Intensity correlations: imaging and quantum optics in astrophysics

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Future Prospects of Intensity Interferometry
October 30th – November 1st 2024
Perimeter Institute for Theoretical Physics

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**

Intensity Correlation team in Nice

INPHYNI


R.K.


W. Guerin


M. Hugbart


G. Labeyrie


S. Tolila

+ former postdocs and PhD :
A. Siciak
A. Dussaux
N. Matthews

Lagrange


F.Vakili


J.P. Rivet


O. Lai


C. Courde


J. Chabé


+ E. S. G. de Almeida
(Valparaíso, Chile)

+ M. Borges
(Rio de Janeiro, Brazil)


+ C. Pfeiffer (Bremen, Germany)

+ D. Rätzel (Bremen, Germany)

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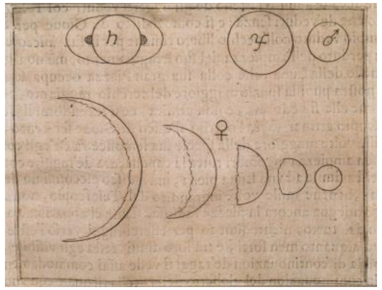
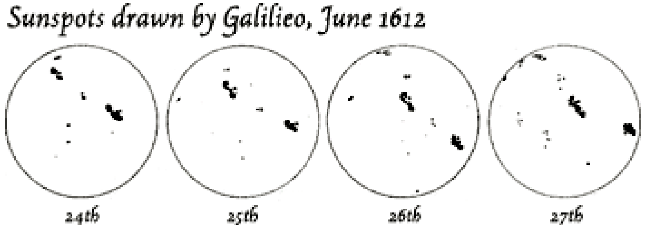
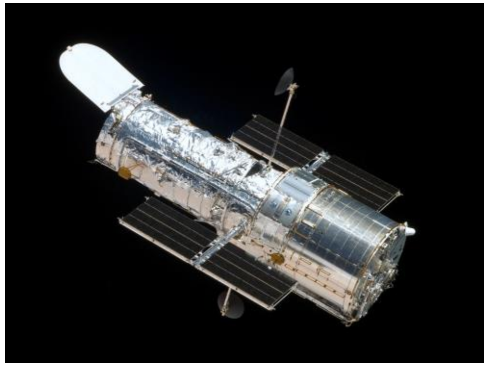
From Galileo (1564-1642) to Hubble Telescope (1990-2026?) & JWST

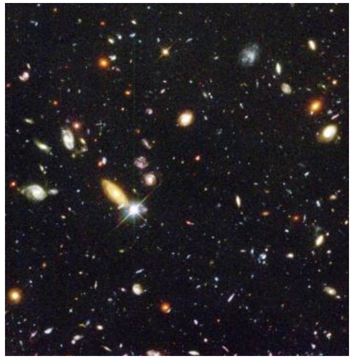
Direct imaging : large telescopes

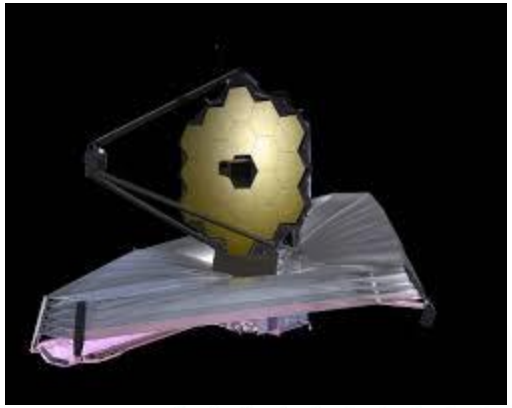


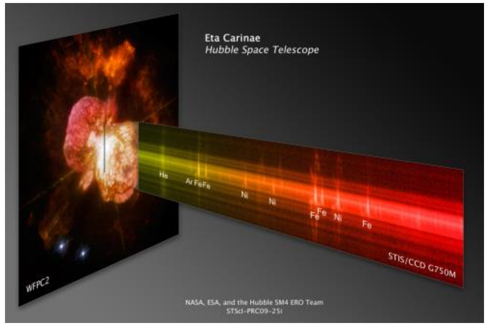
Phases of Venus

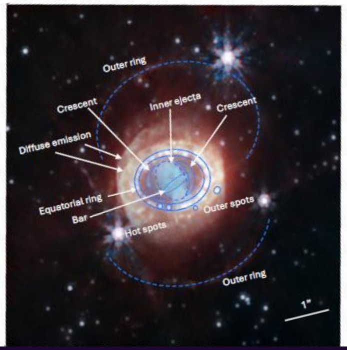




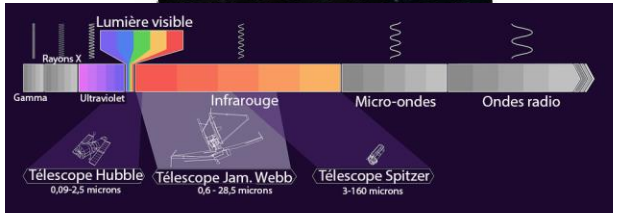








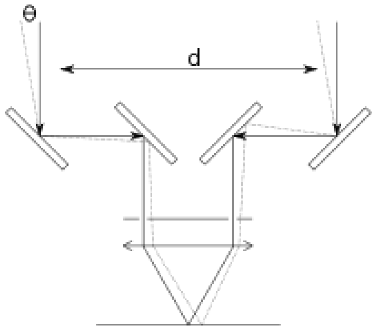
Eta Carinae



Black holes, dark matter,

universe expansion…

Interferometric imaging: large separation



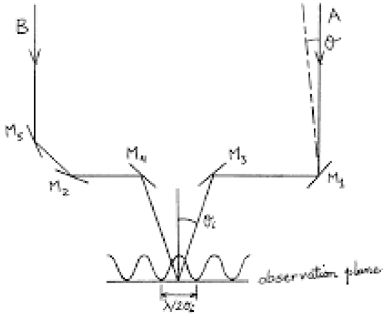
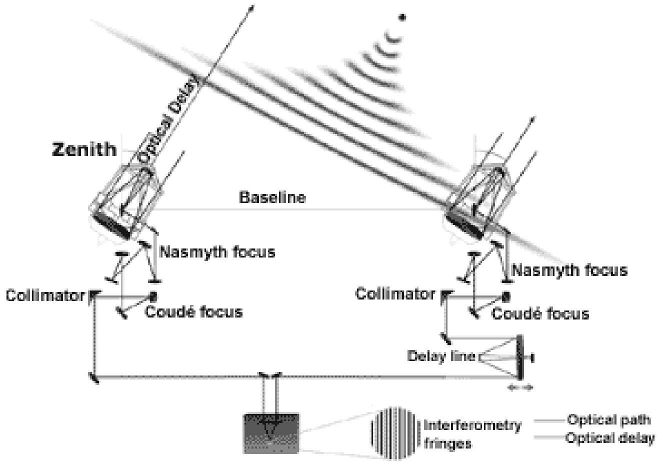
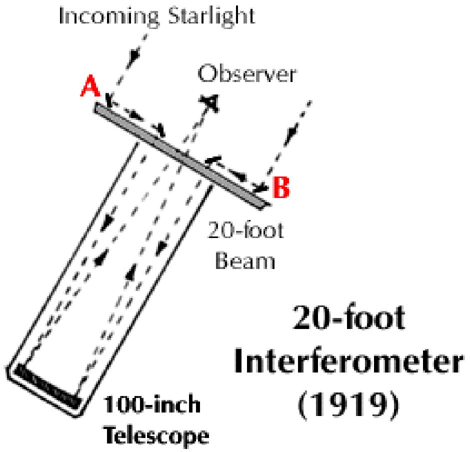
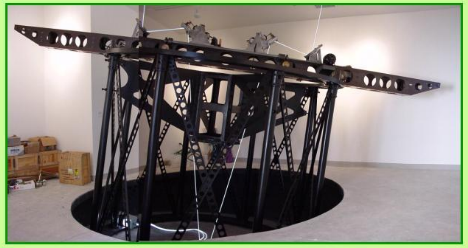


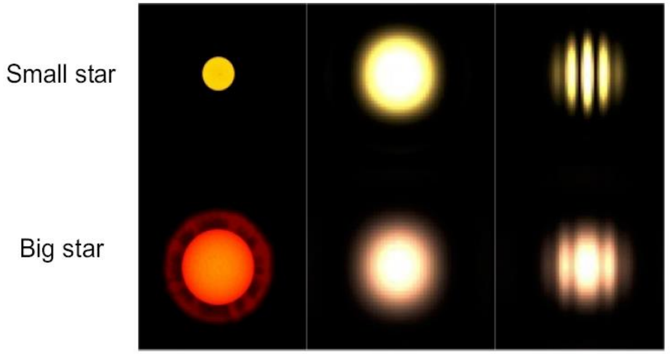
Fig. 3. Inverted Shear Interferometer
Period of fringes varies with σ





Michelson's 20-ft Interferometer





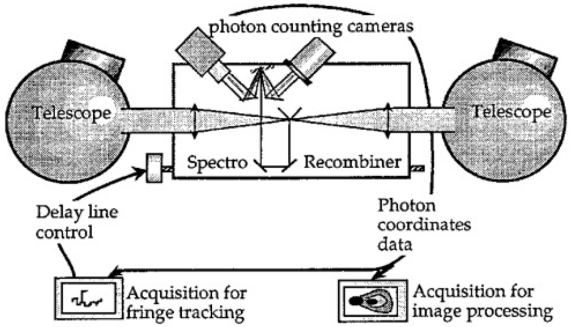
Objects Single Telescope Interf. Fringes

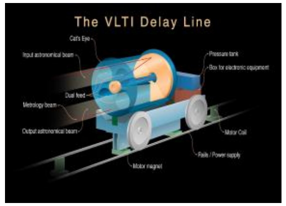
$I_{im}(\alpha) \sim \mathcal{F}(D)$ $I_{im}(\alpha) \sim \mathcal{F}(B)$

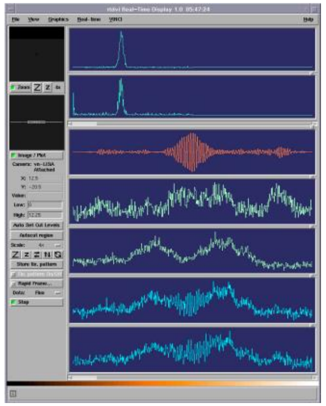
Angular Resolution: $\sim \lambda/D$ $\sim \lambda/B$

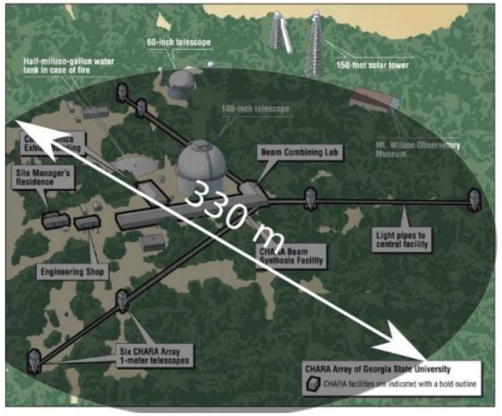
Interferometric imaging: large separation

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



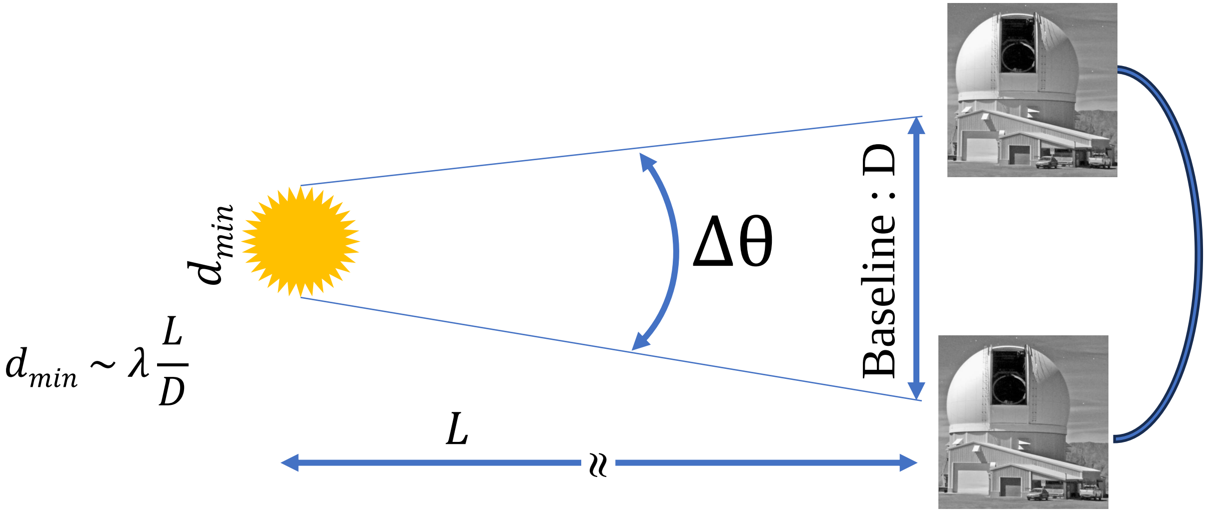






Calern (France)　　Paranal (Chili)　　Mt Wilson (USA)

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

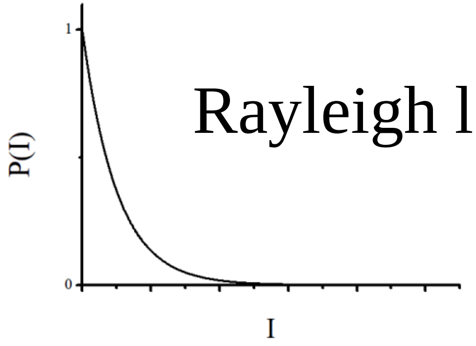


$d_{min} \sim \lambda \frac{L}{D}$

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

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

Speckle statistics

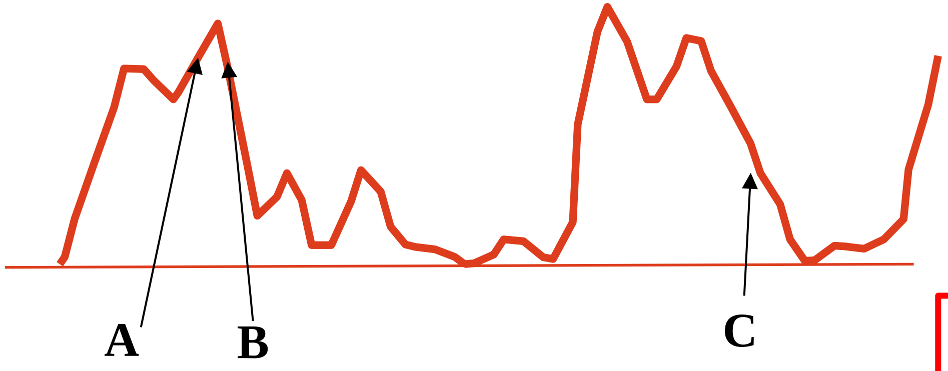


Rayleigh law

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

$$\boldsymbol{\langle I^2\rangle = 2\langle I\rangle^2}$$

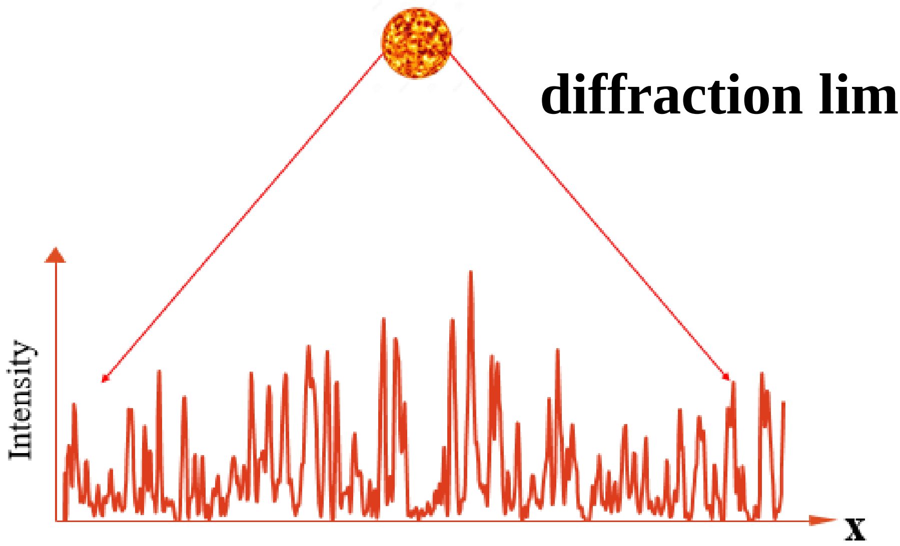
$$\mathrm{var}(I) = \langle I^2\rangle - \langle I\rangle^2 = \langle I\rangle^2$$



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

$$\boxed{\begin{array}{l} \mathbf{g_{AB}(2) = \langle I_A I_B\rangle / \langle I_A\rangle\langle I_B\rangle = 2} \\ \mathbf{g_{AC}(2) = \langle I_A I_C\rangle / \langle I_A\rangle\langle I_C\rangle = 1} \end{array}}$$

Time and spatial scales

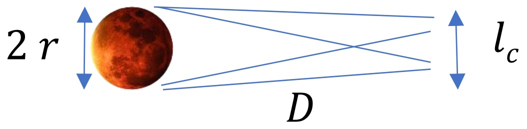


diffraction limit $\theta = \lambda / D$

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

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

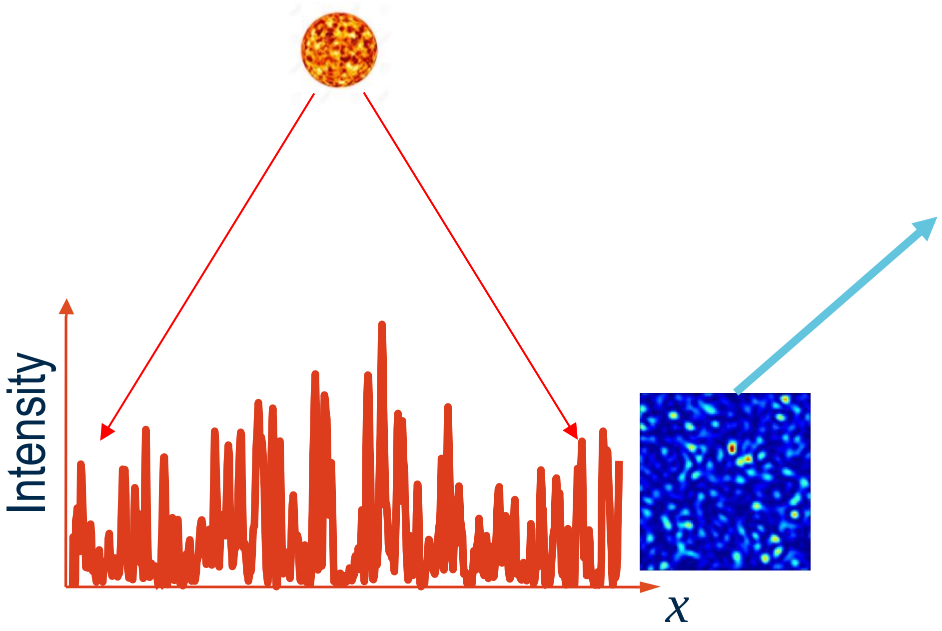
$$l_c = \frac{\lambda D}{\pi r}$$

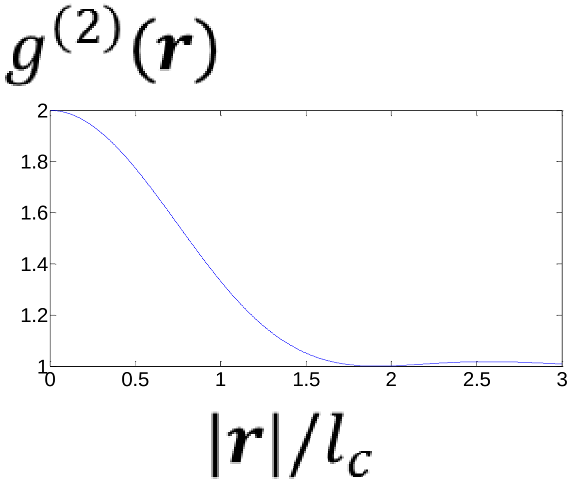


In the spatial domain: $g^{(2)}(\boldsymbol{r}, \tau = 0)$

More formally: van Cittert – Zernike theorem (1934, 1938)

$g^{(2)}(\boldsymbol{r})$ = 1+ | FT(Brightness distribution of the source) |^2



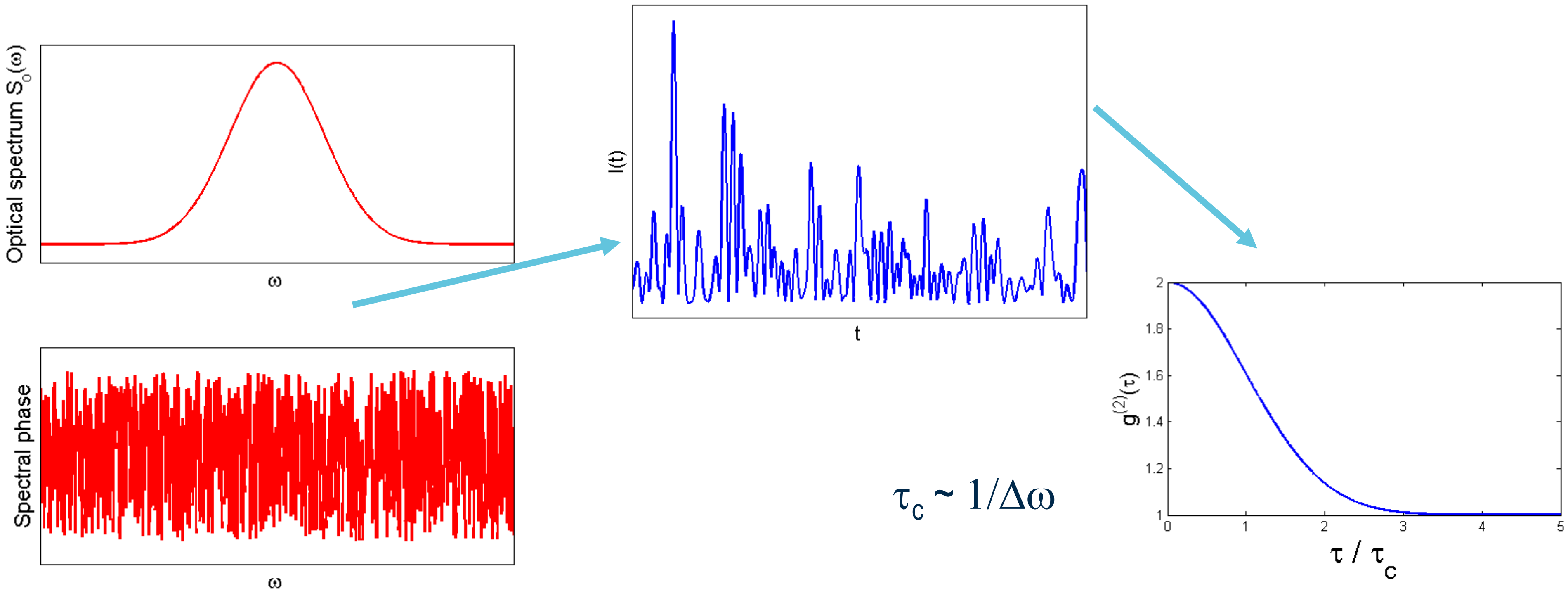


$l_c \sim \lambda\, L/D$

In the time domain: $g^{(2)}(\boldsymbol{r} = 0, \tau)$

More formally: Siegert relation

$g^{(2)}(\tau)$ = 1+ | FT(Power spectrum of the source) $|^2$



$\tau_c \sim 1/\Delta\omega$

Robert Hanbury Brown
radio-astronomer

Richard Q. Twiss
applied mathematician

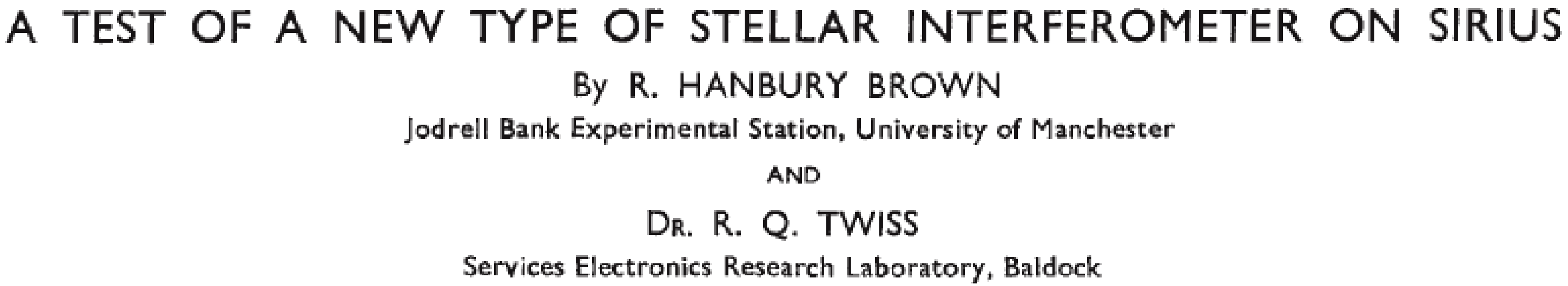
1952: First application of this idea to **radio astronomy**

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

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

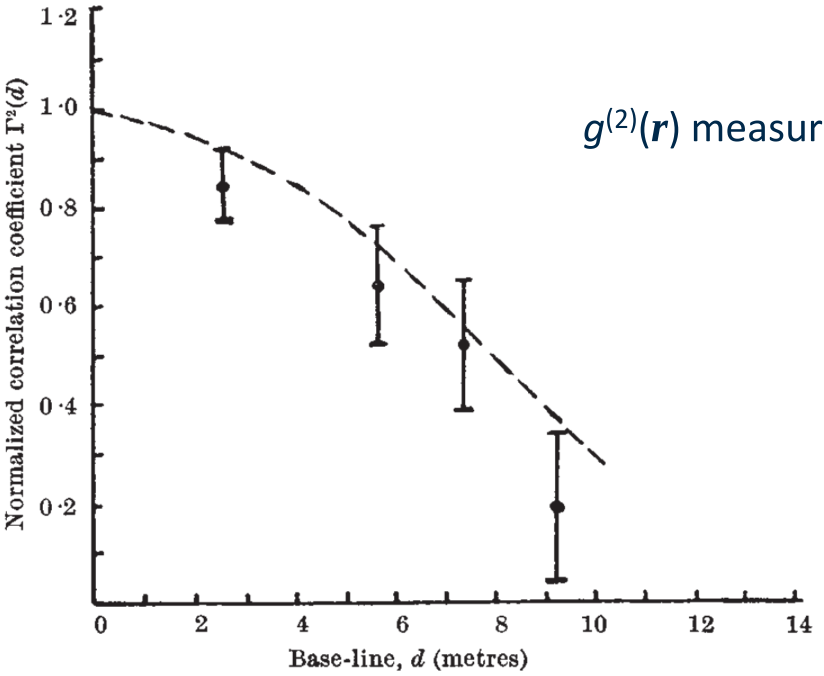
1956: Lab experiment with **light** [Hanbury Brown & Twiss, *Nature* **177**, 27 (Jan. 1956)].

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



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

Two telescopes of 1.56 m diameter
Separation up to 9 m

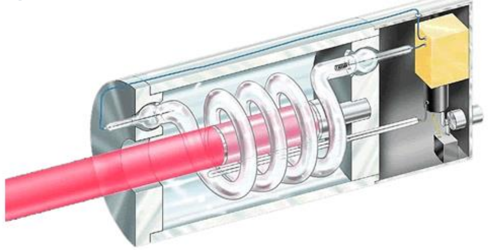
→ First direct measurement of the angular diameter: 6.8 ±0.5 mas

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).

(1960: Invention of the laser, which behaves differently!)



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 )

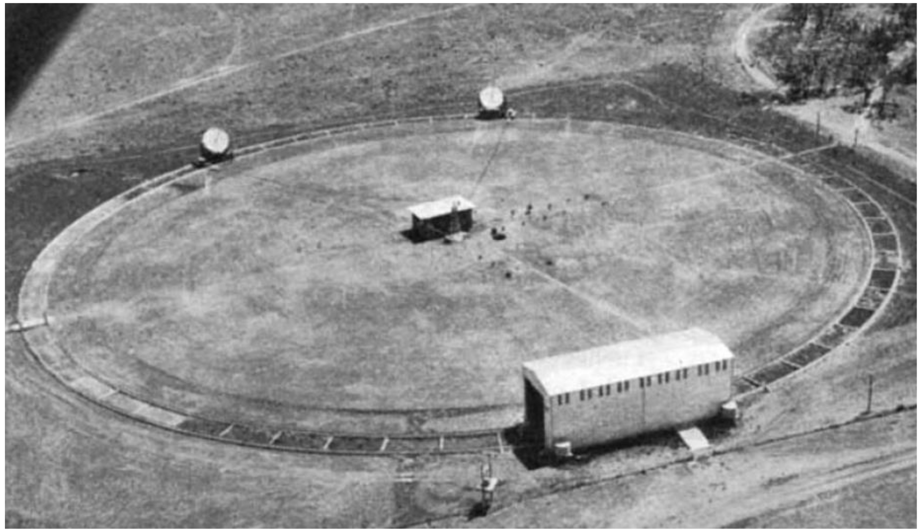
HBT experiment : milestone in the development of quantum optics
&
photon correlations are still the daily bread of quantum opticians

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).

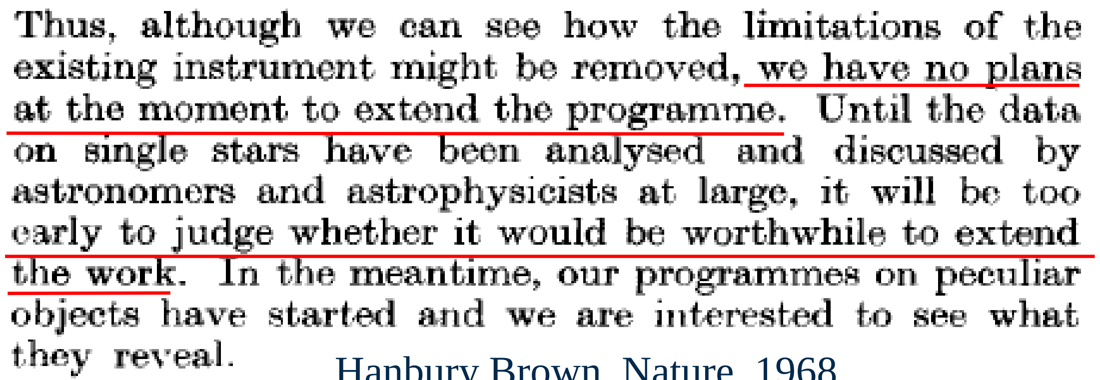
70’ : Intensity interferometry stopped !

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 ☺

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

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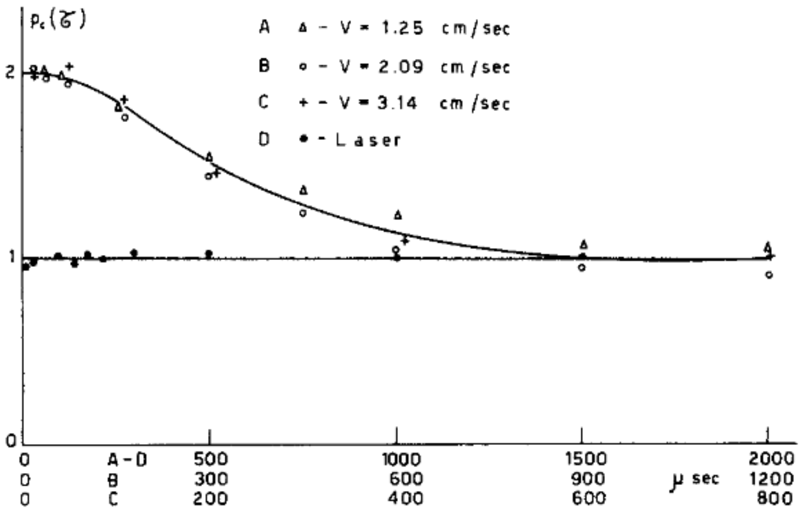
Poisson statistics of laser => $g^{(2)}(\tau=0)=1$

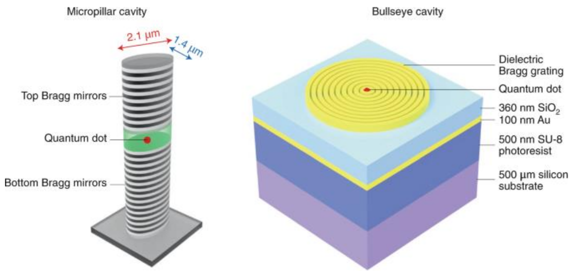
Thermal light => $g^{(2)}(\tau=0)=2$



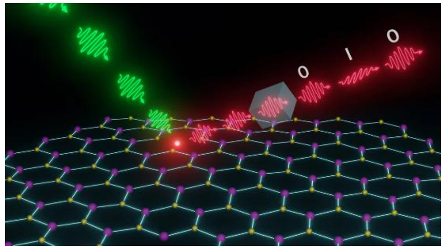
F.T. Arecchi, E. Gatti, A. Sona, Phys. Lett. 20, 27 (1966)

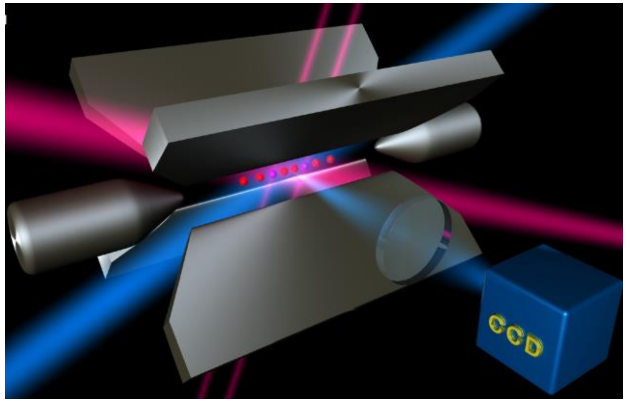
Quantum theory : R. Glauber (1963 => Nobel 2005)

Contrôle d'atomes, ions et photons uniques

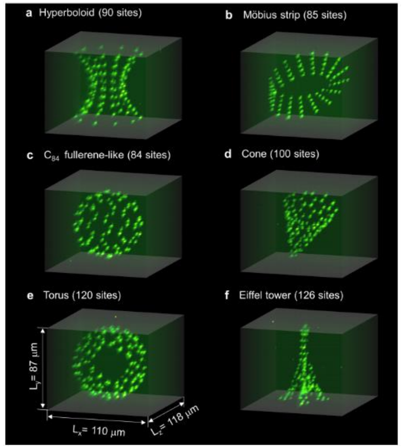


Sources de photons uniques





Ions piégés

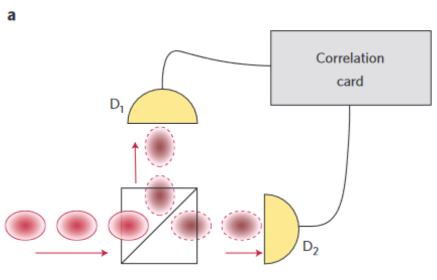


Atomes piégés

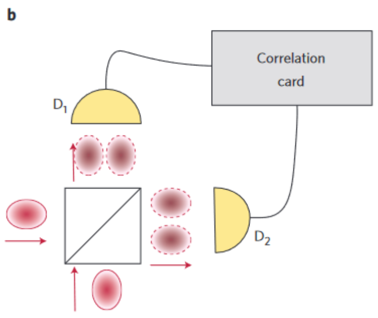
Haroche Wineland

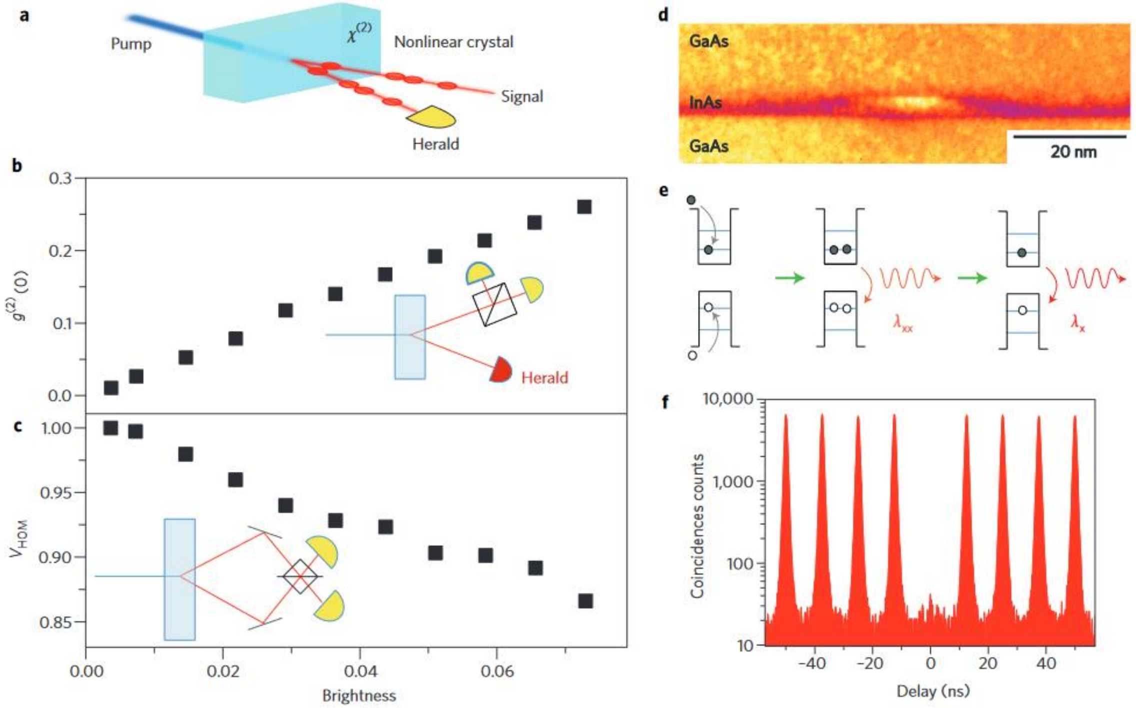
2012

single-photon purity :
HBT



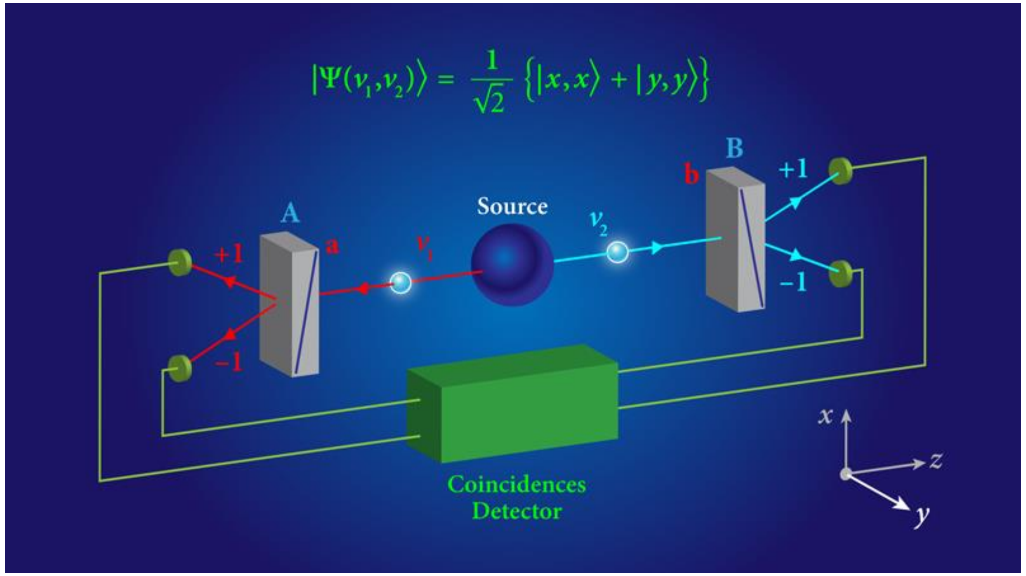
photon indistinguishability:
Hong–Ou–Mandel





P. Senellart et al., Nat. Nano. 12, 1026 (2017)

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



Experiments by Clauser, Aspect

70/80

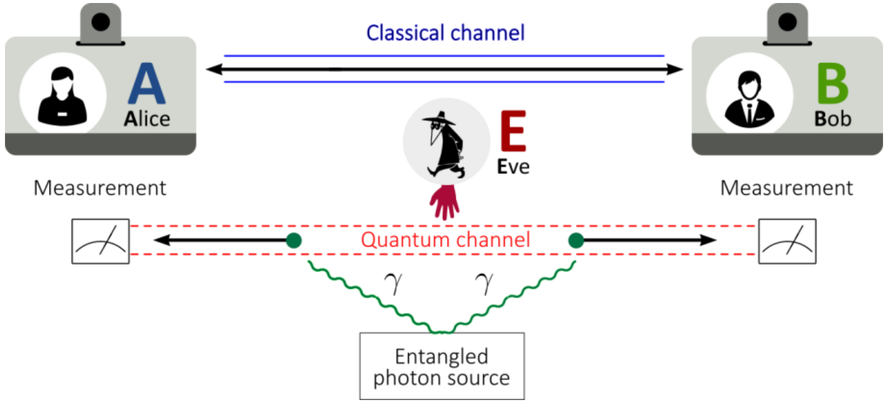
2022

Quantum Mechanics is correct :

No hidden variables

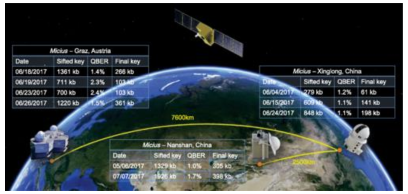
Accept non-locality

Quantum cryptography :



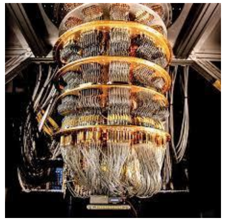
2017

2018

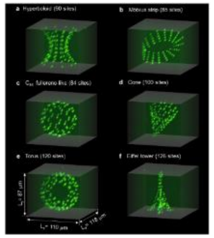


… towards a quantum internet ?

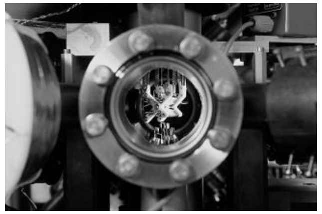
Quantum Computers:



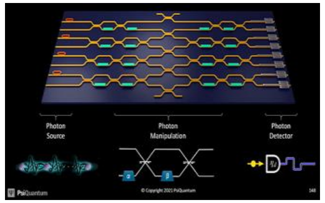
Superconducting qubits (Google, IBM)



Rydberg atoms (Pasqal, QuEra)



Ions (IonQ, AQT)



Photons (PsiQuantum, Xanadu, Orca)

Google

IBM Quantum

PASQAL

QuEra Computing Inc.

IONQ

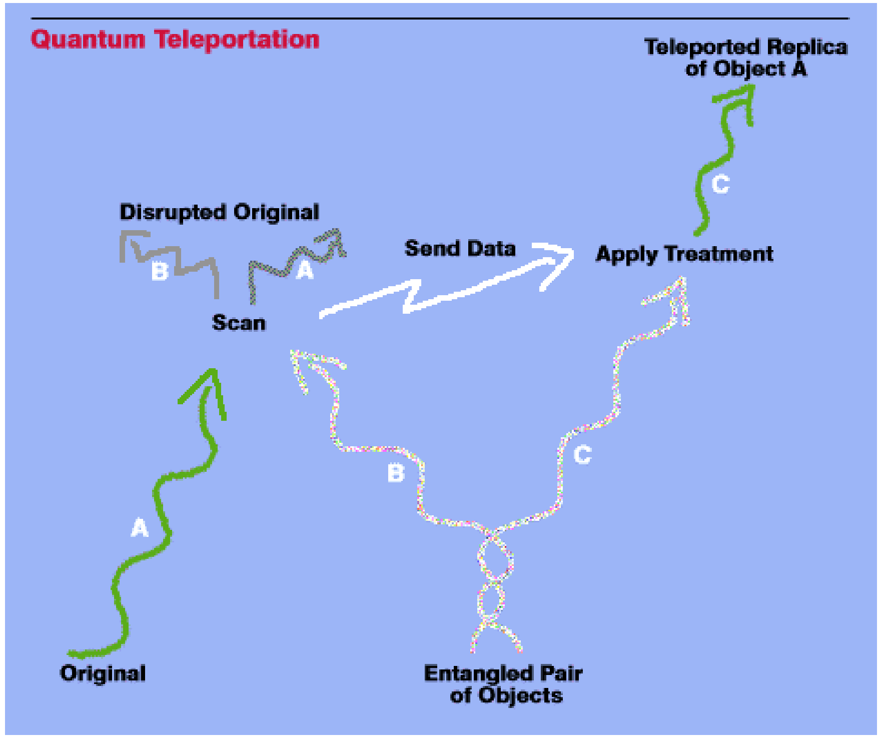
AQT

Ψ PsiQuantum

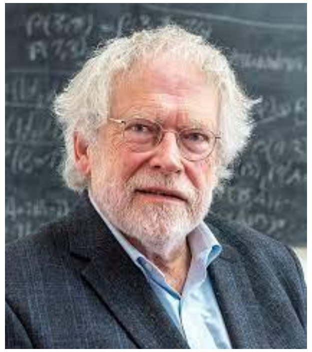
ORCA Computing

3 particule correlations
Teleportation

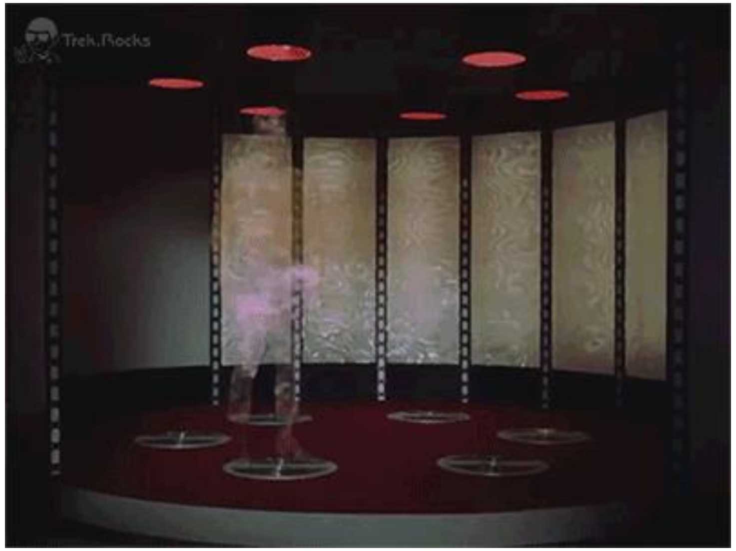
$|\Psi\rangle$



$|\Psi\rangle$




2022



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   - On-sky intensity correlations from 2017-2023

5) State of the art of intensity interferometry in 2024

6) IC4Star project in Nice

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

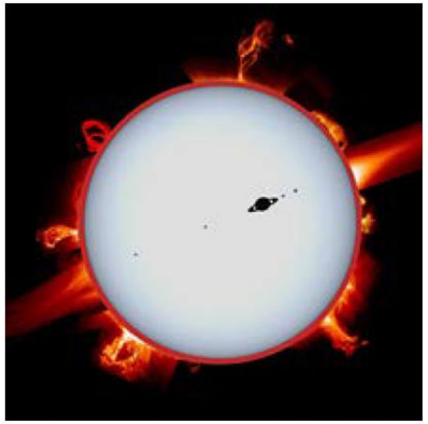
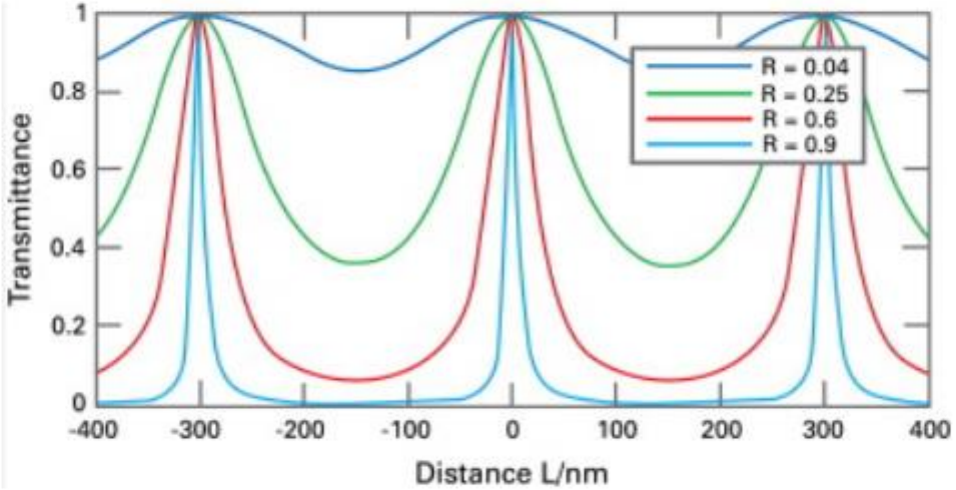


Figure 3. The real meaning of 40 microarcsecond optical resolution: Simulated resolution for an assumed transit of a hypothetical exoplanet across the disk of the relatively nearby star Sirius, using the full Cherenkov Telescope Array as an intensity interferometer. Stellar angular diameter = 6 mas; 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

Photon-correlation spectroscopy

Scanning Fabry Perot cavity



CW Resolution R ~ 100 000

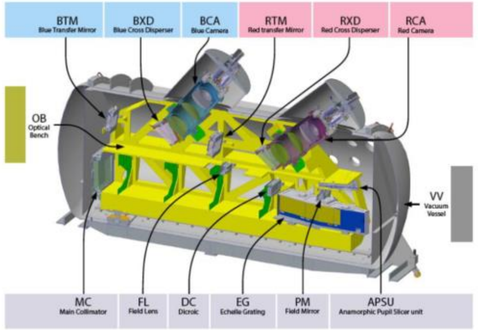
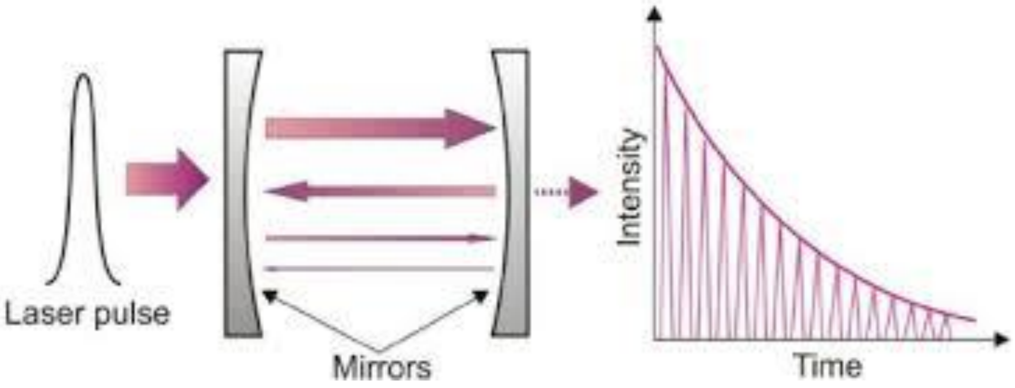


Figure 8: Opto-mechanics of the ESPRESSO spectrograph.

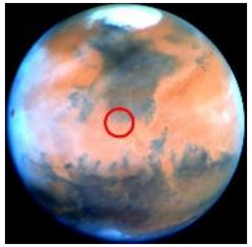
Ring down spectroscopy

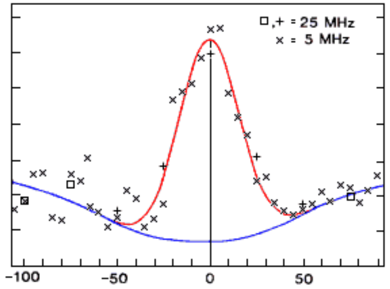


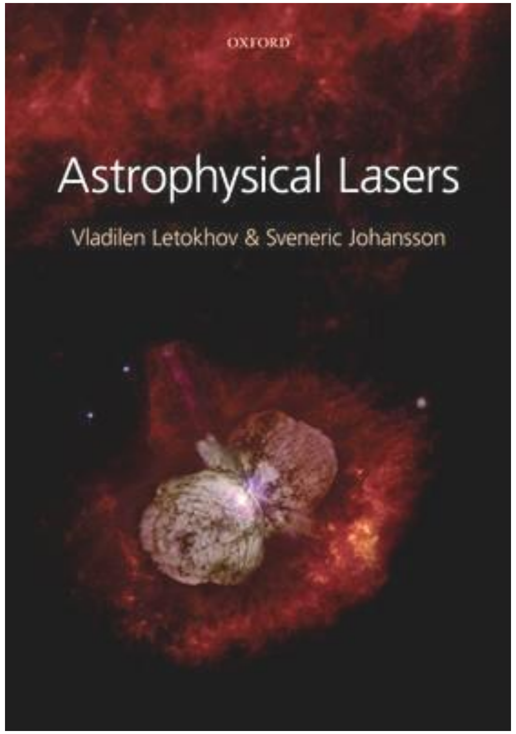
Time resolved spectroscopy :
resolution R=100,000,000

Astrophysical lasers

- Amplification of radiation by stimulated emission ("laser" for astrophysicists) is known in space.
- Amplification at 10 μm in the atmospheres of Mars and Venus (C02) : M. Mumma, et al., Science, 212, 45(1981)
- Multiple scattering (radiation trapping) is also common
- A random laser could happen naturally in space
- Amplification in the near IR in h Carinae (FeII and OI)







Hydrogen Lasers in Emission-Line Objects

Quirrenbach A, Frink S, Thum C (2001) *Spectroscopy of the peculiar emission line star MWC349*. In Gull TR, Johansson S, Davidson K (eds) *Eta Carinae and Other Mysterious Stars: The Hidden Opportunities of Emission Spectroscopy*. ASP Conf Ser **242**: 183–186

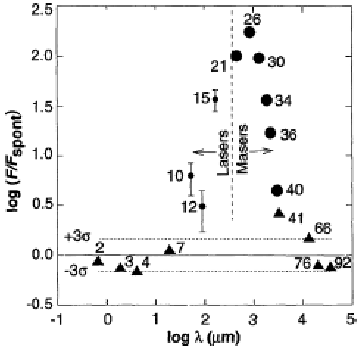


Fig. 8 MWC349A: Log-log plot of the ratio F/F_{spont} where F is the total observed flux in successive hydrogen recombination lines, and F_{spont} the estimated contribution from spontaneous emission. Large dots indicate masing mm and sub-mm lines; small dots are infrared detections. The numbers are the principal quantum numbers for each line's lower level: Strelnitski et al. [149]. Reprinted with permission from Science 272, 1459, © 1996 AAAS

Early attempts for HBT revival with novel fast detectors :

Quanteye : OWL/ELT

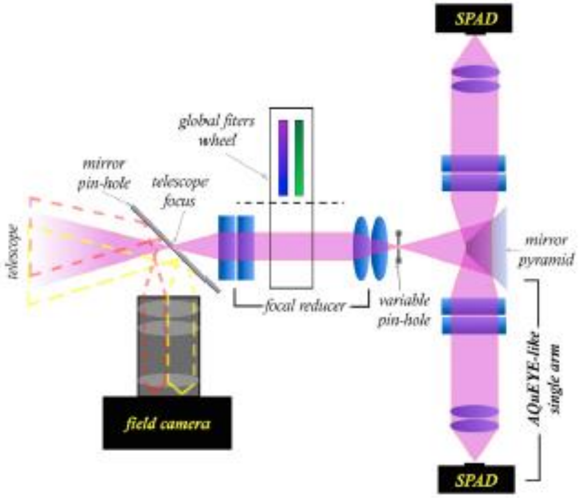
- D. Dravins, et al. 2005, QuantEYE quantum optics instrumentation for astronomy. OWL Instrument Concept Study, Tech. rep., ESO, Document OWL-CSR-ESO-00000-0162
- C. Barbieri, et al. 2006, in The scientific requirements for extremely large telescopes, ed. P. Whitelock, B. Leibundgut, & M. Dennefeld, 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)



SPAD :

Δt ~ 500ps

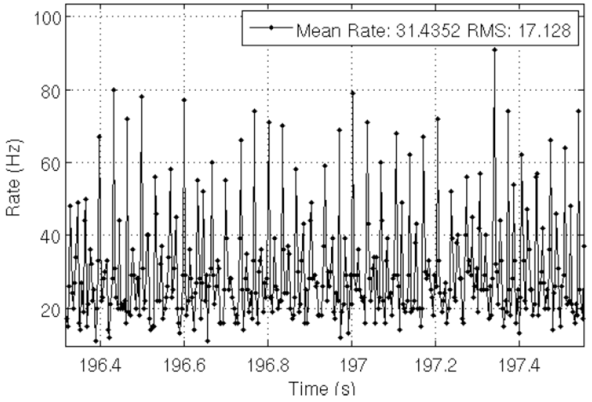
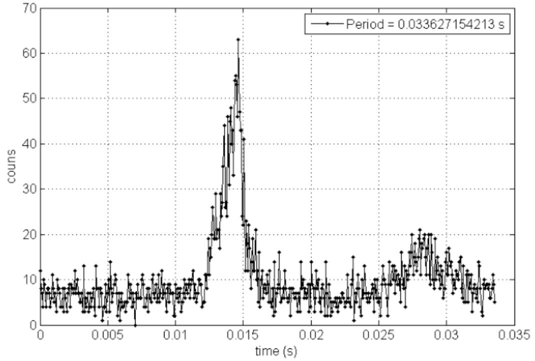
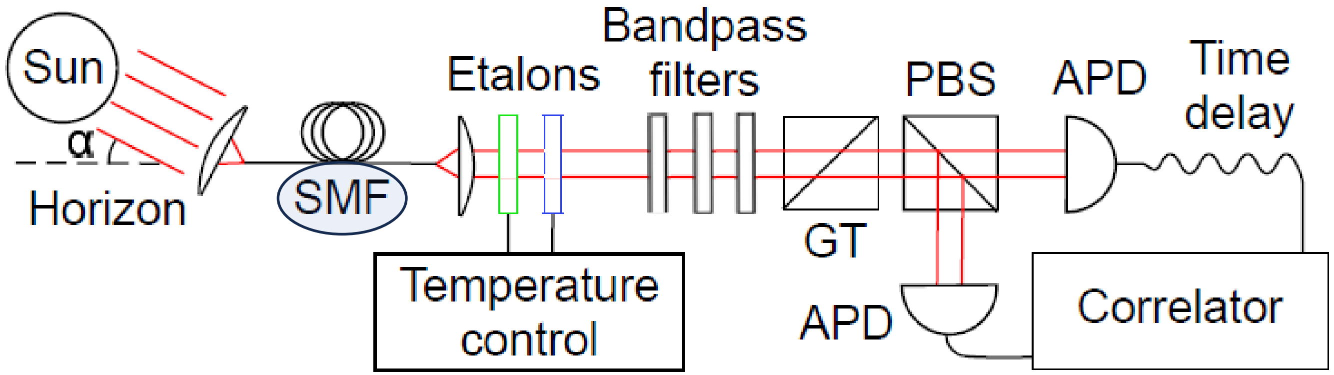


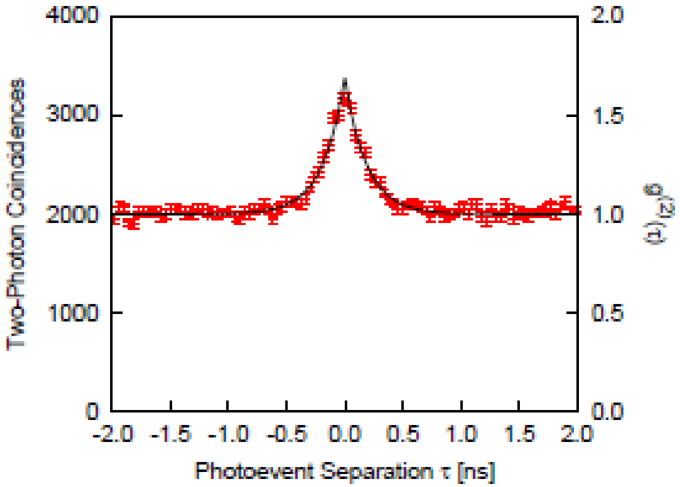
Fig. 9. Individual counts from the Crab Nebula pulsar, with 0.33 ms (1/10 of the period) bin size. The average count rate per time bin is given in the box.



Extreme spectral filtering helps



P. Tan et al., ApJ, 789, L10 (2014)
P. Tan, A. Chan, C. Kurtsiefer , MNRAS, 457, 4291 (2016)



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

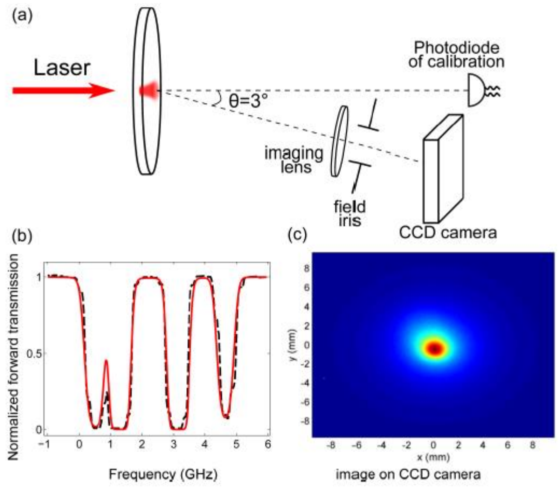
5) State of the art of intensity interferometry in 2024

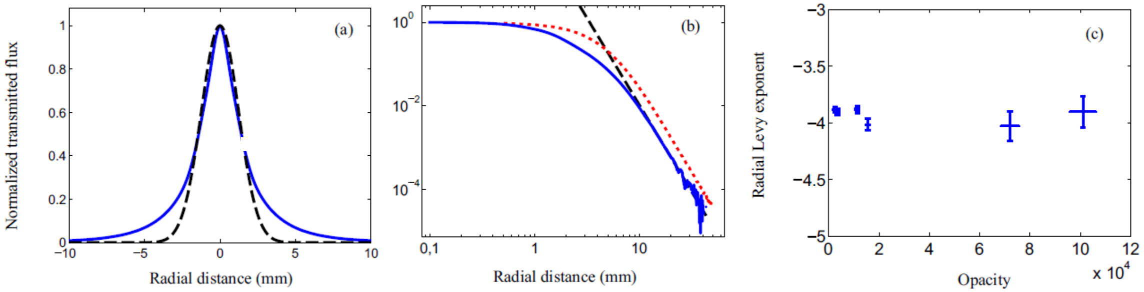
6) IC4Star project in Nice

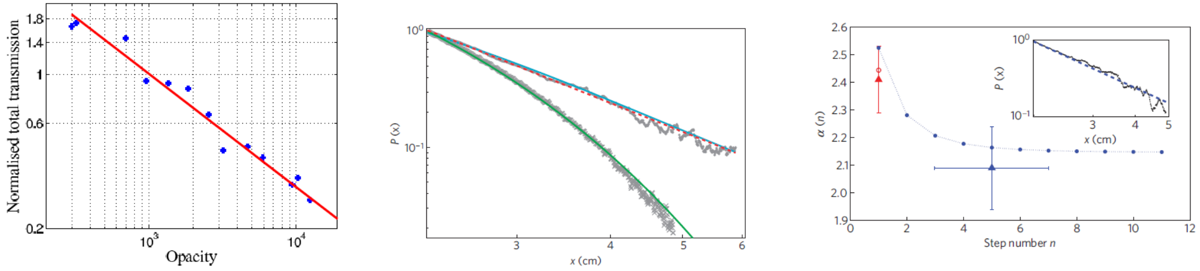
Atomic physics laboratory experiments

Goal : fast (high bandwidth) correlation

Experimental setup : developed for Levy flight experiments

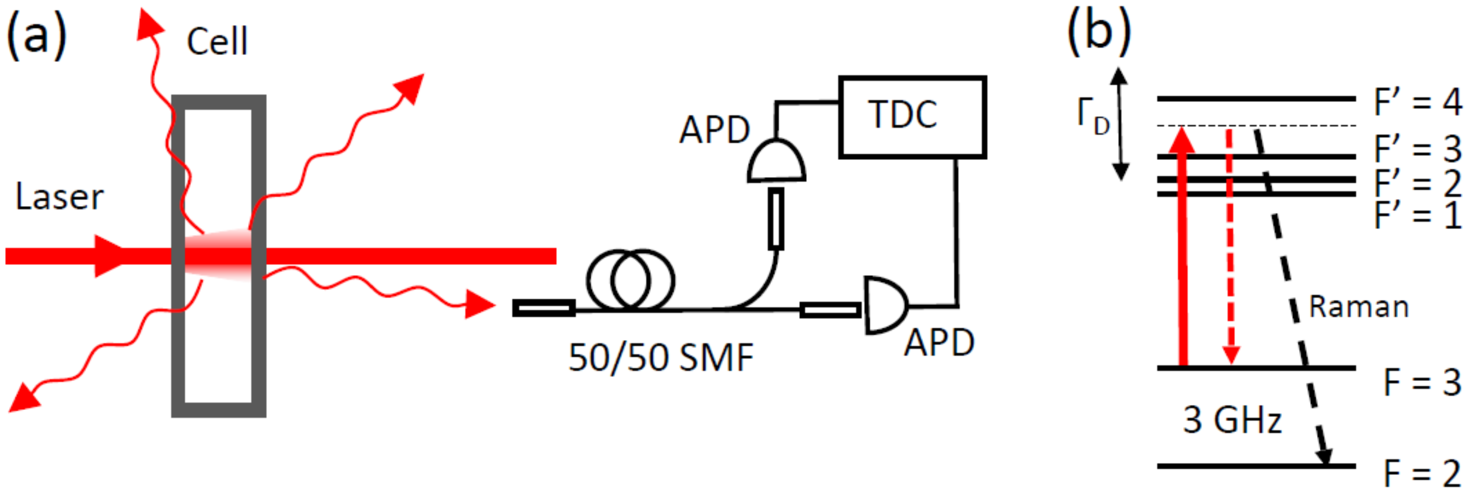


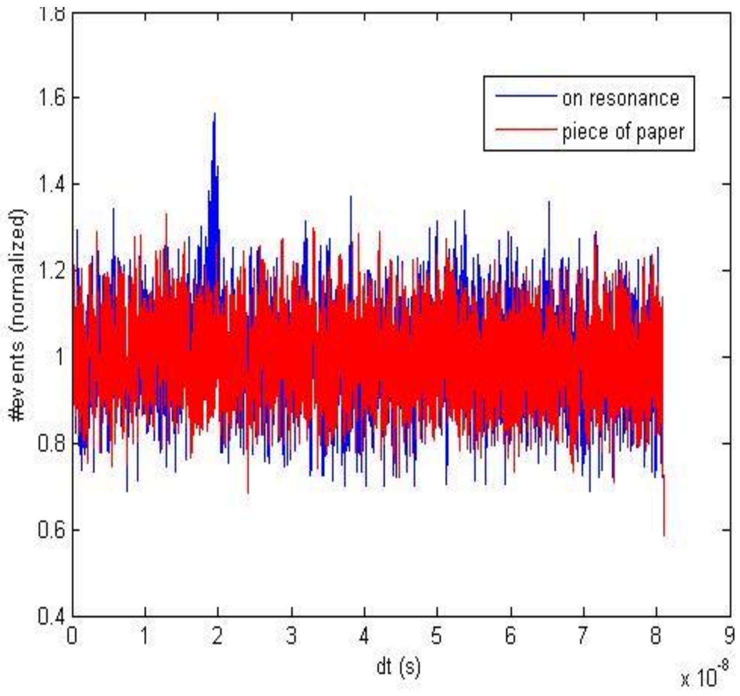


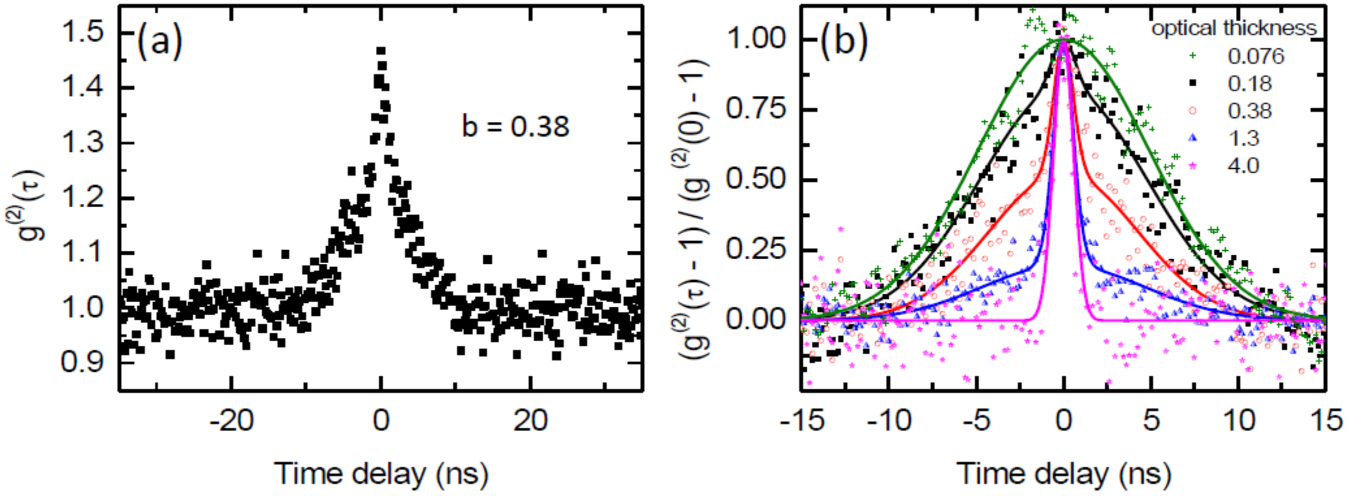


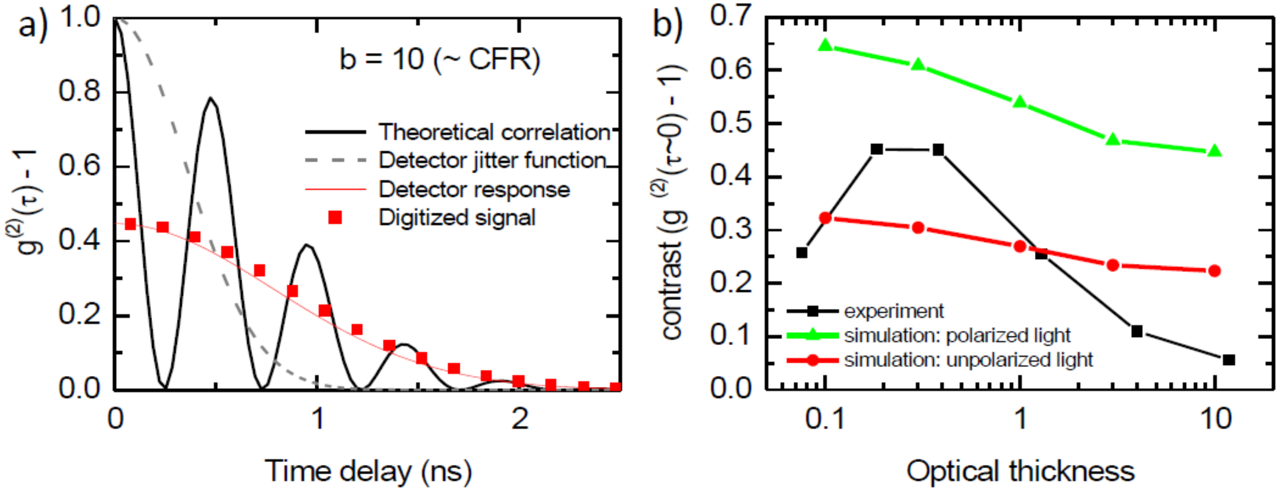
Phys. Rev. E 90, 052114 (2014)

Nat. Phys. 5, 602 (2009)


(a)
Cell
Laser
APD
TDC
50/50 SMF
APD
(b)
Γ_D
F' = 4
F' = 3
F' = 2
F' = 1
Raman
F = 3
3 GHz
F = 2


on resonance
piece of paper
#events (normalized)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0
1
2
3
4
5
6
7
8
9
dt (s)
x 10^-8



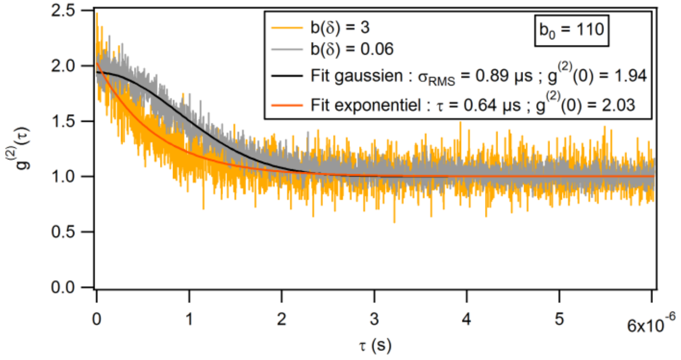


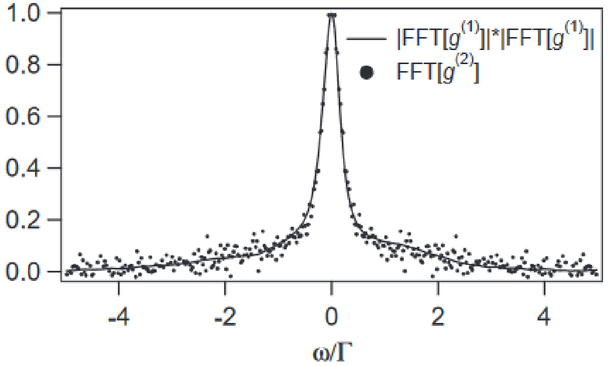
Temporal intensity correlation of light scattered by a hot atomic vapor
A. Dussaux, T. Passerat de Silans, W. Guerin, O. Alibart, S. Tanzilli, F. Vakili, R. Kaiser
Phys. Rev. A 93, 043826 (2016)

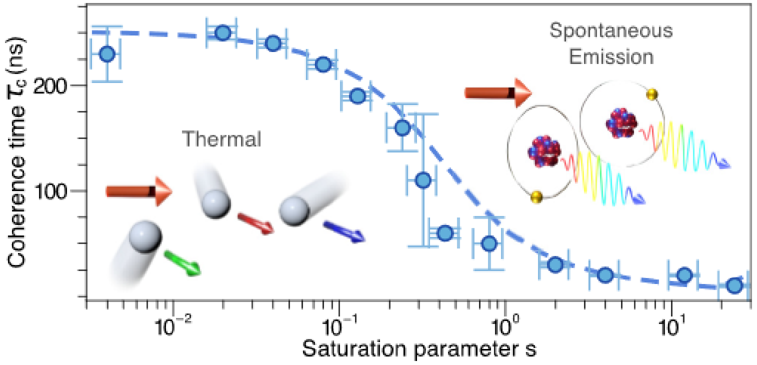
Atomic physics laboratory experiments

From astrophysics to cold atoms : correlation setup implemented on cold atoms ☺

Diffusive wave spectroscopy with cold atoms / testing the Sigert relation







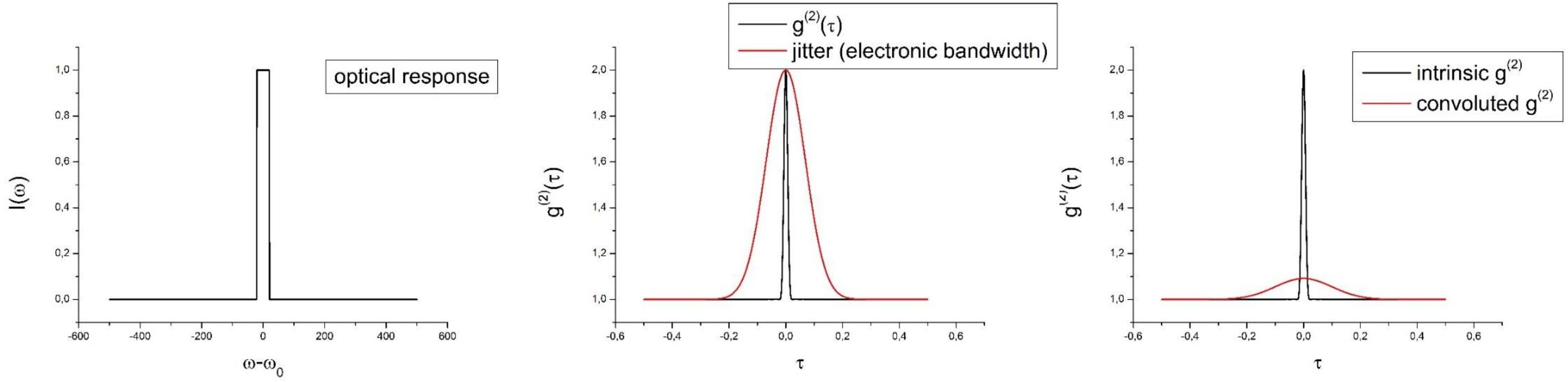
A. Eloy et al., Phys. Rev. A 97, 013810 (2018)
L. Ortiz-Gutierrez et al., New J. Phys. 21, 093019 (2019)
D. Ferreira et al., Am. J. Phys., 88, 831 (2020)
P. Lassegues et al. EPJ D 76, 246(2022)
P. Lassegues et al. Phys. Rev. A 108, 042214 (2023)
M. Morisse et al., EPL 147, 15001(2024)
M. Morisse et al., EPL 147, 15001(2024)

White light laboratory experiments

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

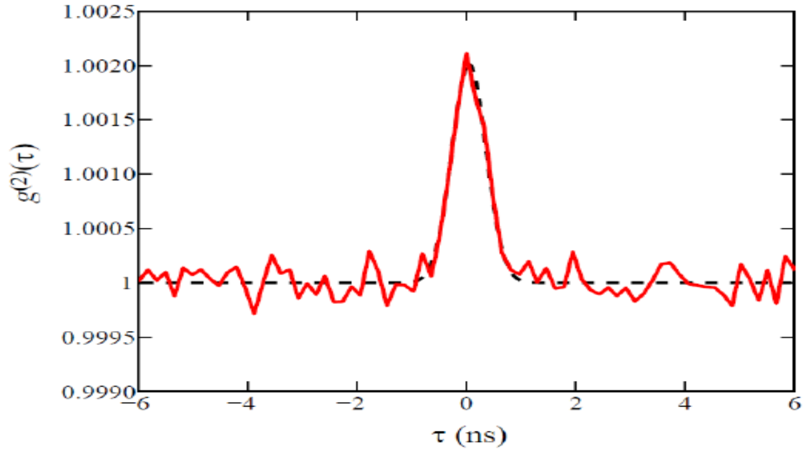
Optical filter @ 1nm : $\tau_c \sim$ ps

Electronic bandwidth (jitter) ~ 100ps



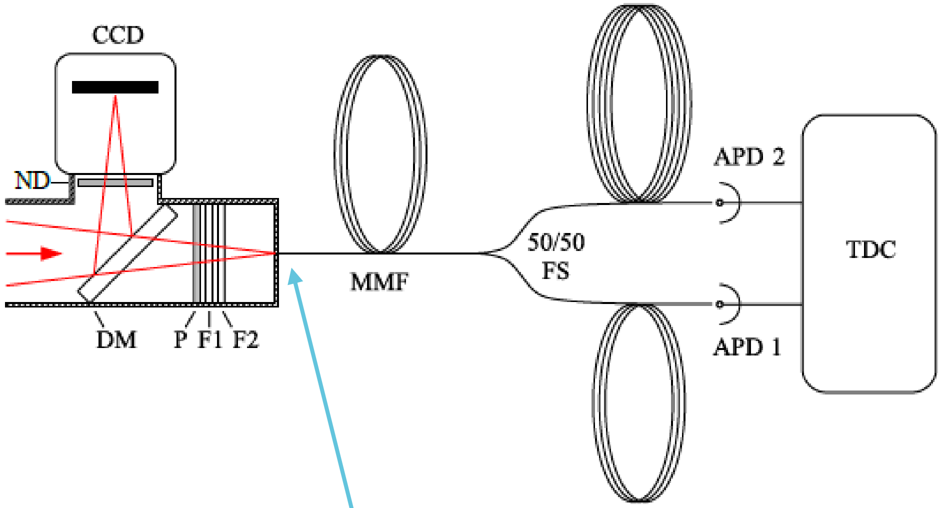
Laboratory experiment with

1nm filtered thermal source



Towards on-sky experiments

Light from the telescope



Focus of the telescope

- → Robust and transportable
- → No moving part

DM: Dichroic beam splitter

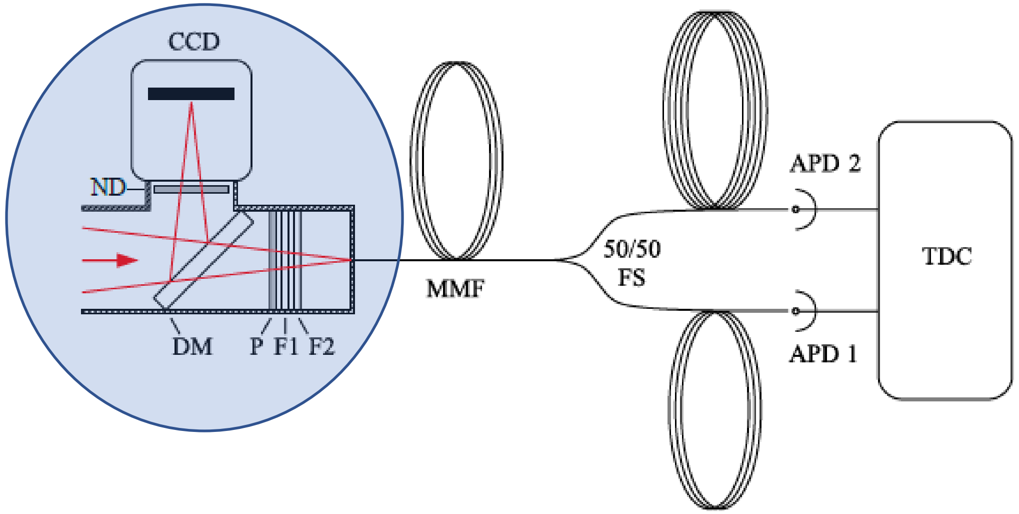
Reflection: $\lambda < 650$ nm
to the guiding camera
Transmission: $\lambda > 650$ nm
to the $g^{(2)}$ measurement

P: Polarizer

To select one polarization mode

F2: Filter

$\lambda_0 = 780$ nm
$\Delta\lambda = 10$ nm
To remove UV and IR photons

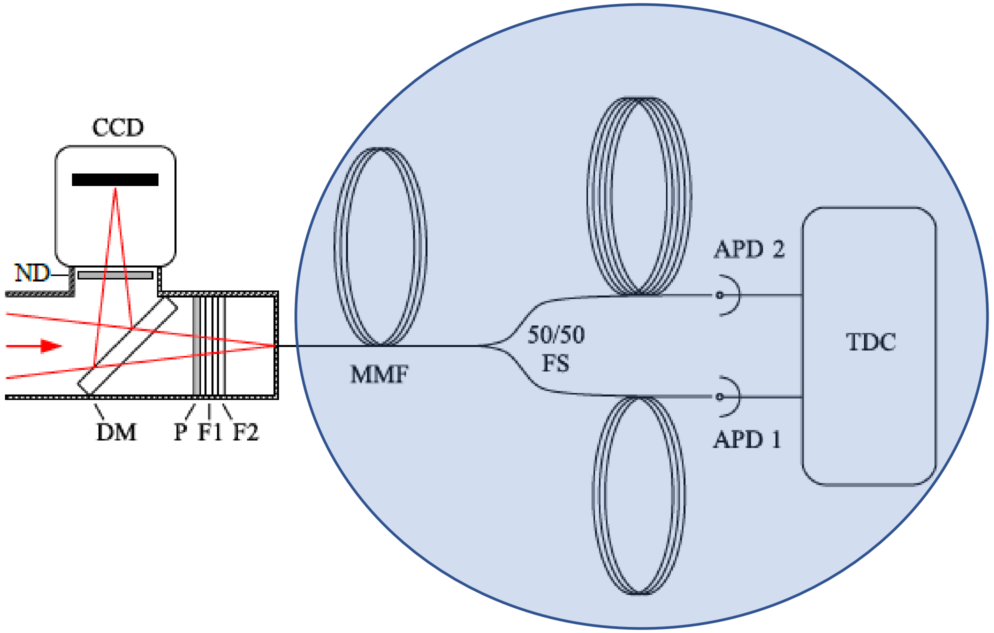


F1: Filter

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

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

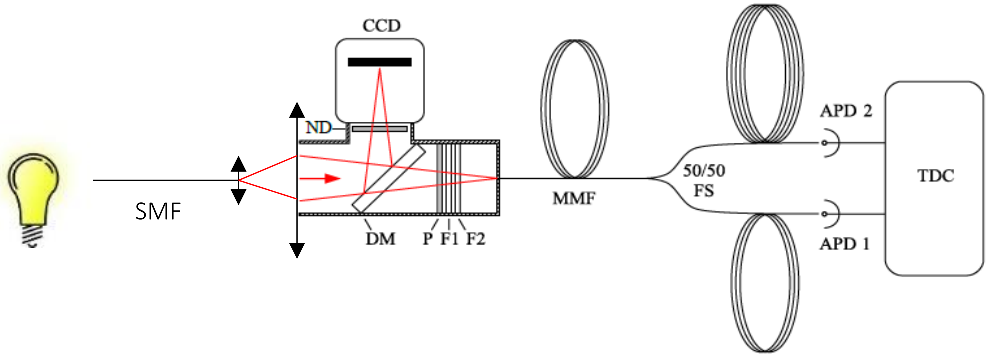
#2: Swabian Instruments, time resolution = 12 ps, less spurious correlations, 40 Mcps

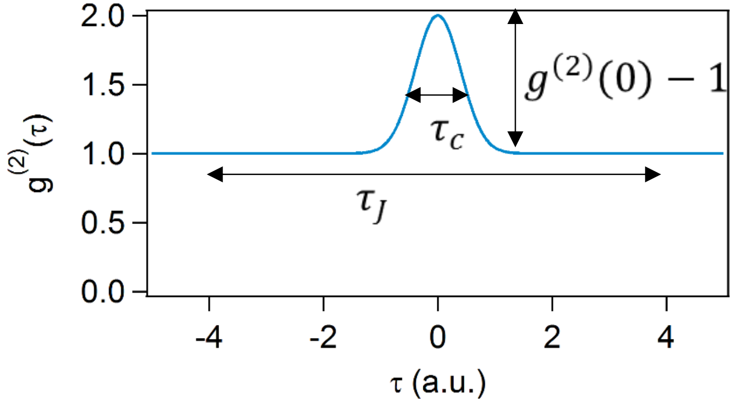
Expected signal

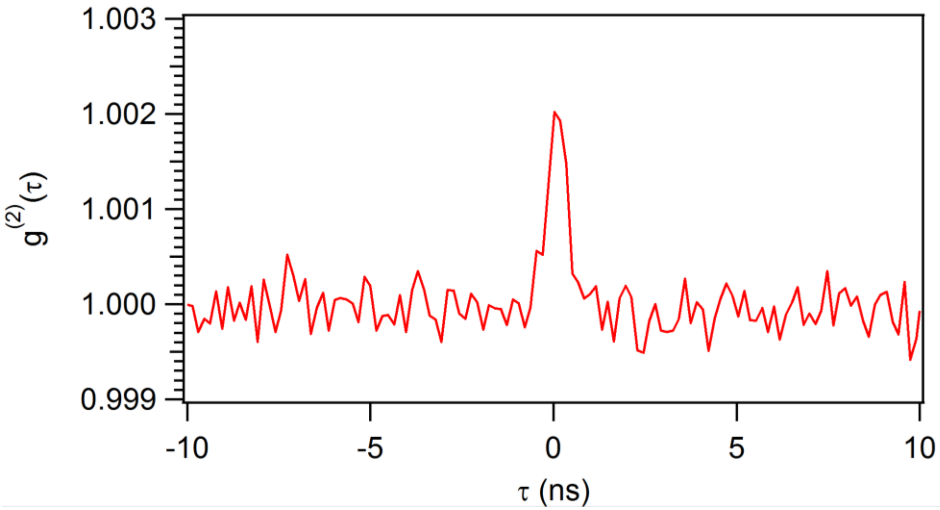
Contrast

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

~ 0.002







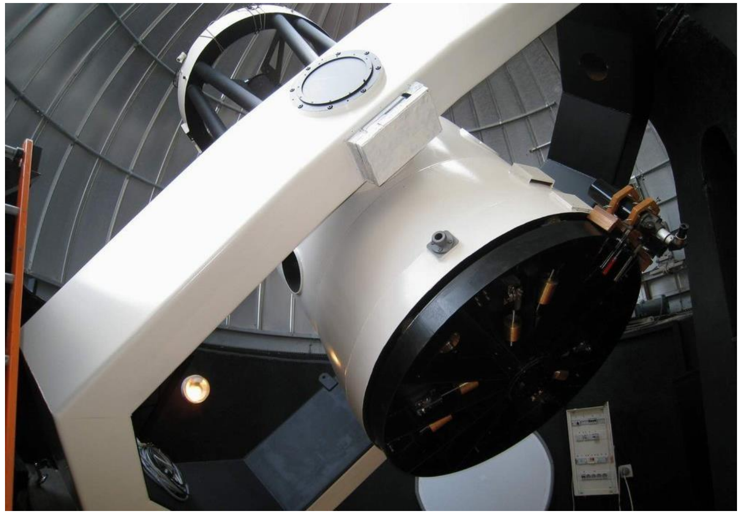
spurious correlations !!!

On sky experiments : C2PU telescopes at Calern

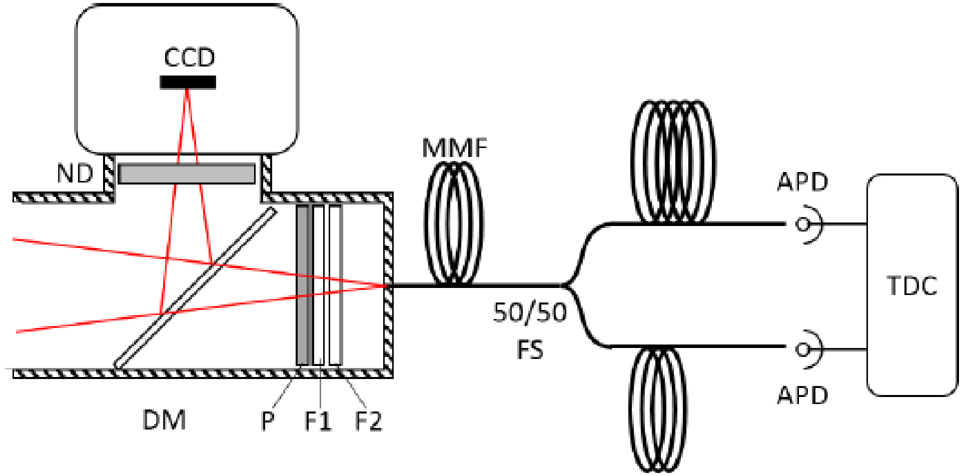
Altitude = 1280 m

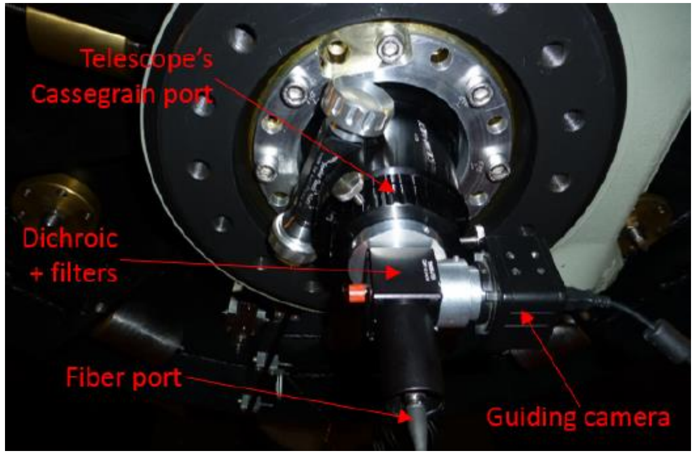
C2PU telescopes

- 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



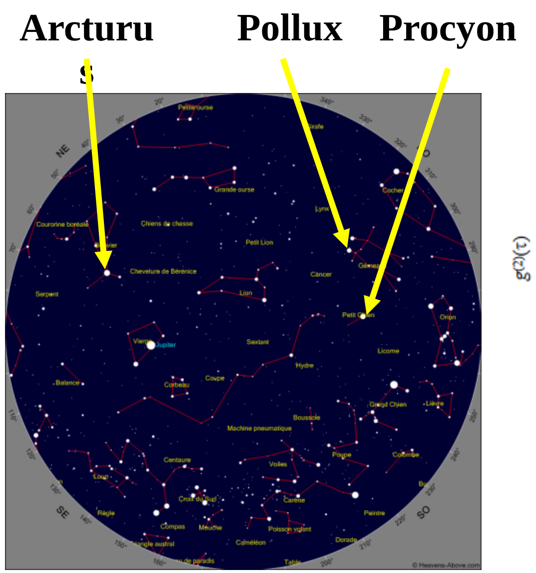
Experiments at C2PU (Calern, France) on February 20th-22nd 2017

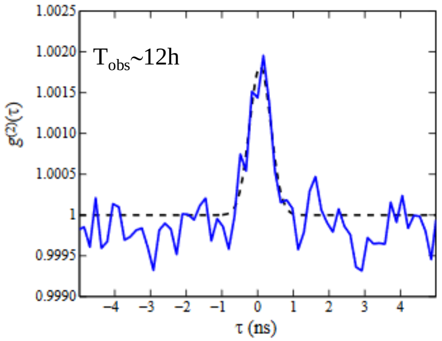




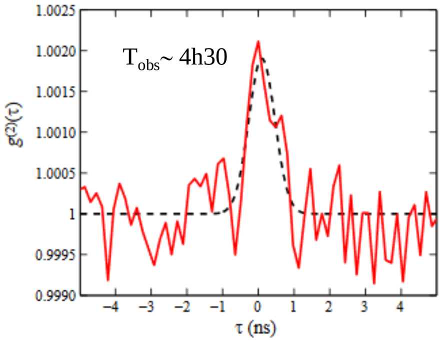
Results : Feb. 2017 : time correlation on 3 bright stars

Arcturus **Pollux** **Procyon**

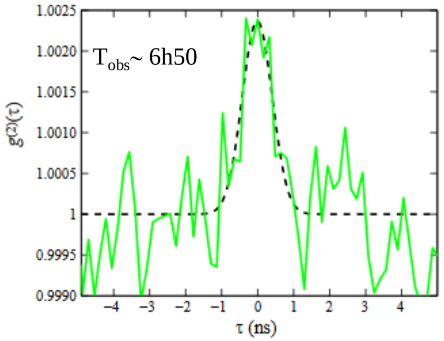




(a) α Boo (Arcturus).

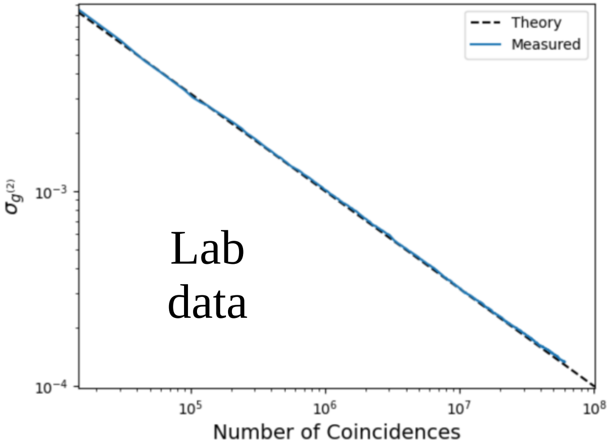


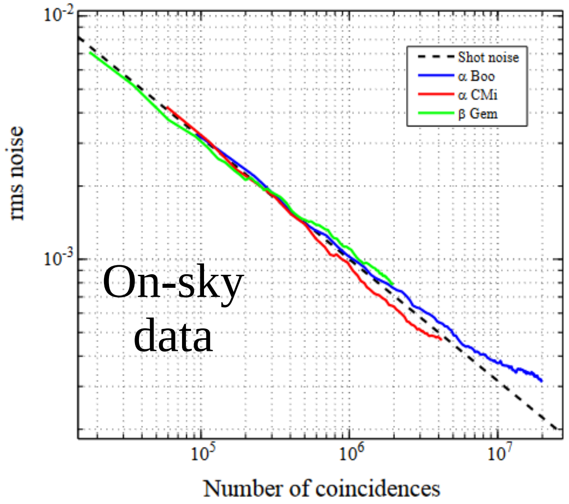
(b) α CMi (Procyon).



(c) β Gem (Pollux).

Shot noise limited

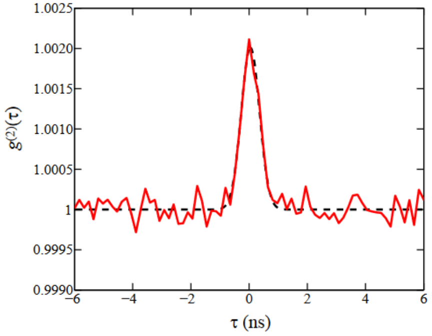




$$SNR = \alpha N_{\mathrm{ph}}(\lambda) A \sqrt{\frac{T_{\mathrm{obs}}}{\tau_{\mathrm{el}}}}$$

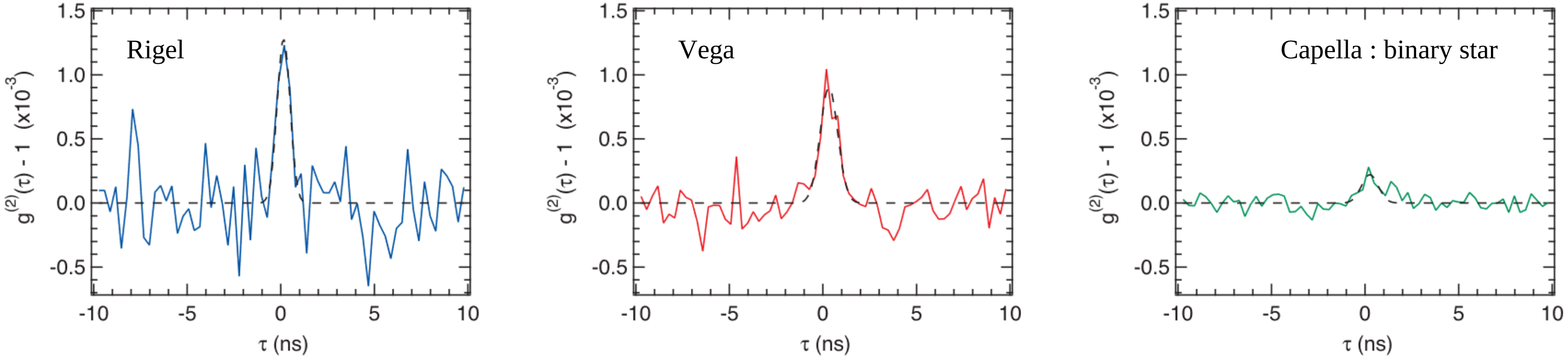
α: detection efficiency
$N_{\mathrm{ph}}(\lambda)$: photon spectral flux (ph/m²/s/Hz)
A : collecting area

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

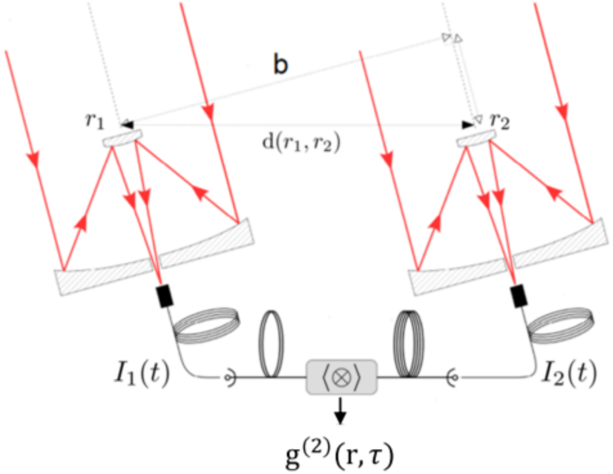


W. Guerin, A. Dussaux, M. Fouche, G. Labeyrie, J.-P. Rivet, D. Vernet, F. Vakili, R. K, Mon. Not. Roy. Astron. Soc. 472, 4126 (2017)

Results : fall 2017 : spatial correlation on 3 bright stars



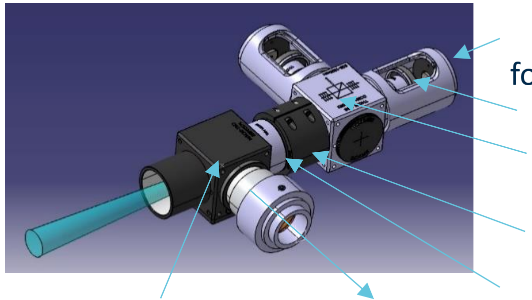
(a) β Ori. (b) α Lyr. (c) α Aur.



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



focusing lens,
f = 20 mm

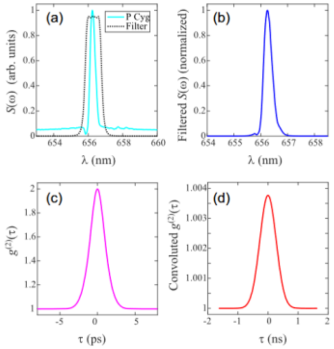
PBS

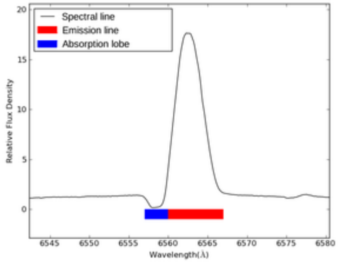
Hα filter

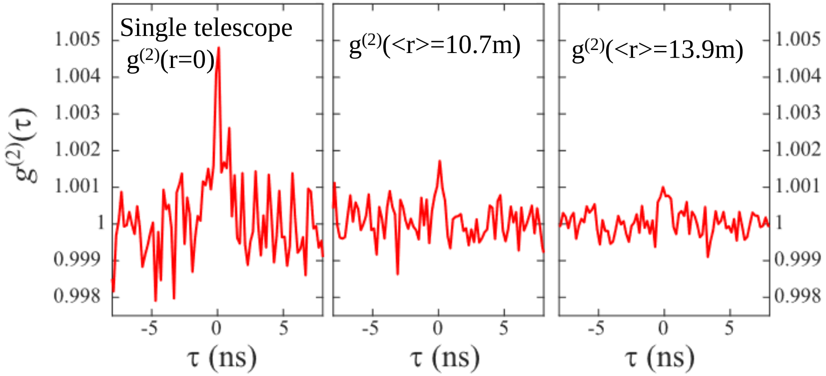
collimating lens,
f = -50 mm

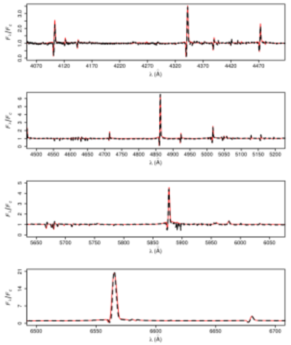
dichroic
splitter

to guiding
CCD

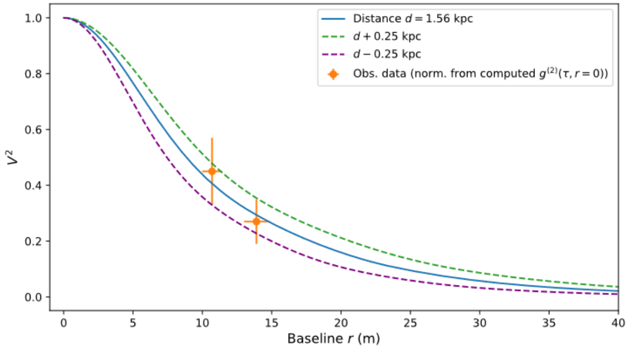








non-LTE
radiative transfer code
CMFGEN

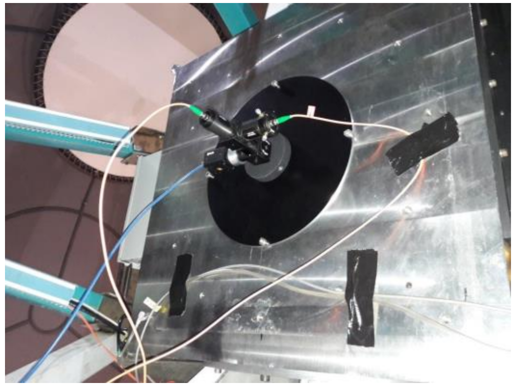


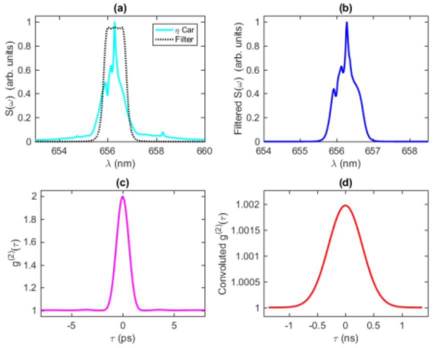
d = 1.56 +/- 0.258 kpc

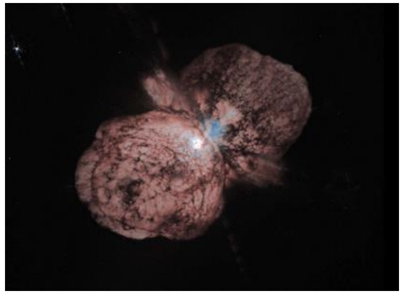
d = 1.36 +/- 0.24 kpc
Gaia DR2 catalogue
d = 1.8 +/- 0.1 kpc
Usually adopted in the literature

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)

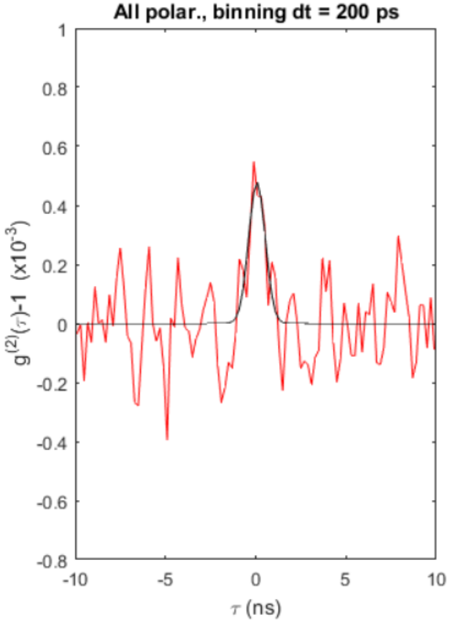
April 2019 : SOAR correlation on H_α emission line of η Carinae







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 ☺ ☺

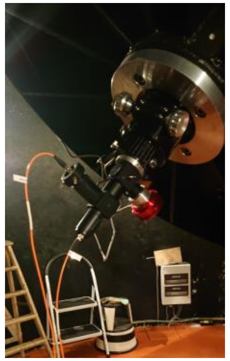
W. Guerin, J.-P. Rivet, M. Hugbart, F. Vakili, E. S. G. de Almeida, A. Domiciano de Souza, G. Labeyrie, N. Matthews,
O. Lai, P.-M. Gori, D. Vernet, J. Chabe, C. Courde, E. Samain, B. V. Castilho, A. M. Magalhaes, E. Janot-Pacheco, A. Carciofi, P. Bourget, N. Schuhler and R. K.,
Proceedings of the annual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

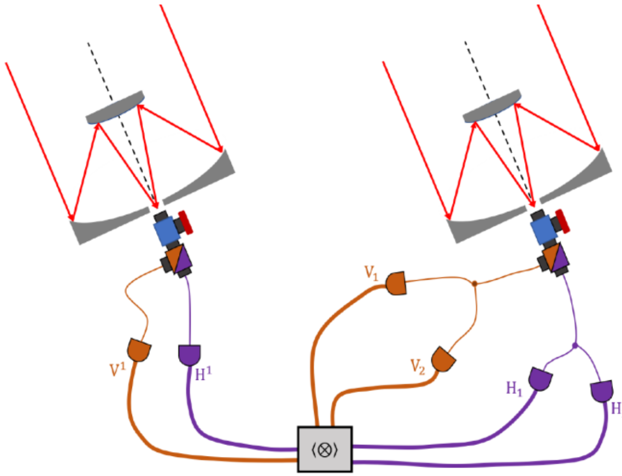
January 2020 : Spatial Correlation on H_α line of Rigel , Betelguese

Novel technical improvement :

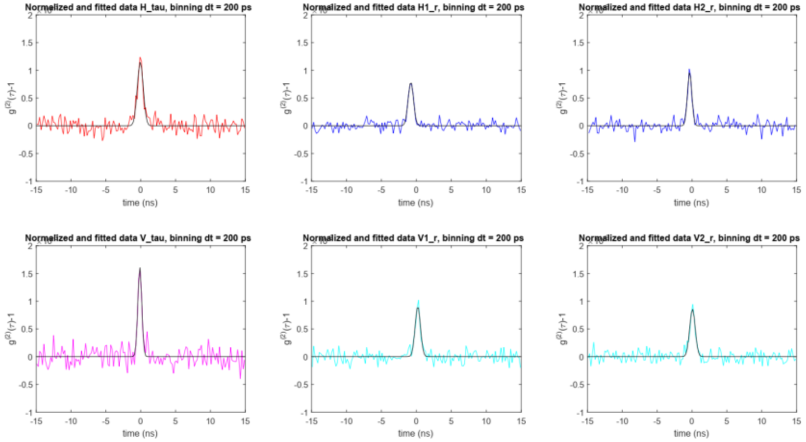
1) dual polarization channel

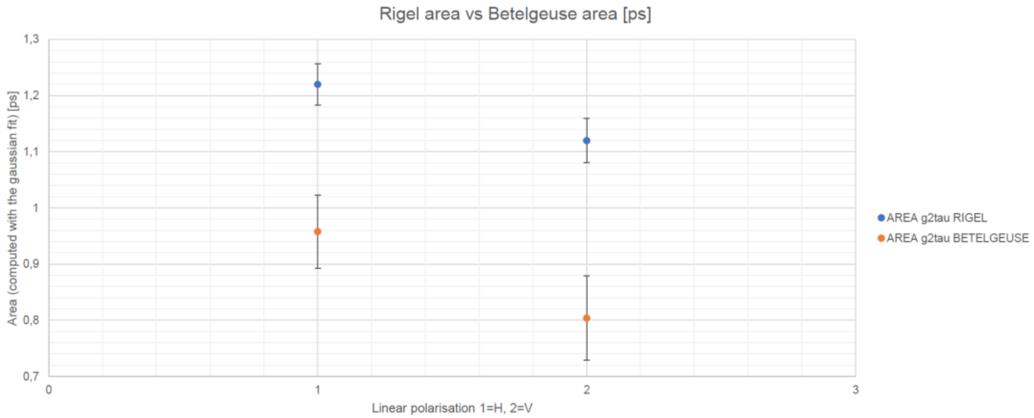
2) Auto calibrating setup : $g^{(2)}(0)$ + $g^{(2)}(r)$



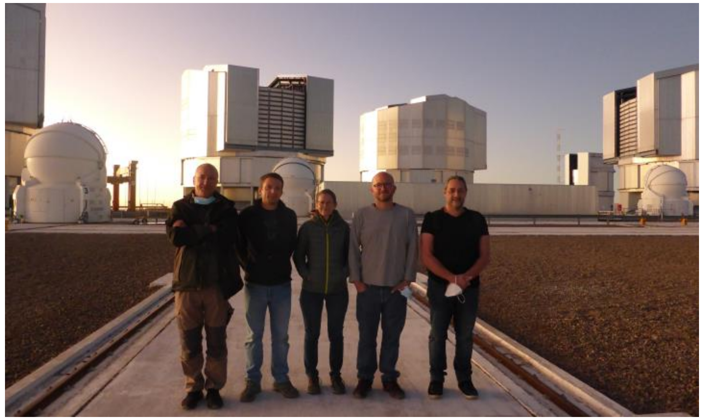


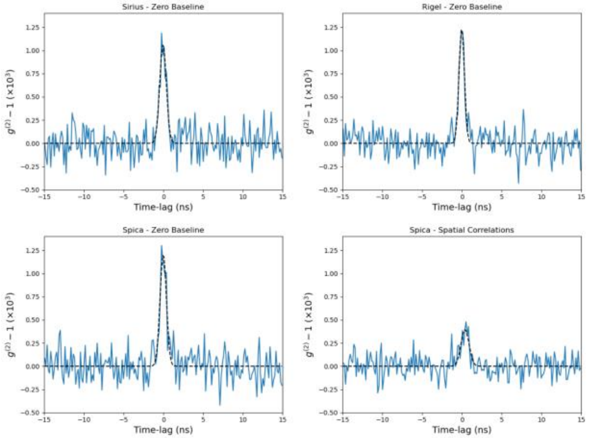
Rigel





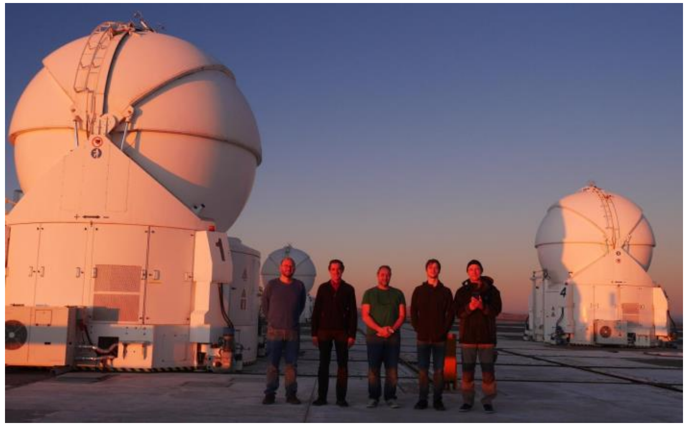
March 2022: Successful interferometric observation at Paranal (VLT)!

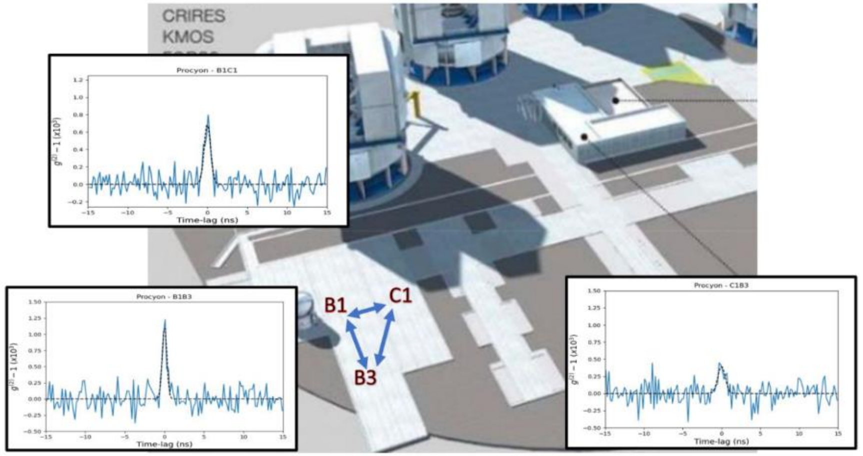




N. Matthews, J.-P. Rivet, M. Hugbart, G. Labeyrie, R. K., O. Lai, F. Vakili, D. Vernet, J. Chabe, C. Courde, N. Schuhler, P. Bourget, W. Guerin, [Proc. SPIE 12183, Optical and Infrared Interferometry and Imaging VIII, 121830G (2022)](),

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**

State of the art in 2024

Stellar Intensity Interferometry Workshop 2024

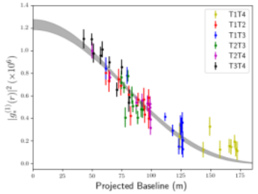
September 9th – 13th, 2024

Porquerolles, France

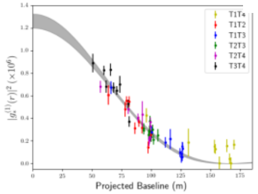
- Demonstration of stellar intensity interferometry with the four VERITAS telescopes,
  A. Abeysekara, et al., Nat, Astronomy 4, 1164 (2020)

λ=416nm

β Canis Majoris

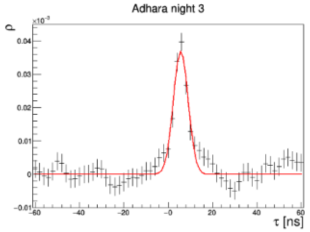


ε Orionis

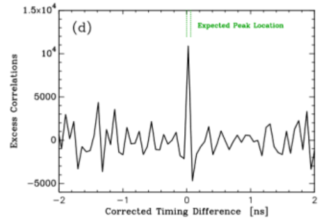


- V. Acciari, et al., Optical intensity interferometry observations using the MAGIC imaging atmospheric cherenkov telescopes,
  MNRAS 491, 1540 (2020)

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

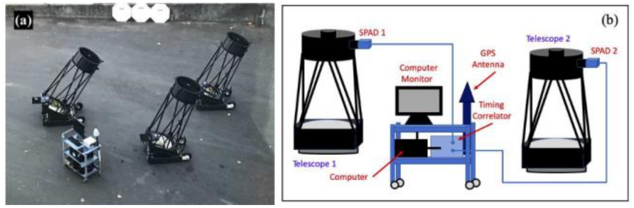


- L. Zampieri et al., Stellar intensity interferometry of Vega in photon counting mode, MNRAS, 506(2), 1585(2021). ASIAGO



- Observations with the Southern Connecticut Stellar Interferometer. I. Instrument Description and First Results

E. P. Horch et al 2022 AJ 163 92



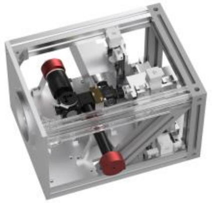
λ=532nm, 3 stars, 2 telescopes (diameter 0.6m)

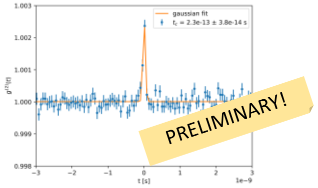
+ Hess Namibia (S. Funk et al.) : 2023

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

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

λ=405nm





Courtesy S.Richter et al.

Outline

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

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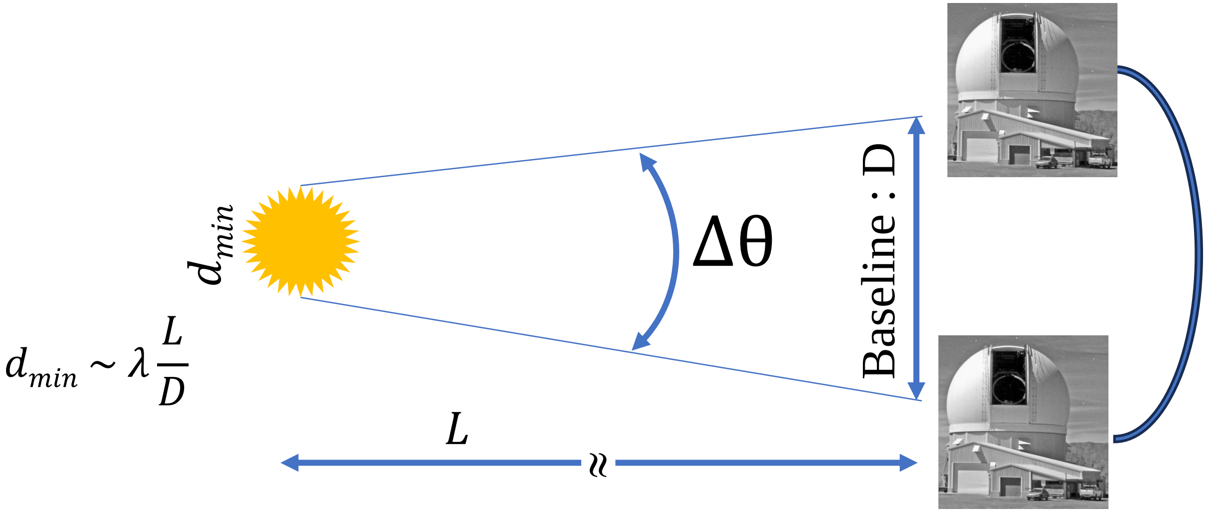
What next : IC4Stars

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



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

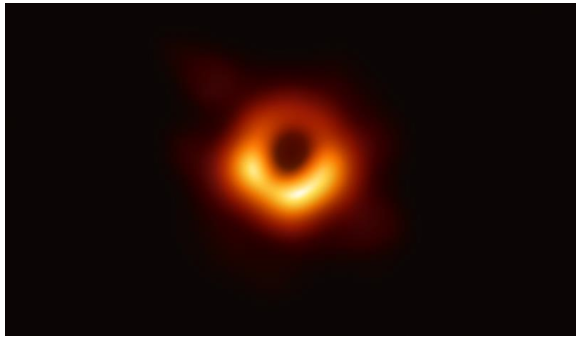
ii. intensity correlations $g^2(r)$
Hanbury Brown & Twiss

- 👍 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

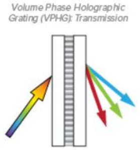
λ~420nm, D ~ km

λ~mm
D=12000 km



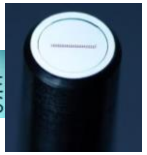
- The price to pay : low signal to noise ratio

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



Wasatch Photonics
1305 North 1000 West, Suite 120, Logan, UT 84321 USA
+1 435-752-4301 | www.wasatchphotonics.com

BERKSHIRE PHOTONICS



Multiplexing
N=16

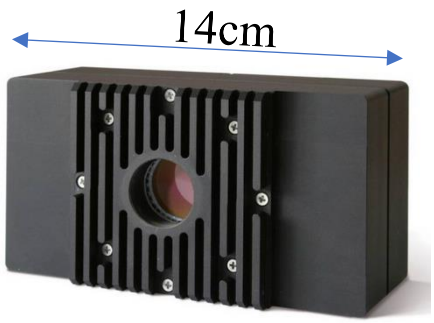
Keck/CFHT
10m/4m

Fast SPD
τ_{el}=20ps

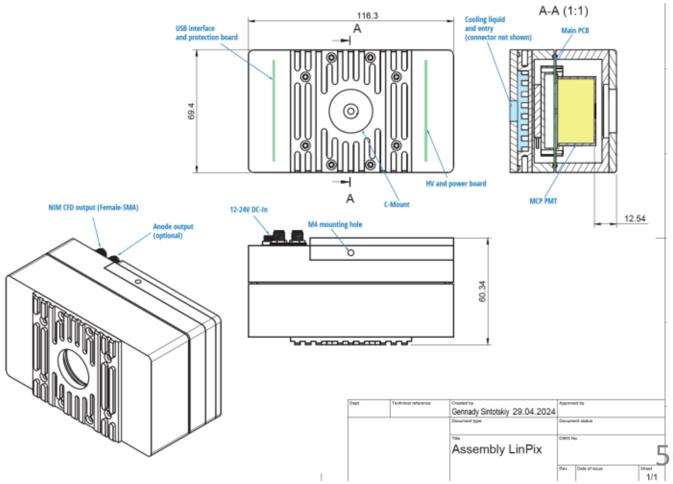
$$SNR\ :\quad \times\ 4 \quad \times 40 \quad \times\ 4 \ \Rightarrow\ \times 640$$

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

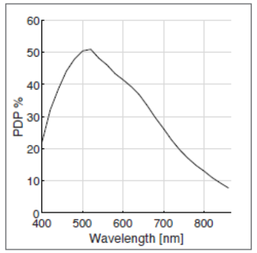
Photonscore : 2 x 16 LINPix



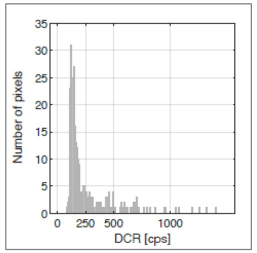
Max. recommended count rate, MHz	100
Shutdown count rate, MHz	110
Discrimination	Integrated CFD
Dark count rate, Hz	< 15 (Blue, Aqua), < 50 (Green), < 200 (Red)
Timing jitter, ps (FWHM)	< 35 (1MHz), < 45 (10MHz), < 75ps (100MHz)
Active area, mm	Ø8
Dead time, ns	< 2



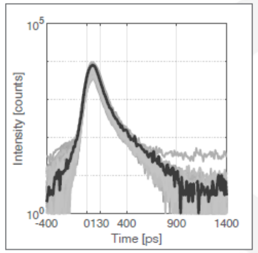
Pi Imaging : 2 SPADλ



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.

SPADλ

Description

SPADλ is a photon-counting linear array with time gating and time tagging. The core of the detector is a SPAD array with 320×1 pixels.

Photon counting with up to 555'000 frames per second and zero readout noise is achieved.

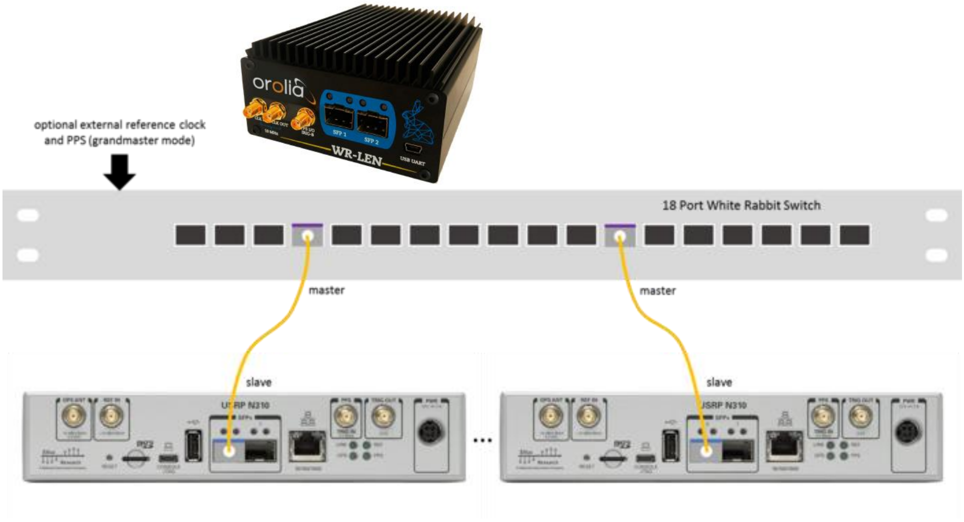
Nanosecond time gating is coupled with 17 ps gate phase shift. Time tagging with 20 ps resolution and 130 ps FWHM precision is available.

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)



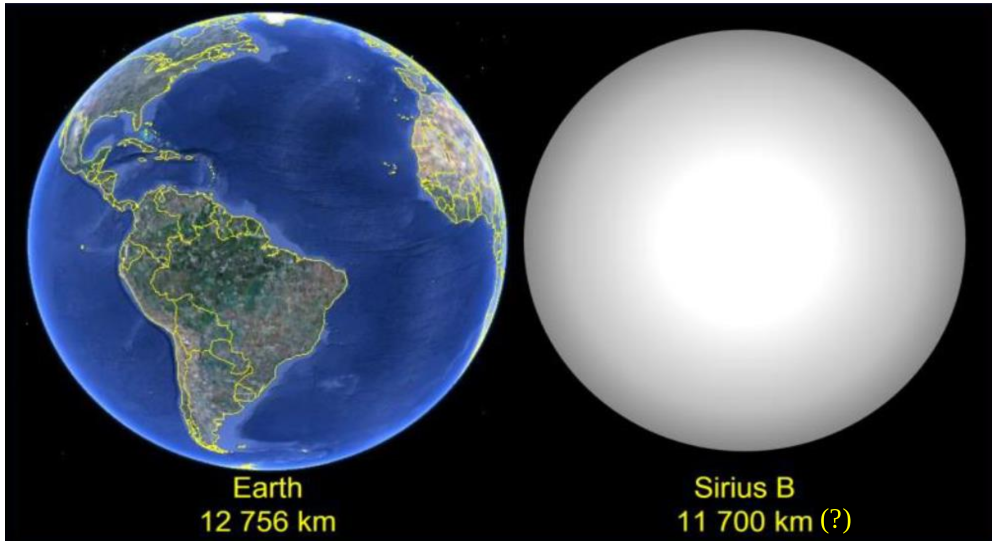
16 ps

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

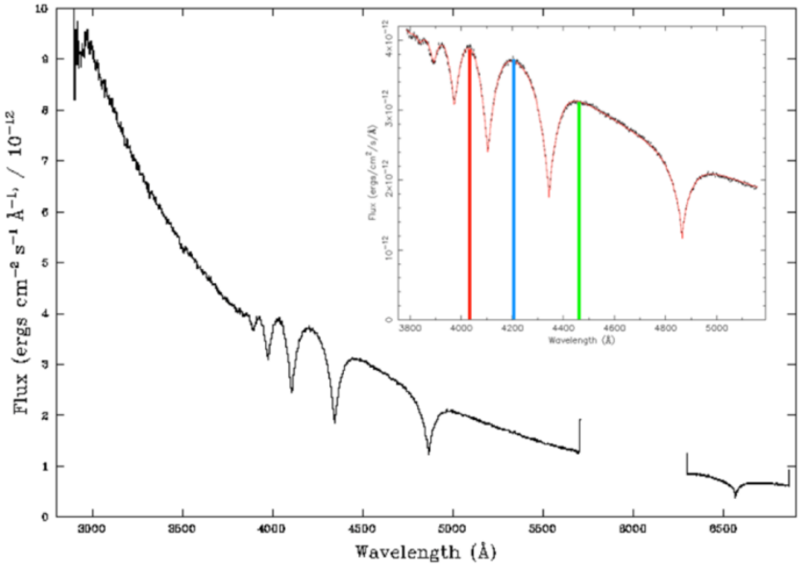
Angular resolution of a white dwarf



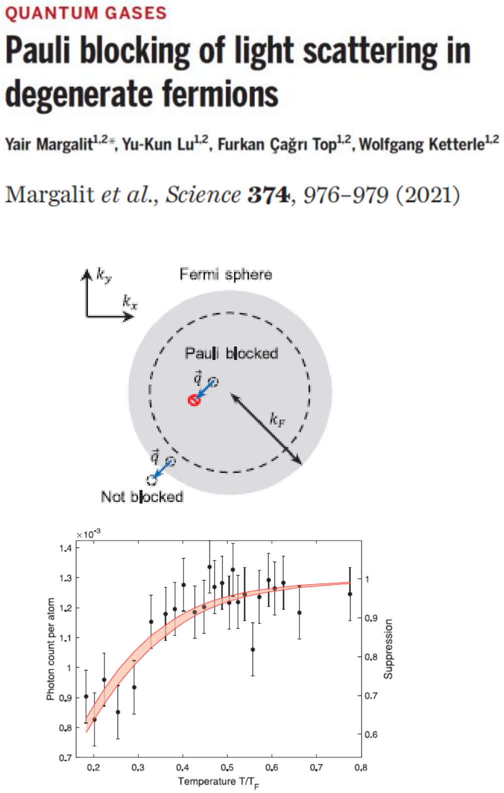
Count rates :
Sirius B
Quantum efficiency : 90%
Throughput : 20%

Keck: 110 000 cps
CHFT : 18 000 cps

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



Pauli blocking for in degenerate Fermi gases

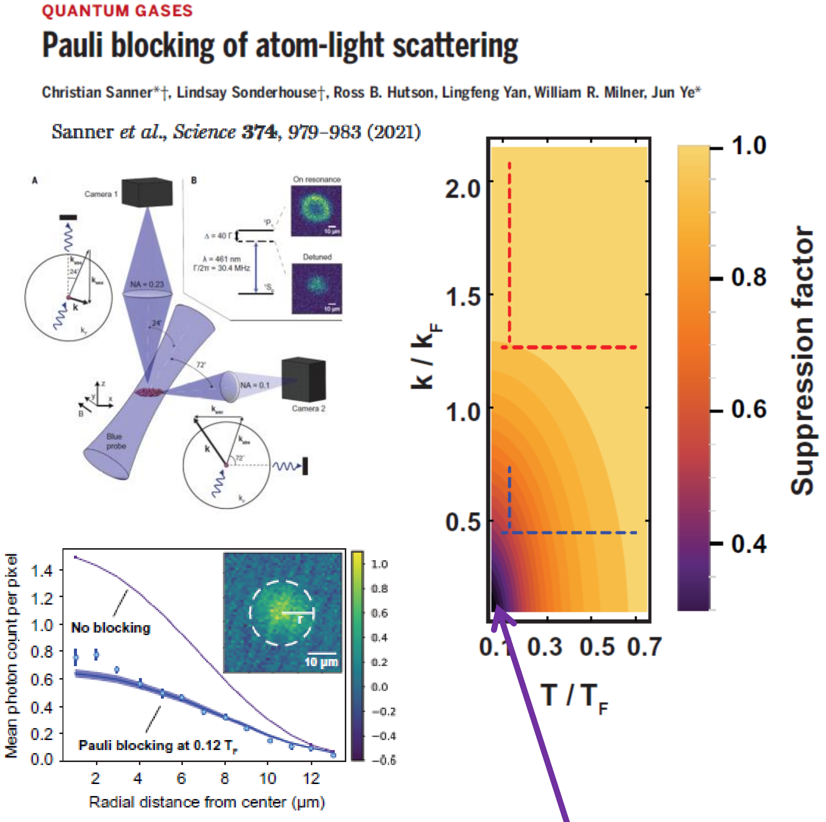


QUANTUM GASES

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)

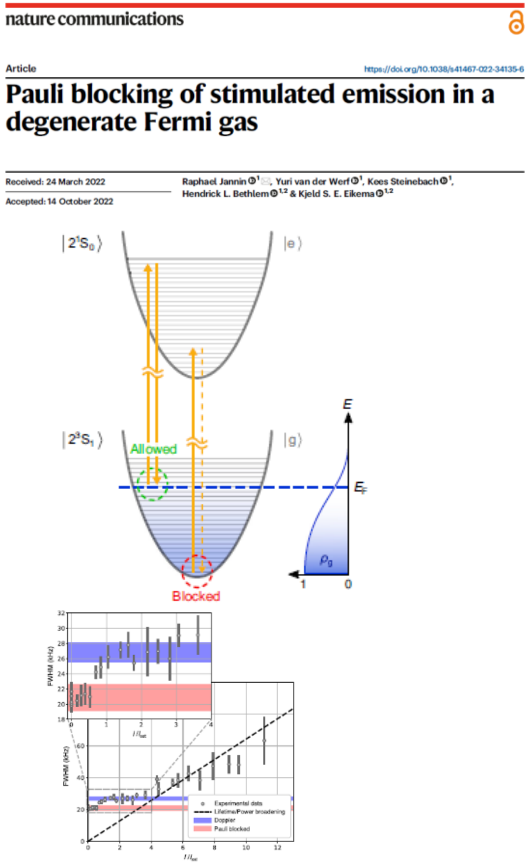


QUANTUM GASES

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)



nature communications

Article

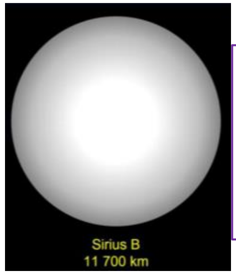
https://doi.org/10.1038/s41467-022-34135-6

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]



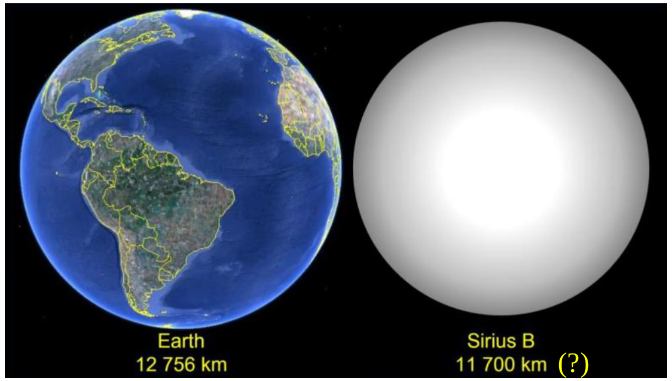
White dwarf :
$T/T_f \sim 10^{-6}$
$k/k_f \sim 10^{-6}$

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

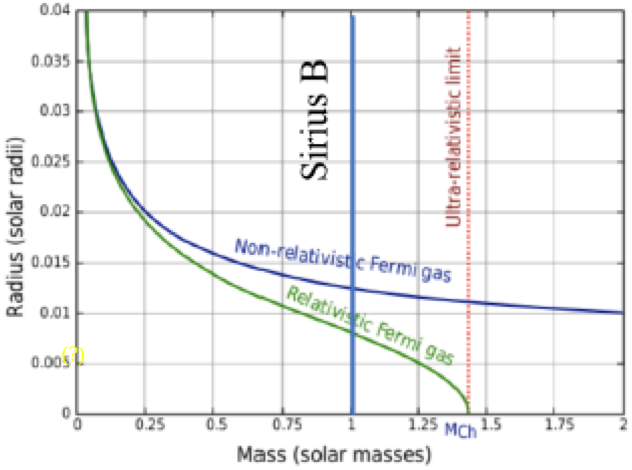
Path-opening on **Sirius B** (white dwarf) : quantum degenerate Fermi gas of electrons

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

Beyond reach of present instruments



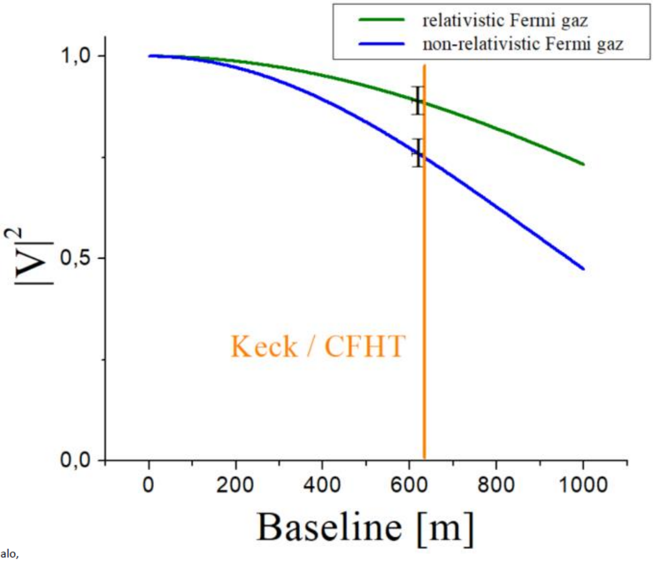
Magnitude=8.4



Mauna Kea @ Hawaii

Photon Bunching

- **@ λ = 420nm**
- **D=630m**



Sincerely,

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Chief of Technical Development
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Sincerely,

Jean-Gabriel Cuby
Executive Director
Canada-France-Hawaii Telescope

Mahalo,

Doug Simons

Doug Simons
Director
University of Hawaiʻi, Institute for Astronomy

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

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COMPREHENSIVE PHOTOMETRIC HISTORIES OF ALL KNOWN GALACTIC RECURRENT NOVAE

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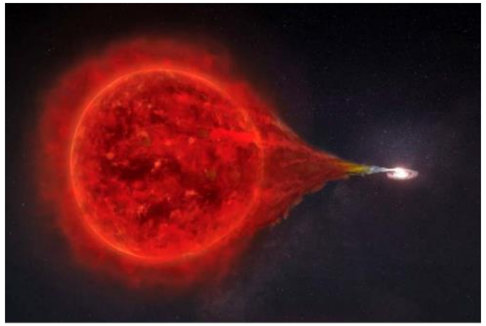
Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA; schaefer@lsu.edu

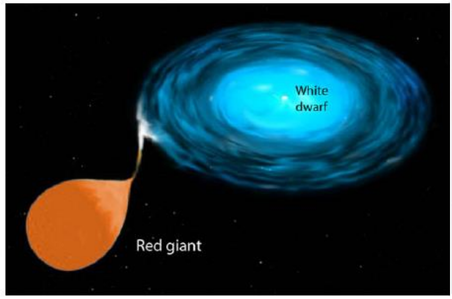
Received 2009 April 6; accepted 2010 January 20; published 2010 March 17

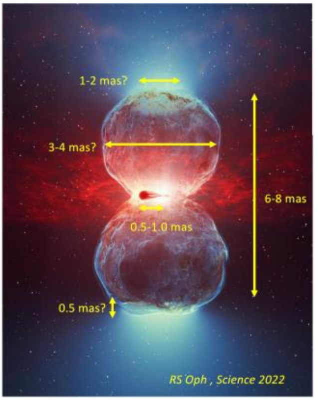
- Binary White Dwarfs
  (before Supernovae type I explosion)



T Cor Bor: recurrent nova?

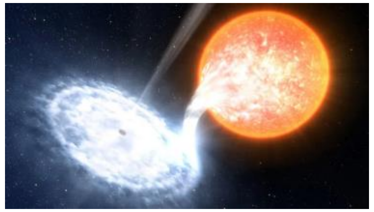
M10



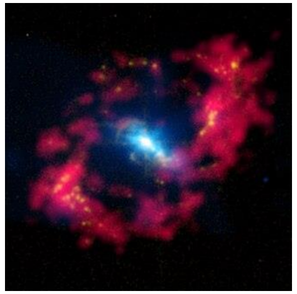


0.55-0.9 mas

- Black hole accretion disks

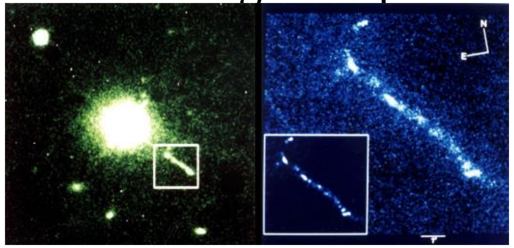


NGC4151



M11.5 / 100 μ″

3C 273 brightest quasar



(supermassive black hole)
M12.9

Outline

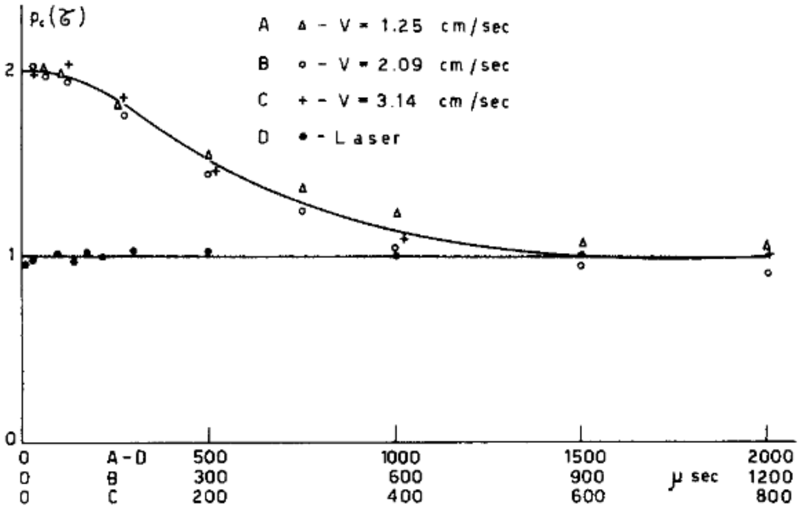
IC4Star project :

1) High angular resolution : white dwarf Sirius B
2) Quantum optics from space : random lasing from Eta Car

Second order coherence $\neq$ first order coherence

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

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

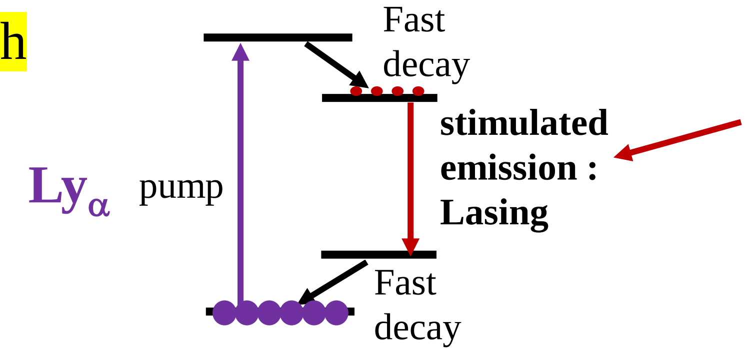


F.T. Arecchi, E. Gatti, A. Sona, Phys. Lett. 20, 27 (1966)

Quantum theory : R. Glauber

Bonus : quantum astro-optics : coherent light sources

- Random laser with 4 level scheme



Fast decay

stimulated emission : Lasing

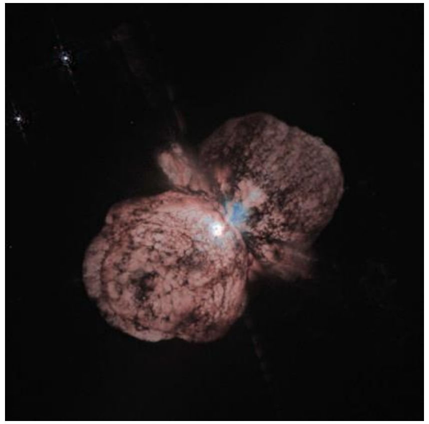
Ly_α pump

Fast decay

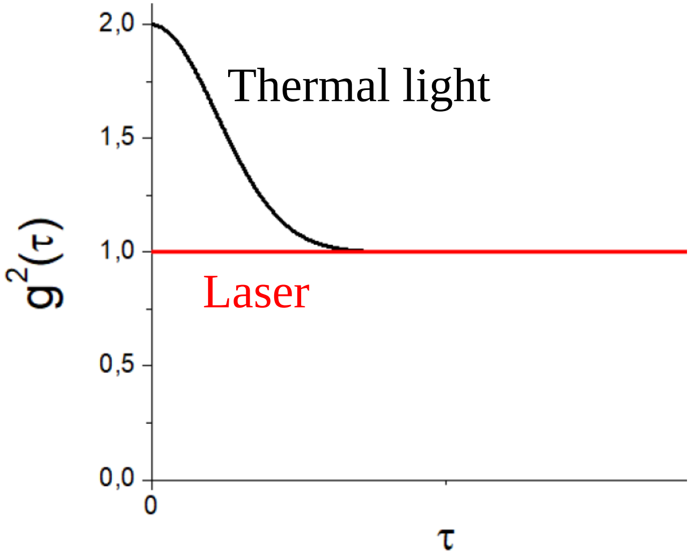
Fe II:

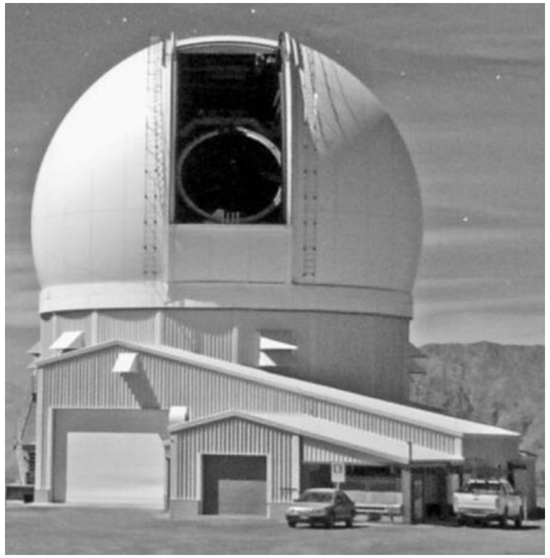
population inversion at 0.99 / 1.6 /1.7 µm

Eta Car



- Lasing signature : **g²(τ)** on a **single** telescope





SOAR
(Chile, southern hemisphere)

g2 vs g1 :
Second vs first order coherence

(i) <E>=0

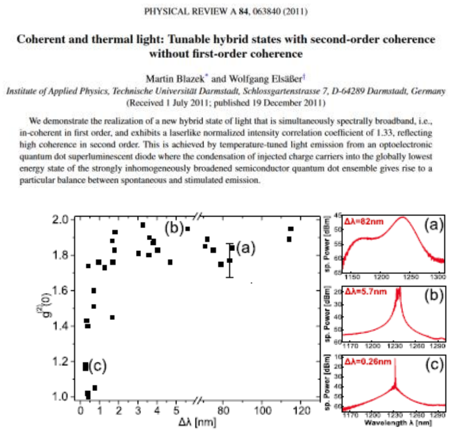
(ii) Gaussian correlations

⇒ Siegert relation: $g^2(\tau)-1 \propto |g^1(\tau)|^2$

Intensity correlations

TF [Optical spectrum I(ω)]

Deviation from Siegert relation: lasing ~~(i)~~ or Non-Gaussian correlations ~~(ii)~~



PHYSICAL REVIEW A **84**, 063840 (2011)

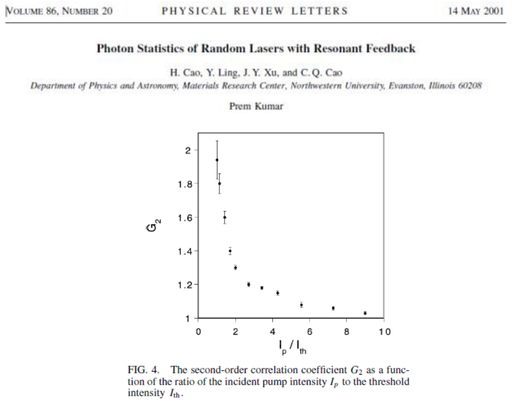
Coherent and thermal light: Tunable hybrid states with second-order coherence without first-order coherence

Martin Blazek* and Wolfgang Elsäßer†

Institute of Applied Physics, Technische Universität Darmstadt, Schlossgartenstrasse 7, D-64289 Darmstadt, Germany

(Received 1 July 2011; published 19 December 2011)

We demonstrate the realization of a new hybrid state of light that is simultaneously spectrally broadband, i.e., in-coherent in first order, and exhibits a laserlike normalized intensity correlation coefficient of 1.33, reflecting high coherence in second order. This is achieved by temperature-tuned light emission from an optoelectronic quantum dot superluminescent diode where the condensation of injected charge carriers into the globally lowest energy state of the strongly inhomogeneously broadened semiconductor quantum dot ensemble gives rise to a particular balance between spontaneous and stimulated emission.



VOLUME 86, NUMBER 20 PHYSICAL REVIEW LETTERS 14 MAY 2001

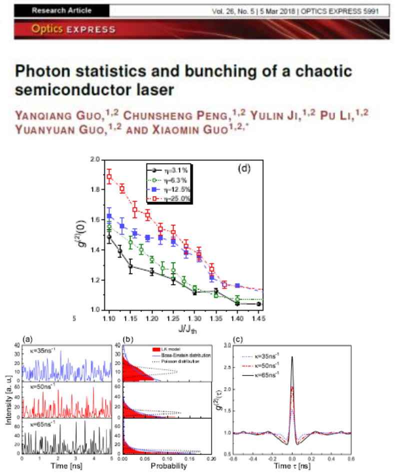
Photon Statistics of Random Lasers with Resonant Feedback

H. Cao, Y. Ling, J. Y. Xu, and C. Q. Cao

Department of Physics and Astronomy, Materials Research Center, Northwestern University, Evanston, Illinois 60208

Prem Kumar

FIG. 4. The second-order correlation coefficient G_2 as a function of the ratio of the incident pump intensity I_p to the threshold intensity I_{th}.

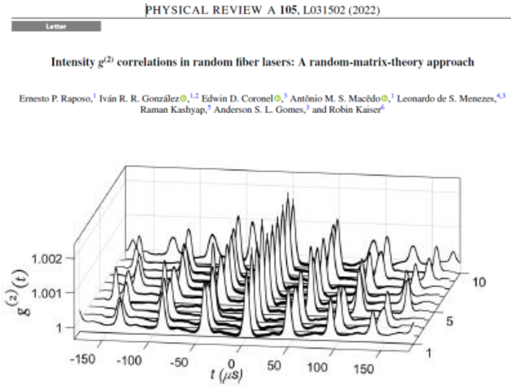


Research Article Vol. 26, No. 5 | 5 Mar 2018 | OPTICS EXPRESS 5991

Optics EXPRESS

Photon statistics and bunching of a chaotic semiconductor laser

YANQIANG GUO,[1,2] CHUNSHENG PENG,[1,2] YULIN JI,[1,2] PU LI,[1,2] YUANYUAN GUO,[1,2] AND XIAOMIN GUO[1,2,*]

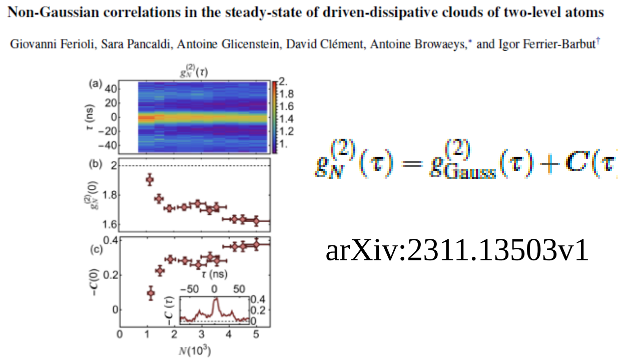


PHYSICAL REVIEW A **105**, L031502 (2022)

Letter

Intensity $g^{(2)}$ correlations in random fiber lasers: A random-matrix-theory approach

Ernesto P. Raposo,[1] Iván R. R. González,[1,2] Edwin D. Coronel,[3] Antônio M. S. Macêdo,[1] Leonardo de S. Menezes,[4,3] Raman Kashyap,[5] Anderson S. L. Gomes,[3] and Robin Kaiser[6]

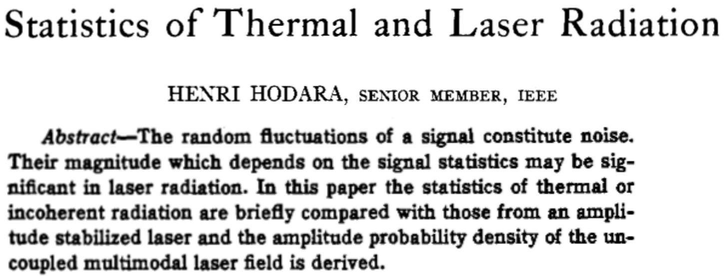


Non-Gaussian correlations in the steady-state of driven-dissipative clouds of two-level atoms

Giovanni Ferioli, Sara Pancaldi, Antoine Glicenstein, David Clément, Antoine Browaeys,* and Igor Ferrier-Barbut†

$$g_N^{(2)}(\tau) = g_{\mathrm{Gauss}}^{(2)}(\tau) + C(\tau)$$

arXiv:2311.13503v1



Statistics of Thermal and Laser Radiation

HENRI HODARA, SENIOR MEMBER, IEEE

***Abstract*—The random fluctuations of a signal constitute noise. Their magnitude which depends on the signal statistics may be significant in laser radiation. In this paper the statistics of thermal or incoherent radiation are briefly compared with those from an amplitude stabilized laser and the amplitude probability density of the uncoupled multimodal laser field is derived.**

Proc. IEEE 53, 696 (1965)

Hodara formula :

Relative intensity noise

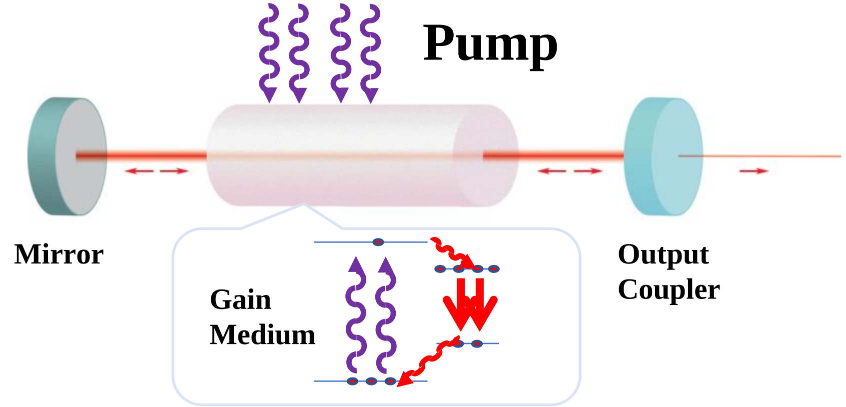
$$\mathrm{RIN}_{\mathrm{general}} = \frac{2e}{\langle i\rangle} + \frac{\langle i_{\mathrm{sp}}\rangle^2}{\langle i\rangle^2}\cdot\frac{1}{\Delta\nu} = \frac{2e}{\langle i\rangle} + \frac{\beta^2}{\Delta\nu}$$

β=1 ⇔ Siegert relation

β=0 ⇔ laser

Random lasing

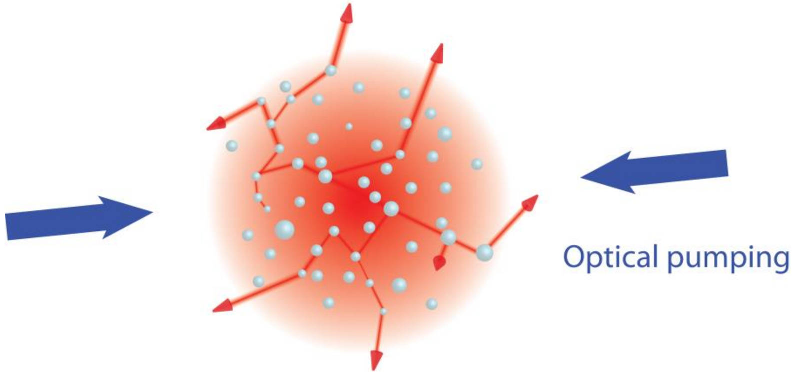
- Cavity Laser



Ingredients:

- Gain Medium
- Cavity
  → Feedback & Mode Selection

- Random Laser



- Gain Medium
- **Multiple scattering**

V.S. Letokhov, Sov. Phys. JETP ***26****, 835-840 (1968)*

1939–2009

Atomic physics laboratory experiments

Goal : find spectroscopic signatures of gaseous random lasing


nature physics

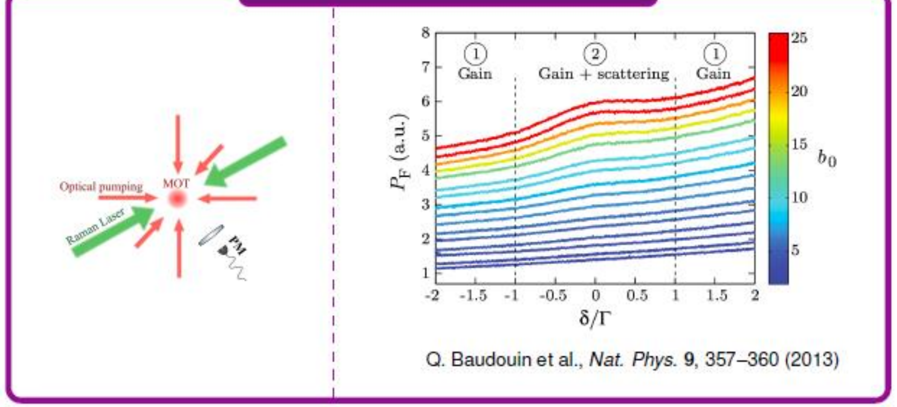
LETTERS

PUBLISHED ONLINE: 5 MAY 2013 | DOI:10.1038/NPHYS2614

A cold-atom random laser

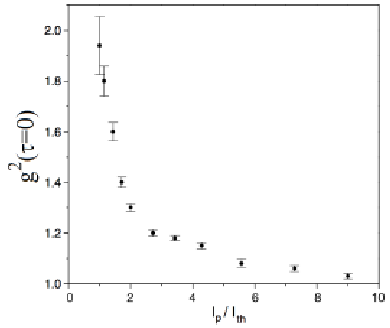
Q. Baudouin, N. Mercadier†, V. Guarrera†, W. Guerin and R. Kaiser*

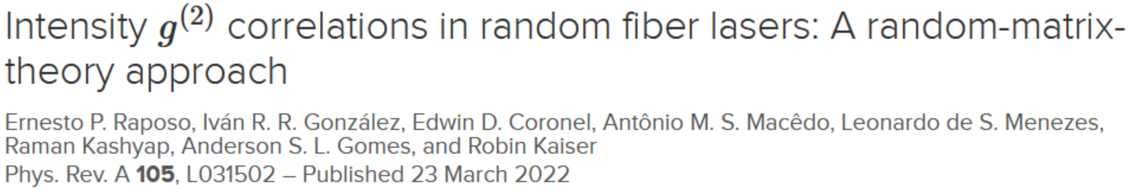
Observation of cold ^{85}Rb RL



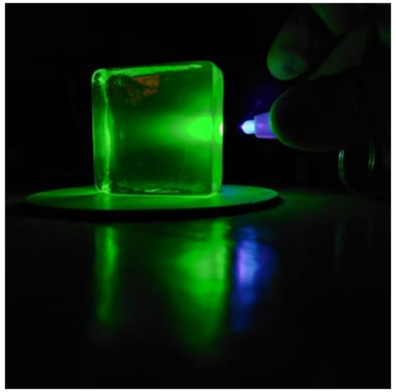
Q. Baudouin et al., *Nat. Phys.* **9**, 357–360 (2013)

H. Cao et al., *Phys. Rev. Lett.* **86**, 4524 (2001)




Intensity $g^{(2)}$ correlations in random fiber lasers: A random-matrix-theory approach

Ernesto P. Raposo, Iván R. R. González, Edwin D. Coronel, Antônio M. S. Macêdo, Leonardo de S. Menezes, Raman Kashyap, Anderson S. L. Gomes, and Robin Kaiser
Phys. Rev. A **105**, L031502 – Published 23 March 2022

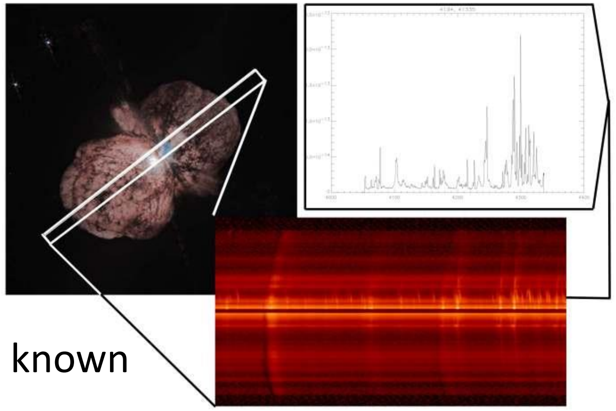


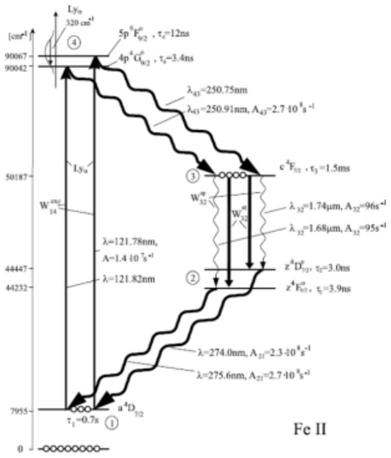
Bunching	$g^2(0)=2$	
Superbunching	$g^2(0) > 2$	
No bunching	$g^2(0)=1$	?

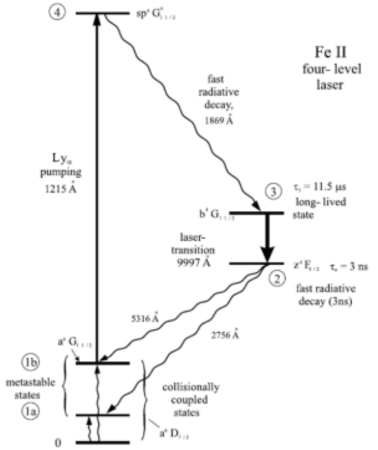
Goal : find quantum optics signatures in star light

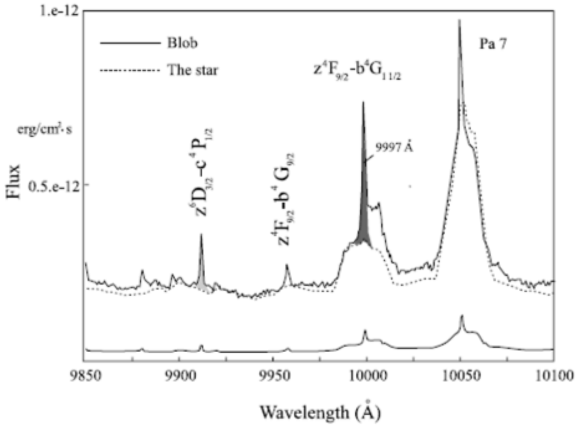
Eta Carinae

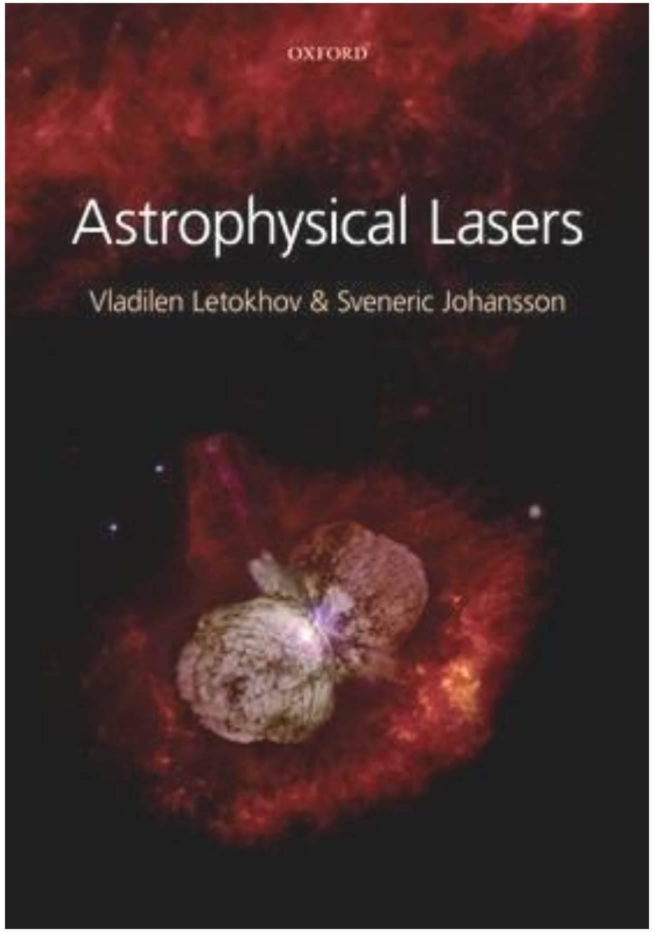
one of the most massive and luminous stars known










OXFORD

Astrophysical Lasers

Vladilen Letokhov & Sveneric Johansson

PAPER • OPEN ACCESS

Space QUEST mission proposal: experimentally testing decoherence due to gravity

Siddarth Koduru Joshi[1,2], Jacques Pienaar[1], Timothy C Ralph[3], Luigi Cacciapuoti[4], Will McCutcheon[2], John Rarity[2], Dirk Giggenbach[5], Jin Gyu Lim[6], Vadim Makarov[7], Ivette Fuentes[1]

Show full author list

Published 12 June 2018 • © 2018 The Author(s). Published by IOP Publishing Ltd on behalf of Deutsche Physikalische Gesellschaft

New Journal of Physics, Volume 20, June 2018

Citation Siddarth Koduru Joshi *et al* 2018 *New J. Phys.* **20** 063016

DOI 10.1088/1367-2630/aac58b

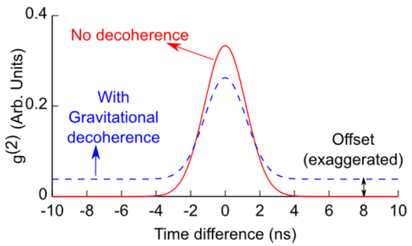


Figure 3. Illustration of the gravitational decoherence effect. Consider a temporal cross correlation histogram $g^{(2)}$ between the arrival times of photons at the OGS and on the ISS. The area of the peak represents the number of photon pairs while the number of singles events is obtained from the photon counting module. The gravitational decoherence effect from [4], should result in a decrease in the number of photon pairs (area) without altering the singles rate, the position of or the width of the peak. This is depicted in the above figure where the red (solid) curve shows the $g^{(2)}$ in the absence of a gravitational field gradient (i.e., without gravitational decoherence effect) and the blue (dashed) curve shows the effect of gravitational decoherence between an OGS and the ISS at the zenith 400 km away using a source of time entangled photon pairs with a coherence time of 0.8 ps. The offset shown here is grossly exaggerated and for illustrative purposes only. Therefore, to observe the gravitational decoherence effect we cannot rely on measuring the change in noise/background accidental count rates, instead we rely on measuring the change in area between the two curves. We emphasize that the gravitational decoherence effect can still be observed despite a detector jitter of several ns. Reducing the jitter only improves the signal to noise ratio (SNR) by reducing the accidental coincidence rate (which contributes to the offset).

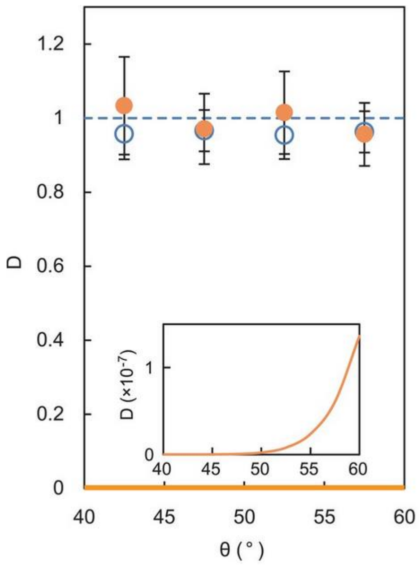
HOME > SCIENCE > VOL. 366, NO. 6461 > SATELLITE TESTING OF A GRAVITATIONALLY INDUCED QUANTUM DECOHERENCE MODEL

REPORT

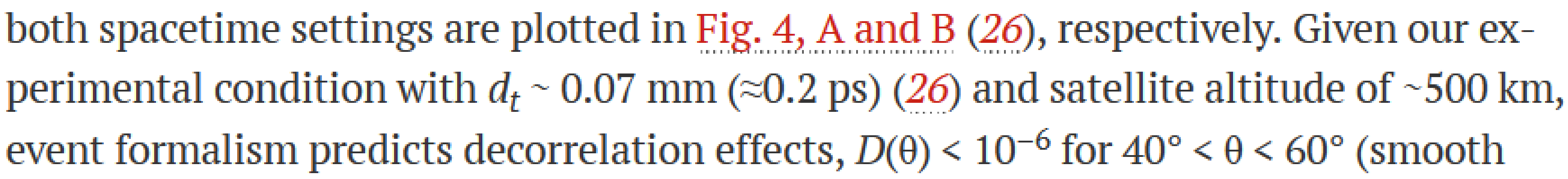
Satellite testing of a gravitationally induced quantum decoherence model

PING XU, YIQIU MA, JI-GANG REN, HAI-LIN YONG, TIMOTHY C. RALPH, SHENG-KAI LIAO, JUAN YIN, WEI-YUE LIU, WEN-QI CAI, [...], AND JIAN-WEI PAN +13 authors Authors Info & Affiliations

SCIENCE • 19 Sep 2019 • Vol 366, Issue 6461 • pp. 132-135 • DOI: 10.1126/science.aay5820



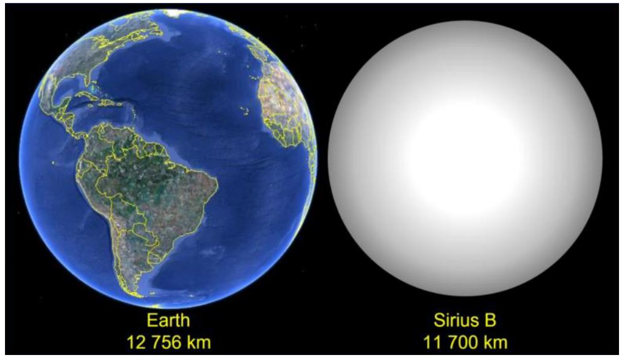
. Inset: magnified view of the predictions of event formalism.



both spacetime settings are plotted in Fig. 4, A and B (*26*), respectively. Given our experimental condition with d_t ~ 0.07 mm (≈0.2 ps) (*26*) and satellite altitude of ~500 km, event formalism predicts decorrelation effects, $D(\theta) < 10^{-6}$ for 40° < θ < 60° (smooth

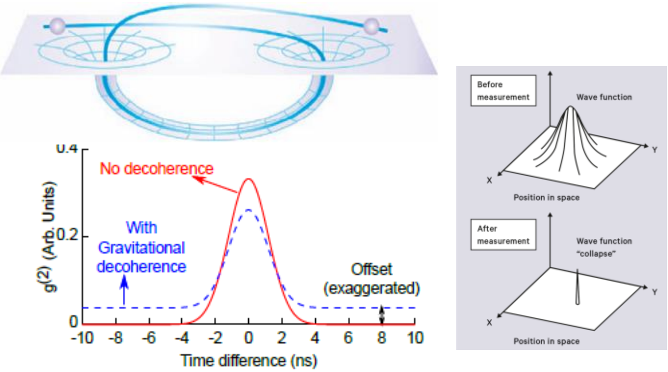
Beyond IC4Stars

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



Probe quantum gravity

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



New J. Phys. 20, 063016 (2018)

EU COST action : CA23115 - Relativistic Quantum Information

Thank you for your attention

Open positions (PhD, postdoc)