Intensity Correlations for Stars

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Outline

1) **Optical astrophysical imaging and Hanbury-Brown and Twiss experiments**
2) **Intensity correlations**
3) **HBT revival : on-sky intensity correlations from 2017-2023**
4) **IC4Star project**
    - **Ultrahigh angular resolution : Sirius B**
    - **Quantum optics : random lasing in space**

Intensity Correlation team in Nice




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former postdocs and PhD :
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A. Dussaux
N. Matthews

Lagrange




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+ external collaborators:

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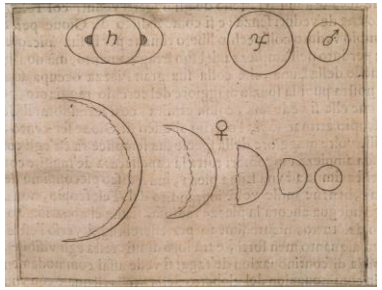
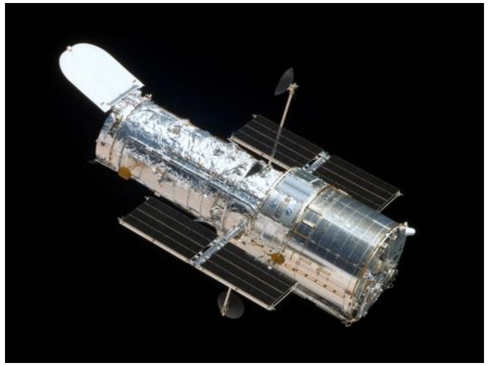
From Galileo (1564-1642) to Hubble Telescope (1990-2026?) & JWST

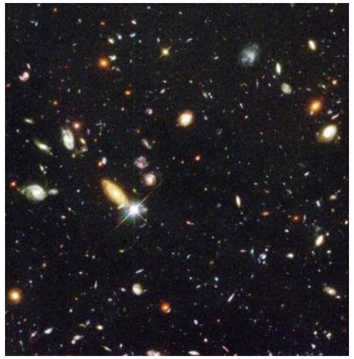
Direct imaging : large telescopes

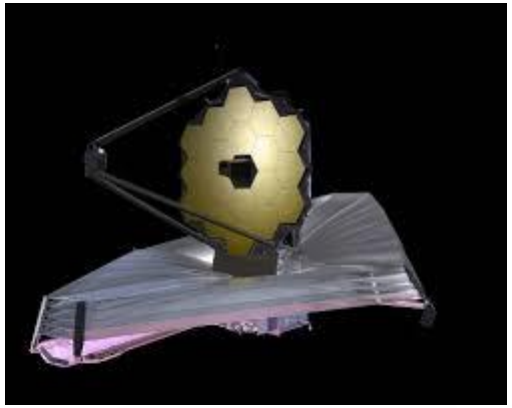


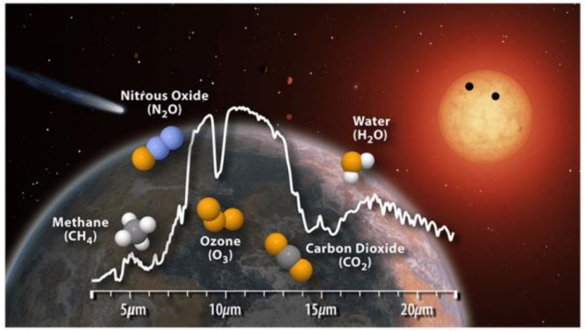
Phases of Venus

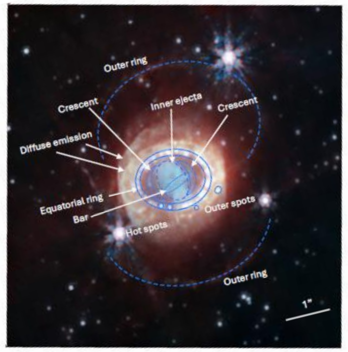
Sunspots drawn by Galilieo, June 1612



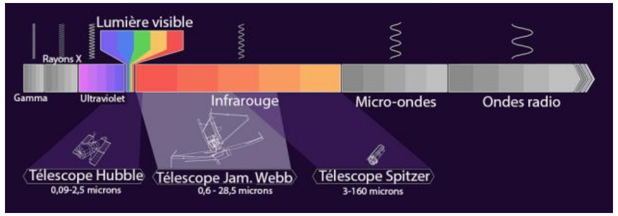




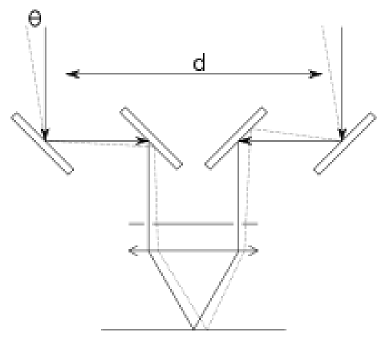


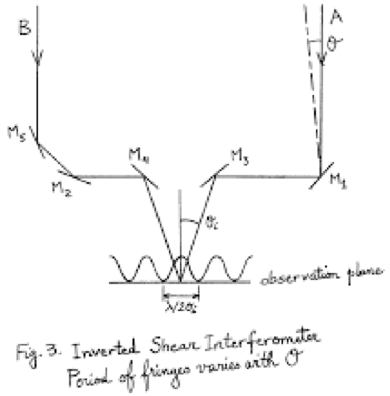


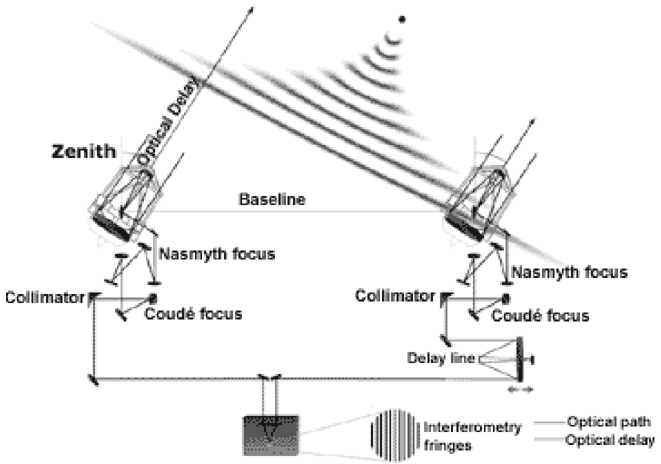
Black holes, dark matter, exoplanets, universe expansion, biosignatures …

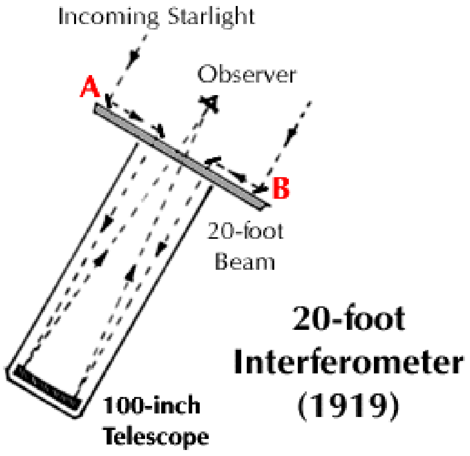


Interferometric imaging: large separation



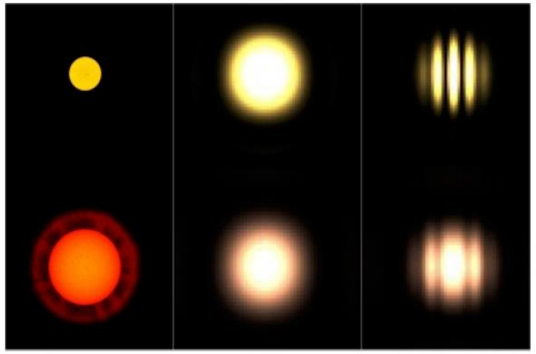






Small star

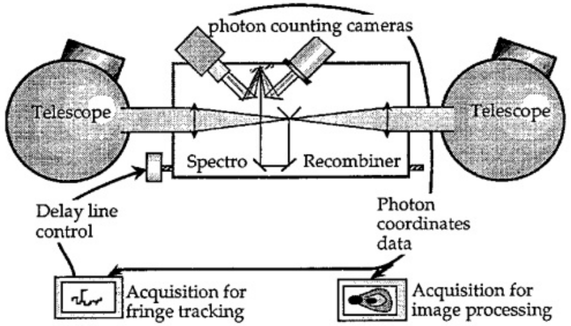
Big star

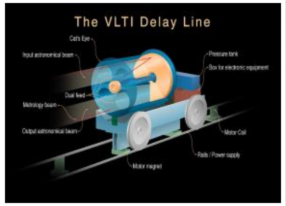


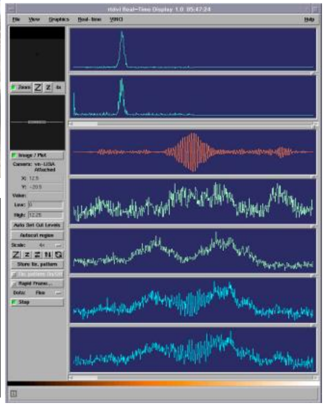
Objects	Single Telescope	Interf. Fringes
	$I_{im}(\alpha) \sim \mathcal{F}(D)$	$I_{im}(\alpha) \sim \mathcal{F}(B)$
Angular Resolution:	$\sim \lambda/D$	$\sim \lambda/B$

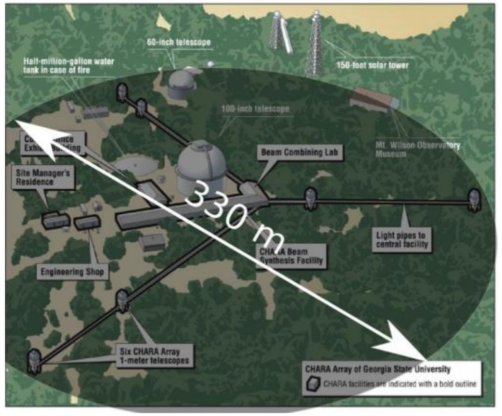
Interferometric imaging: large separation

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



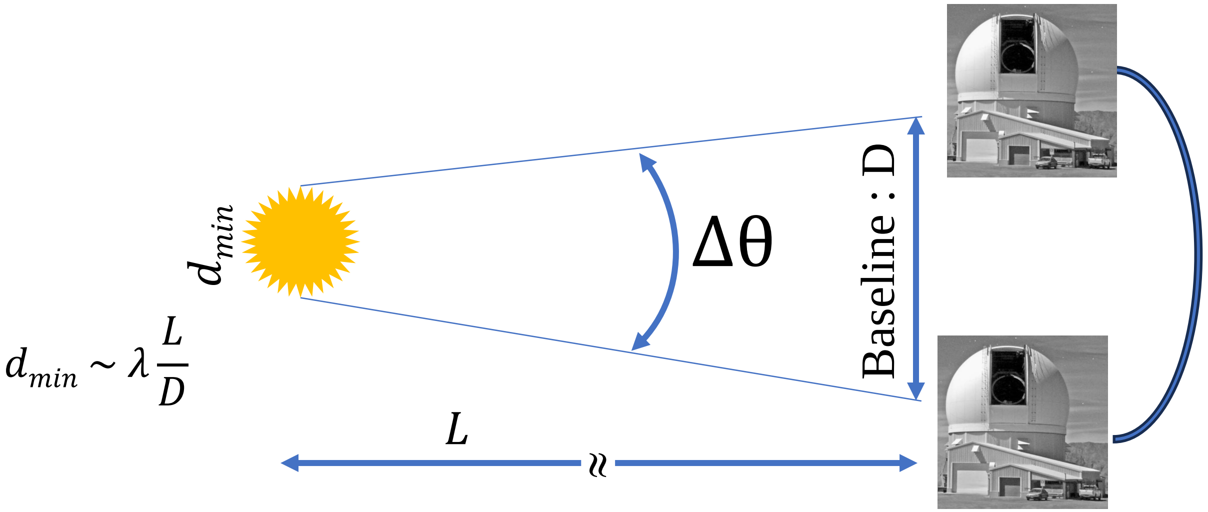






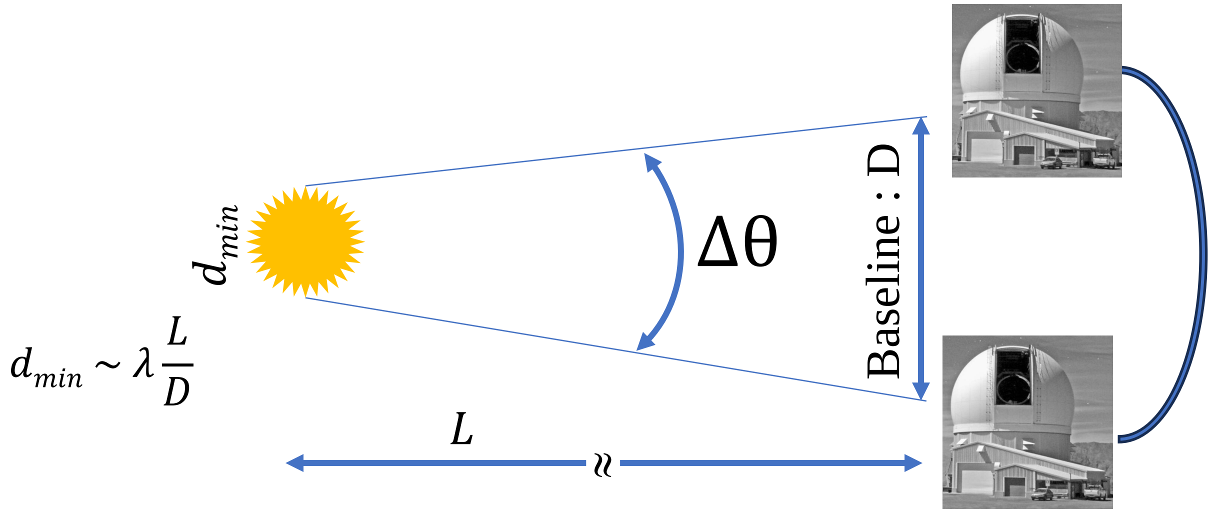
Calern (France) **Chili** **Mt Wilson (USA)**

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



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

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

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)].

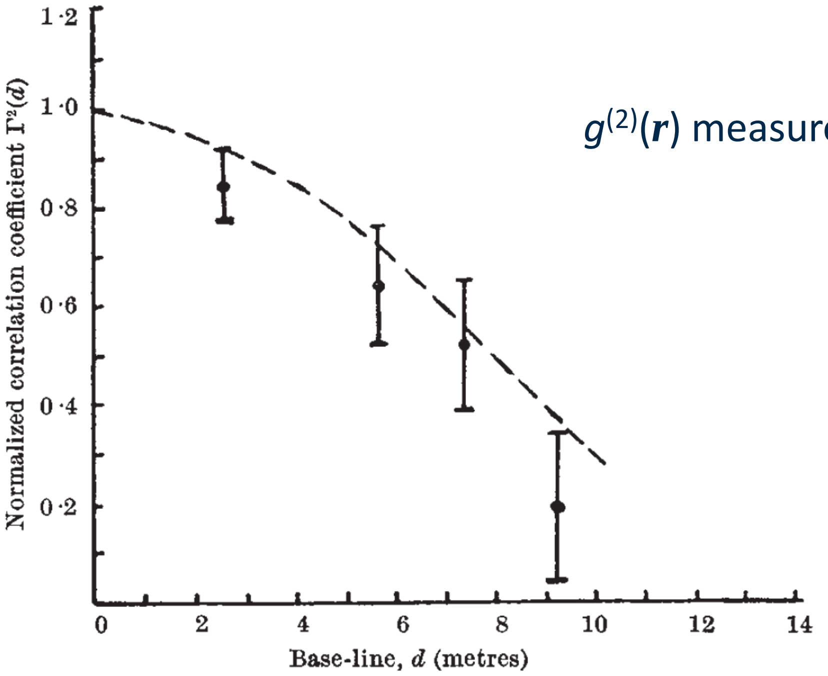
1954: The theory behind it [Hanbury Brown & Twiss, *Phil. Mag*. **45**, 663 (1954)].

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

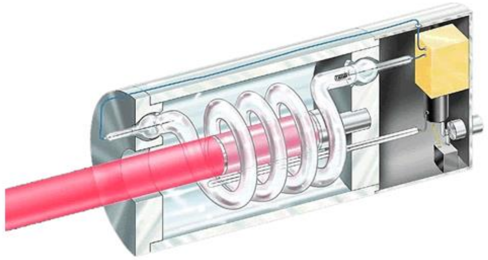
→ First direct measurement of the angular diameter: 6.8 ±0.5 mas

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

1956-1957: Some **controversy** on the Hanbury Brown & Twiss effect

- 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  **)**

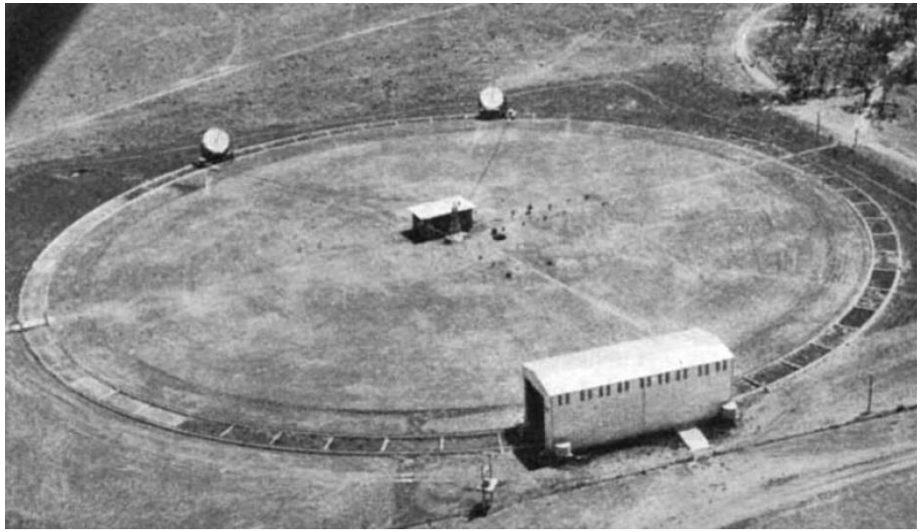
HBT experiment : milestone in the development of quantum optics
&
photon correlations are still the daily bread of quantum opticians

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 ☺

Interferometric imaging

- Stability / atmospheric turbulence (at λ) ☹ ☹
- Complex delay lines required €€€ ☹ ☹ ☹
- Large Baselines ☺ ☺
- Excellent Signal to Noise Ratio ☺ ☺ ☺ ☺ ☺

Intensity correlations

- Insensitive to atmospheric turbulence ☺ ☺
- Insensitive to telescope imperfections ☺
- No new infrastructure required €€€ ☺ ☺ ☺
- Efficient at short wavelengths (blue) ☺
- Very large baselines ☺ ☺ ☺ ☺
- Poor Signal to Noise Ratio ☹ ☹ ☹ ☹ ☹ ☹ ☹

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and Hanbury-Brown and Twiss experiments

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- Ultrahigh angular resolution : Sirius B
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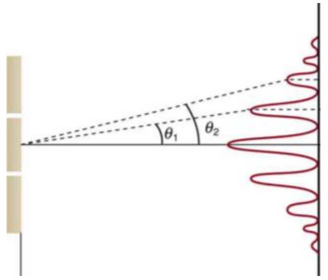
Intensity correlations : how does it work ?

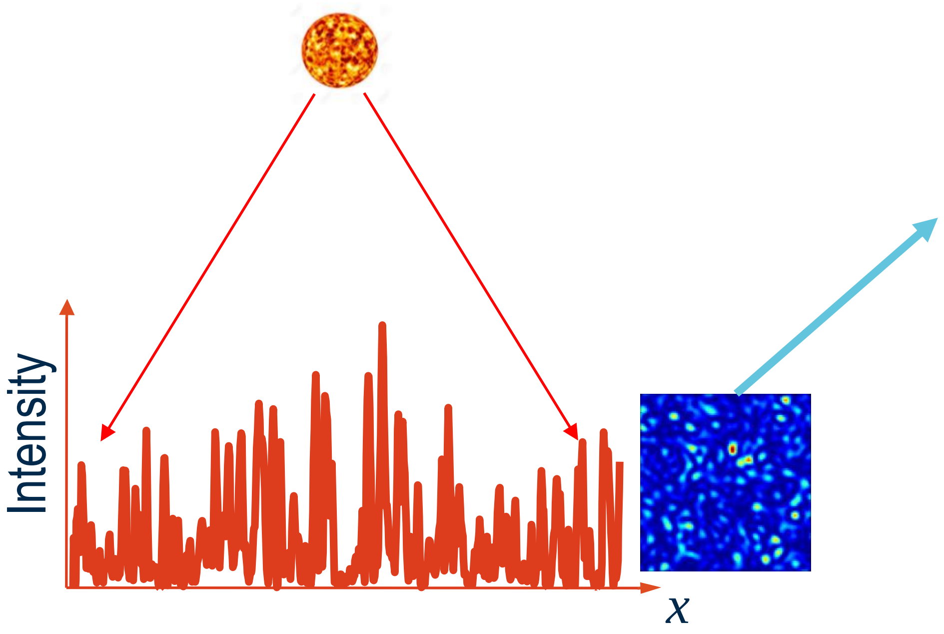
Spatially incoherent source (random phases)

Interference between 2 points from the sources: fringes

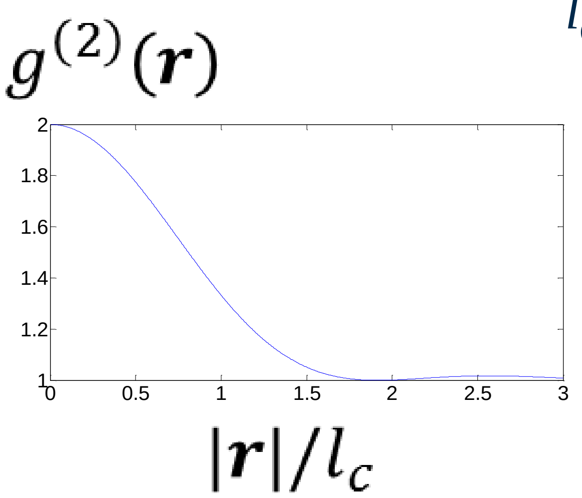


Extended source = many couples of points → complex disordered pattern ('speckle').

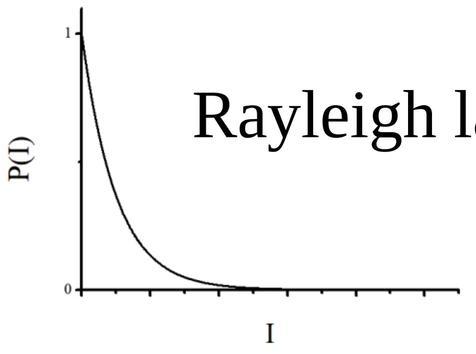
→ Not a white noise ! **Correlation length** l_c ('size of the speckle grain')



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



Speckle statistics

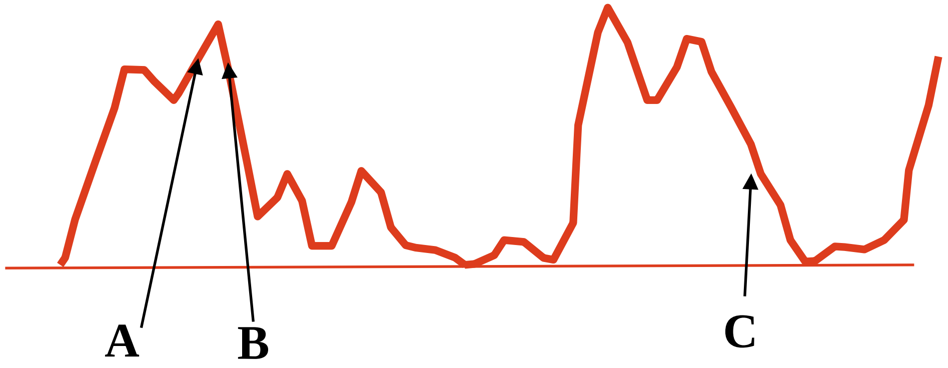


Rayleigh law

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

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

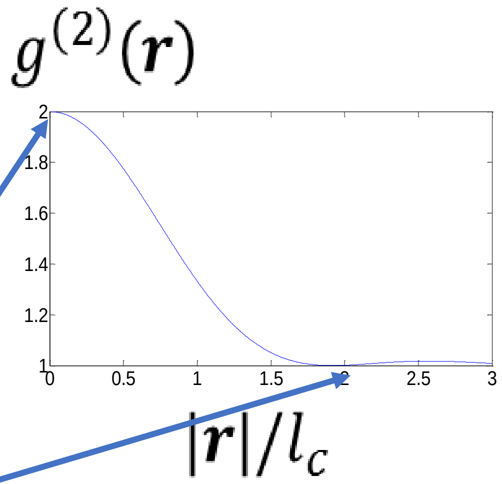
Photon bunching $g^{(2)}(0)=2$



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

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

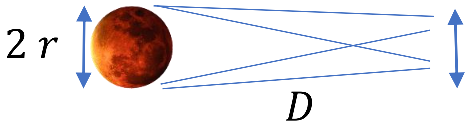
$$g_{AC}(2) = \langle I_A I_C \rangle / \langle I_A \rangle \langle I_C \rangle = 1$$

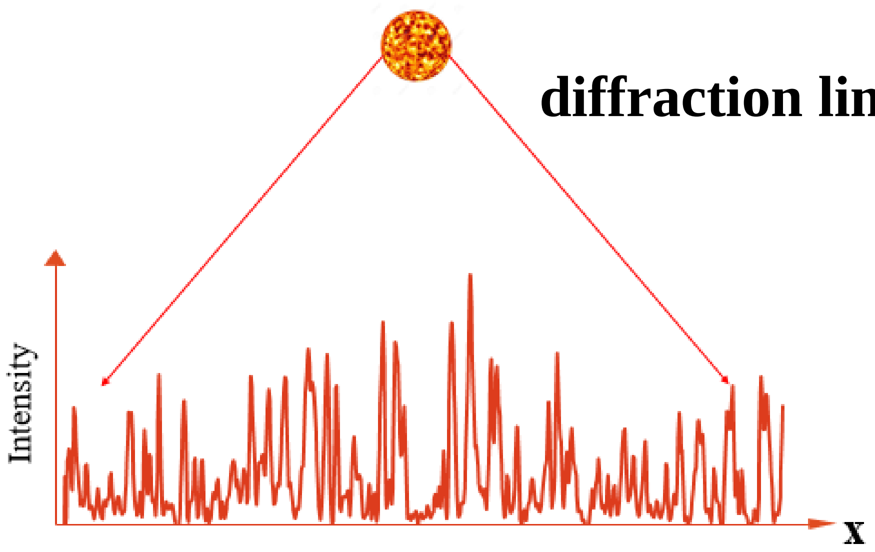


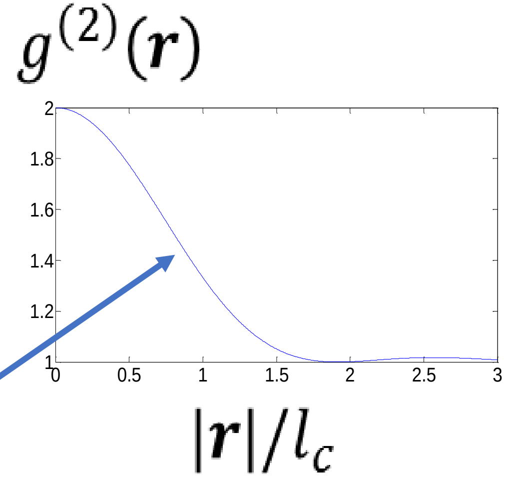
Spatial scales

diffraction limit $\theta = \lambda / D$

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

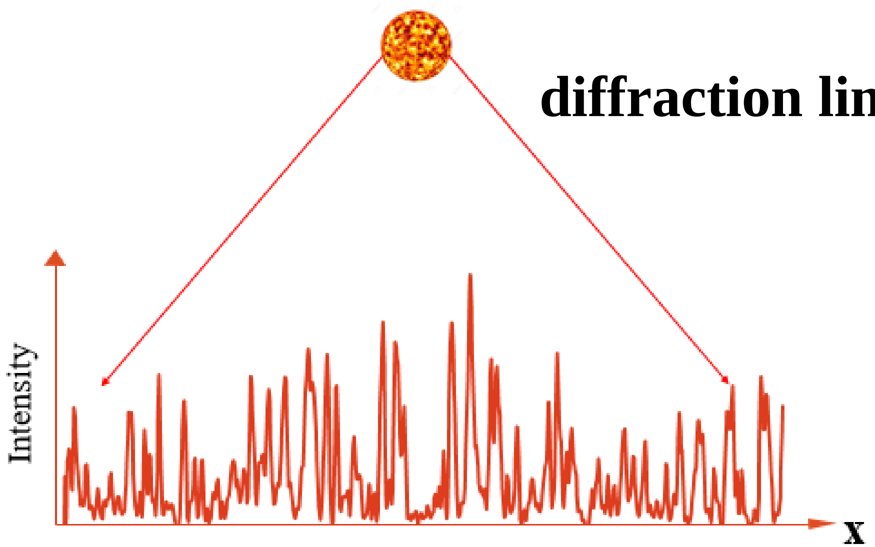




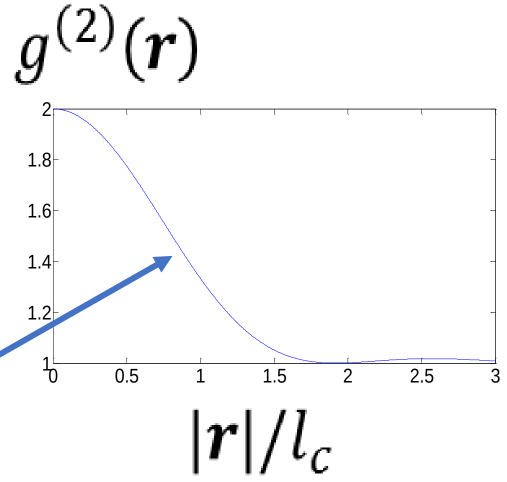


Speckle grain size : $l_c \sim \theta\, L \sim L\ \lambda / D$

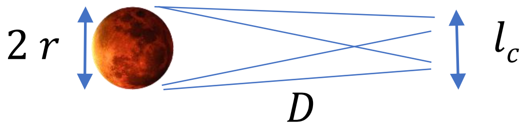
Spatial scales



diffraction limit $\theta = \lambda / D$

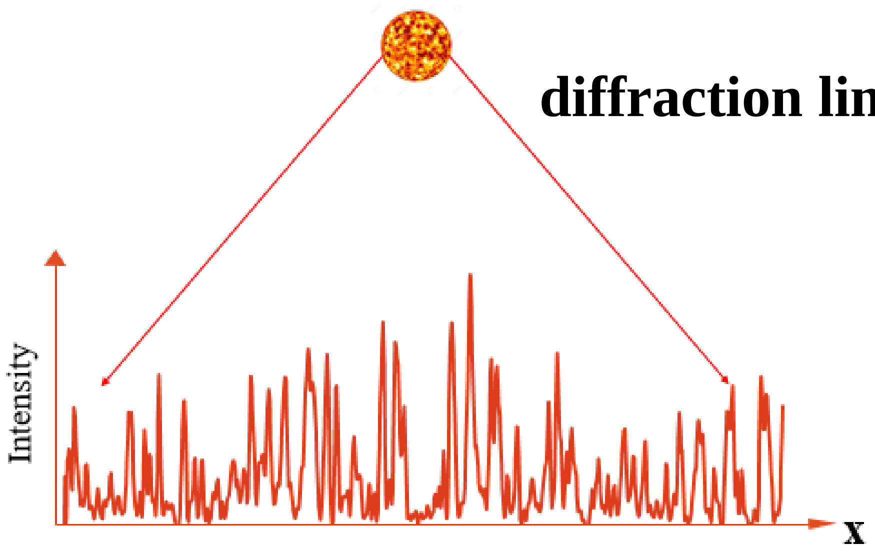


$$l_c = \frac{\lambda D}{\pi r}$$

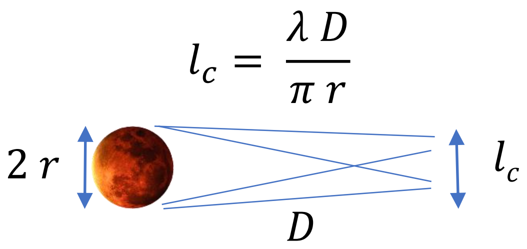


Speckle grain size : $l_c = \theta L \sim \lambda L / D$

Time scales



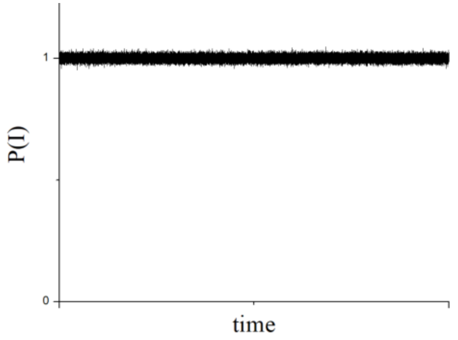
diffraction limit $\theta = \lambda / D$

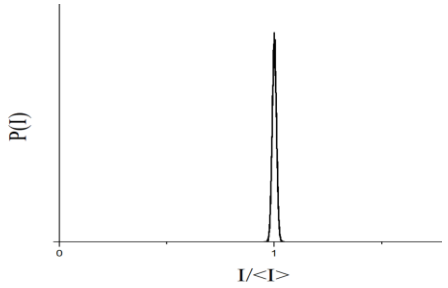


Speckle grain size : $l_c = \theta L \sim \lambda L / D$

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

Laser photon statistics





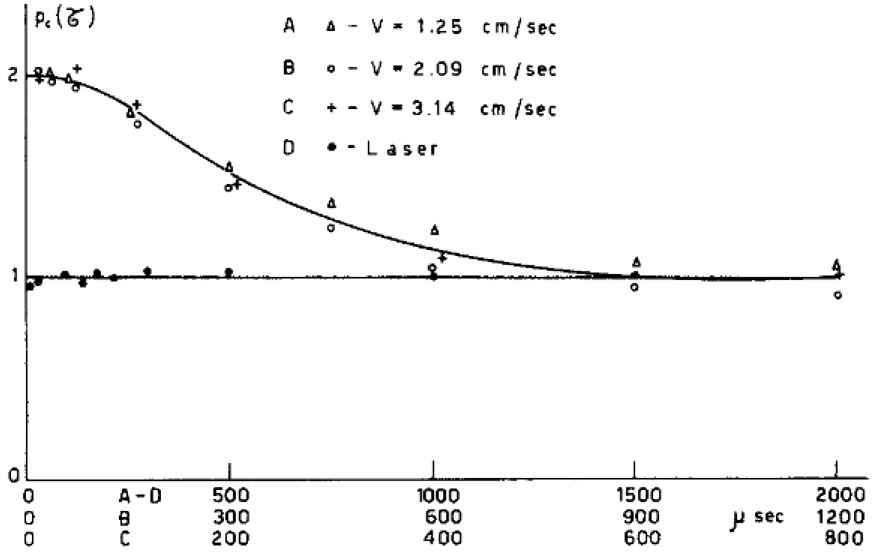
$P(I) \approx 1 + \delta I$

$\langle I^2 \rangle \approx \langle I \rangle^2$

No photon bunching
$g^{(2)}(\tau)=1$

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

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



Initial Experiments with lasers: Armstrong 1965

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

Intensity correlations vs field correlations

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

  van Cittert – Zernike theorem (1934, 1938)

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

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

  Siegert relation :

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

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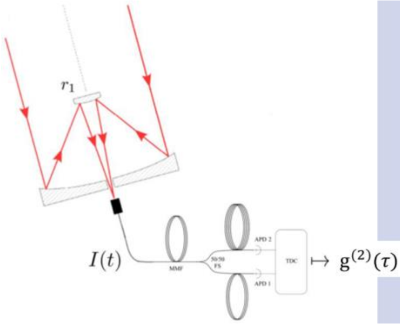
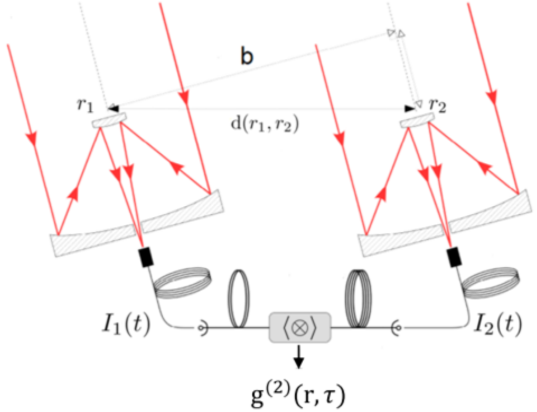
Second generation of intensity correlations for astrophysics

Goal : revive intensity correlation to

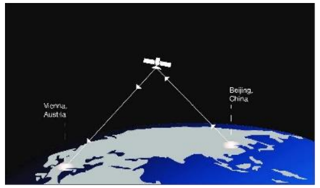
- **Overcome baseline limitations by amplitude interferometry : $g^{(2)}(r)$**
- **Open a quantum optics eye to space observations : $g^{(2)}(\tau)$**





Why now :

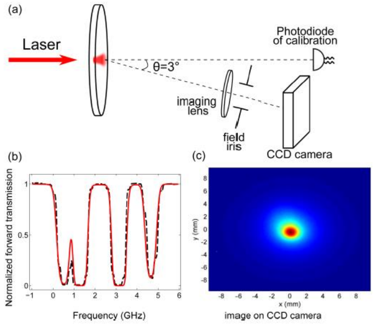
- **Take advantage of quantum optics detection toolbox (fast photon counting)**
- **Record full temporal correlation function**
- **Combined expertise (astrophysics, atomic and quantum physics) available in Nice**
- **Maturing astrophysical community (CTA: Veritas / Magic, Asiago, …)**
- **Quantum Optics in Space for quantum communications and Deep Space communication**

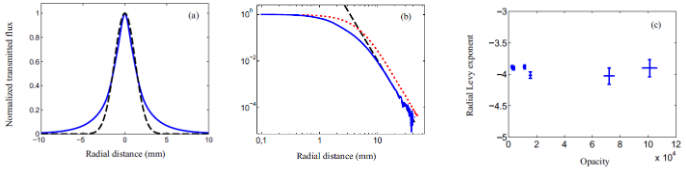


Atomic physics laboratory experiments : $g^2(\tau)$

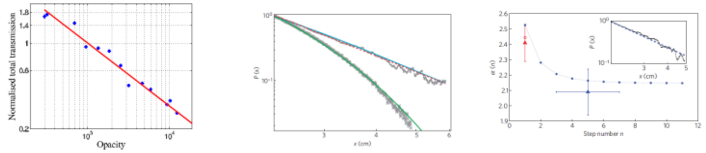
Goal : fast (high bandwidth) correlation

Experimental setup : developed for Levy flight experiments

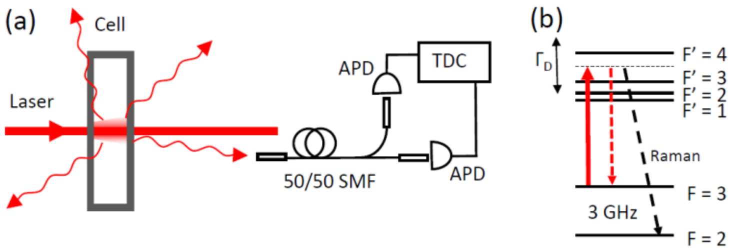


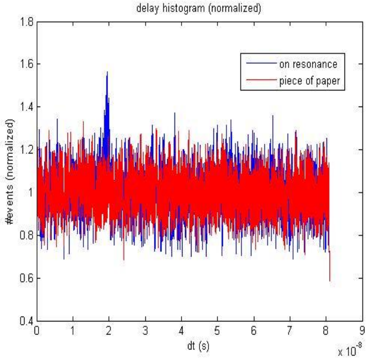


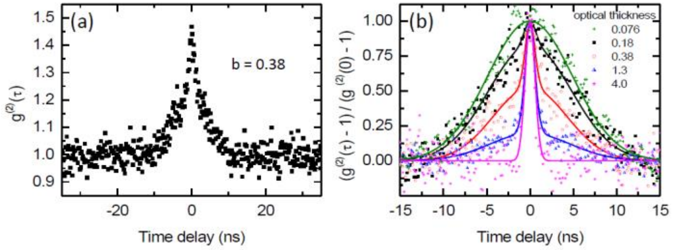
Nat. Phys. 5, 602 (2009)



Phys. Rev. E 90, 052114 (2014)





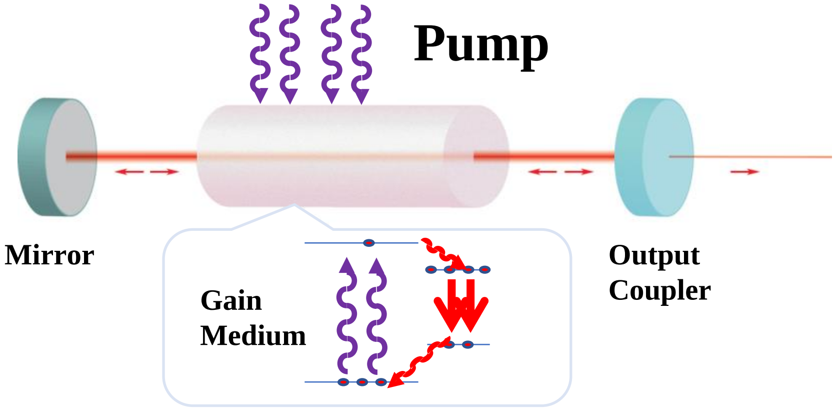


$\tau_e \approx 350$ ps

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. K.,
Phys. Rev. A 93, 043826 (2016)

More lab experiments : Random lasers

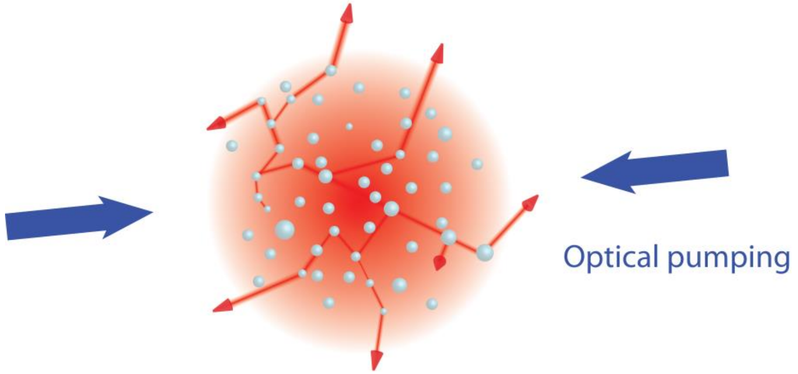
- Cavity Laser



Ingredients:

- Gain Medium
- Cavity
  → Feedback & Mode Selection

- Random Laser



- Gain Medium
- **Multiple scattering**

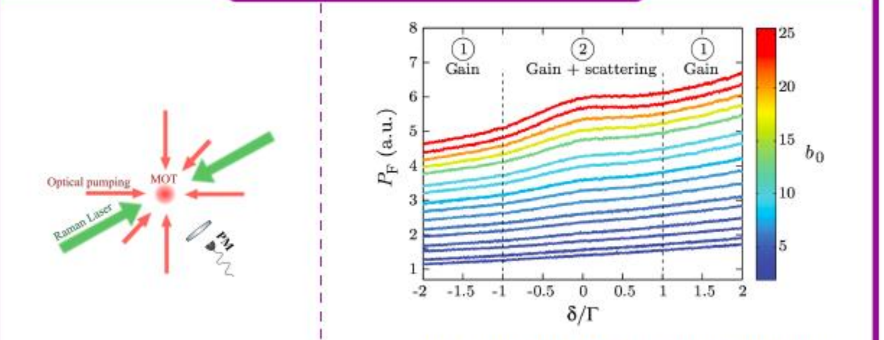
*V.S. Letokhov, Sov. Phys. JETP **26**, 835-840 (1968)*

1939–2009

Atomic physics laboratory experiments

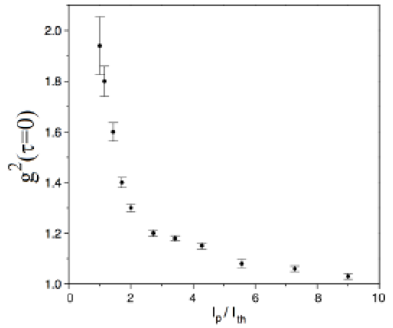
Goal : find spectroscopic signatures of gaseous random lasing

Observation of cold ^{85}Rb RL



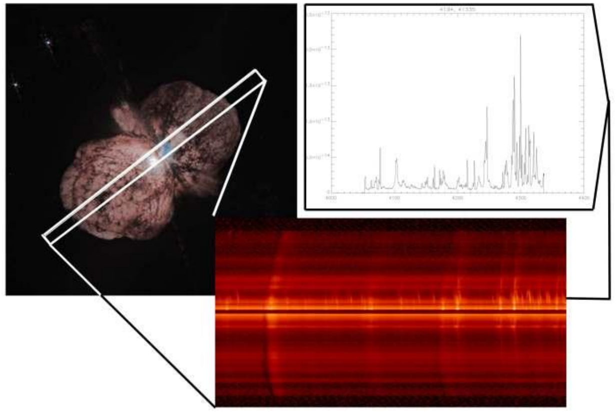
Q. Baudouin et al., *Nat. Phys.* 9, 357–360 (2013)

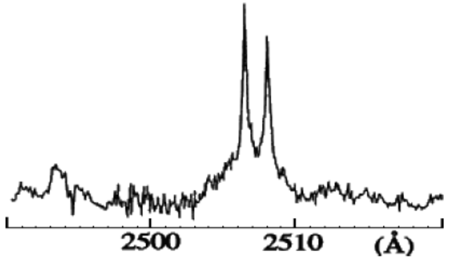
H. Cao et al., *Phys. Rev. Lett.* 86, 4524 (2001)



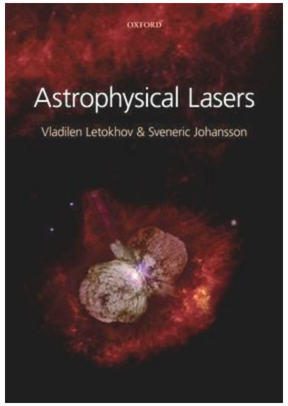
Eta Carinae

one of the most massive and luminous stars known



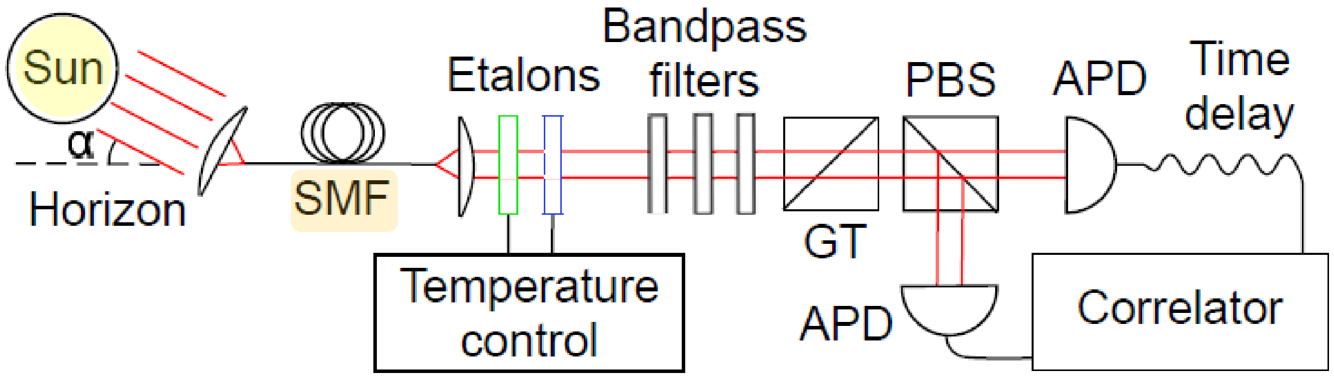


Spectre Ultraviolet d'η Carinae observé par l'IUE (International Ultraviolet Explorer)

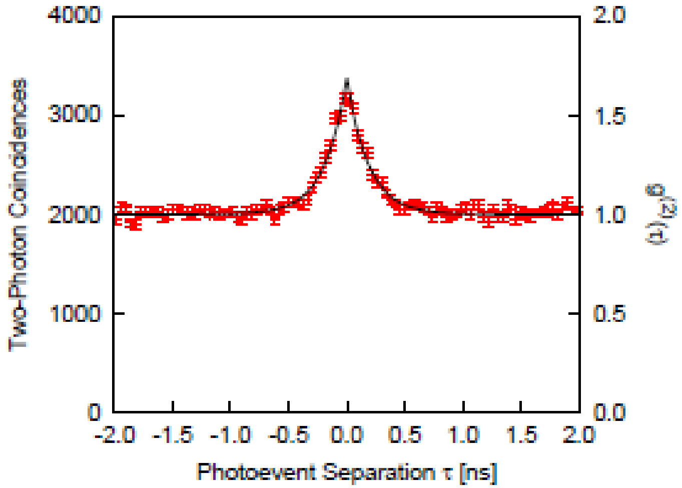


From the lab to on sky observations

State of the art in 2017



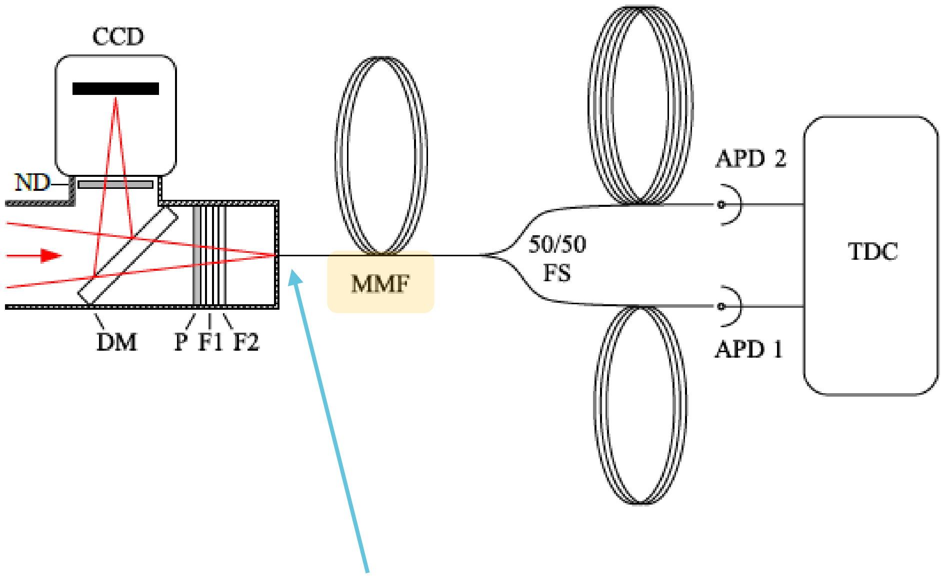
P. Tan et al., ApJ, 789, L10 (2014)
P. Tan, A. Chan, C. Kurtsiefer , MNRAS, 457, 4291 (2016)



Our telescope correlator

Multimode fiber

Light from the telescope

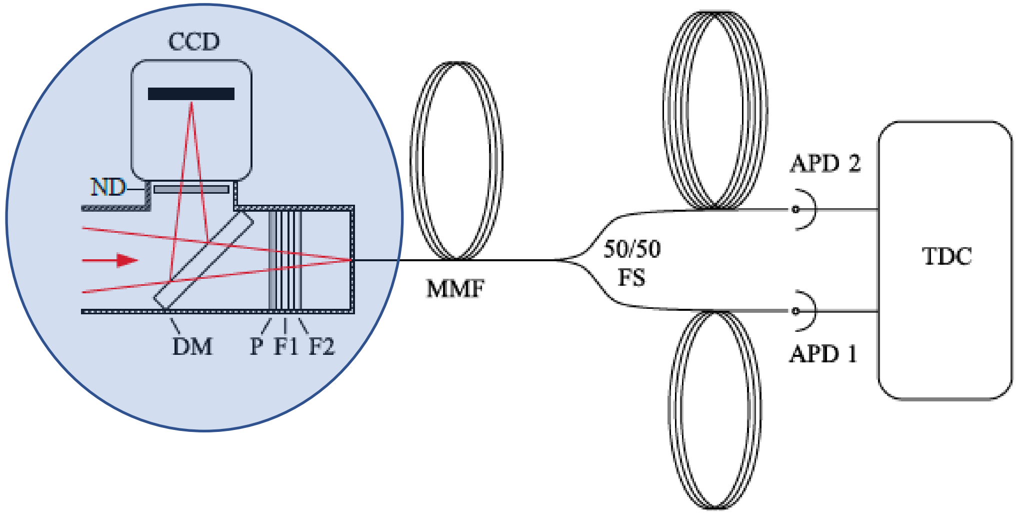


Focus of the telescope

→ 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

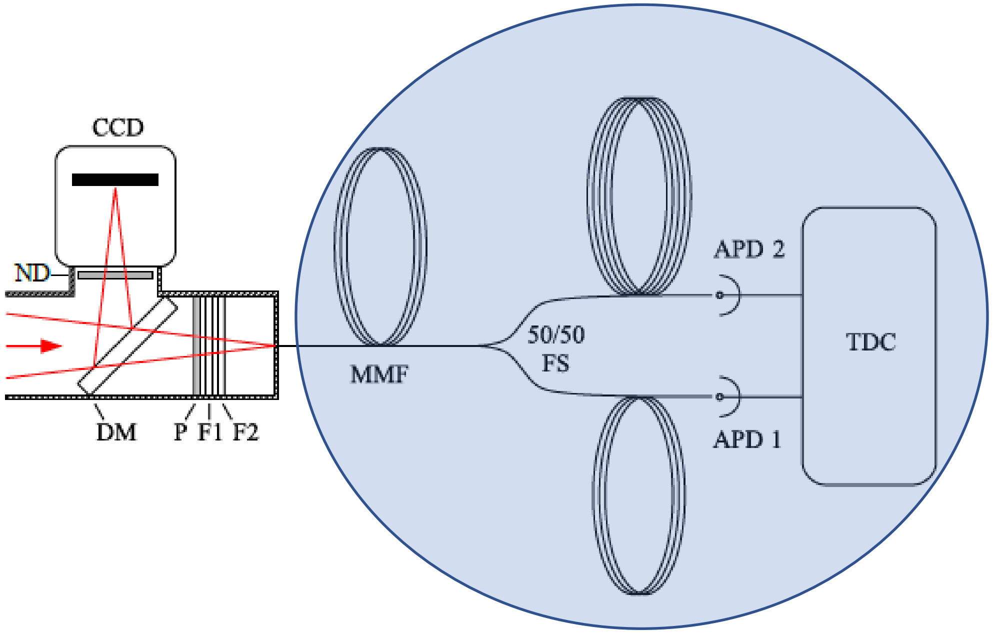
F1: Filter

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

Detection setup

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 $\tau_J \sim 350$ ps

TDC: Time to Digital Converter

#1: ID Quantique, time resolution = 81 ps

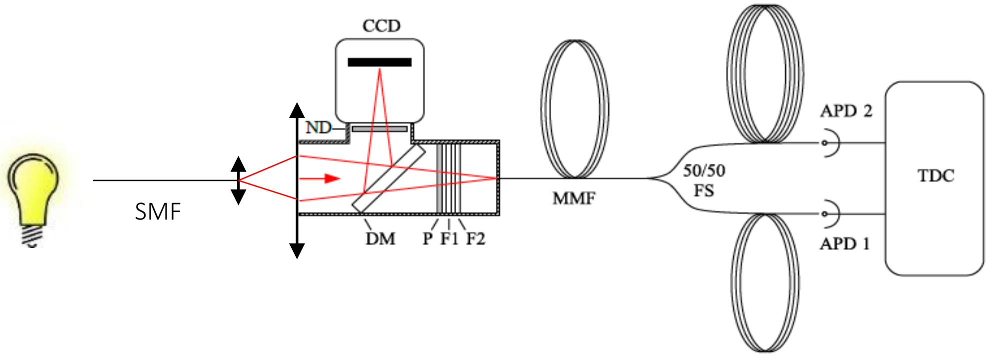
#2: Swabian Instruments, time resolution = 12 ps, less spurious correlations, 40 Mcps

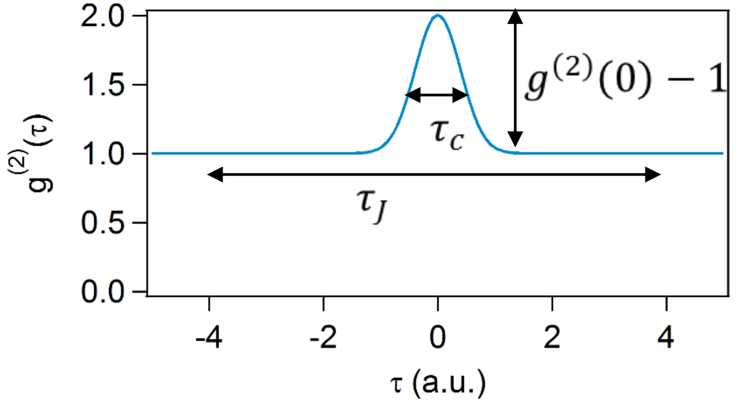
Expected signal

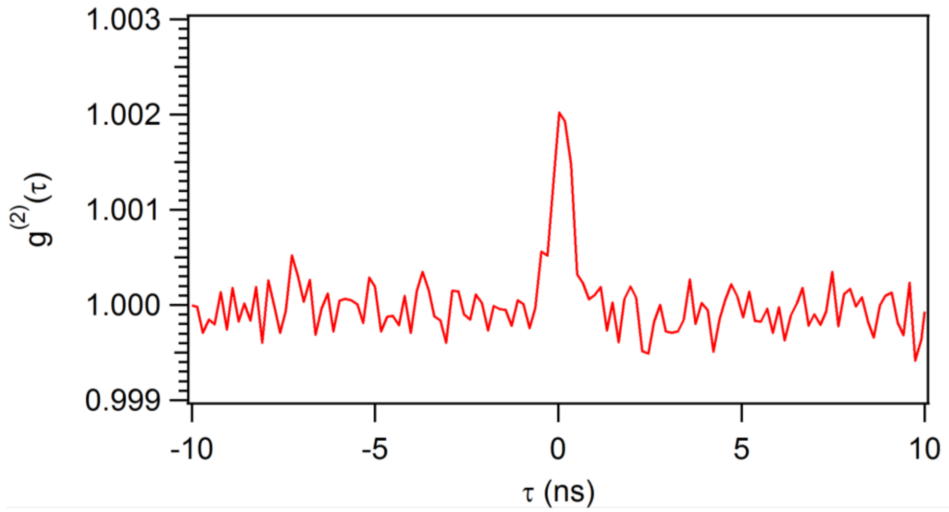
Contrast

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

~ 0.002



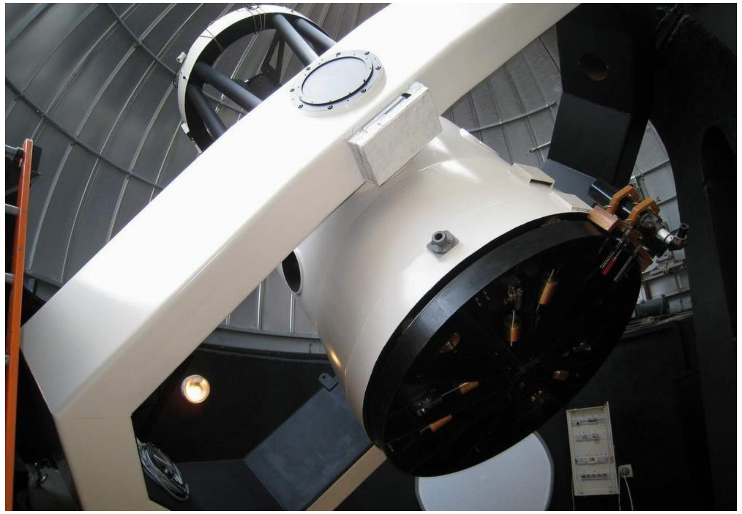




spurious correlations !!!

C2PU telescopes at Calern

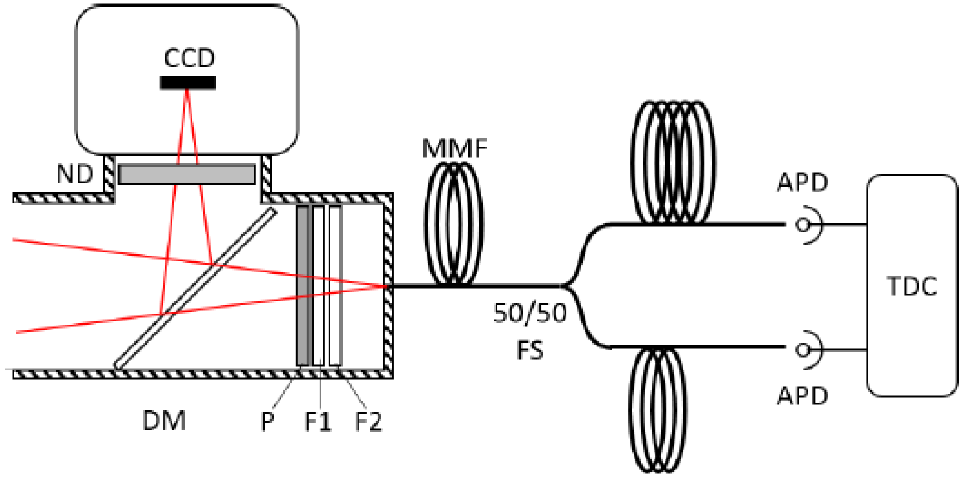
Altitude = 1280 m

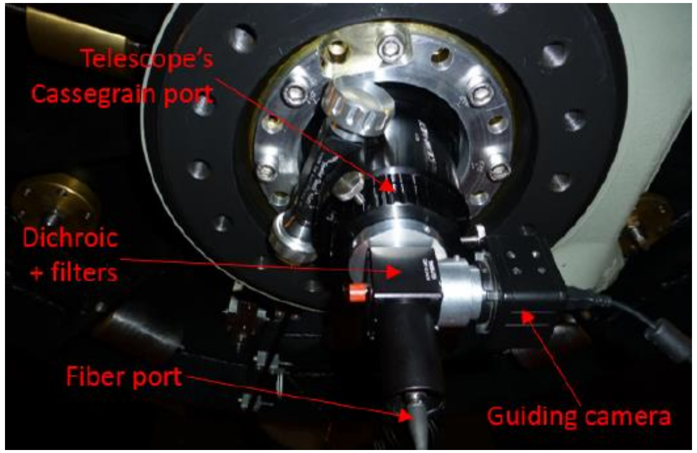


<u>C2PU telescopes</u>

- 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 µm

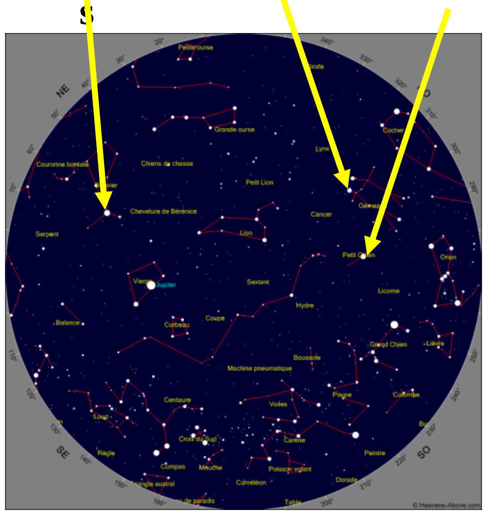
Experiments at C2PU (Calern, France) on February 20th-22nd 2017

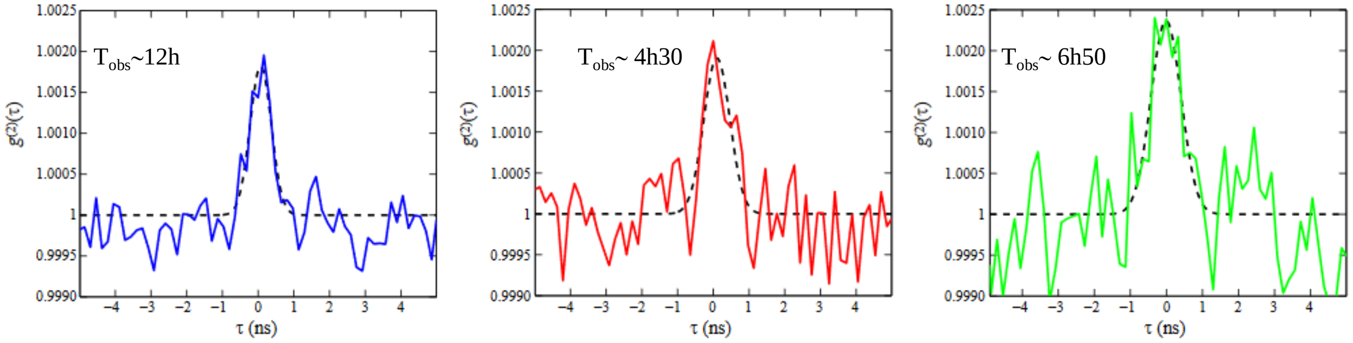




Results : Feb. 2017 : time correlation on 3 bright stars

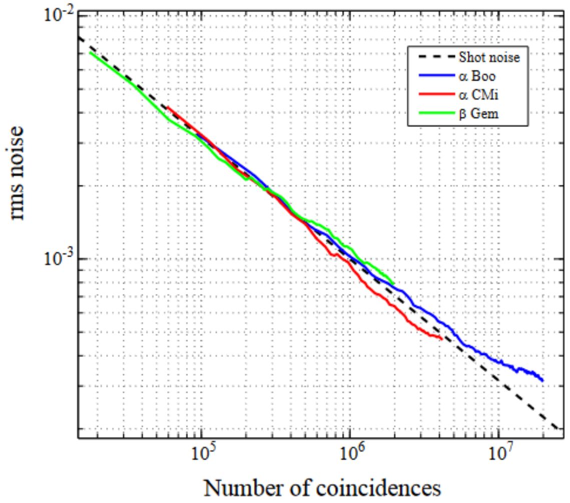
Arcturus **Pollux** **Procyon**





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

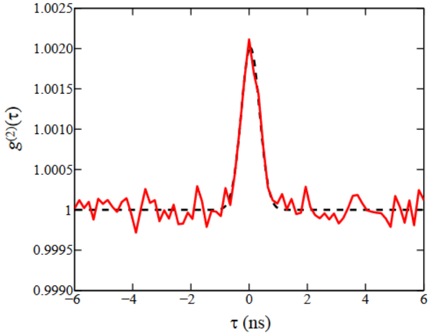
Shot noise limited



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

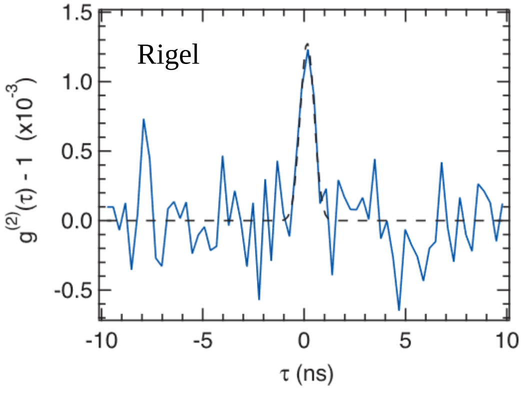
α: detection efficiency
$N_{ph}(\lambda)$: photon spectral flux (ph/m²/s/Hz)
A : collecting area

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

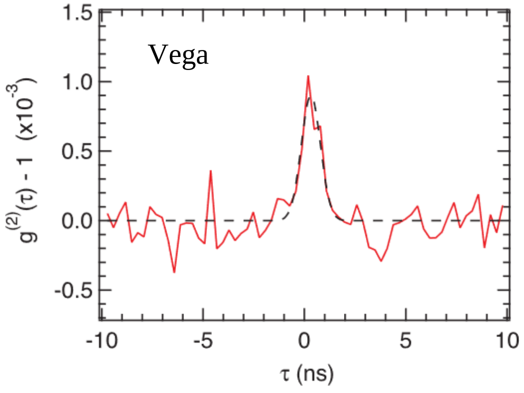


W. Guerin, A. Dussaux, M. Fouche, G. Labeyrie, J.-P. Rivet, D. Vernet, F. Vakili, R. K, Mon. Not. Roy. Astron. Soc. 472, 4126 (2017)

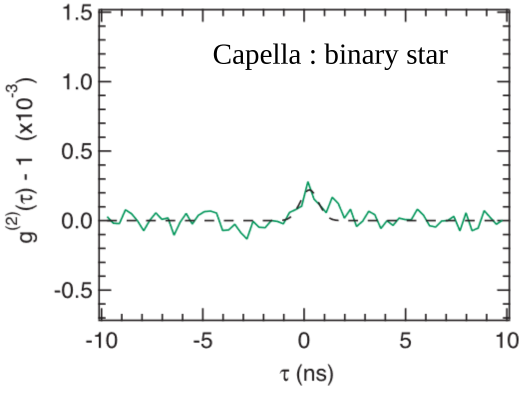
Results : fall 2017 : spatial correlation on 3 bright stars



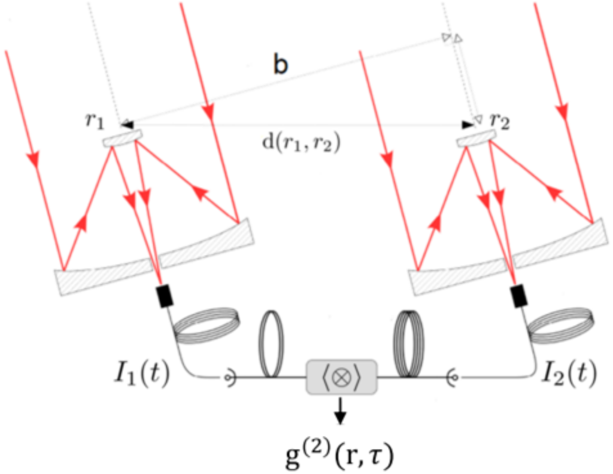
(a) β Ori.



(b) α Lyr.



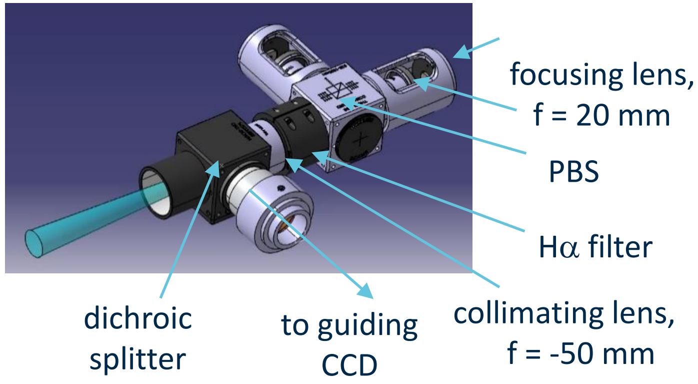
(c) α Aur.

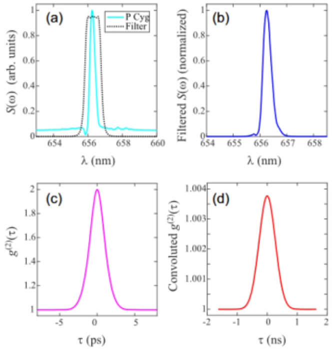


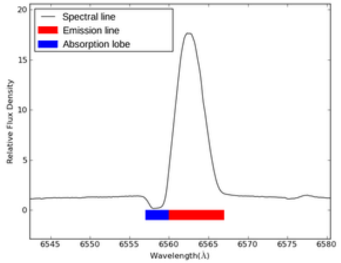
First angular measurement of stars since HBT !!!

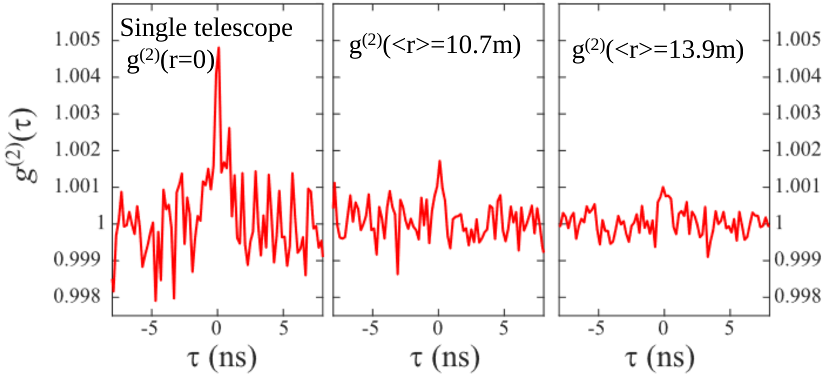
W. Guerin, J.-P. Rivet, M. Fouche, G. Labeyrie, D. Vernet, F. Vakili, R. K., Mon. Not. Roy. Astron. Soc. 480, 245 (2018)

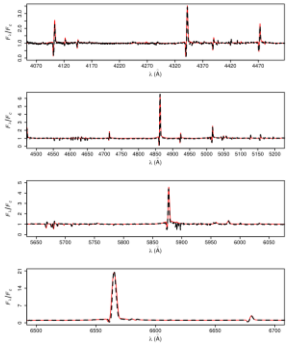
Results : Summer 2018 : spatial correlation on H_α emission line of P Cygni



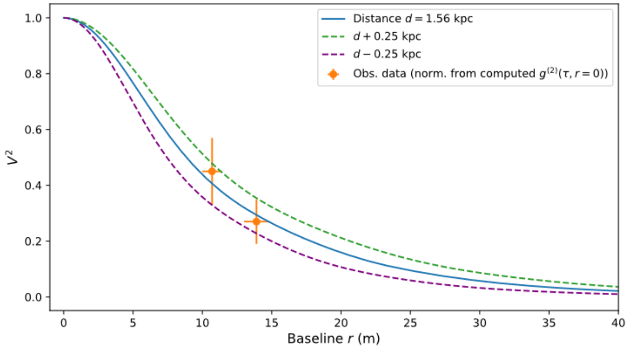








non-LTE
radiative transfer code
CMFGEN

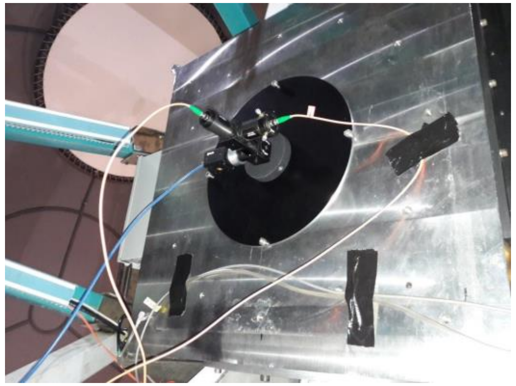


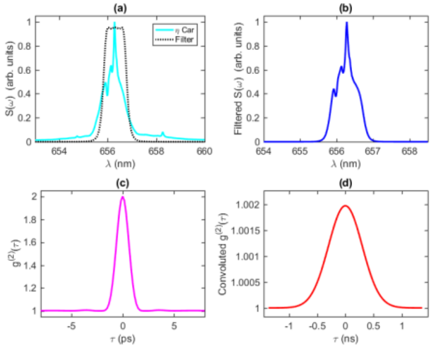
d = 1.56 +/- 0.258 kpc

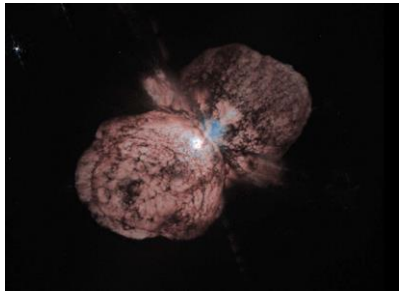
d = 1.36 +/- 0.24 kpc
Gaia DR2 catalogue
d = 1.8 +/- 0.1 kpc
Usually adopted in the literature

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)

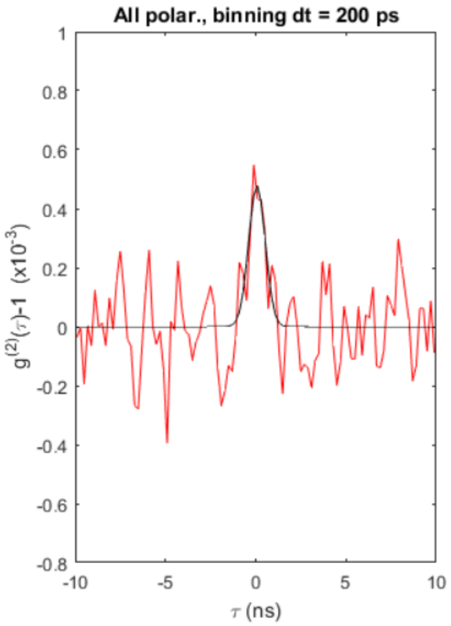
April 2019 : SOAR correlation on H_α emission line of η Carinae







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 ☺ ☺

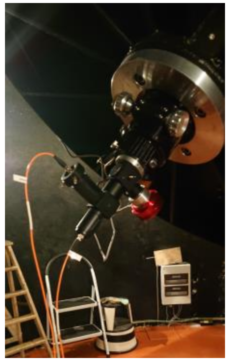
W. Guerin, J.-P. Rivet, M. Hugbart, F. Vakili, E. S. G. de Almeida, A. Domiciano de Souza, G. Labeyrie, N. Matthews, O. Lai, P.-M. Gori, D. Vernet, J. Chabe, C. Courde, E. Samain, B. V. Castilho, A. M. Magalhaes, E. Janot-Pacheco, A. Carciofi, P. Bourget, N. Schuhler and R. K., Proceedings of the annual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

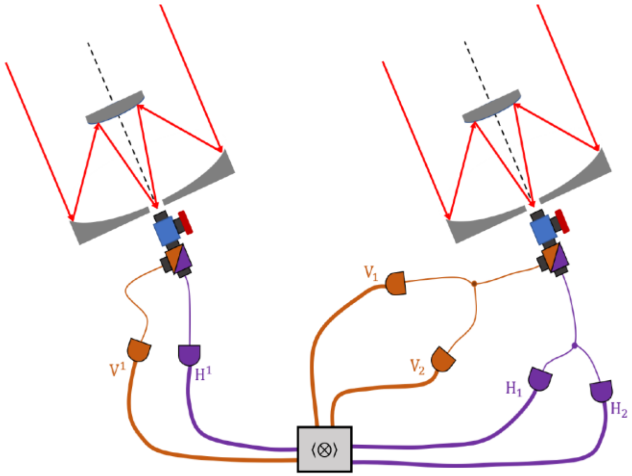
January 2020 : Spatial Correlation on H_α line of Rigel , Betelguese

Novel technical improvement :

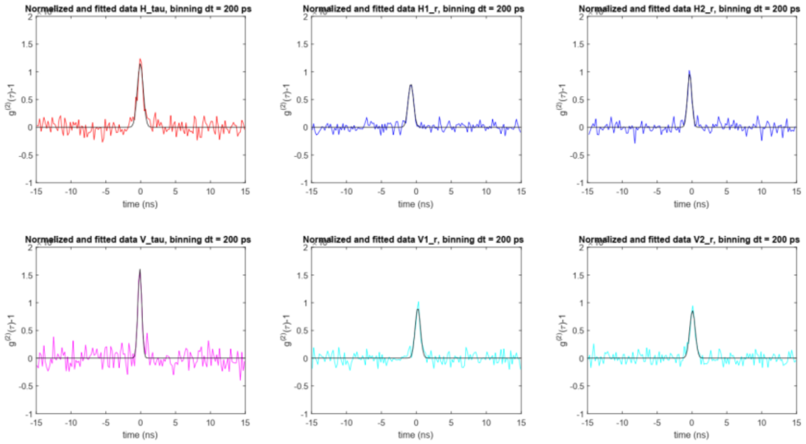
1) dual polarization channel

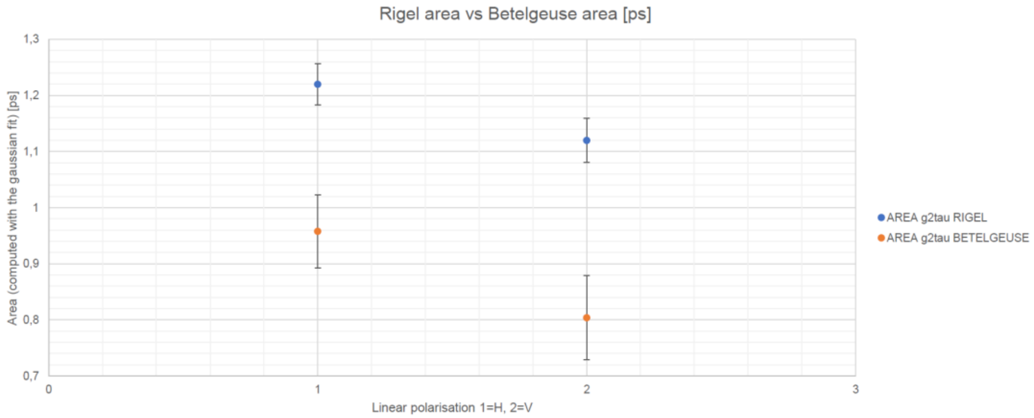
2) Auto calibrating setup : $g^{(2)}(0)$ + $g^{(2)}(r)$



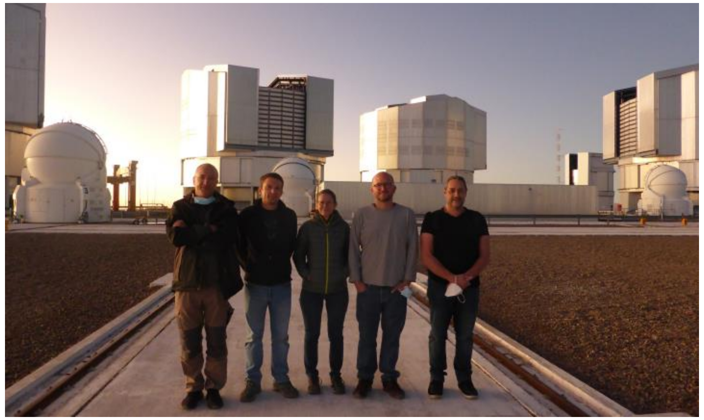


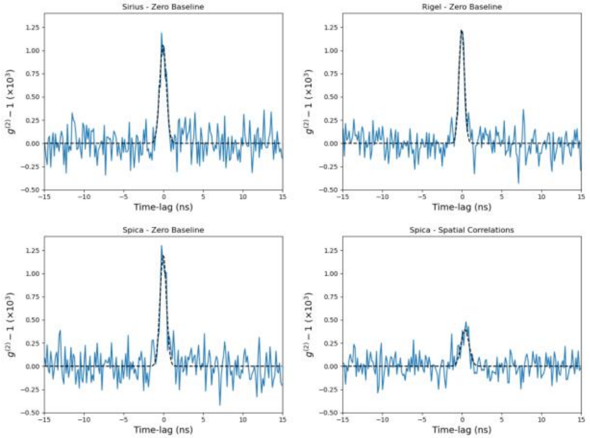
Rigel





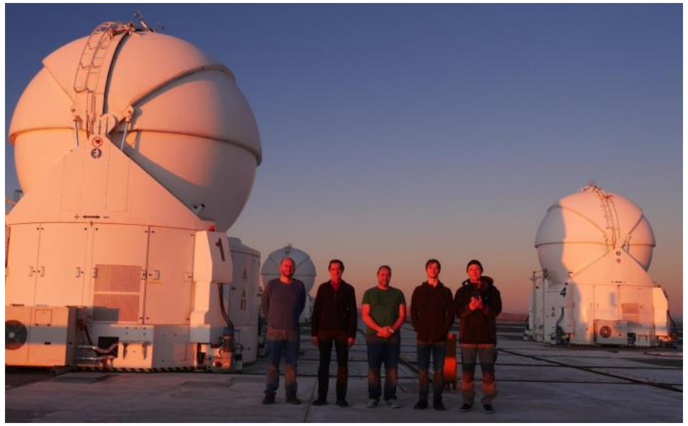
March 2022: Successful interferometric observation at Paranal (VLT)!

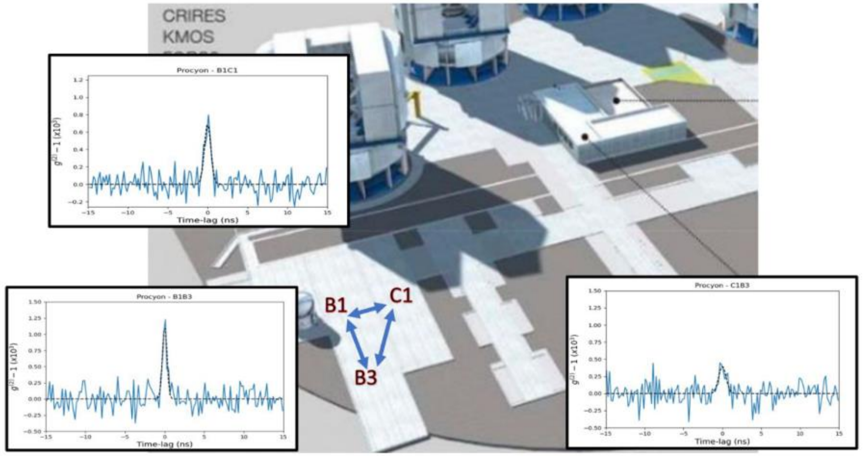




N. Matthews, J.-P. Rivet, M. Hugbart, G. Labeyrie, R. K., O. Lai, F. Vakili, D. Vernet, J. Chabe, C. Courde, N. Schuhler, P. Bourget, W. Guerin, [Proc. SPIE 12183, Optical and Infrared Interferometry and Imaging VIII, 121830G (2022)](),

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

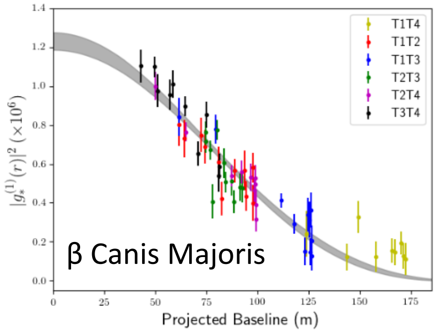


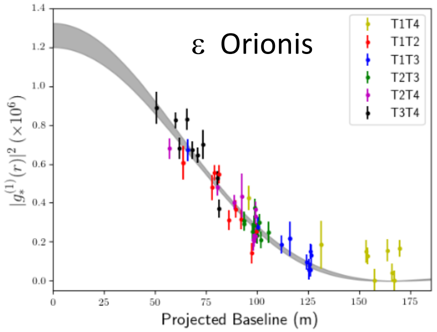


State of the art in 2024

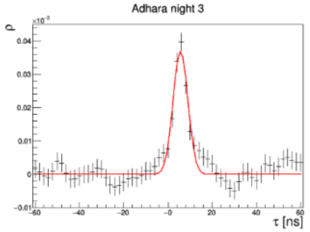
- Demonstration of stellar intensity interferometry with the four VERITAS telescopes, A. Abeysekara, et al., Nat, Astronomy 4, 1164 (2020)

λ=416nm



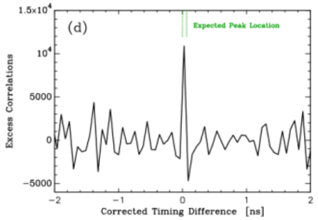


- V. Acciari, et al., Optical intensity interferometry observations using the MAGIC imaging atmospheric cherenkov telescopes, MNRAS 491, 1540 (2020)



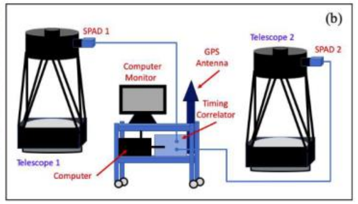
λ=430nm, 3 stars, 2 telescopes (diameter 17m)

- Zampieri, L., Naletto, G., Burtovoi, A., Fiori, M., & Barbieri, C., 2021. Stellar intensity interferometry of Vega in photon counting mode, MNRAS, 506(2), 1585. ASIAGO



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

E. P. Horch et al 2022 AJ 163 92

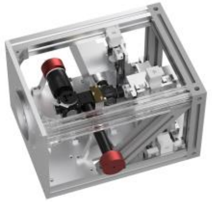


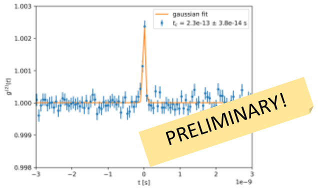
λ=532nm, 3 stars, 2 telescopes (diameter 0.6m)

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

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

λ=405nm





Courtesy S.Richter et al.

Outline

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

2) Intensity correlations

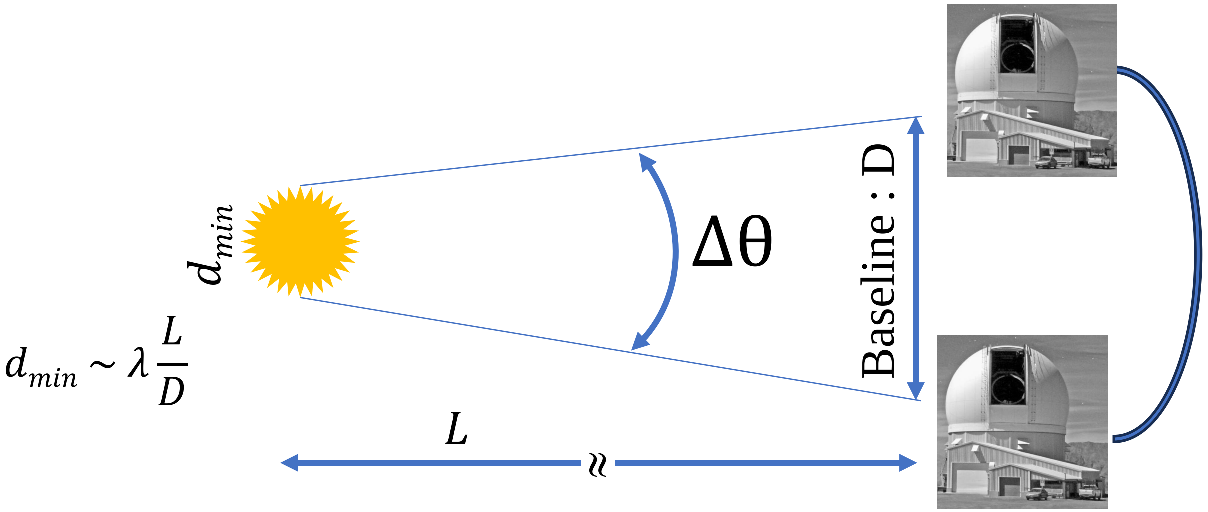
3) HBT revival : on-sky intensity correlations from 2017-2023

4) IC4Star project

   - Ultrahigh angular resolution : Sirius B
   - Quantum optics : random lasing in space

What next : IC4Stars

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



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

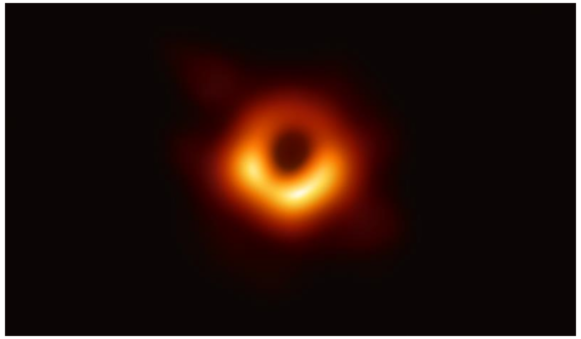
ii. intensity correlations $g^2(r)$
Hanbury Brown & Twiss

- 👍 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

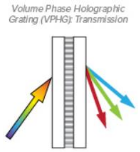
λ~420nm, D ~ km

λ~mm
D=12000 km



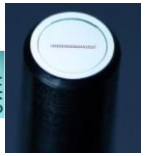
- The price to pay : low signal to noise ratio

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



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

SNSPD
τ_{el}=20ps

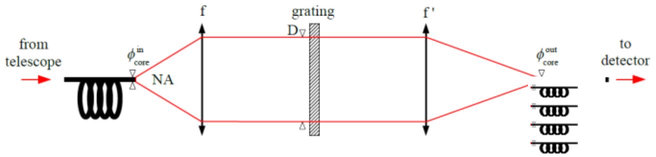
€€€

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

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

Multiplexing

- Option 1 : Fiber coupling



grating angular dispersion : $disp = d\theta / d\lambda = 1.42$ mrad/nm

effective spectral width : $\Delta\lambda = \phi^{out}_{core} / (f' . disp)$ if $\phi^{in}_{core} . (f'/f) << \phi^{out}_{core}$

constraints :
$f < D / NA$ — *no photon loss from input fiber to spectrograph*
$f' << f . (\phi^{out}_{core} / \phi^{in}_{core})$ — *negligible effect of input "slit" on spectrum*

example : $\phi^{in}_{core} = \phi^{out}_{core} = 100$ µm ; NA = 0.29 ; D = 10 cm

$f = 40$ cm → $f = 1.16 . (D / NA)$

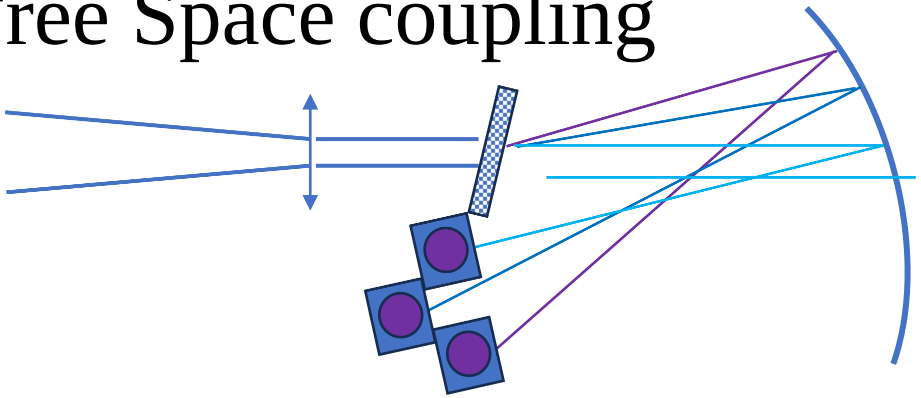
$f' = 10$ cm → $\Delta\lambda = 0.7$ nm

$f'/f = 0.25 << 1$

To be done

- double system,
- Efficiency ☹
- calibration
- Stabilility
- Compact ☺

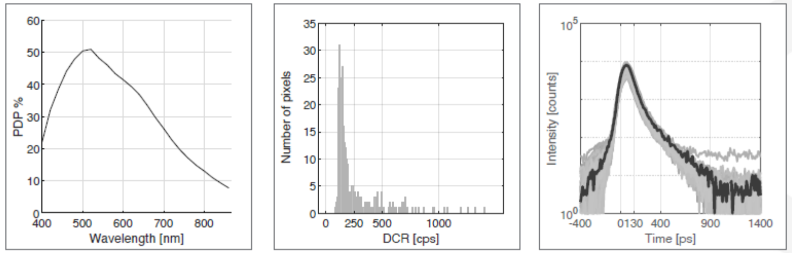
- Option 2 : Free Space coupling



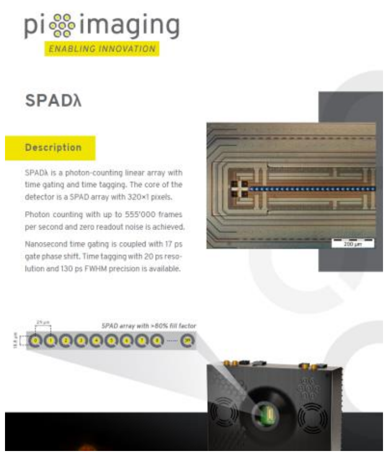
To be done

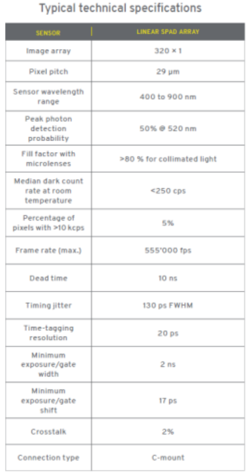
- Dispersion to be adapted on detectors
- calibration
- Stabilility
- Efficiency ☺
- Bulky ☹

Pi Imaging : η<40%



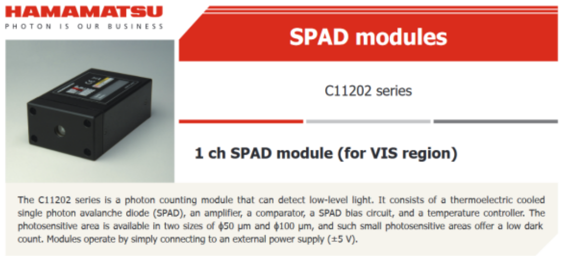
Photon detection probability. | Typical distribution of dark count rate over the SPAD array. | Timing jitter over all the pixels, with an average of 130 ps FWHM.



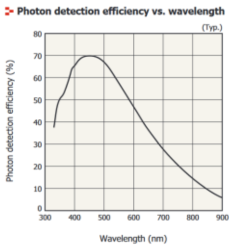


Typical technical specifications

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



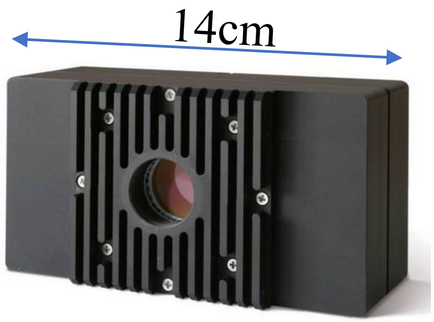
Hamamatsu : C11202 : η=60%, τ>400ps, dark counts ☹



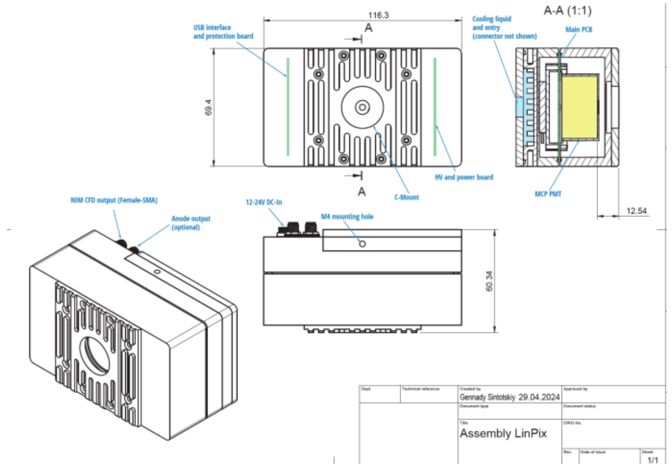
Electrical and optical characteristics (Typ. Ta=25 °C, λ=λp, Vs=±5 V, unless otherwise noted)

Parameter		Symbol	Condition	C11202-050			C11202-100			Unit
				Min.	Typ.	Max.	Min.	Typ.	Max.	
Spectral response range		λ			320 to 900			320 to 900		nm
Peak sensitivity wavelength		λp		-	450	-	-	450	-	nm
Chip temperature (setting temperature)*2 *3		Tchip		-	-20	-	-	-20	-	°C
Photon detection efficiency		PDE		60	70	-	60	70	-	%
Dark count		-		-	7	25	-	30	100	cps
Afterpulse probability		-	100 ns to 500 ns	-	0.1	-	-	0.1	-	%
Comparator output		-			TTL compatible			TTL compatible		-
Maximum count rate		-		-	30	-	-	20	-	Mcps
Current consumption	Positive power supply	Ic	Vs=+5 V	-	+200	+1000	-	+200	+1000	mA
	Negative power supply		Vs=-5 V	-	-20	-40	-	-20	-40	

Photonscore : 2 x 16 LINPix

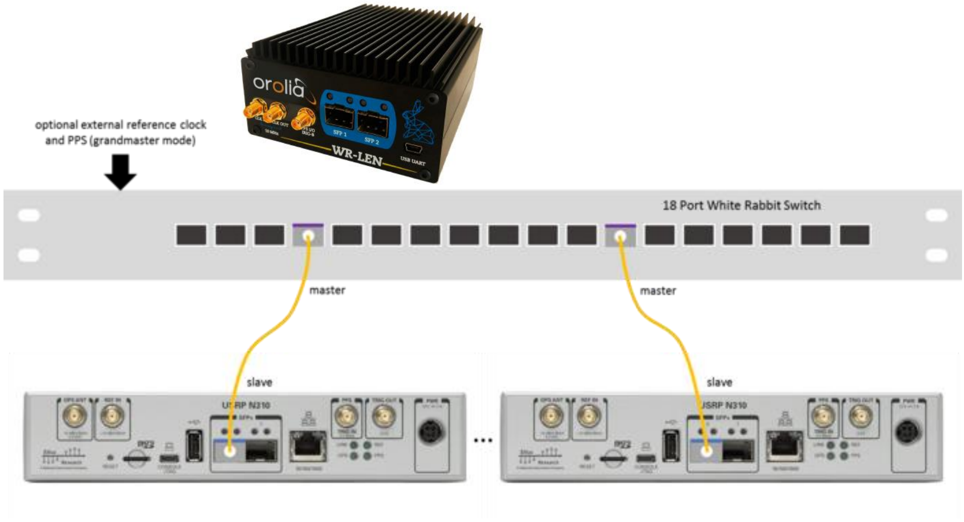


Max. recommended count rate, MHz	100
Shutdown count rate, MHz	110
Discrimination	Integrated CFD
Dark count rate, Hz	< 15 (Blue, Aqua), < 50 (Green), < 200 (Red)
Timing jitter, ps (FWHM)	< 35 (1MHz), < 45 (10MHz), < 75ps (100MHz)
Active area, mm	⌀8
Dead time, ns	< 2



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

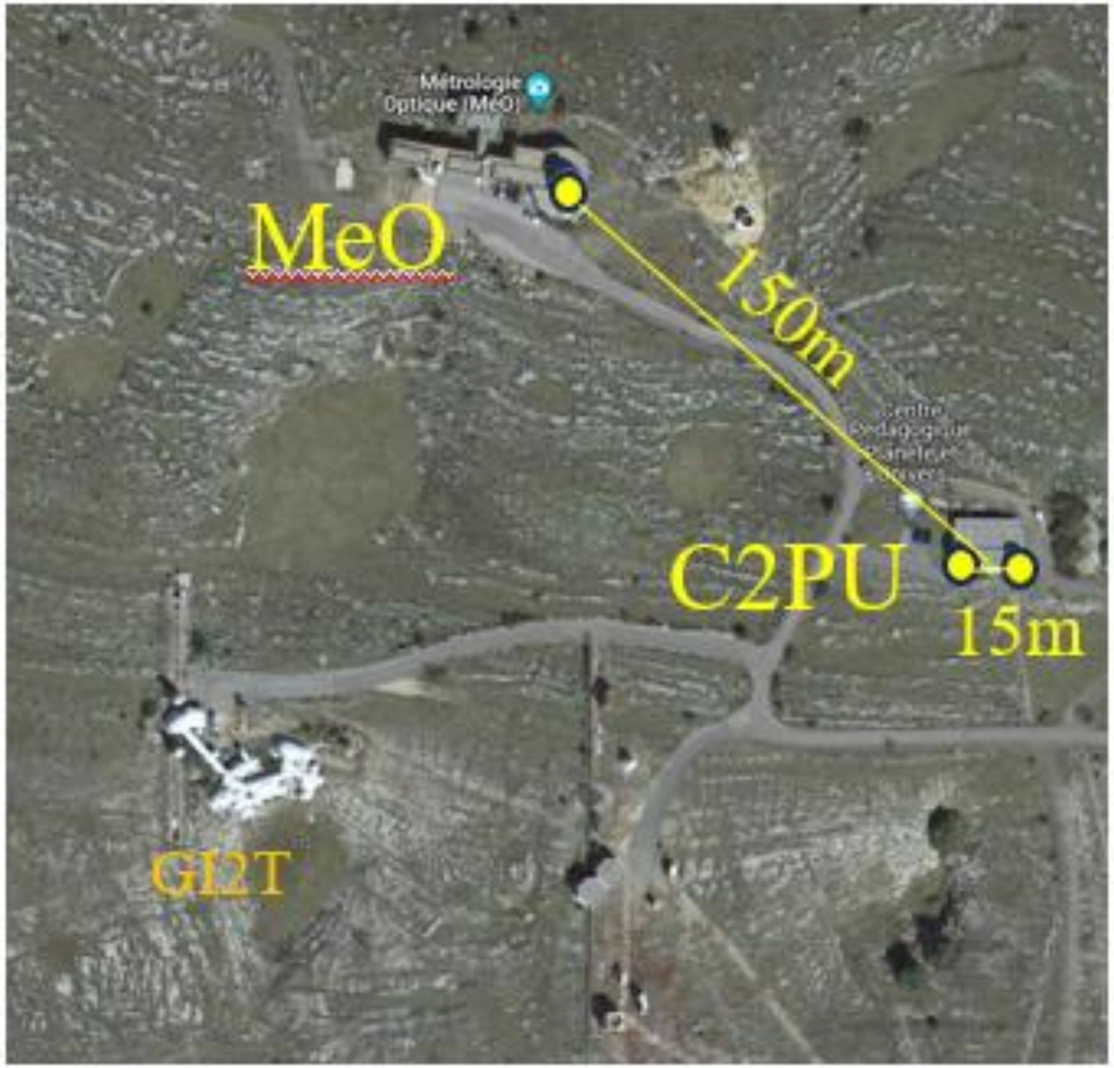
1 ps

Benchmarking @ Calern

- WP2.1 : $g^2(r)$

yellow hypergiant : γ Cas : M4.5, 2.4 m″

O-type star : 10Lac : M4.88 0.11 m″



The Astrophysical Journal, 869:37 (13pp), 2018 December 10
https://doi.org/10.3847/1538-4357/aaec04

Angular Sizes and Effective Temperatures of O-type Stars from Optical Interferometry with the CHARA Array

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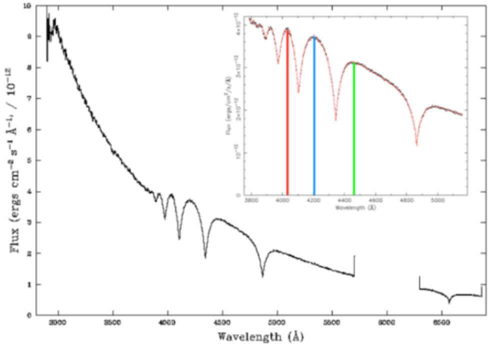
[5] Department of Physics and Astronomy and Pittsburgh Particle Physics, Astrophysics, and Cosmology Center (PITT PACC), University of Pittsburgh, Pittsburgh, PA 15260, USA
Received 2018 August 20; revised 2018 October 22; accepted 2018 October 22; published 2018 December 10

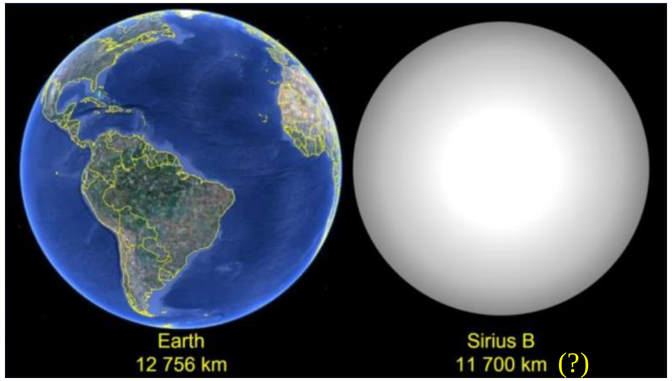
Identifier	Star Name	HD Number	Spectral Classification	V (mag)	$B-V$ (mag)	$V-K$ (mag)	T_{eff} (kK)	θ_{UD} (mas)
a	ξ Per	24912	O7.5 III(n)((f)	4.06	0.02	0.11	34.3 ± 0.8	0.216 ± 0.016
b	α Cam	30614	O9 Ia	4.29	0.05	0.05	29.4 ± 1.0	0.250 ± 0.014
c	λ Ori A	36861	O8 III((f))	3.47	0.01	−0.56	34.5 ± 0.8	0.219 ± 0.015
d	ζ Ori A	37742	O9.2 Ib	1.88	−0.11	−0.44	29.5 ± 1.0	0.546 ± 0.029
e	ζ Oph	149757	O9.2 IVnn	2.56	0.02	−0.06	32.1 ± 1.3	0.454 ± 0.010
f	10 Lac	214680	O9 V	4.88	−0.21	−0.62	35.5 ± 0.5	0.532 ± 0.010
								0.11 ± 0.02

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

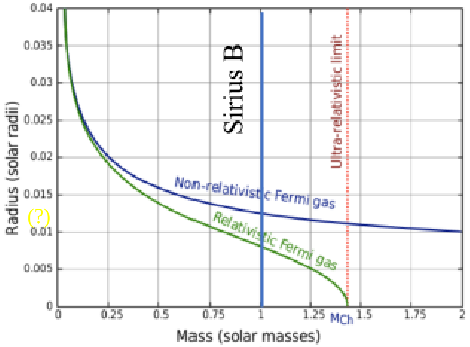


SNR ≈ 6
in 1 hour
observation time !!!!

Beyond reach of present instruments

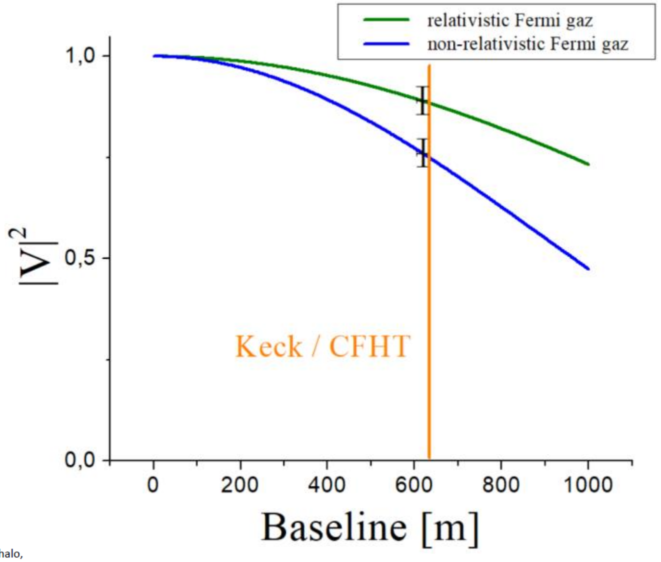


Magnitude=8.4



Photon Bunching

- **@ λ = 420nm**
- **D=630m**



Mauna Kea @ Hawaii

Sincerely,
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Chief Scientist and Deputy Director
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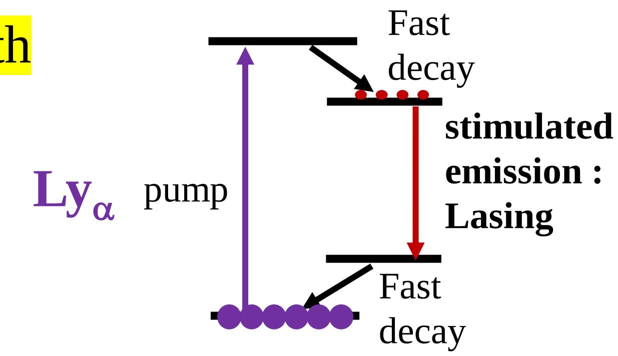
Sincerely,
Jean-Gabriel Cuby
Executive Director
Canada-France-Hawaii Telescope

Mahalo,
Doug Simons
Director
University of Hawai'i, Institute for Astronomy

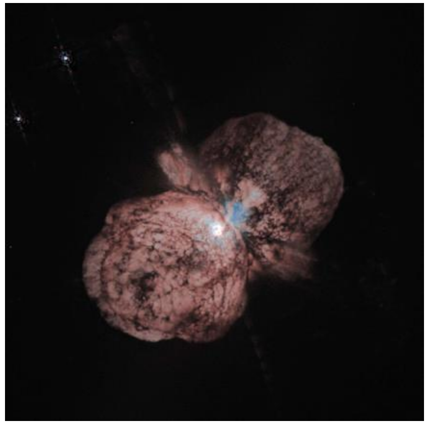
Bonus : quantum astro-optics : coherent light sources

- Random laser with 4 level scheme

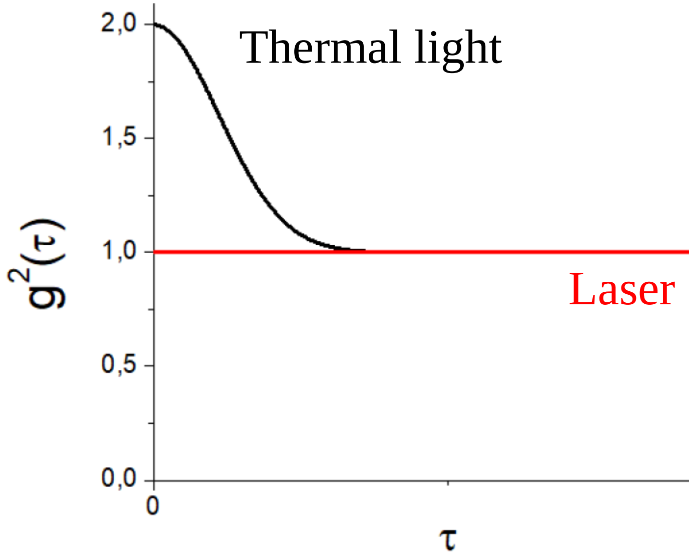


Fe II:
population inversion at 0.99 / 1.6 /1.7 μm

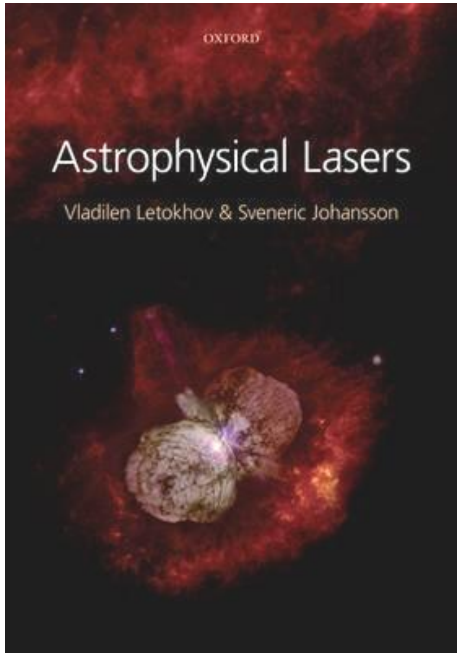
Eta Car



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

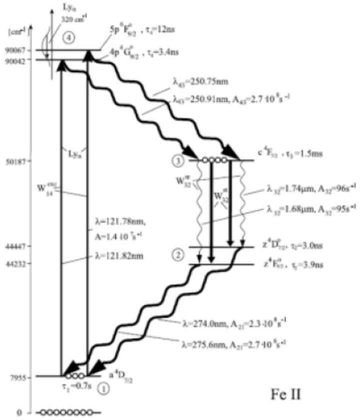


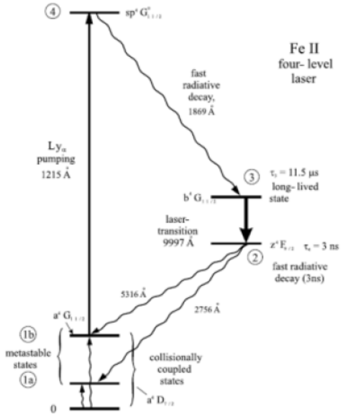
Challenge :
Find **emission lines** with
population inversion

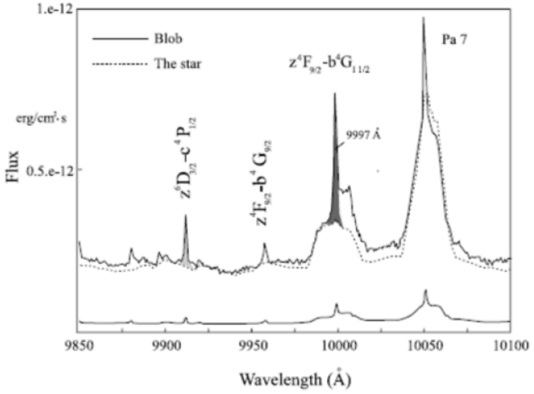


Eta Car : Fe II:

population inversion at
0.99 / 1.6 /1.7 μm







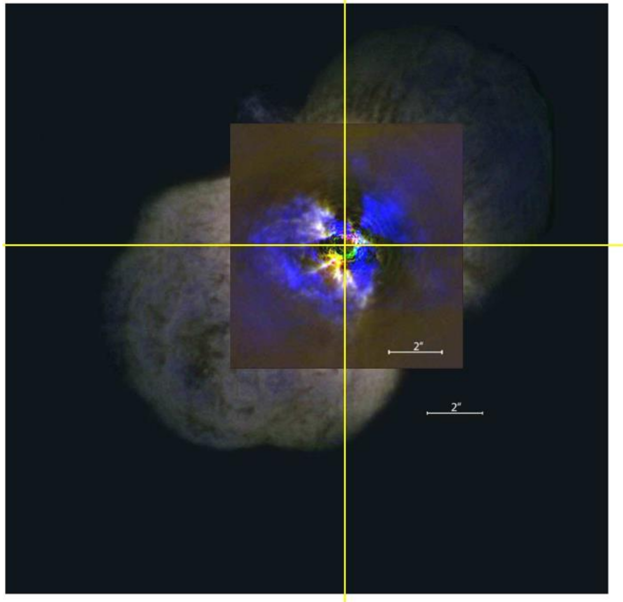


Fig. 2a.— The combined Brγ, H_2, [Fe II] image without the continuum subtraction; Brγ (red), H_2 (green),and [Fe II] (blue). North is up and east is left.

+ systematic study to be performed : Marcelo Borges (Rio de Janeiro, Brazil)

SNSPD technology

SINGLE QUANTUM
Excellence in photon detection

The SNSPD technology

Photon detection with efficiency and time resolution

The Single Quantum multi-channel SNSPD system combines high detection efficiency, high time resolution, low dark count rate, and a high count rate. **It can detect single photons with higher than 90% efficiency over a broad spectral range and an ultra-high timing resolution of less than 15 ps.**

The detection principle is based on the transition of a nanowire from the superconductive to the resistive state upon the absorption of a single photon. The detectors are pigtailed with an optical fiber and operated in a closed-cycle cryostat at 2.5 Kelvin. The design enables continuous operation for up to 10,000 hours and requires no liquid helium consumption. This makes it a turn-key solution for optical measurements.

IDQ

Pixel Photonics

Products | Applications | SNSPD Technology | Company | Career | Contact

We got one goal: detect and count single photons. Therefore, we developed a waveguide-integrated superconducting nanowire single photon detector (WI-SNSPD) – enhancing the variability, scalability and robustness of the photonic integrated circuits and excelling in photon detection. Want to find out why our detector is the best? Keep reading.

Table top detector

For those who value versatility

The table top version of our single photon detector comes with a separated helium compressor and therefore produces less heat, noise and vibrations, that could interfere with the detection.

Rack detector

For those who value mobility

Rack compatible, this version integrates a cryostat, vacuum system, compressor and electronics into a single housing, immensely reduces the complexity and size of the detector.

Broad capability

From the visible wavelength range of 400 nm up to the NIR wavelength range of 2,000 nm, our detectors ensure high system detection efficiency without the need to change the module.

High scalability

Due to the waveguide-integrated approach, our technology is highly scalable. This means that hundreds of detectors can be implemented in one single system, consuming only a small amount of space.

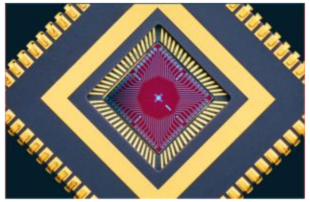
Top efficiency

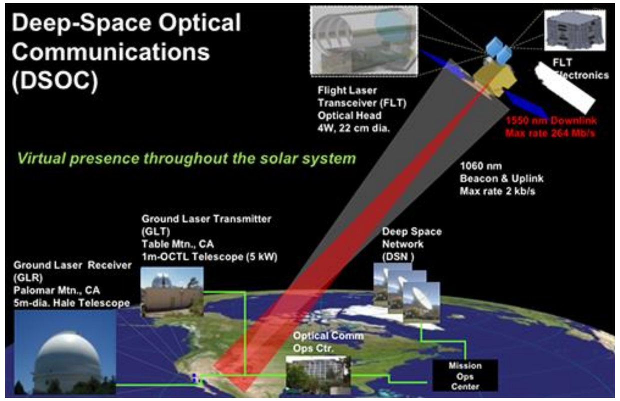
Due to our unique waveguide-integration approach, the internal quantum efficiency can be engineered to always be 100 % for any wavelength.

Timing resolution

Our detectors have an excellent timing resolution with timing jitter typically on the order of tens of picoseconds. Even jitter below 30 ps is possible.

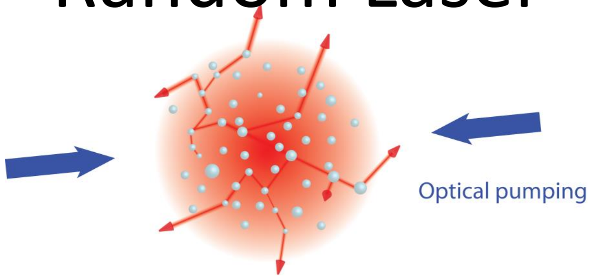
Photon Spot





Random lasing

- Random Laser



- Gain Medium
- **Multiple scattering**

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

1939–2009

Pioneer in Laser physics : Basov
(Nobel prize 1964, with C. Townes , Prokhorov)

Letter | Published: 05 May 2013

A cold-atom random laser

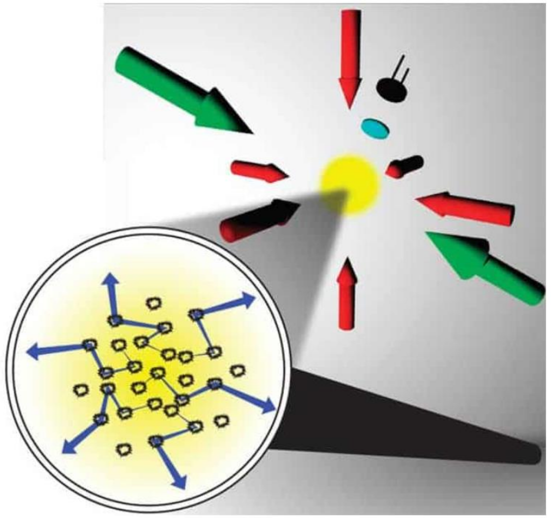
Q. Baudouin, N. Mercadier, V. Guarrera, W. Guerin & R. Kaiser

Nature Physics **9**, 357–360 (2013) | Cite this article

STARS AND SOLAR PHYSICS | RESEARCH UPDATE

Cold-atom random laser simulates stellar clouds

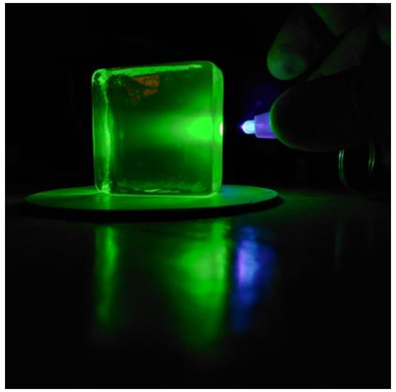
09 May 2013



Stimulating and scattering: an atomic random laser in action. (Courtesy: Q Baudouin *et al.*/*Nature Physics*)

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

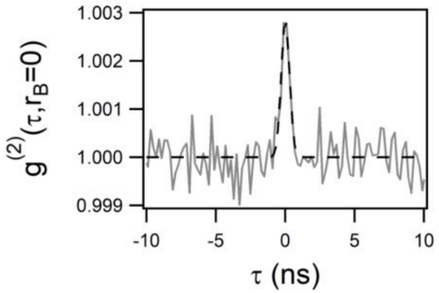
Ernesto P. Raposo, Iván R. R. González, Edwin D. Coronel, Antônio M. S. Macêdo, Leonardo de S. Menezes, Raman Kashyap, Anderson S. L. Gomes, and Robin Kaiser
Phys. Rev. A **105**, L031502 – Published 23 March 2022



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

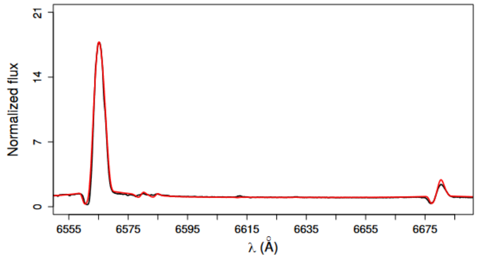
Benchmarking @ Calern

- WP3.1 : $g^2(\tau)$



P-Cygni : M4.82
(η-Car of the north)

H_α λ=656.3 nm



Combined spectroscopy and intensity interferometry to determine the distances of the blue supergiants P Cygni and Rigel FREE

E S G de Almeida, M Hugbart, A Domiciano de Souza, J-P Rivet, F Vakili, A Siciak, G Labeyrie, O Garde, N Matthews, O Lai, D Vernet, R Kaiser, W Guerin
Author Notes

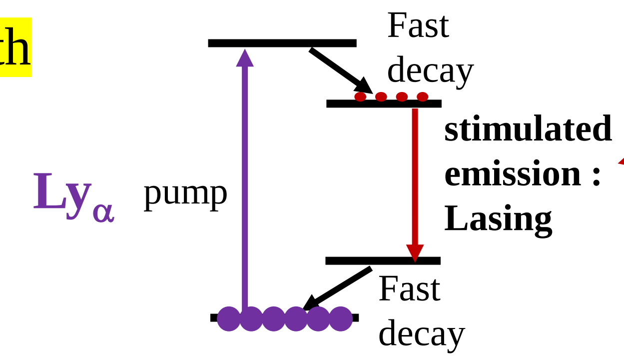
Monthly Notices of the Royal Astronomical Society, Volume 515, Issue 1, September 2022, Pages 1–12, https://doi.org/10.1093/mnras/stac1617

Photon correlations $g^2(\tau)$ around 0.99 / 1.6 /1.7 µm

With SNSPDs

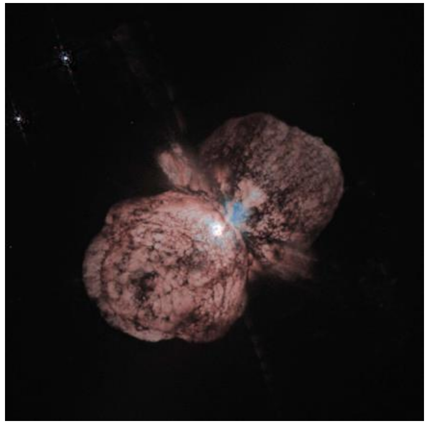
Intensity correlations at SOAR

- Random laser with 4 level scheme

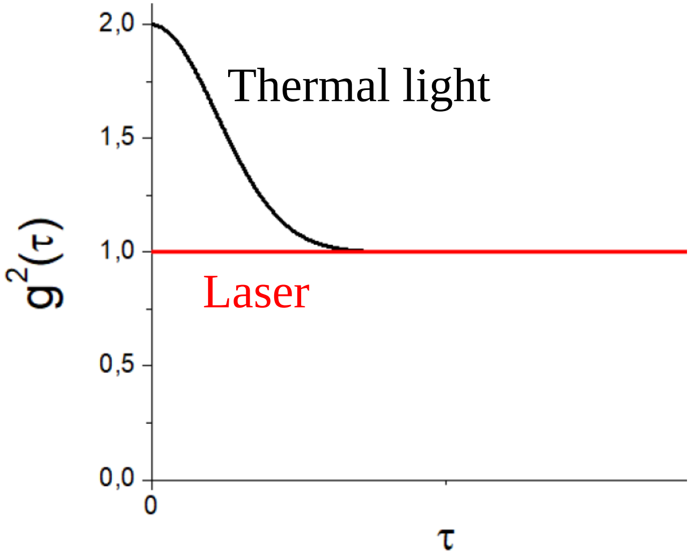


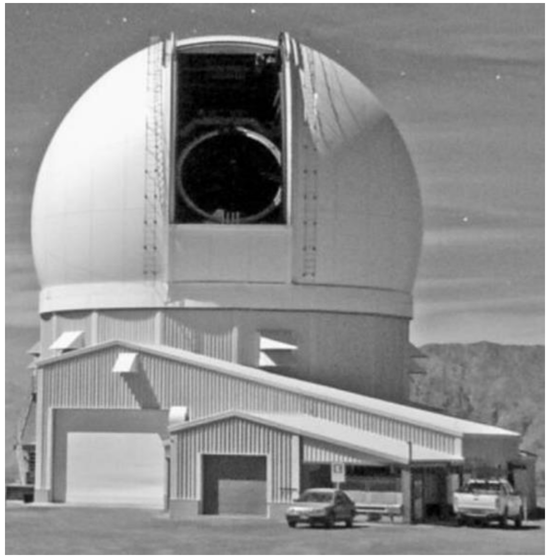
Fe II:
population inversion at 0.99 / 1.6 /1.7 µm

Eta Car
M_H=2.51



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

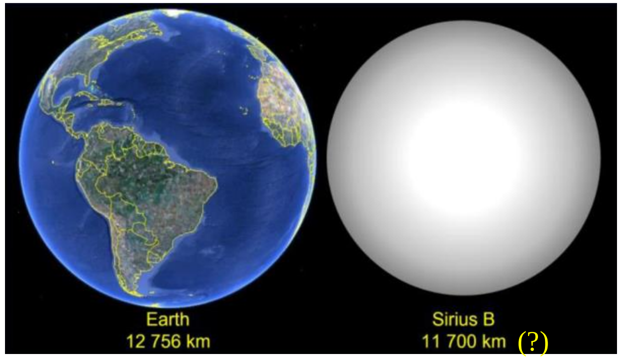




SOAR
(Chile, southern hemisphere)

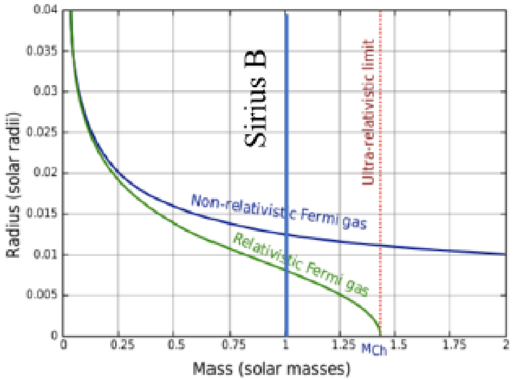
Main expected result of IC4Stars

- **High angular resolution in astrophysics : $g^2(r)$ $\tau=0$**

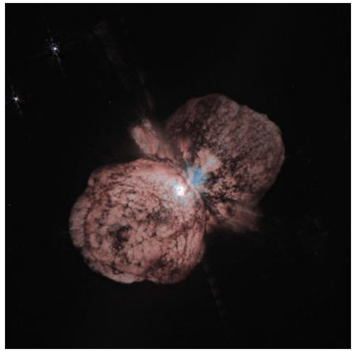


Magnitude=8.4 $\Delta\theta=30\mu''$

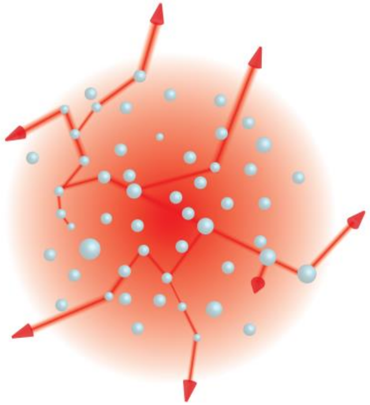
Validate white dwarf model



- **Quantum optics in astrophysics : $g^2(\tau)$ $r=0$**

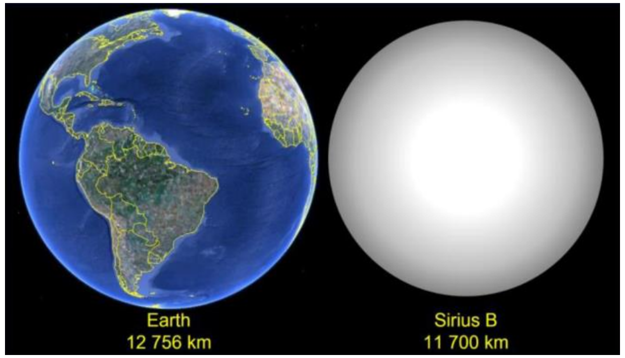


Detection of coherent light sources in astrophysics

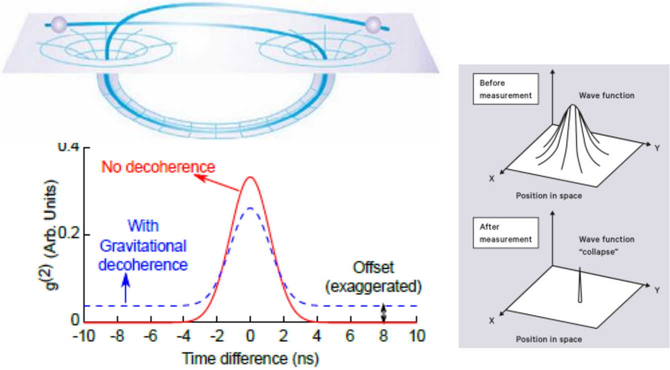


Beyond IC4Stars

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



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



New J. Phys. 20, 063016 (2018)

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

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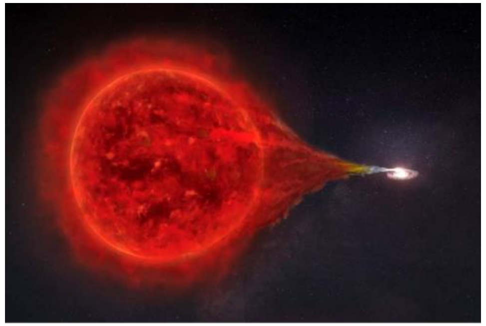
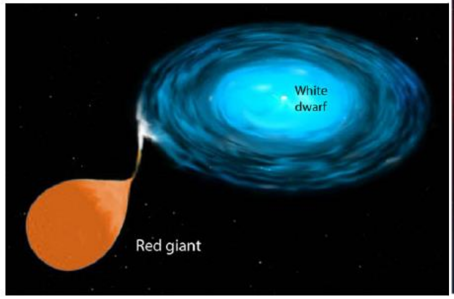
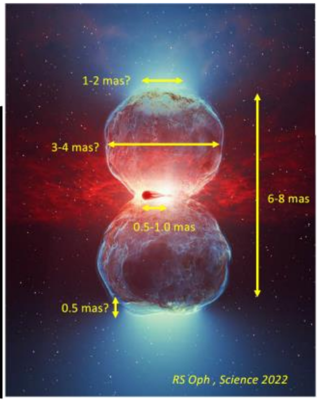
Received 2009 April 6; accepted 2010 January 20; published 2010 March 17

- Binary White Dwarfs
  (before Supernovae type I explosion)



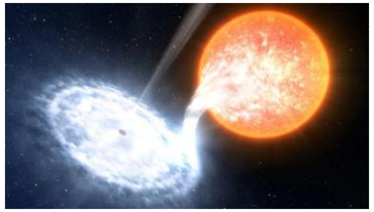
T Cor Bor: recurrent nova?
M10



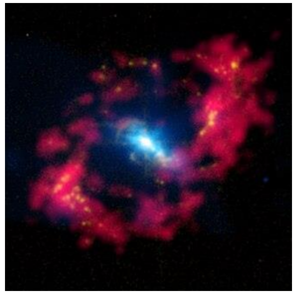


0.55-0.9 mas

- Black hole accretion disks

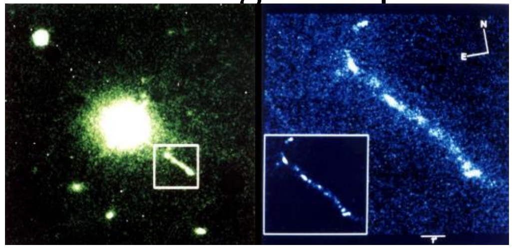


NGC4151



M11.5 / 100 μ″

3C 273 brightest quasar



(supermassive black hole)
M12.9

Exciting targets for ultrahigh angular resolution in astrophysics :

- Wolf Rayet Stars
  (before Supernovae type II explosion)

WR 124

M12 / 20 μ″

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COMPREHENSIVE PHOTOMETRIC HISTORIES OF ALL KNOWN GALACTIC RECURRENT NOVAE

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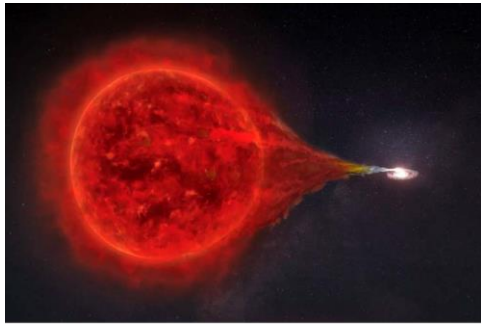
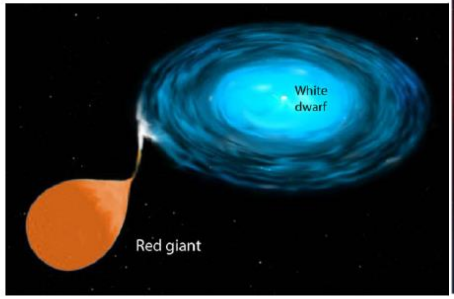
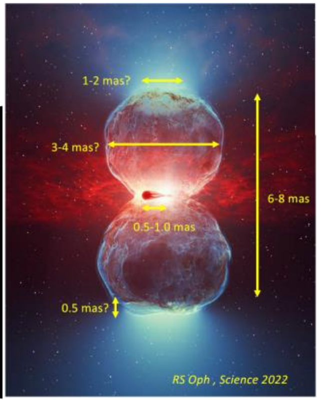
- Binary White Dwarfs
  (before Supernovae type I explosion)



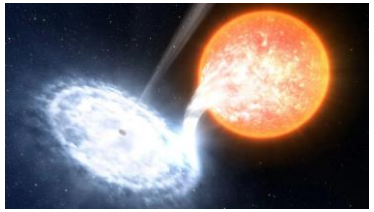
T Cor Bor: recurrent nova?
M10



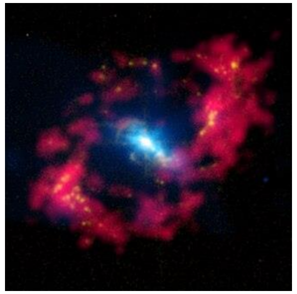


0.55-0.9 mas

- Black hole accretion disks

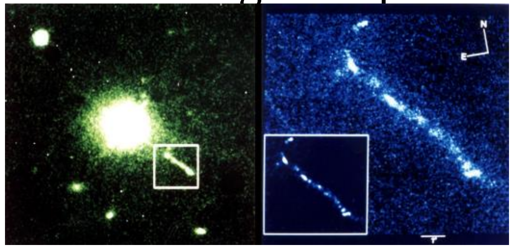


NGC4151



M11.5 / 100 μ″

3C 273 brightest quasar



(supermassive black hole)
M12.9

Thank you for your attention