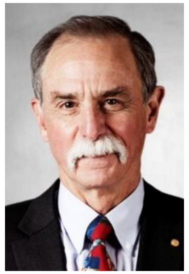
6) IC4Star project in Nice

Contrôle d’atomes, ions et photons uniques



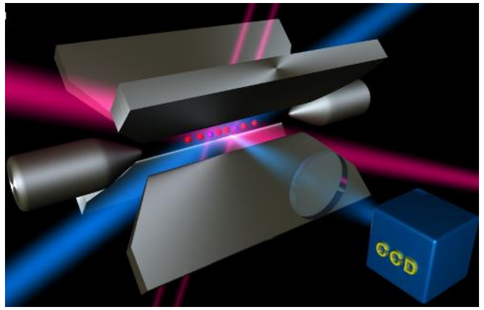
Single photons



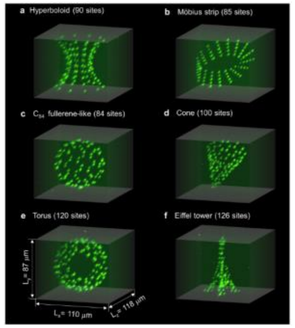


2012

Haroche Wineland



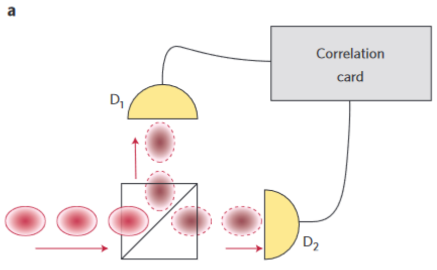
Trapped Ions

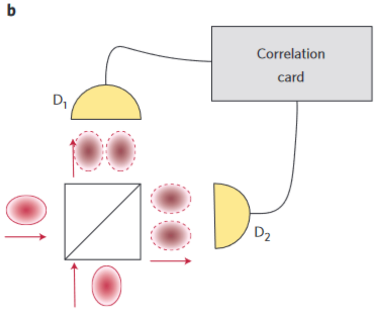


Trapped Atoms

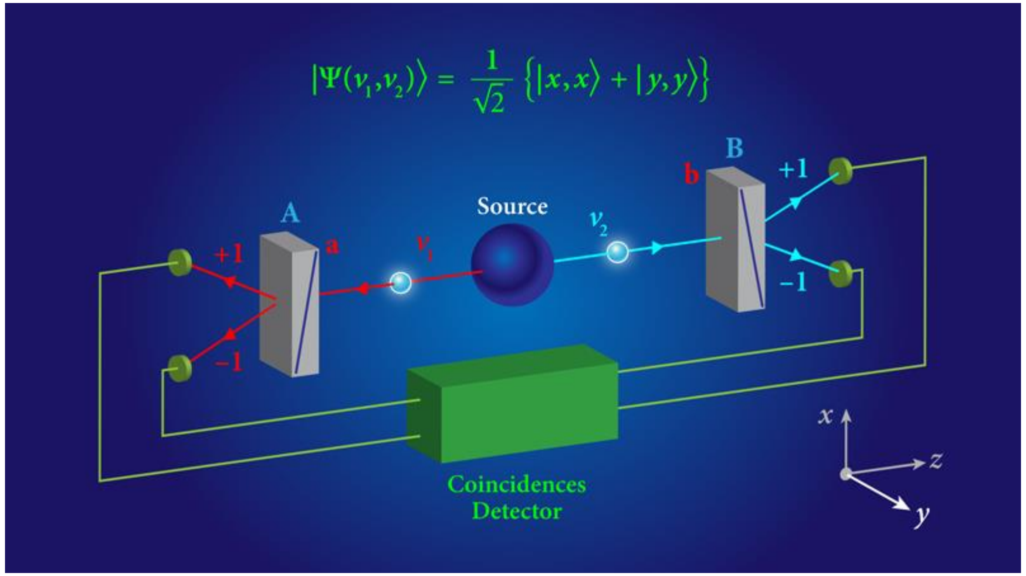
single-photon purity :
HBT

photon indistinguishability:
Hong–Ou–Mandel





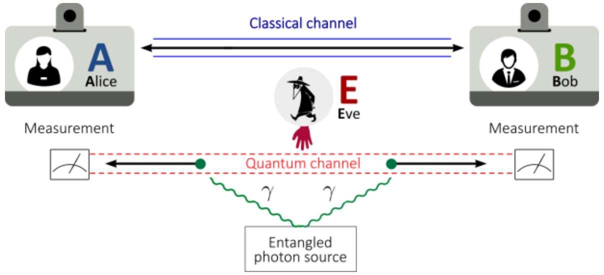
2 particle correlations: classical vs quantum
Philosophical debate until Bell (1964)




2022

Quantum Mechanics is correct : No hidden variables
Accept non-locality

⇒ **Quantum cryptography**
⇒ **Quantum Computers**



Outline

1) Optical astrophysical imaging
   and Hanbury Brown and Twiss experiments

2) 80' : Intensity correlations for quantum physics

3) **Renewal of intensity correlations for astrophysics**

4) HBT revival @ Nice (2015-2024):
   Laboratory intensity correlation experiments (2015/2016)
   On-sky intensity correlations from 2017-2023

5) State of the art of intensity interferometry in 2024

6) IC4Star project in Nice

Limitations of Interferometric imaging

- Stability requirement (at λ)
- Atmospheric turbulence (at λ)
- Requires delicate and large optical delay lines

An alternative for astrophysical imaging: Intensity correlations

- Insensitive to stability of telescope distance
- Insensitive to atmospheric turbulence
- Insensitive to telescope imperfections
- Efficient at short wavelengths (blue)
- Can use existing and future infrastructure

The prize to pay: low SNR => longer integration times

A dynamic advocate for intensity correlations in astrophysics

(with a strong motivation by CTA)

D. Dravins :

- Dravins D. High Time Resolution Astrophysics, D. Phelan et al., (eds.), Springer 2008, https://arxiv.org/abs/astro-ph/0701220
- D. Dravins, S. LeBohec, H. Jensen, P. Nunez, Stellar Intensity Interferometry: Prospects for sub-milliarcsecond optical imaging, New Astronomy Reviews, 56, 143 (2012), arXiv:1207.0808
- Dravins D., Lagadec T., Nuñez P. D., 2015a, A & A, 580, A99
- Dravins D., Lagadec T., Nuñez P. D., 2015b, Nat. Commun., 984, 216
- D. Darvins, Intensity interferometry: Optical imaging with kilometer baselines, Proc. 9907, Optical and Infrared Interferometry and Imaging V; 99070M (2016), arxiv.1607.03490

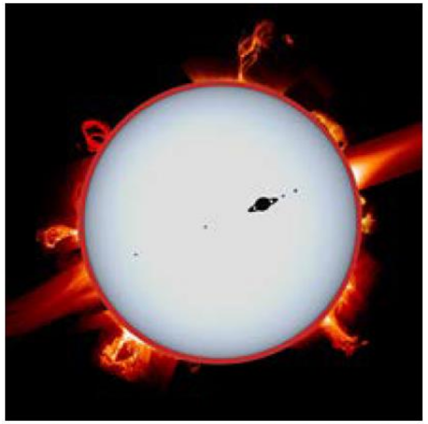
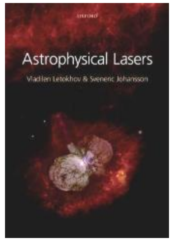


Figure 3. The real meaning of 40 microarcsecond optical resolution: Simulated resolution for an assumed transit of a hypothetical exoplanet across the disk of the relatively nearby star Sirius, using the full Cherenkov Telescope Array as an intensity interferometer. Stellar angular diameter = 6 mas; assumed planet of Jupiter size and oblateness; equatorial diameter = 350 μas; Saturn-type rings; four Earth-size moons. The stellar surface is assumed surrounded by a solar-type chromosphere, shining in an emission line. The 40 μas resolution provides some 150 pixels across this stellar diameter.

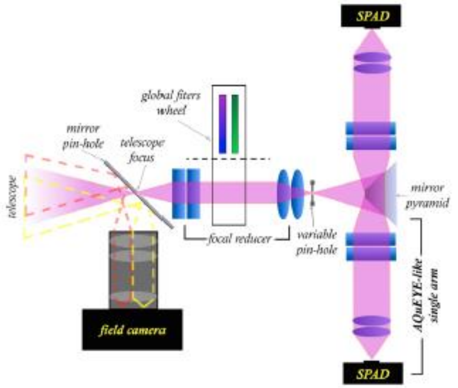
- Astrophysical lasers
- Short (and bright) pulses
- Photon bubbles
- Photon-correlation spectroscopy



Early attempts for HBT revival with novel fast detectors :

Quanteye : OWL/ELT

- D. Dravins, et al. 2005, QuantEYE quantum optics instrumentation for astronomy. OWL Instrument Concept Study, Tech. rep., ESO, Document OWL-CSR-ESO-00000-0162
- C. Barbieri, et al. 2006, in The scientific requirements for extremely large telescopes, ed. P. Whitelock, B. Leibundgut, & M. Dennefeld, IAU Symp., 232, 506
- G. Naletto, et al. 2006, in Ground-Based and Airborne Instrumentation For Astronomy, SPIE 6269, 62691W–1/9



Aqueye: Asiago (Italy) 182 cm telescope

- G. Naletto et al. 2007, in Photon counting applications, Quantum Optics, and Quantum Cryptography, SPIE, 6583, 65830B–1/14
- C. Barbieri et al. 2007b, Mem. SAIt. Suppl., 11, 190
- C. Barbieri et al. 2009, J. Mod. Opt., 56, 261
- C. Barbieri et al. 2009, in Science with the VLT in the ELT Era, Astrophysics and Space Science Proceedings, 249

Iqueye : La Silla (Chili) 358cm telescope

- G. Naletto et al., A&A 508, 531–539 (2009)

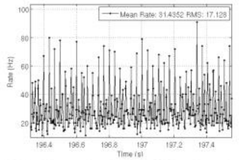
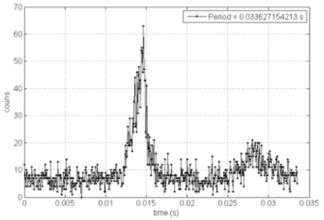
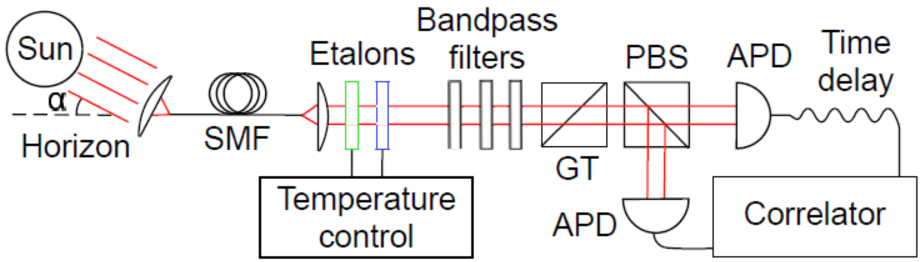


Fig. 9. Individual counts from the Crab Nebula pulsar, with 0.33 ms (1/10 of the period) bin size. The average count rate per time bin is given in the box.



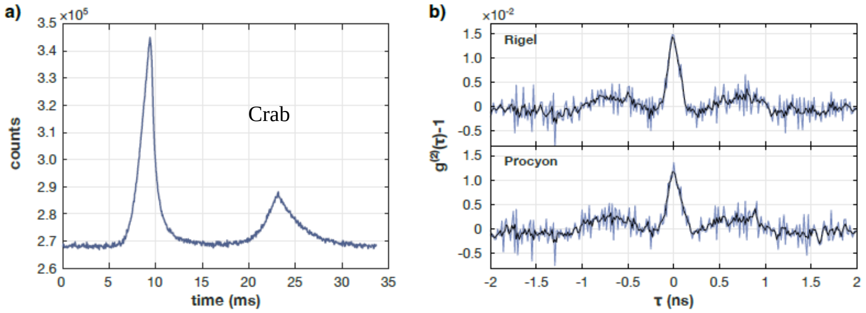
Singapore

- P. Tan et al., ApJ, 789, L10 (2014), MNRAS, 457, 4291 (2016)



JPL: DSOC : Palomar (US) Hale : 500cm telescope

- E. Wollmann et al., opt. Exp. 32, 48185 (2024)



SNSPD :

$\Delta t \sim 120$ps

Outline

1) Optical astrophysical imaging
and Hanbury Brown and Twiss experiments

2) 80' : Intensity correlations for quantum physics

3) Renewal of intensity correlations for astrophysics

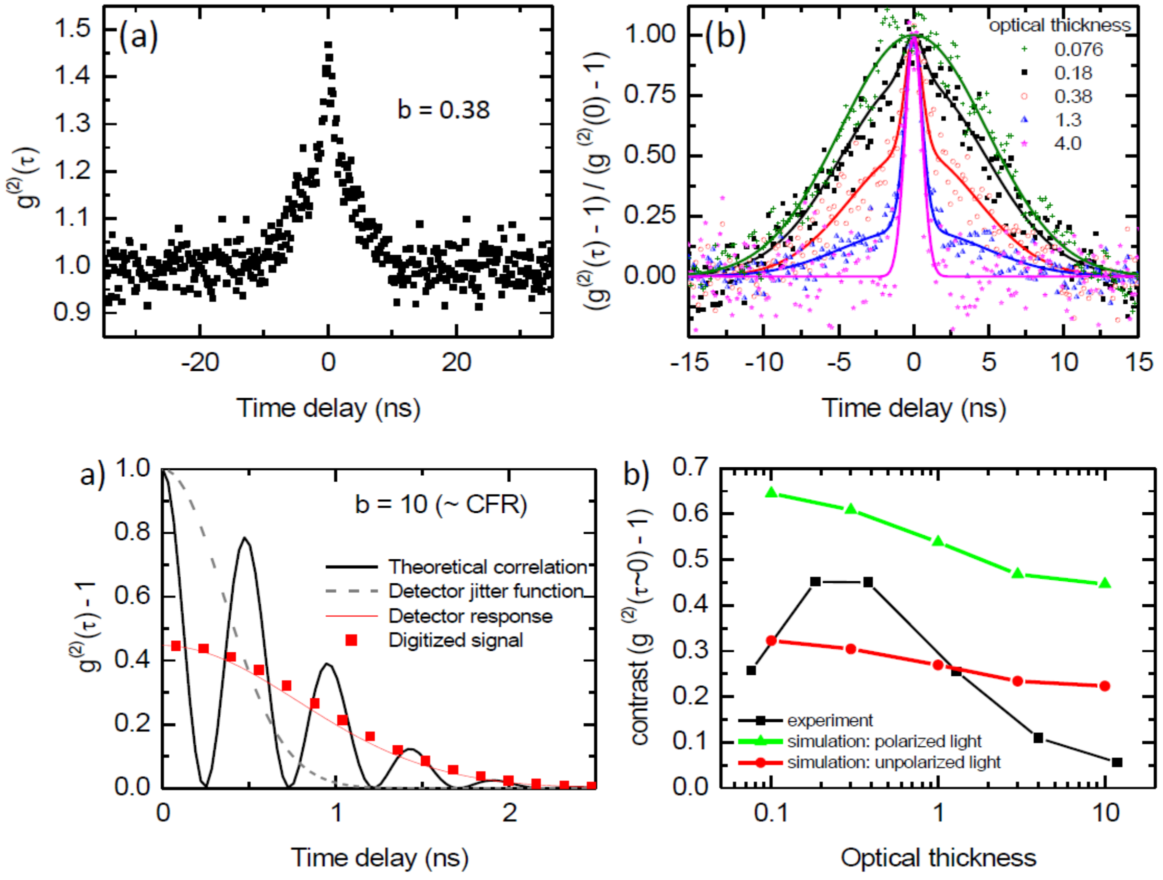
4) **HBT revival @ Nice (2015-2024):**
   Laboratory intensity correlation experiments (2015/2016)
   On-sky intensity correlations from 2017-2023

5) State of the art of intensity interferometry in 2024

6) IC4Star project in Nice

Atomic physics laboratory experiments

fast (high bandwidth) correlation



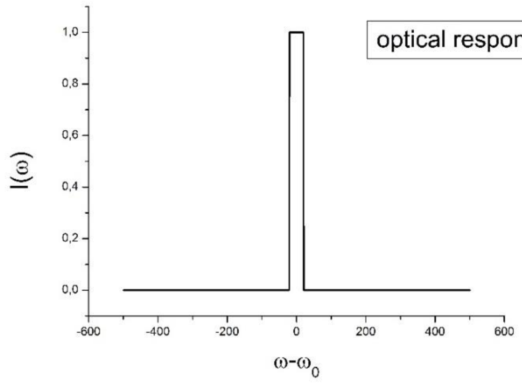
Temporal intensity correlation of light scattered by a hot atomic vapor
A. Dussaux, T. Passerat de Silans, W. Guerin, O. Alibart, S. Tanzilli, F. Vakili, R. Kaiser
Phys. Rev. A 93, 043826 (2016)

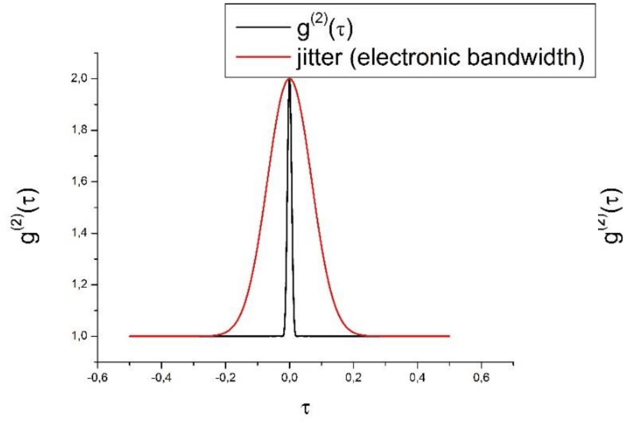
White light laboratory experiments

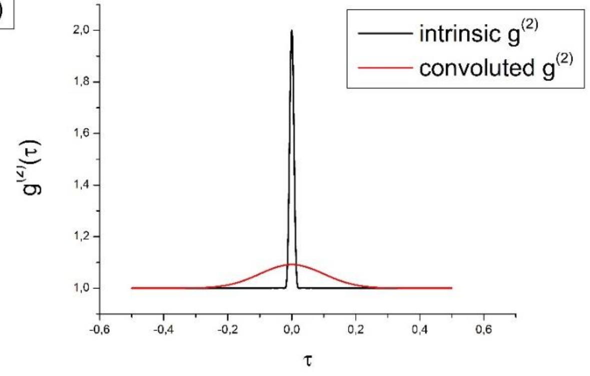
$g^{(2)}(r=0, \tau)$: technical limitations

Optical filter @ 1nm : τ_c ~ ps

Electronic bandwidth (jitter) ~ 100ps

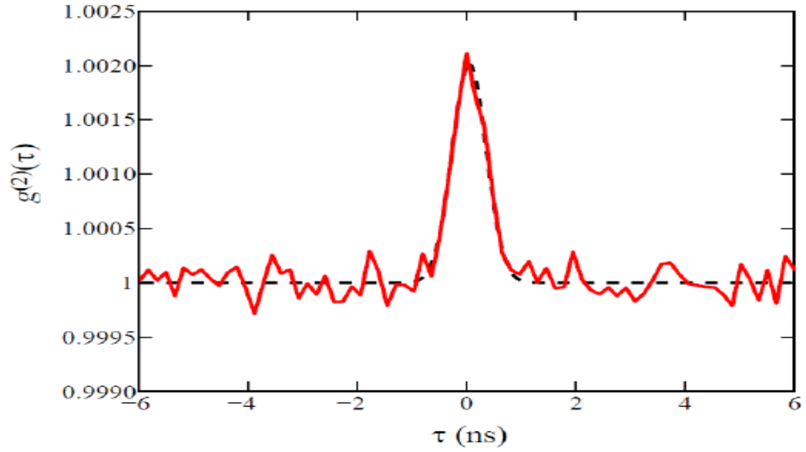






Laboratory experiment with

1nm filtered thermal source



Towards on-sky experiments

DM: Dichroic beam splitter

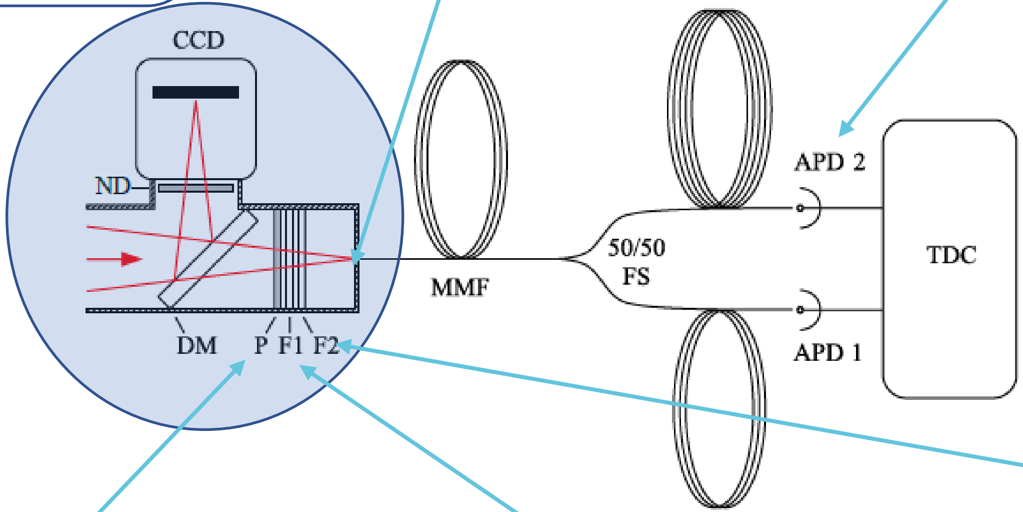
Reflection: λ < 650 nm
to the guiding camera
Transmission: λ > 650 nm
to the $g^{(2)}$ measurement

Focus of the telescope

APD: Single photon detector

Excelitas
Quantum efficiency $\eta \sim 60$ %
Deadtime ~ 20 ns
Jitter $\tau_J \sim 500$ ps

Light from the telescope



TDC: Time to Digital Convertor

#1: ID Quantique, time resolution = 81 ps

#2: Swabian Instruments, time resolution = 12 ps, less spurious correlations, 40 Mcps

P: Polarizer

To select one polarization mode

F2: Filter

λ_0 = 780 nm
$\Delta\lambda$ = 10 nm
To remove UV and IR photons

F1: Filter

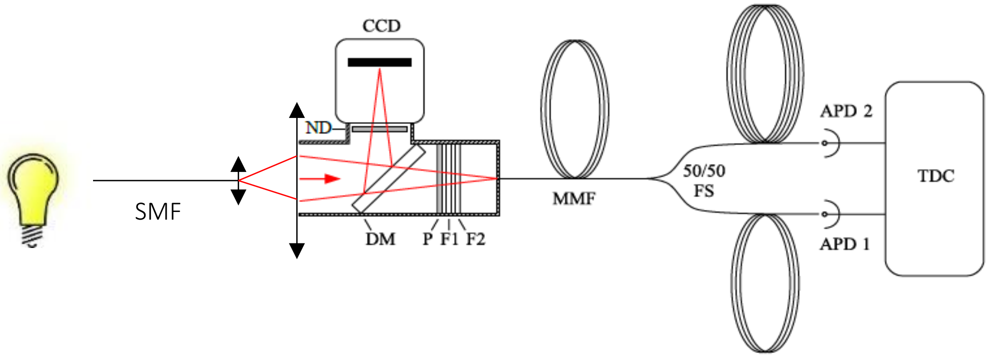
λ_0 = 780 nm
$\Delta\lambda$ = 1 nm
$\tau_c \sim \lambda_0^2/c\Delta\lambda \sim 1$ ps

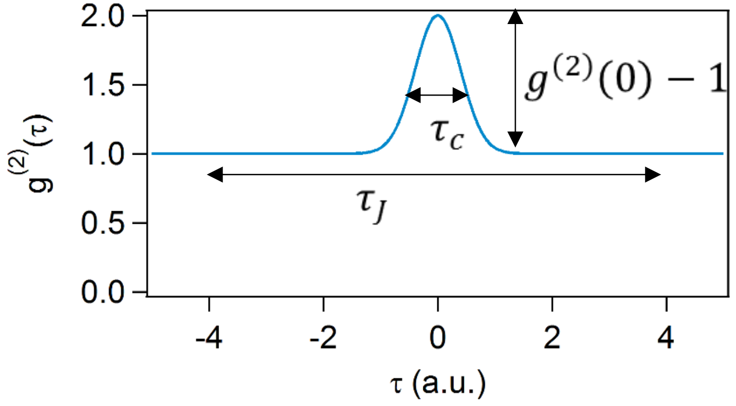
Expected signal

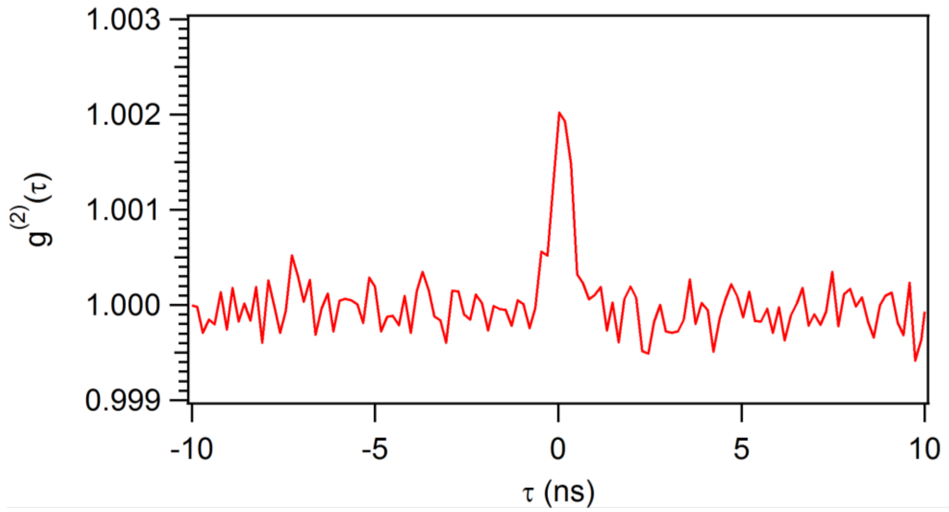
Contrast

$$C = g^{(2)}(0) - 1 \sim \frac{\tau_c}{\tau_J}$$

~ 0.002

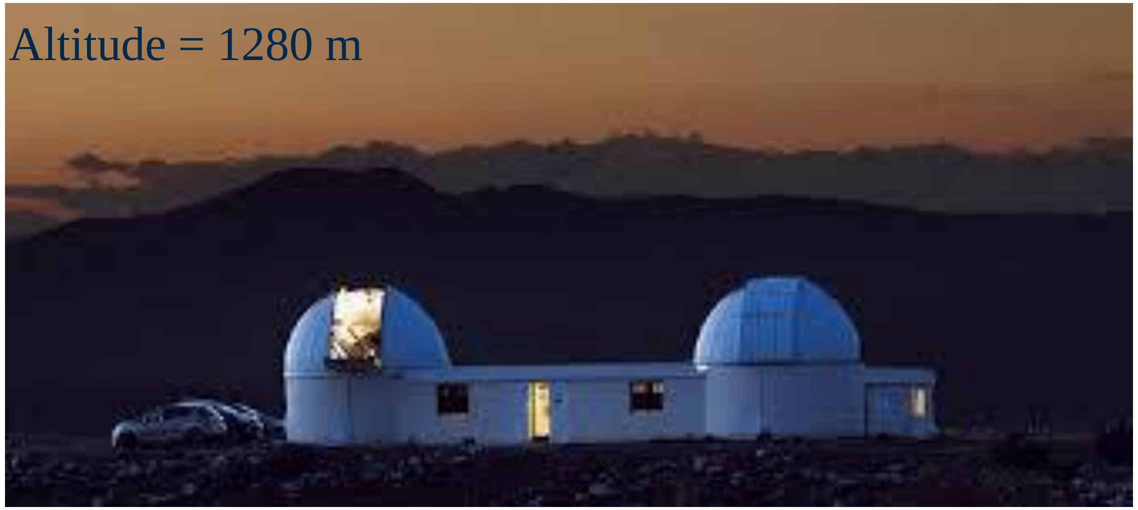


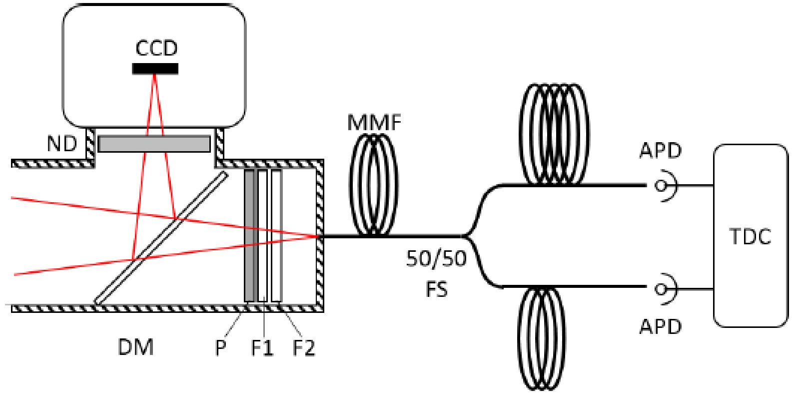


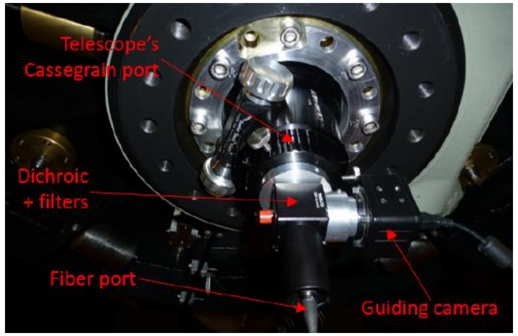


spurious correlations !!!

On sky experiments : C2PU @ Calern February 20th-22nd 2017





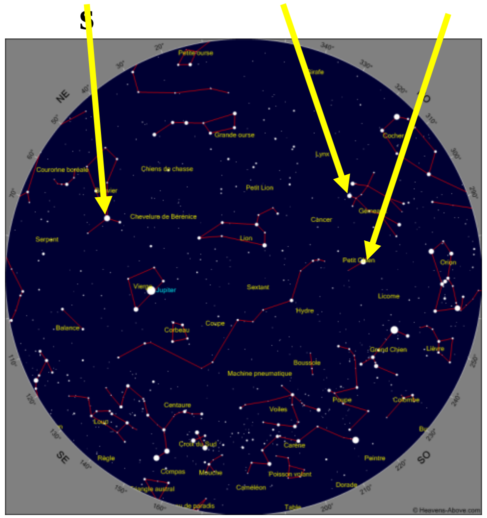


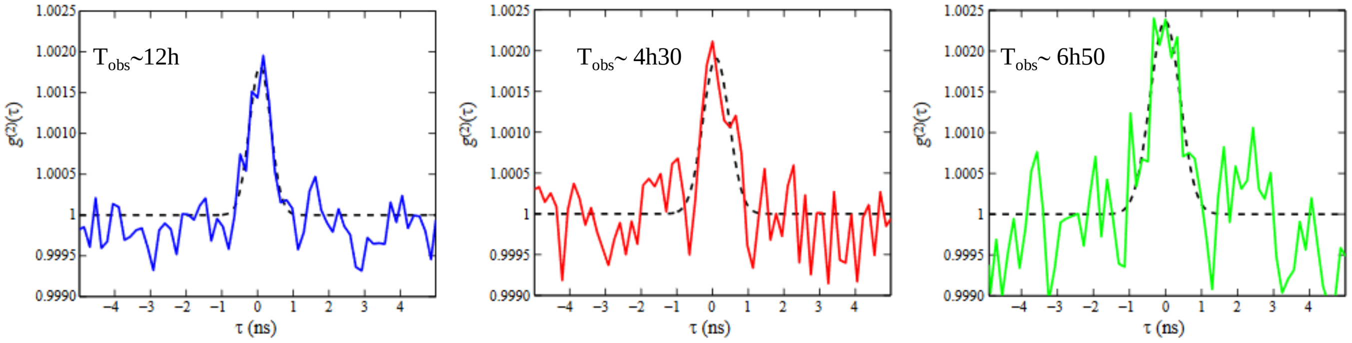
<u>C2PU telescopes</u>

- Ø = 1 m
- Cassegrain configuration + focal reducer → f = 5.6 m
- NA = 0.09 ; f/5.6
- PSF = 42 µm for seeing = 1.5''
- Fiber core = 100 mm

Results : Feb. 2017 : time correlation on 3 bright stars

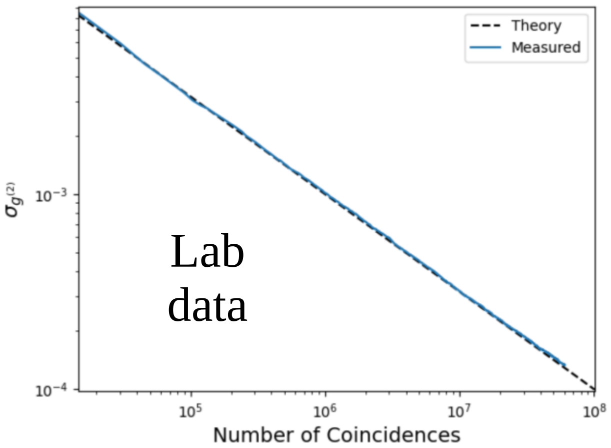
Arcturu
s
Pollux
Procyon

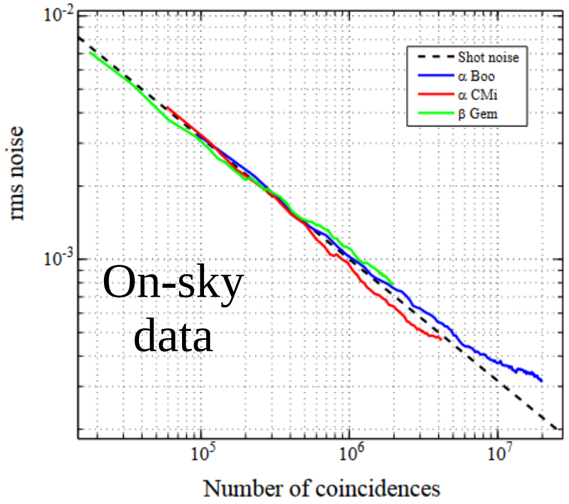




(a) α Boo (Arcturus). (b) α CMi (Procyon). (c) β Gem (Pollux).

Shot noise limited

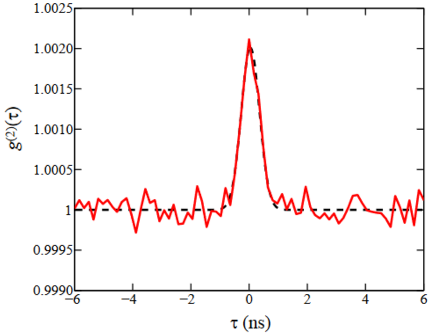




$$SNR = \alpha N_{\mathrm{ph}}(\lambda) A \sqrt{\frac{T_{\mathrm{obs}}}{\tau_{\mathrm{el}}}}$$

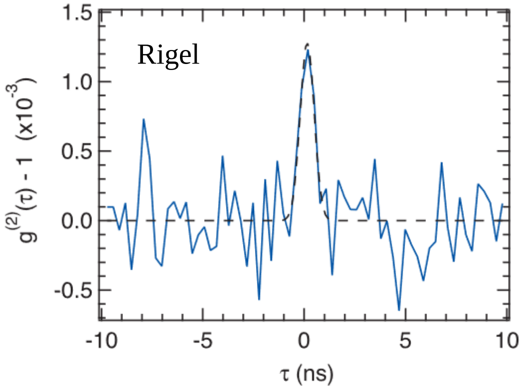
α: detection efficiency
$N_{ph}(\lambda)$: photon spectral flux (ph/m^2/s/Hz)
A : collecting area

Laboratory calibration:
Convoluted $g^{(2)}(\tau)$

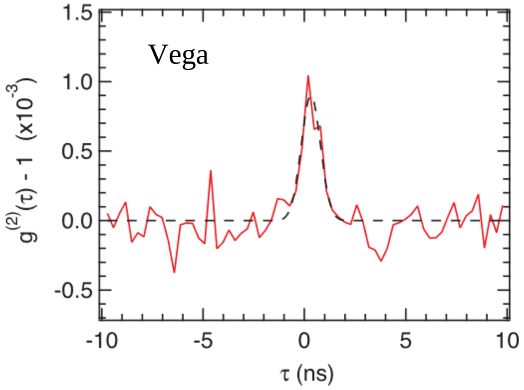


W. Guerin, A. Dussaux, M. Fouche, G. Labeyrie, J.-P. Rivet, D. Vernet, F. Vakili, R. K, Mon. Not. Roy. Astron. Soc. 472, 4126 (2017)

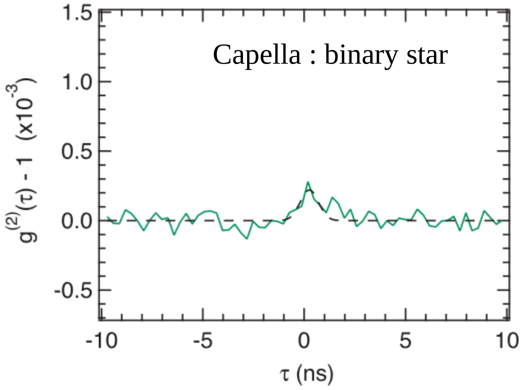
Results : fall 2017 : spatial correlation on 3 bright stars



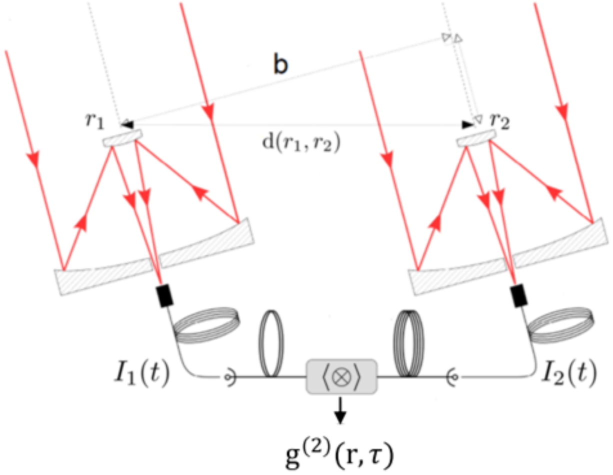
(a) β Ori.



(b) α Lyr.



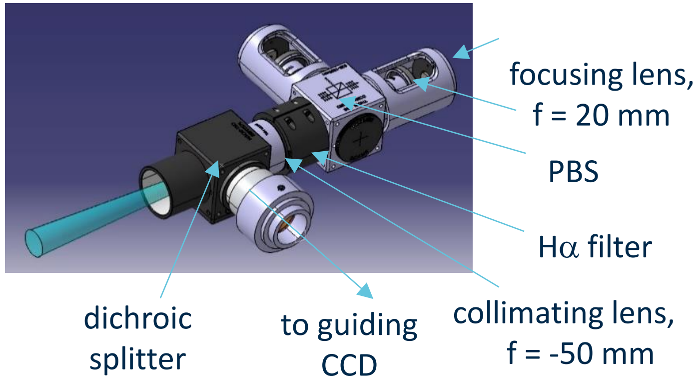
(c) α Aur.

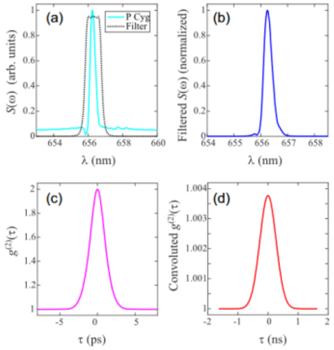


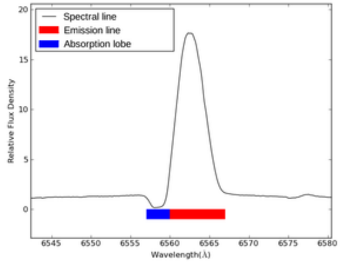
First angular measurement of stars since HBT !!!

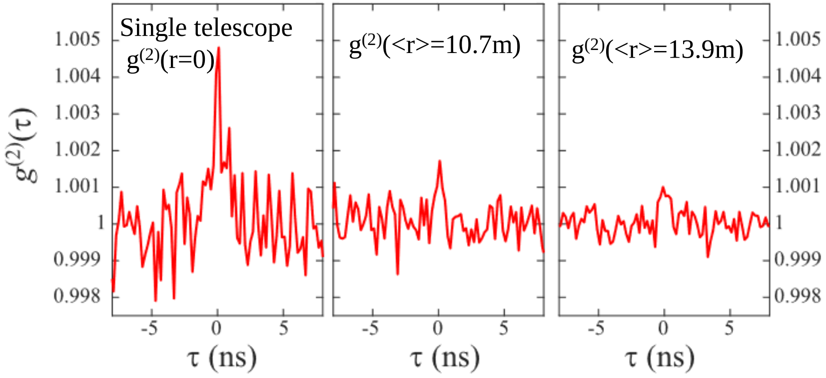
W. Guerin, J.-P. Rivet, M. Fouche, G. Labeyrie, D. Vernet, F. Vakili, R. K., Mon. Not. Roy. Astron. Soc. 480, 245 (2018)

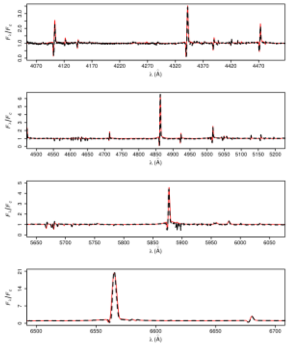
Results : Summer 2018 : spatial correlation on H_α emission line of P Cygni



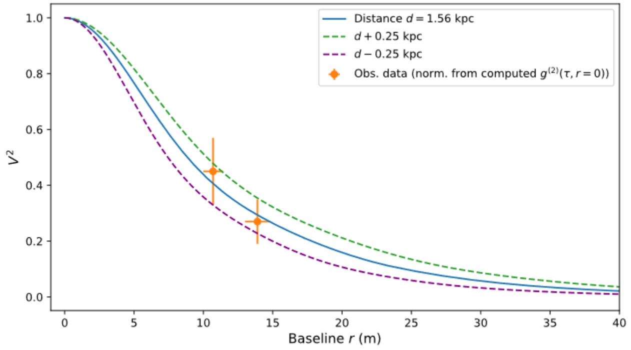








non-LTE
radiative transfer code
CMFGEN

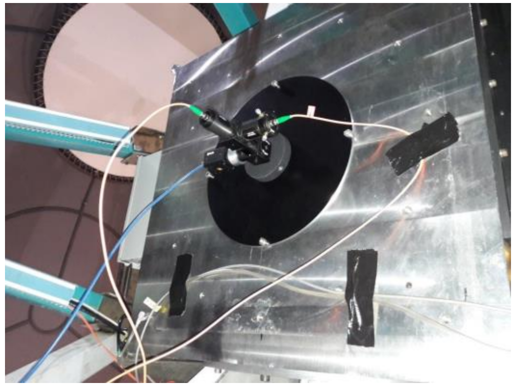


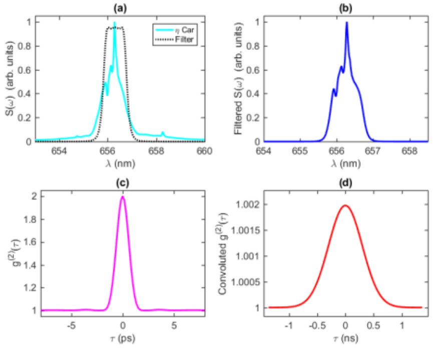
d = 1.56 +/- 0.258 kpc

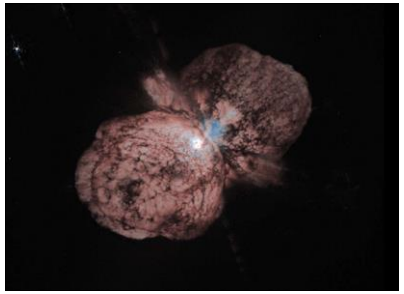
d = 1.36 +/- 0.24 kpc
Gaia DR2 catalogue
d = 1.8 +/- 0.1 kpc
Usually adopted in the literature

J.-P. Rivet, A. Siciak, E. S. G. de Almeida, F. Vakili, A. Domiciano de Souza, M. Fouche, O. Lai, D. Vernet, R. K., W. Guerin, Mon. Not. Roy. Astron. Soc. 494, 218 (2020)

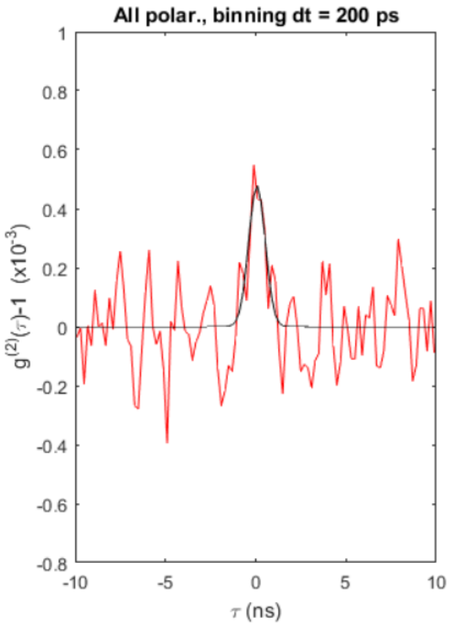
April 2019 : SOAR correlation on H_α emission line of η Carinae







η Carinae



1 night trial
Bad night ☹ : turbulence, coulds : only 4 hours of observation

However : fast implementation on SOAR !
Bunching observed on η Car H_α line ☺ ☺

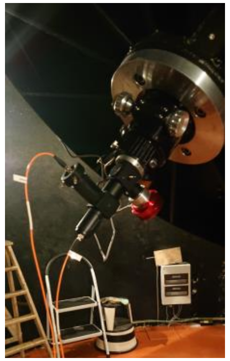
W. Guerin, J.-P. Rivet, M. Hugbart, F. Vakili, E. S. G. de Almeida, A. Domiciano de Souza, G. Labeyrie, N. Matthews,
O. Lai, P.-M. Gori, D. Vernet, J. Chabe, C. Courde, E. Samain, B. V. Castilho, A. M. Magalhaes, E. Janot-Pacheco, A. Carciofi, P. Bourget, N. Schuhler and R. K.,
Proceedings of the annual meeting of the French Society of Astronomy & Astrophysics 2021

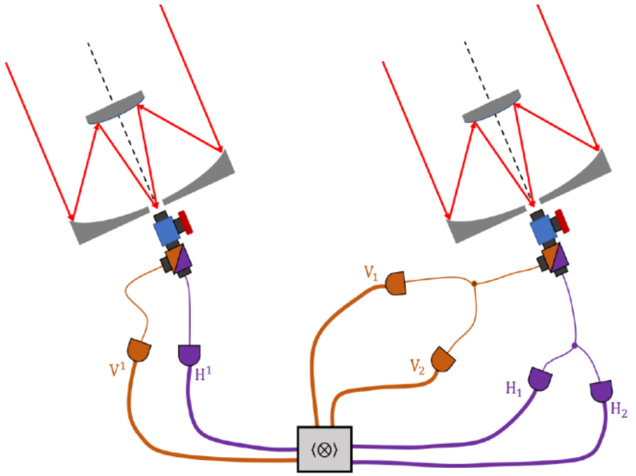
January 2020 : Spatial Correlation on H_{α} line of Rigel , Betelguese

Novel technical improvement :

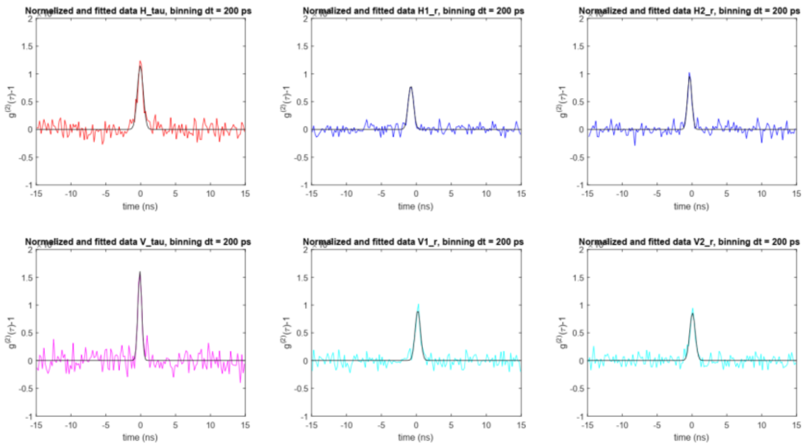
1) dual polarization channel

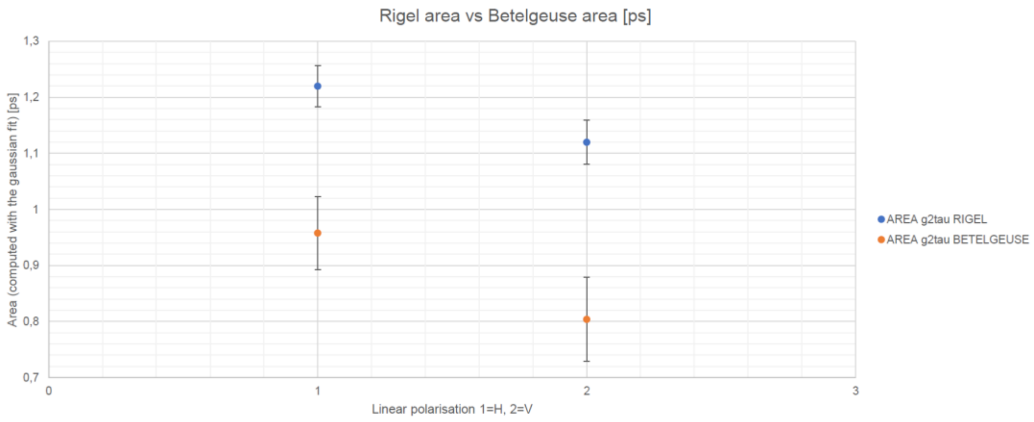
2) Auto calibrating setup : $g^{(2)}(0)$ + $g^{(2)}(r)$



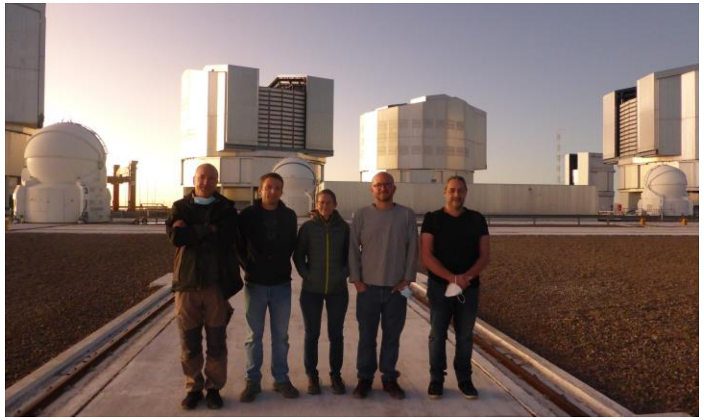


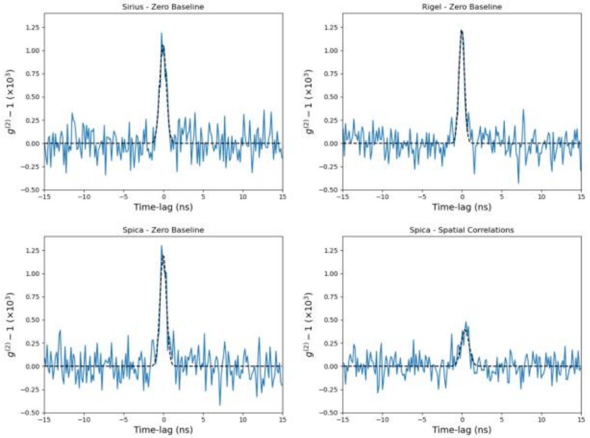
Rigel





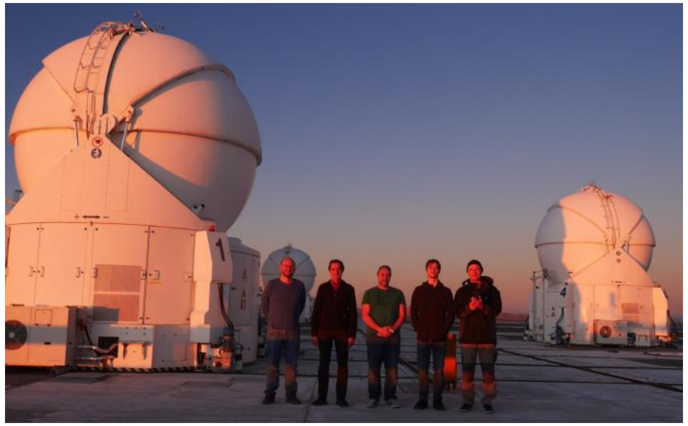
March 2022: Successful interferometric observation at Paranal (VLT)!

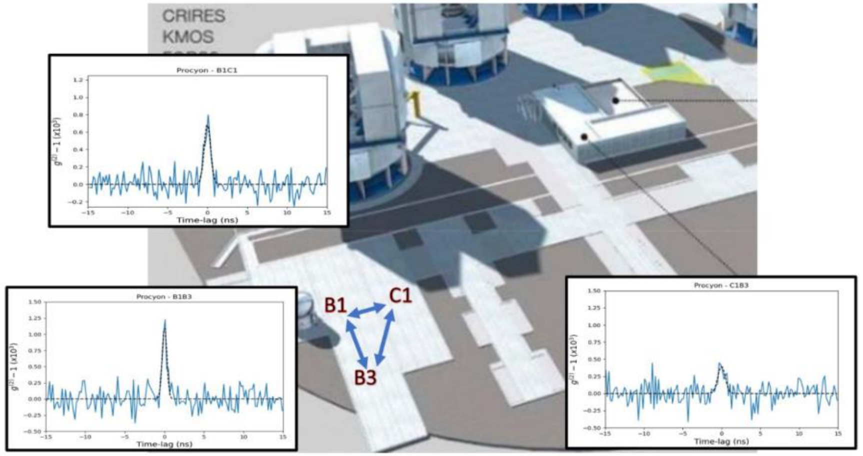




N. Matthews, J.-P. Rivet, M. Hugbart, G. Labeyrie, R. K., O. Lai, F. Vakili, D. Vernet, J. Chabe, C. Courde, N. Schuhler, P. Bourget, W. Guerin, Proc. SPIE 12183, Optical and Infrared Interferometry and Imaging VIII, 121830G (2022),

May 2023: Successful interferometric observation with 3 telescopes at Paranal!





Outline

1) Optical astrophysical imaging
and Hanbury Brown and Twiss experiments

2) 80’ : Intensity correlations for quantum physics

3) Renewal of intensity correlations for astrophysics

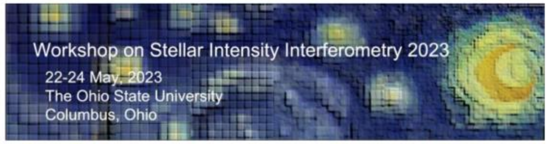
4) HBT revival @ Nice (2015-2024):
Laboratory intensity correlation experiments (2015/2016)
On-sky intensity correlations from 2017-2023

5) **State of the art of intensity interferometry in 2024**

6) IC4Star project in Nice

Growing community

Stellar Intensity Interferometry



Workshop Details | Registration | Accommodations | List of Participants | Agenda

Participants in the Workshop on Stellar Intensity Interferometry 2023

Stellar Intensity Interferometry

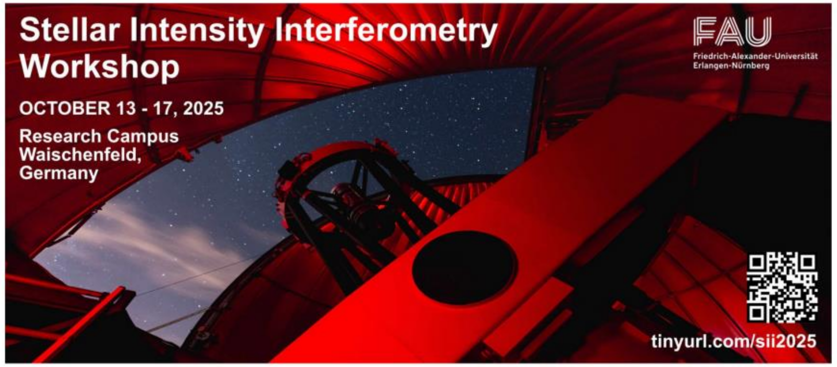
Workshop 2024

September 9th – 13th, 2024

Porquerolles, France

Stellar Intensity Interferometry Workshop 2025

13–17 oct. 2025
Research Campus Waischenfeld (Germany) of the Fraunhofer Society
Fuseau horaire Europe/Berlin



Recent advancements in photodetection technologies and spectroscopy hold the promise of transforming intensity interferometry, thereby revolutionizing observational Astronomy by enabling observations to resolve significantly fainter objects than currently possible. This workshop serves as a platform to unite experts in photodetection, theoretical and observational astronomy, as well as observers and theorists from diverse disciplines, to explore the multifaceted capabilities of intensity interferometry.

The workshop's focus spans three key objectives:

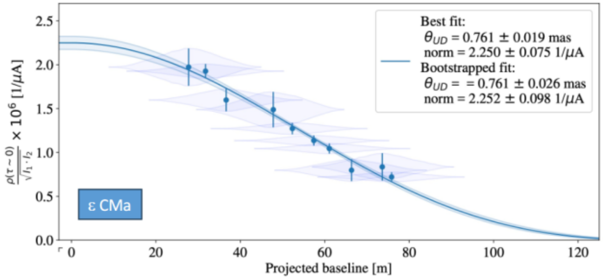
- Develop and disseminate novel ideas concerning science cases unique to intensity interferometry.
- Synthesize insights from observers and photodetector experts concerning the requisite technologies and experimental techniques which will allow for new science with intensity interferometry.
- Initiate a concentrated effort to propel the development of large telescope arrays dedicated to intensity interferometry.

This workshop will be exclusively organized in plenary sessions, providing ample time for engaging discussions among participants.

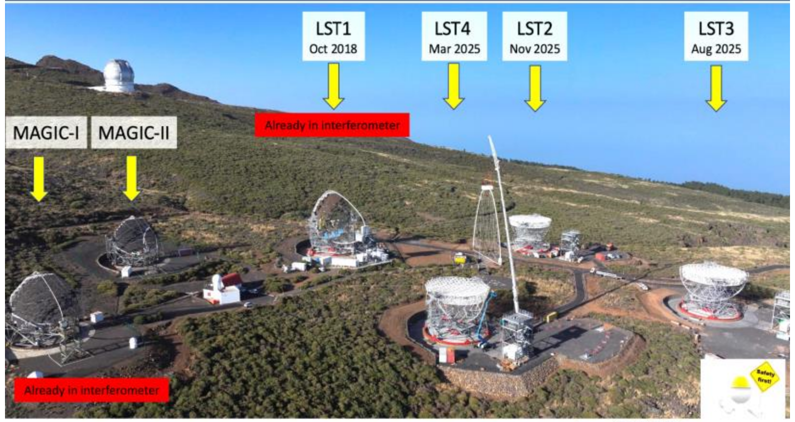
Juan Cortina & **Alejo Cifuentes**: *Intensity interferometry observations with MAGIC and the CTAO-North LSTs*

First science results with MAGIC

"Performance and first measurements of the MAGIC Stellar Intensity Interferometer", arXiv:2402.04755 and MNRAS 11 March 2024

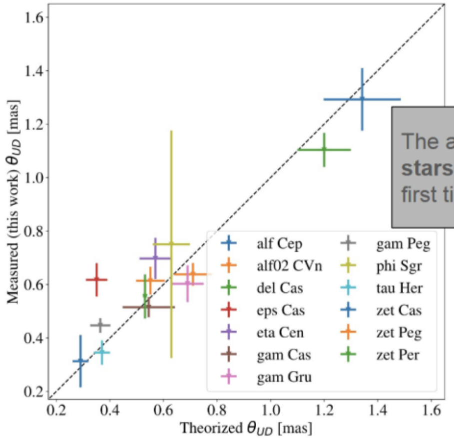


Ongoing deployment of the LSTs in La Palma

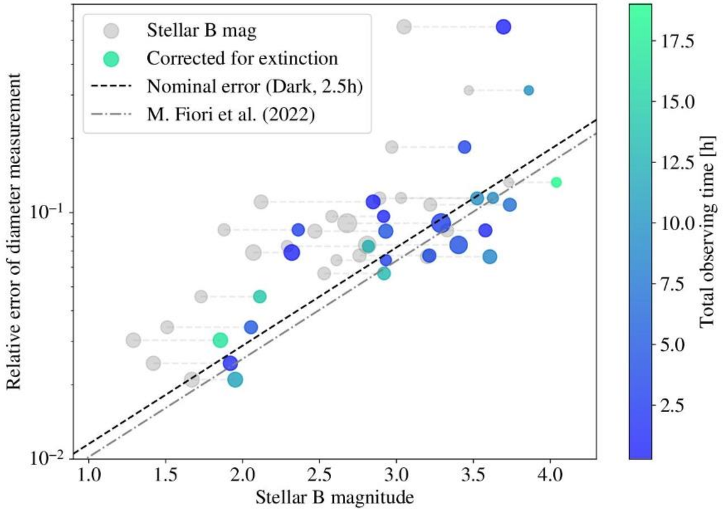


August 22nd, 2024

MAGIC SII: New measurements

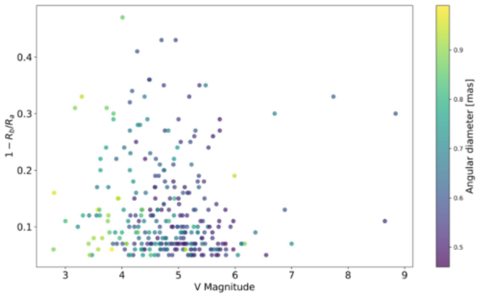


The angular diameter of **13 stars** was measured for the first time in the **B band**.



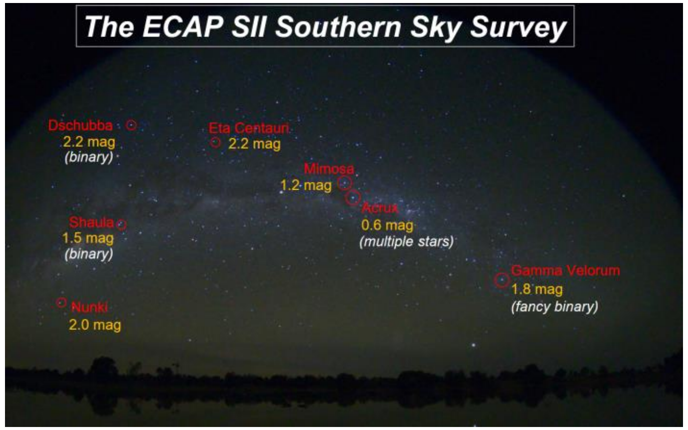
Science with MAGIC + 4LSTs SII: Fast rotators

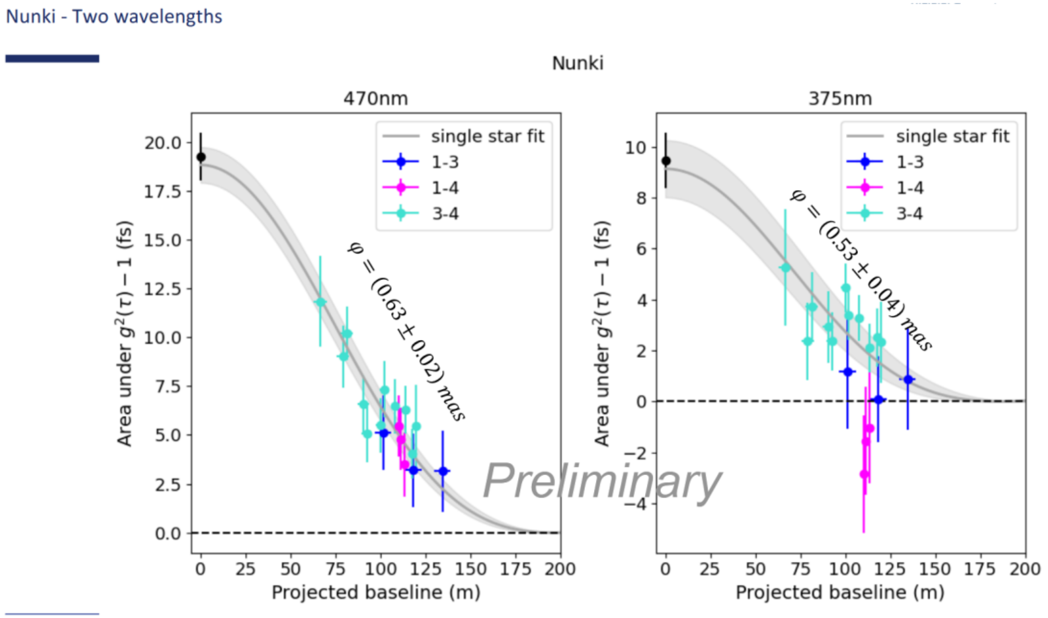
Targets identified by van Belle, Astron. Astrop. Rev 20 (2012) 51



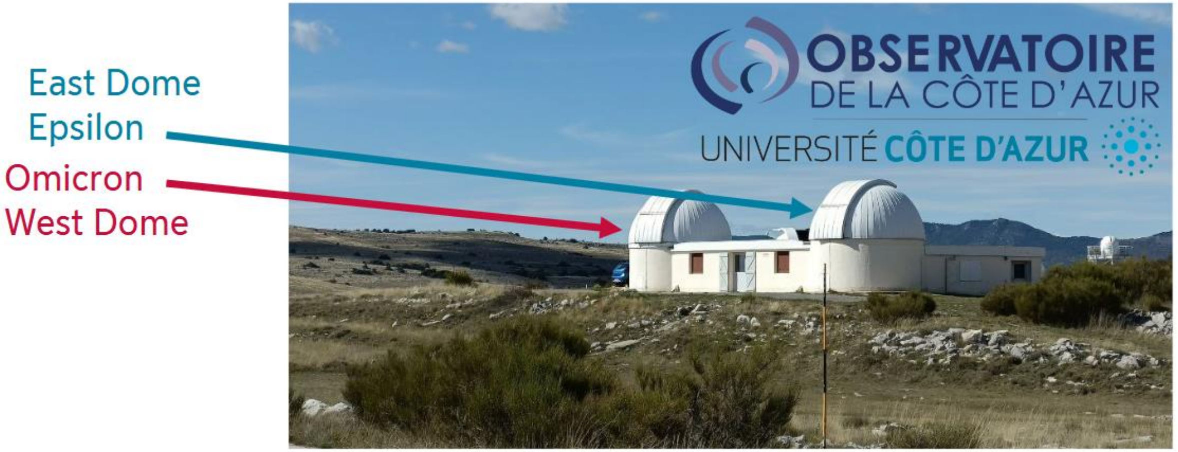
Multiple targets within reach of MAGIC + LST-1, most targets within reach of MAGIC + 4LSTs.

Andreas Zmija & Naomi Vogel: *Intensity Interferometry with the H.E.S.S. telescopes*

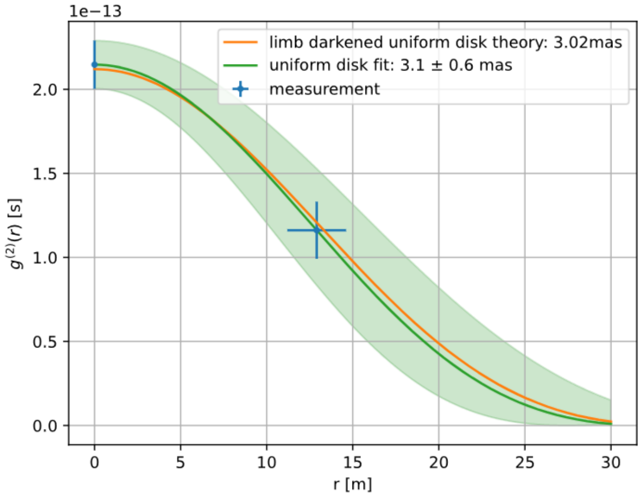




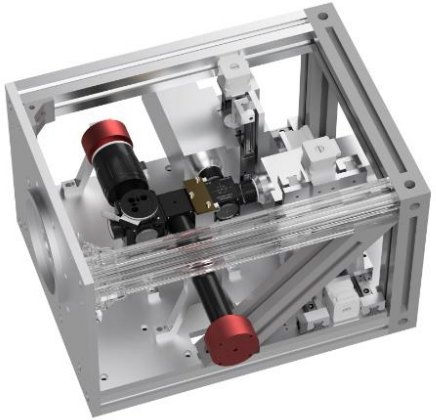
Sebastian Karl & Verena Leopold: *Spatial photon correlati using nearly dead time free ultra-high throughput single p detection*

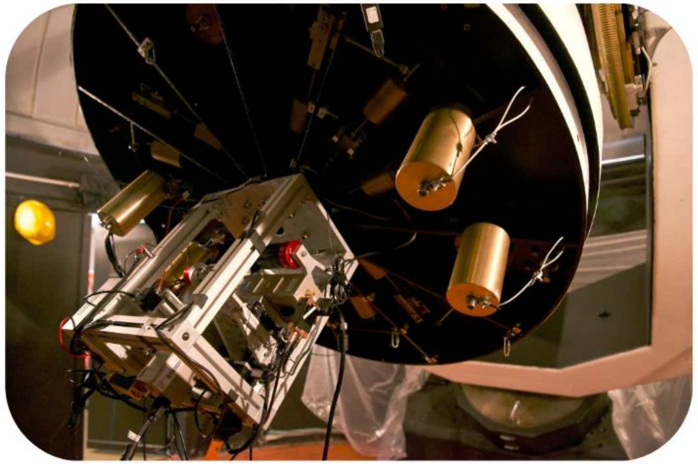


Visibility curve for Vega

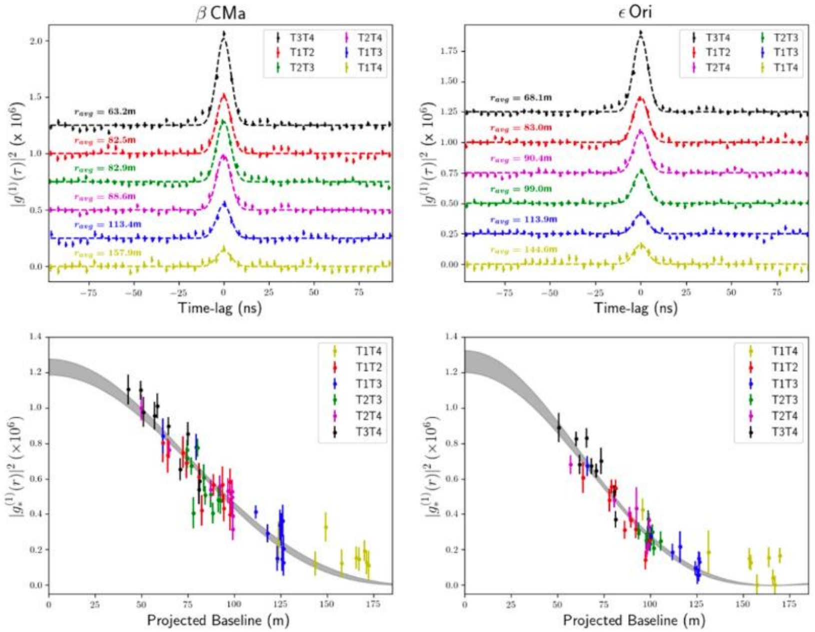


Measurement Setup



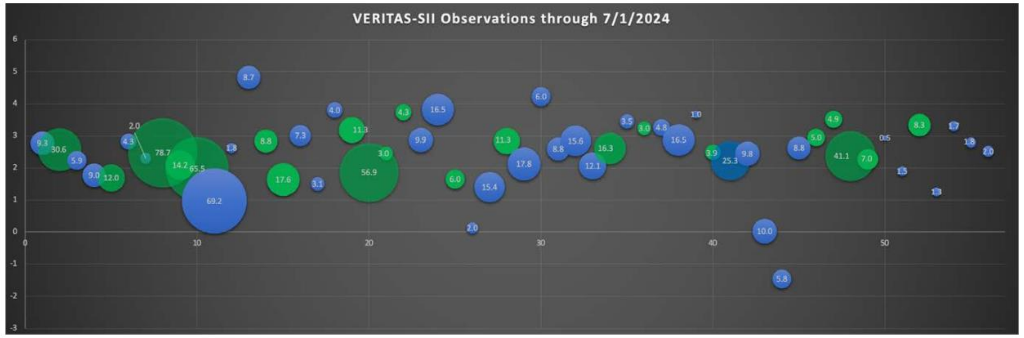


Dave Kieda & Josie Rose: *The VERITAS SII Observatory*



VSII Observations (Jul 1, 2024)

m_V



Primary star classification: O9 O9.5 B0 B0.5 B1 B2 B3 B7 B8 B9 A0 A1 A2 A8

Single star

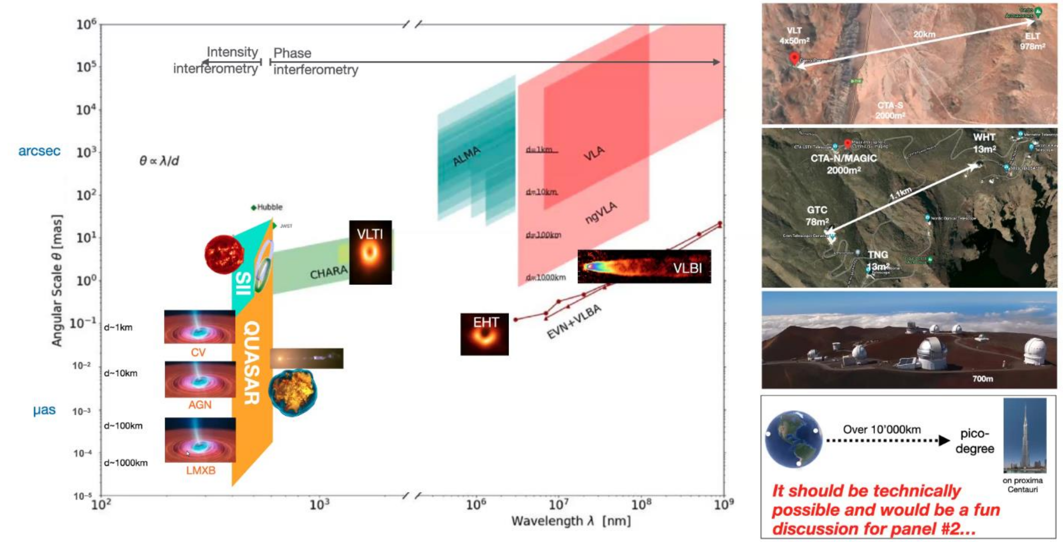
Binary/multiple star

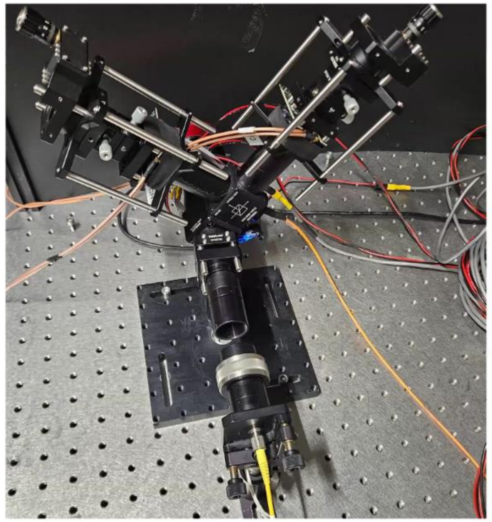
Circle area is the number of each star's exposure (hrs) (12/1/19 – 7/1/24)

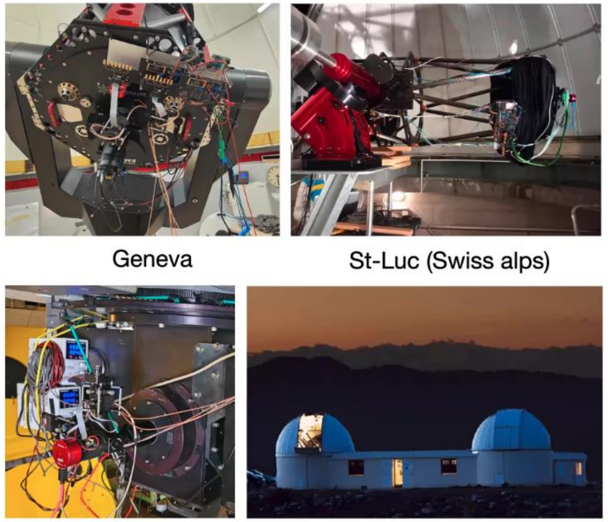
- 56 different targets
- 33 single
- 23 binary/multiple
- Total 732.3 hrs exposure
- 125.8 hours 2023-2024 obs season

Roland Walter, Etienne Lyard, Vitalii Sliusar & Gilles Koziol: *The QUASAR project: Resolving Accretion Disks with Quantum Optics*

In the optical, a baseline of 4km provides the same resolution as the EHT

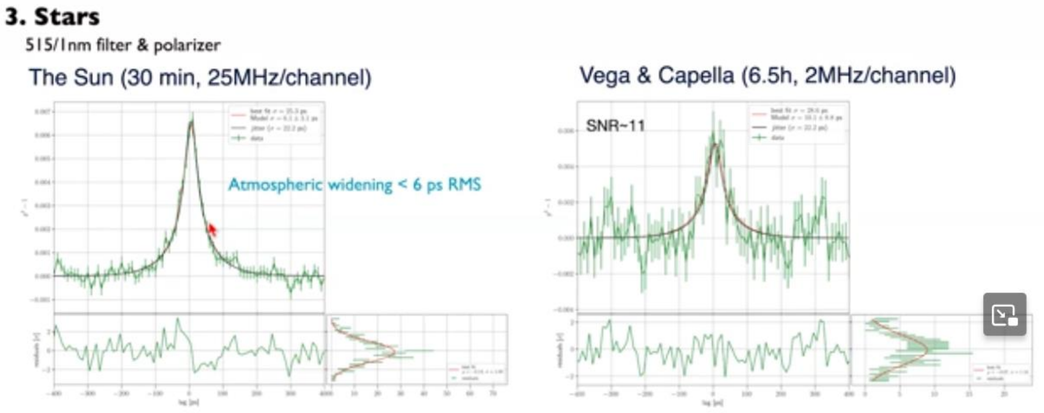






Geneva St-Luc (Swiss alps)

Skinakas (Crete) C2PU Calern (France)

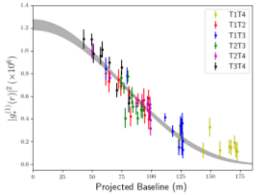


The jitter at the telescope was 22ps rather than 12ps because of a wrong setting of the voltage

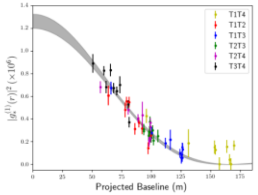
State of the art in 2024

- Demonstration of stellar intensity interferometry with the four VERITAS telescopes,
  A. Abeysekara, et al., Nat, Astronomy 4, 1164 (2020)

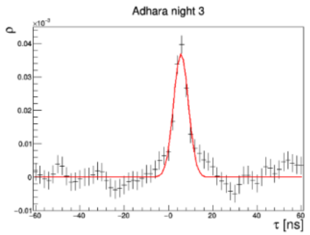
β Canis Majoris



ε Orionis



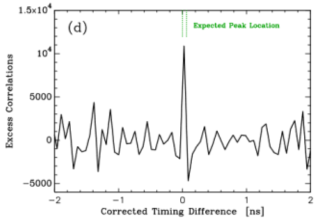
λ=416nm



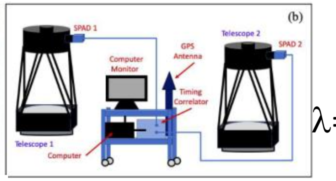
- V. Acciari, et al., Optical intensity interferometry observations using the MAGIC imaging atmospheric cherenkov telescopes, MNRAS 491, 1540 (2020)

λ=430nm, 3 stars, 2 telescopes (diameter 17m)

- L. Zampieri et al., Stellar intensity interferometry of Vega in photon counting mode, MNRAS, 506(2), 1585(2021). ASIAGO



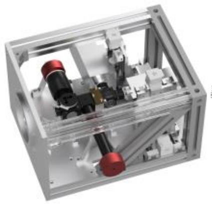
- Observations with the Southern Connecticut Stellar Interferometer. I. Instrument Description and First Results
  E. P. Horch et al 2022 AJ 163 92

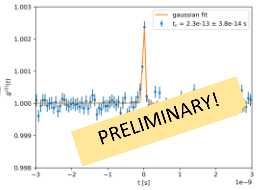


λ=532nm, 3 stars, 2 telescopes (diameter 0.6m)

+ Hess Namibia (S. Funk et al.) : 2023

+ Erlangen +C2PU (J. v. Zanthier et al.) : 2024





Courtesy S.Richter et al.

λ=405nm

+ Zurich + Crete / C2PU (R. Walter et al.) :2024

Outline

1) Optical astrophysical imaging
and Hanbury Brown and Twiss experiments

2) 80' : Intensity correlations for quantum physics

3) Renewal of intensity correlations for astrophysics

4) HBT revival @ Nice (2015-2024):
Laboratory intensity correlation experiments (2015/2016)
On-sky intensity correlations from 2017-2023

5) State of the art of intensity interferometry in 2024

6) **IC4Star project in Nice**

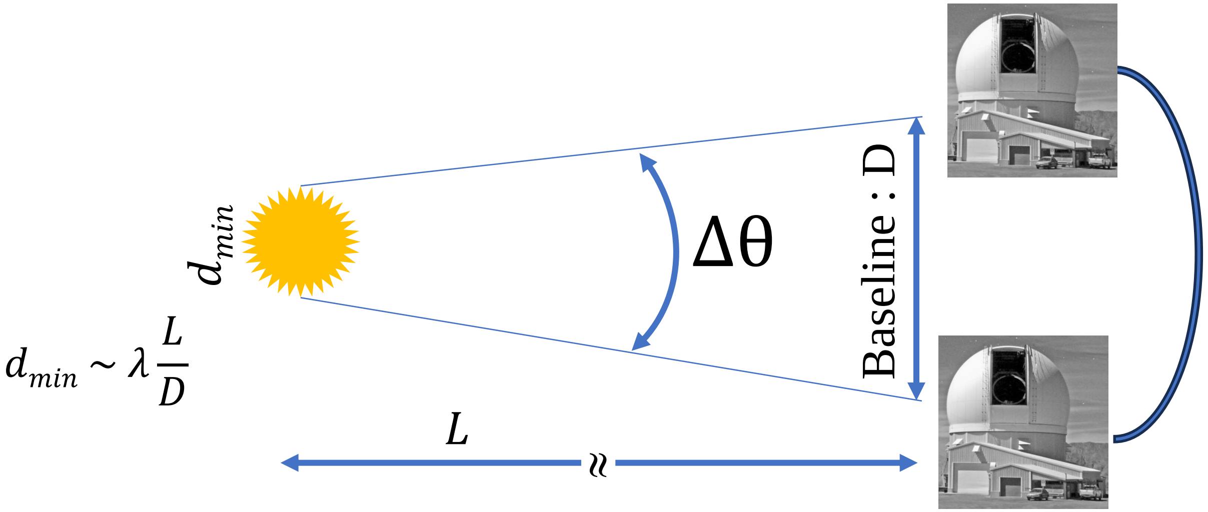
Outline

IC4Star project :

1) **High angular resolution : white dwarf Sirius B**
2) **Quantum optics from space : only single telescope required**

What next : IC4Stars

High angular resolution for stars : $\Delta\theta \sim \frac{\lambda}{D}$



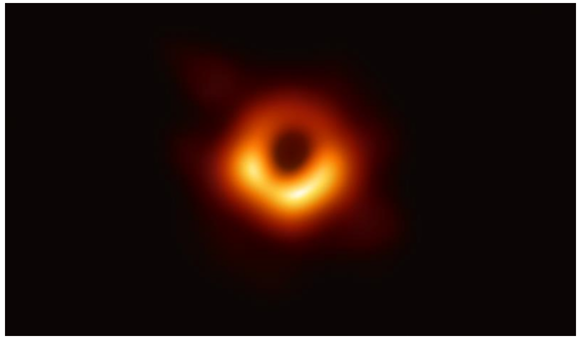
i. interferometric recombination
(VLTI, Chara, NPOI < 300m)

ii. intensity correlations $g^2(r)$
Hanbury Brown & Twiss

- 👍 Resilient to atmospheric turbulence (+ no adaptative optics required)
- 👍 Scalable to larger distances (ELT/VLT and beyond)
- 👍 Use of existing infrastructure
- 👍 **μ″ resolution** : similar to Event Horizon Telescope

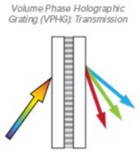
$\lambda \sim 420nm, D \sim km$

$\lambda \sim mm$
D=12000 km



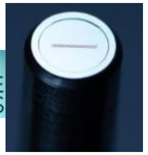
- The price to pay : low signal to noise ratio

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



Wasatch Photonics

BERKSHIRE PHOTONICS



Multiplexing
N=16

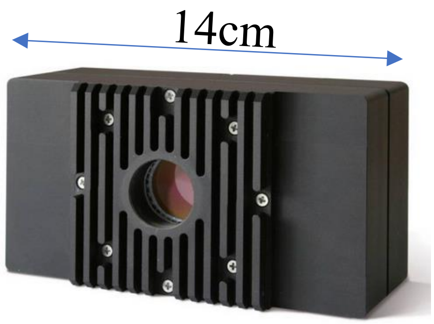
Keck/CFHT
10m/4m

Fast SPD
τ_{el}=20ps

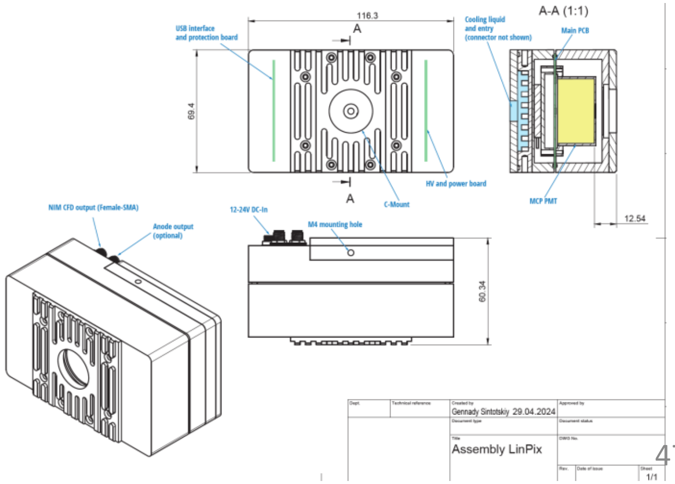
$$SNR : \quad \times\ 4 \quad \times 40 \quad\quad \times\ 4 \ \Rightarrow\ \times 640$$

$$T_{obs} \quad \div\, 400\,000$$

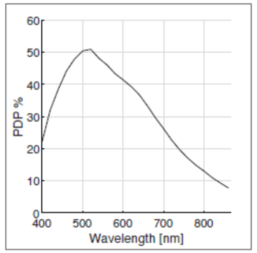
Photonscore : 2 x 16 LINPix



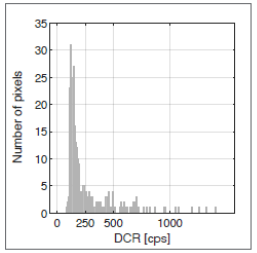
Max. recommended count rate, MHz	100
Shutdown count rate, MHz	110
Discrimination	Integrated CFD
Dark count rate, Hz	< 15 (Blue, Aqua), < 50 (Green), < 200 (Red)
Timing jitter, ps (FWHM)	< 35 (1MHz), < 45 (10MHz), < 75ps (100MHz)
Active area, mm	Ø8
Dead time, ns	< 2



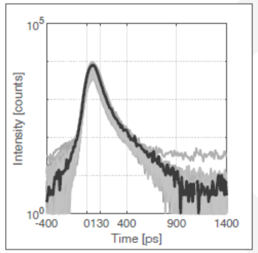
Pi Imaging : 2 SPADλ



Photon detection probability.



Typical distribution of dark count rate over the SPAD array.



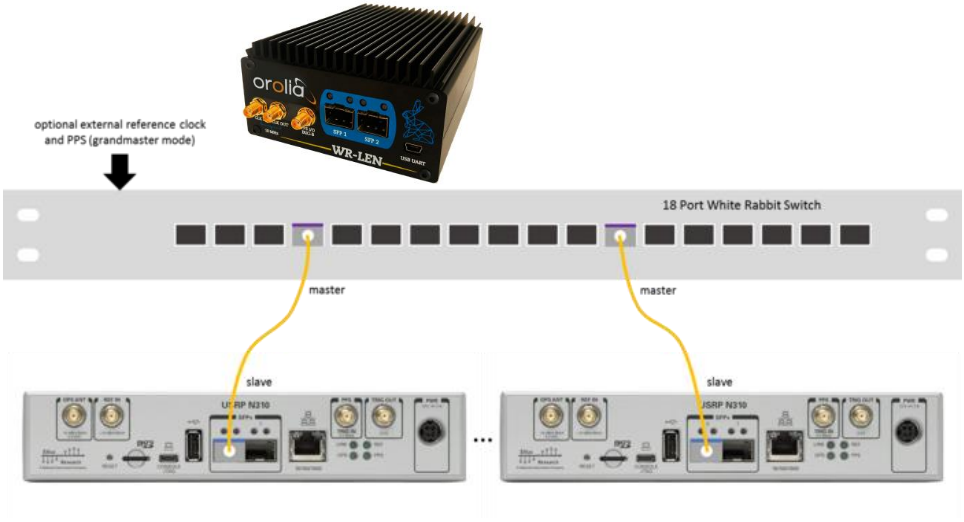
Timing jitter over all the pixels, with an average of 130 ps FWHM.

Typical technical specifications

SENSOR	LINEAR SPAD ARRAY
Image array	320 × 1
Pixel pitch	29 µm
Sensor wavelength range	400 to 900 nm
Peak photon detection probability	50% @ 520 nm
Fill factor with microlenses	>80 % for collimated light
Median dark count rate at room temperature	<250 cps
Percentage of pixels with >10 kcps	5%
Frame rate (max.)	555'000 fps
Dead time	10 ns
Timing jitter	130 ps FWHM
Time-tagging resolution	20 ps
Minimum exposure/gate width	2 ns
Minimum exposure/gate shift	17 ps
Crosstalk	2%
Connection type	C-mount

Synchronisation @ ps over 1km

1)



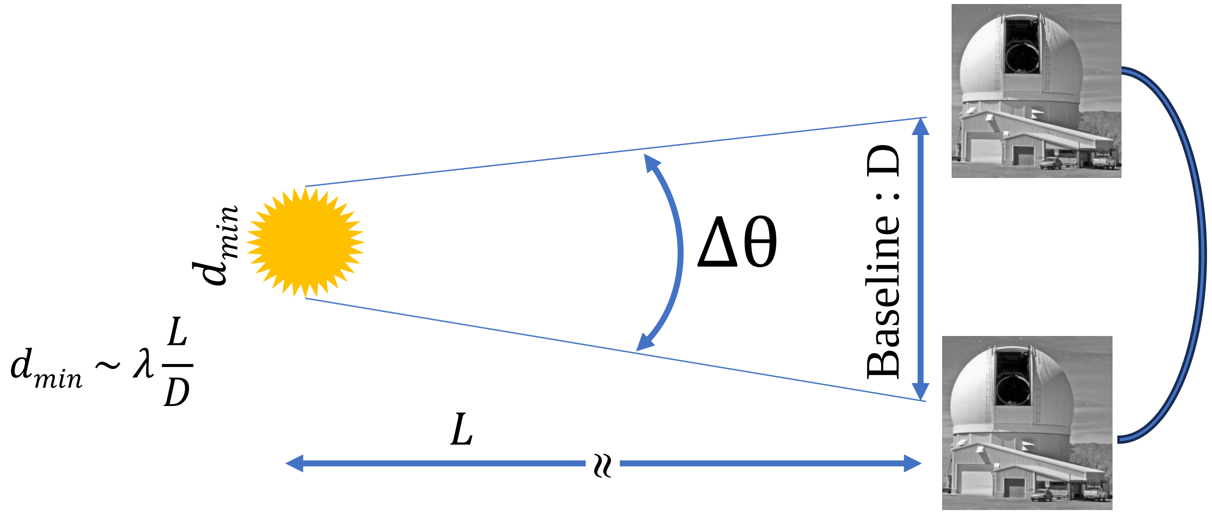
16 ps

2)

	Synchro White Rabbit Orolia COTS	Datation Swabian		Custom Sigmaworks Datation et Synchro
RMS timing PPS	< 40ps	42ps (100ps Test Géoazur)		< 1ps
RMS timing 10 MHz	15ps			< 1ps
Stabilité @ 1s	10ps	X		< 1ps
Stabilité @ long terme	20-45ps ?	X		<30fs
Cadence		70 Mhz		Min: 5 Mhz
Remarque				USB3
Canaux				2 x 16 canaux différentiel ou single ended
Coûts	~25k€ (5 switch)	80 k€ ?		~200k€
Développement	OTS	OTS		2 ans

1 ps

Geodesy : mm precision



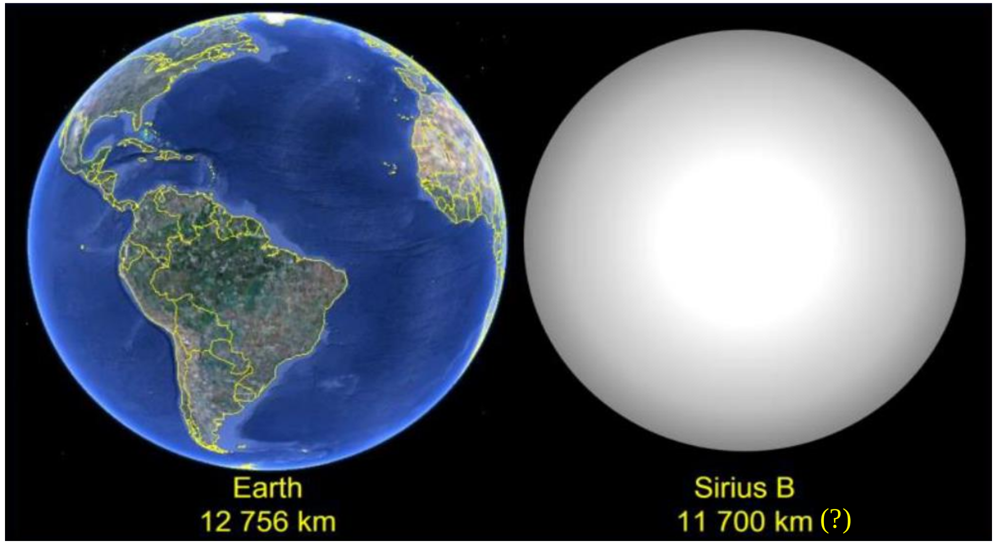
HBT interferometry resilient to atmospheric turbulence

… up to some point:

coherence time : δτ ~ jitter ~ 10ps
coherence length ~ c δτ ~ 3mm

Where are the telescopes ??? With mm precision ?
Requires geodesy of relative focal positions ?

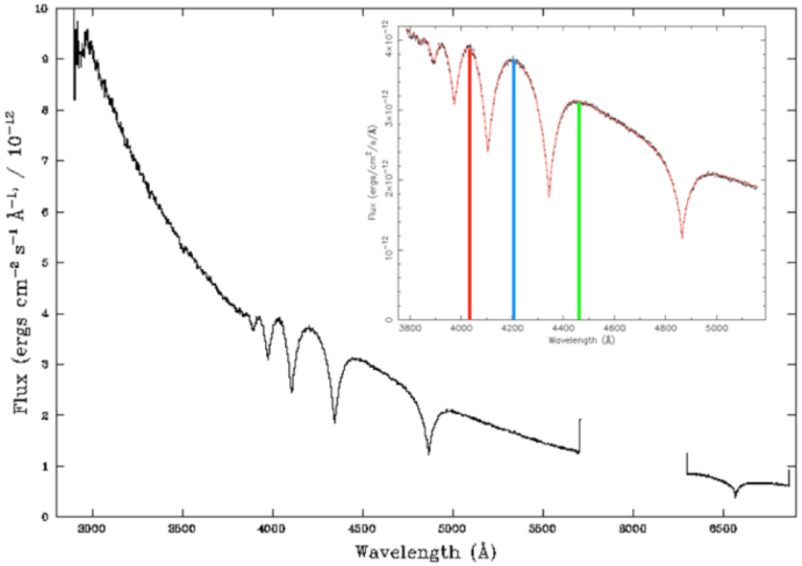
Angular resolution of a white dwarf



Count rates :
Sirius B
Quantum efficiency : 90%
Throughput : 20%

Keck: 110 000 cps
CHFT : 18 000 cps

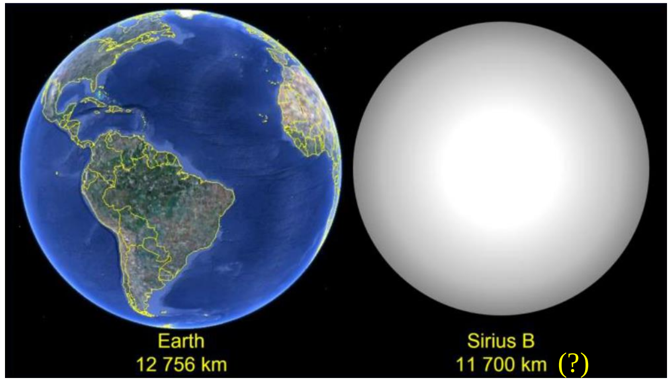
D=11700km
L=8.6 light years= 8 10^16m
Δθ=30μ″



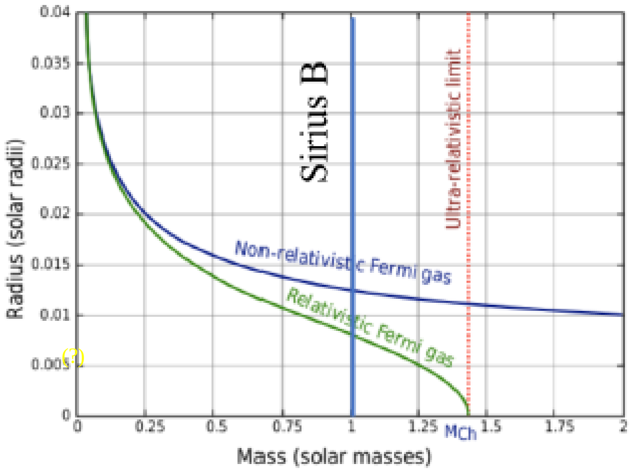
Path-opening on **Sirius B** (white dwarf) : quantum degenerate Fermi gas of electrons

SNR ≈ 6
in 1 hour
observation time !!!!

Beyond reach of present instruments



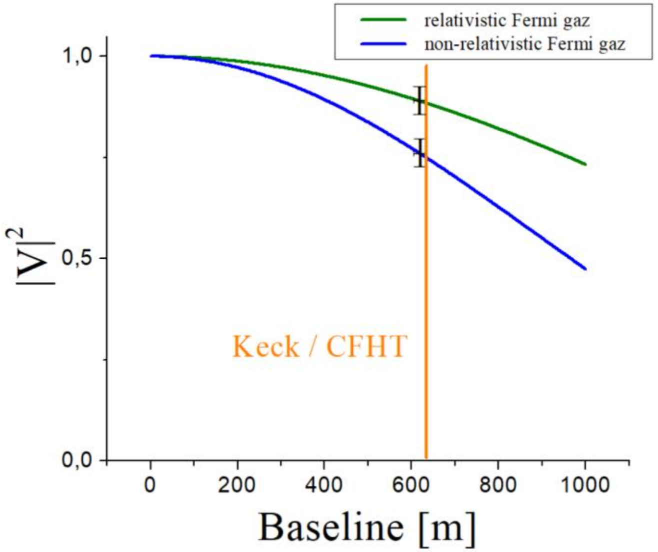
Magnitude=8.4



Mauna Kea @ Hawaii

Photon Bunching

- **@ λ = 420nm**
- **D=630m**



Exciting targets for ultrahigh angular resolution in astrophysics :

- Wolf Rayet Stars
  (before Supernovae type II explosion)

WR 124

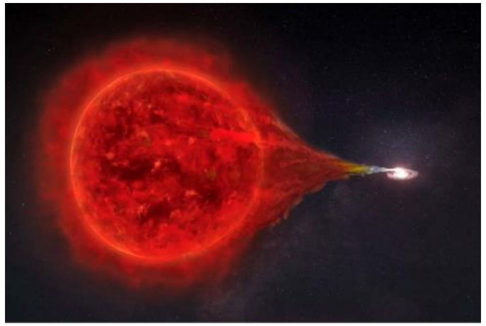
M12 / 20 μ″

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 187:275–373, 2010 April doi:10.1088/0067-0049/187/2/275

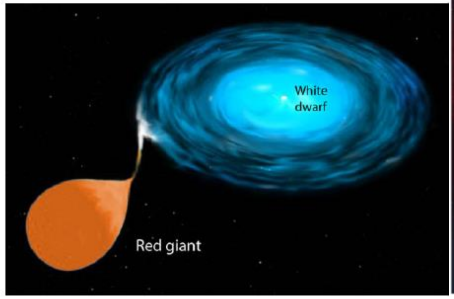
COMPREHENSIVE PHOTOMETRIC HISTORIES OF ALL KNOWN GALACTIC RECURRENT NOVAE

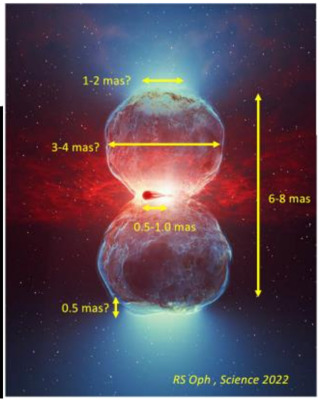
BRADLEY E. SCHAEFER
Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA; schaefer@lsu.edu
Received 2009 April 6; accepted 2010 January 20; published 2010 March 17

- Binary White Dwarfs
  (before Supernovae type I explosion)



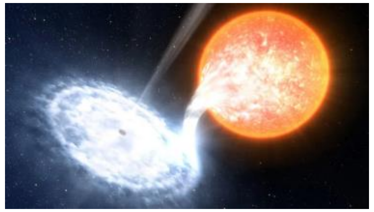
T Cor Bor: recurrent nova?
M10



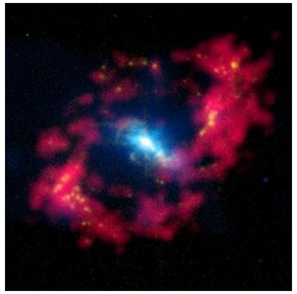


0.55-0.9 mas

- Black hole accretion disks

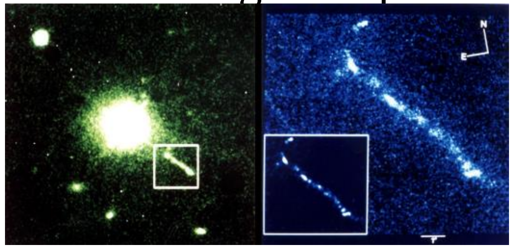


NGC4151



M11.5 / 100 μ″

3C 273 brightest quasar



(supermassive black hole)
M12.9

Outline

IC4Star project :

1) **High angular resolution : white dwarf Sirius B**
2) **Quantum optics from space : only single telescope required**

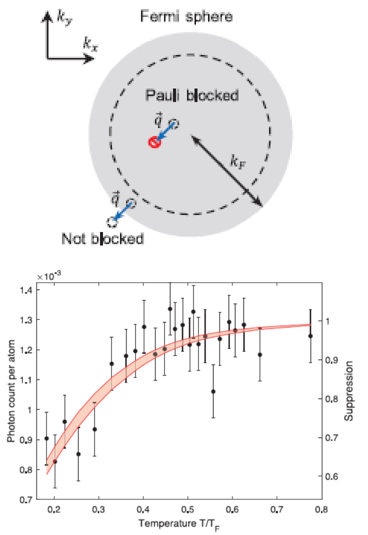
Pauli blocking for in degenerate Fermi gases

QUANTUM GASES

Pauli blocking of light scattering in degenerate fermions

Yair Margalit[1,2]*, Yu-Kun Lu[1,2], Furkan Çağrı Top[1,2], Wolfgang Ketterle[1,2]

Margalit *et al.*, *Science* **374**, 976–979 (2021)

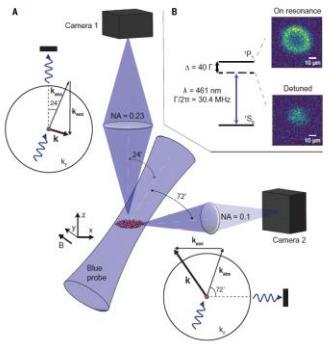


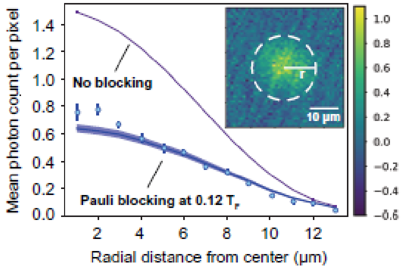
QUANTUM GASES

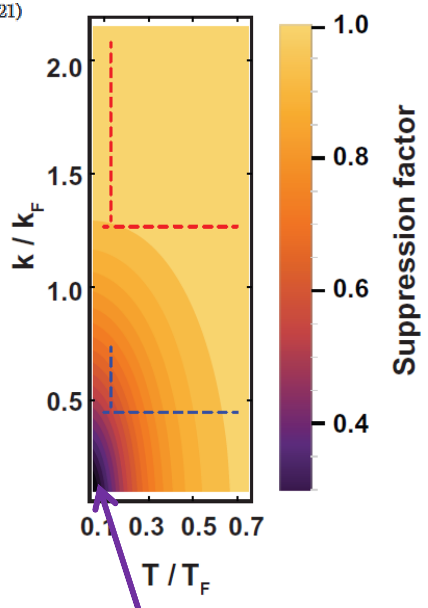
Pauli blocking of atom-light scattering

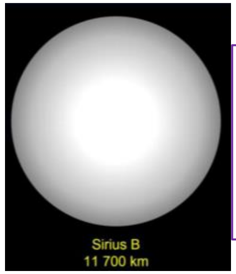
Christian Sanner*†, Lindsay Sonderhouse†, Ross B. Hutson, Lingfeng Yan, William R. Milner, Jun Ye*

Sanner *et al.*, *Science* **374**, 979–983 (2021)









White dwarf :
$T/T_f \sim 10^{-6}$
$k/k_f \sim 10^{-6}$

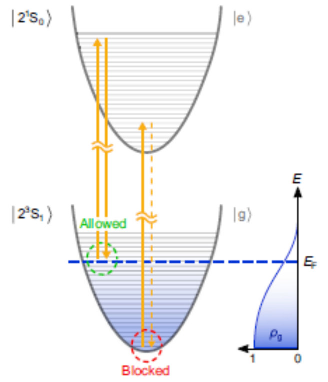
nature communications

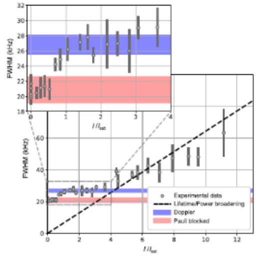
Article https://doi.org/10.1038/s41467-022-34135-6

Pauli blocking of stimulated emission in a degenerate Fermi gas

Received: 24 March 2022
Accepted: 14 October 2022

Raphael Jannin, Yuri van der Werf, Kees Steinebach, Hendrick L. Bethlem[1,2] & Kjeld S. E. Eikema[1,2]



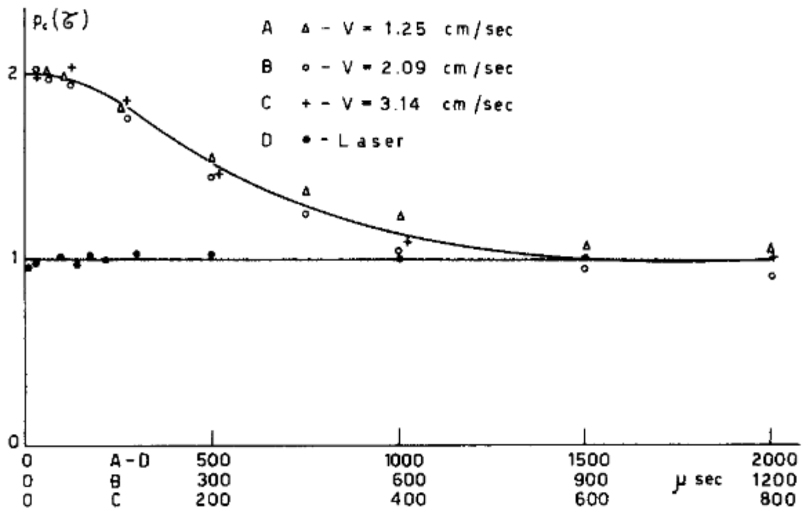


Light we see from Sirius B only from an outer shell of 100-300m

Second order coherence $\neq$ first order coherence

Poisson statistics of laser => $g^{(2)}(\tau=0)=1$

Thermal light => $g^{(2)}(\tau=0)=2$

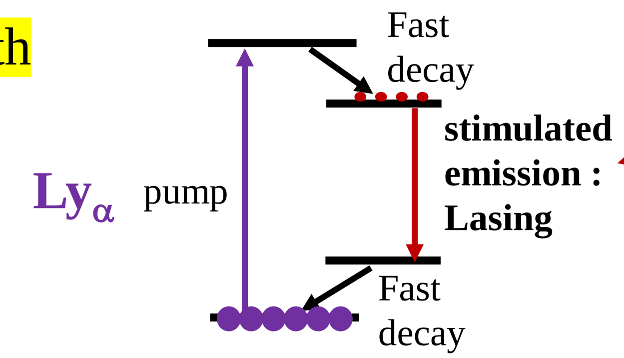


F.T. Arecchi, E. Gatti, A. Sona, Phys. Lett. 20, 27 (1966)

Quantum theory : R. Glauber

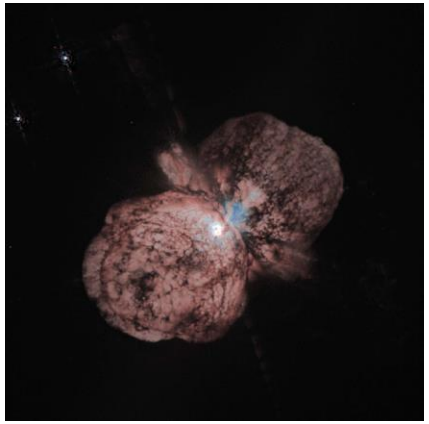
Bonus : quantum astro-optics : coherent light sources

- Random laser with 4 level scheme

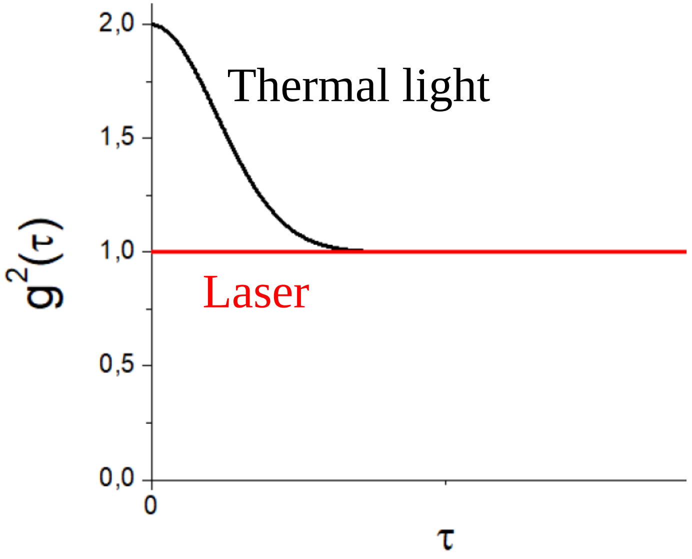


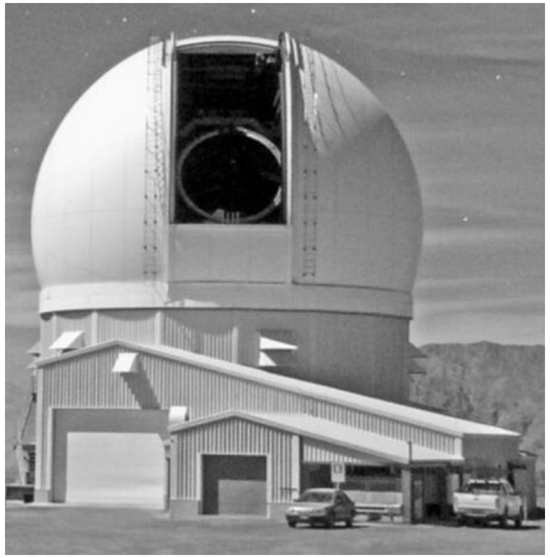
Fe II:
population inversion at 0.99 / 1.6 /1.7 µm

Eta Car



- Lasing signature : **$g^2(\tau)$** on a **single** telescope



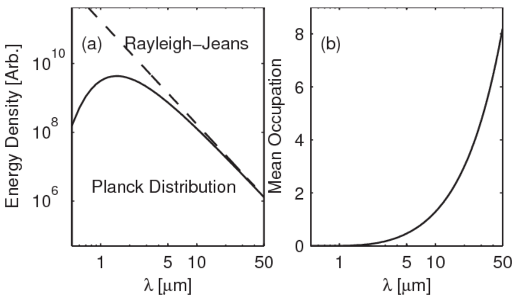


SOAR
(Chile, southern hemisphere)

Photon statistics

Planck law (Bose-Einstein statistics at zero chemical potential)

$$\langle N_\nu \rangle = \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$



T=2500K

Intensity correlations modified for hot stars / low energy photons

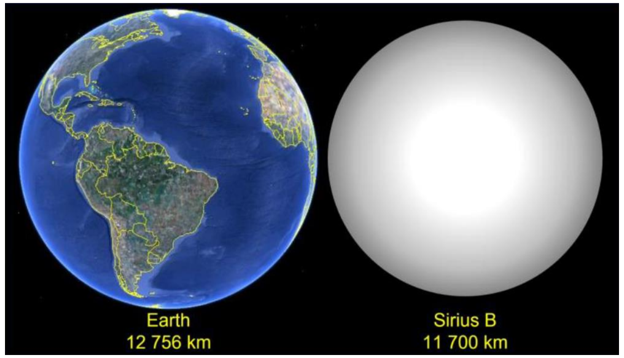
- T= 40000K (Sirius B) : λ = 359 nm
- T= 90000K (γ Vel) : λ = 159 nm

Nevertheless, the small departures from strict Poisson statistics can lead to important observable effects, as we shall see in Chapter 14. Of course, the situation changes at sufficiently high temperatures, when $\langle n_{\mathbf{k}s} \rangle$ becomes proportional to T, as can be seen from Eq. (13.1–8). However, extraordinarily high temperatures, such as those encountered in thermonuclear fusion reactions, are needed before the optical photon occupation numbers become large. The number $\langle n_{\mathbf{k}s} \rangle$ is still only of order unity at optical wavelengths at a temperature of about 30 000 K.

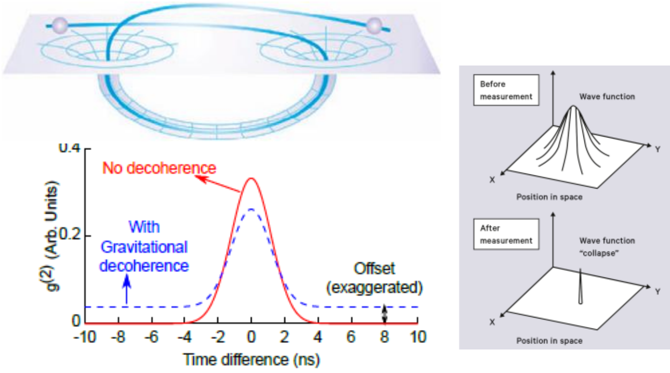
Mandel&Wolf, 1995

Beyond IC4Stars

- **Ultra-high angular resolution in astrophysics : $g^2(r)$**



- **Quantum eye on astrophysics : $g^2(\tau)$**



New J. Phys. 20, 063016 (2018)

+ Gravitational background wave detection ?

+ Pauli blocking in degenerate Fermi gases

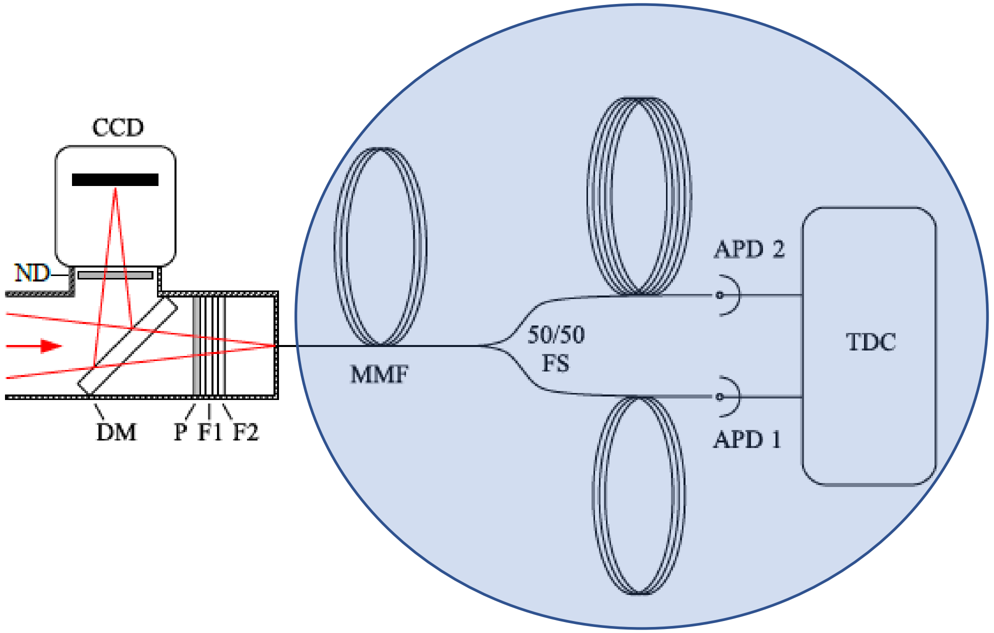

Thank you for your attention
Open positions (PhD, postdoc)

50/50 FS: Multimode fiber beamsplitter

To overcome the APD dead time

APD: Single photon detector

Excelitas
Quantum efficiency $\eta \sim 60$ %
Deadtime ~ 20 ns
Jitter $\tau_J \sim 500$ ps



TDC: Time to Digital Convertor

#1: ID Quantique, time resolution = 81 ps

#2: Swabian Instruments, time resolution = 12 ps, less spurious correlations, 40 Mcps