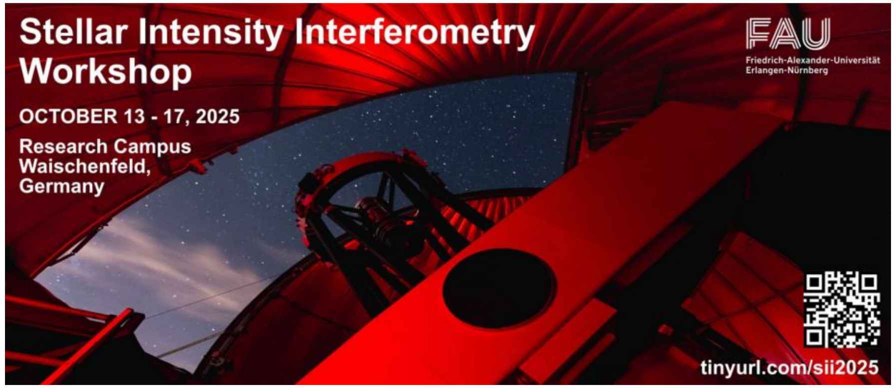
Intensity correlations: imaging and quantum optics in astrophysics

Robin Kaiser

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



cnrs UNIVERSITÉ CÔTE D'AZUR

PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

ANR erc

Outline

1) Optical astrophysical imaging
   and Hanbury Brown and Twiss experiments

2) Renewal of intensity correlations for astrophysics

3) IC4Star project in Nice :
   4.1 ultrahigh angular resolution
   4.2 quantum optics

Intensity Correlation team in Nice

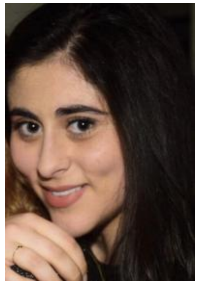
INPHYNI
INSTITUT DE PHYSIQUE DE NICE


R.K.


W.Guerin


M.Hugbart


G.Labeyrie


S.Tolila


I.Ellafi


R.Roudeix


F.Izraelevitch

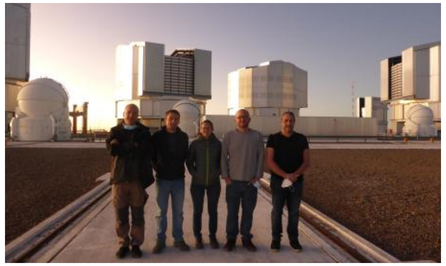

A.Zmija

Lagrange

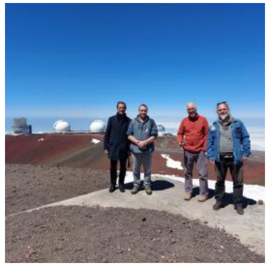
LAGRANGE


J.P. Rivet


F.Vakili




O. Lai



GeoAZUR
TERRE - OCÉAN - ESPACE


C. Courde


J. Chabé

+ Collaborations :

+ M. Borges
(Rio de Janeiro, Brazil)

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

+ S. Reynaud
(ENS, Paris)

Outline

1) Optical astrophysical imaging
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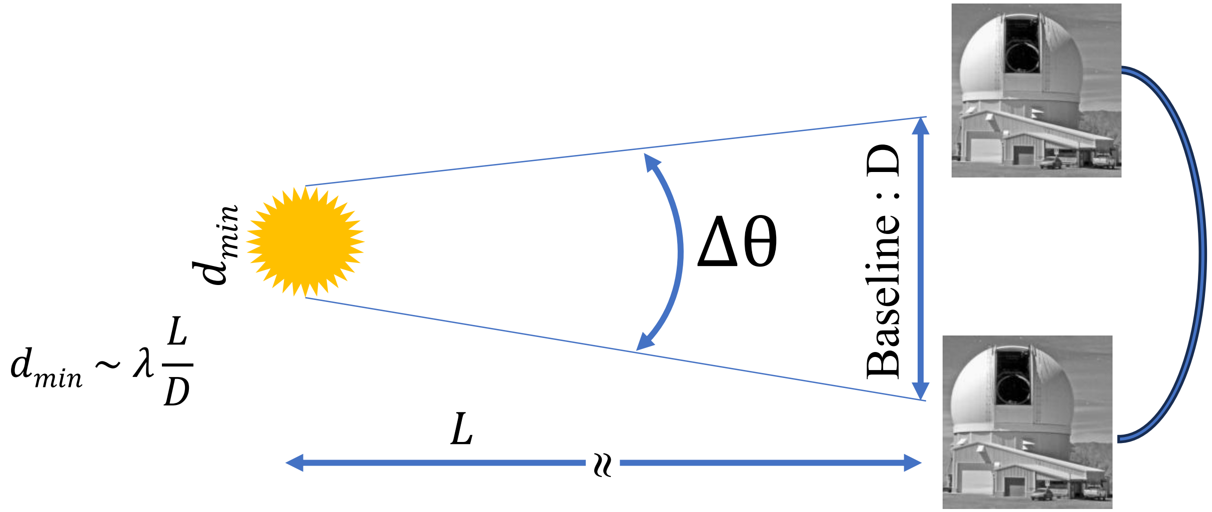
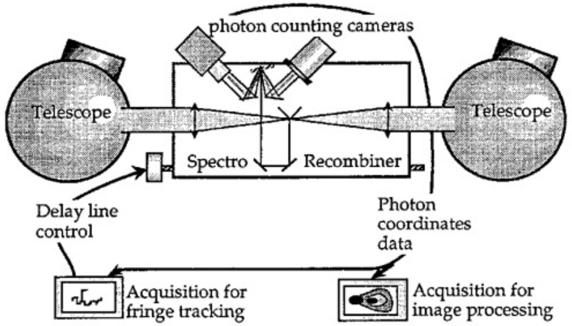
High angular resolution for stars : $\Delta\theta \sim \frac{\lambda}{D}$

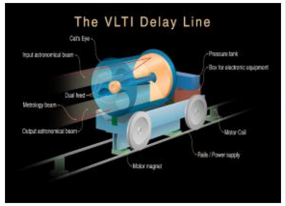


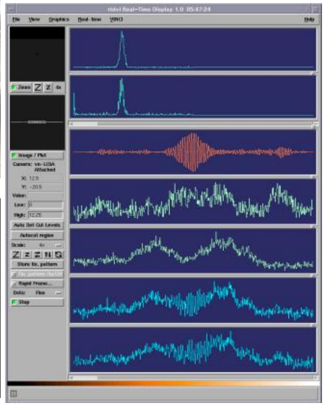
i. interferometric recombination
(VLTI, Chara, NPOI < 300m)

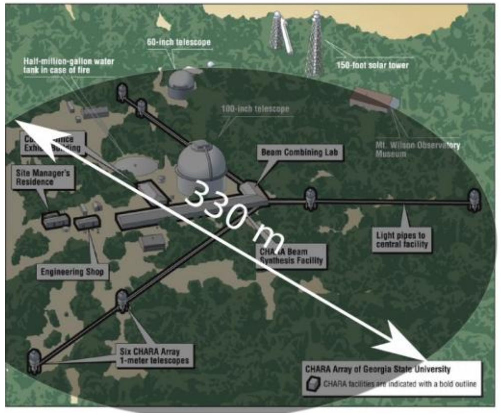
Interferometric imaging: large separation

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



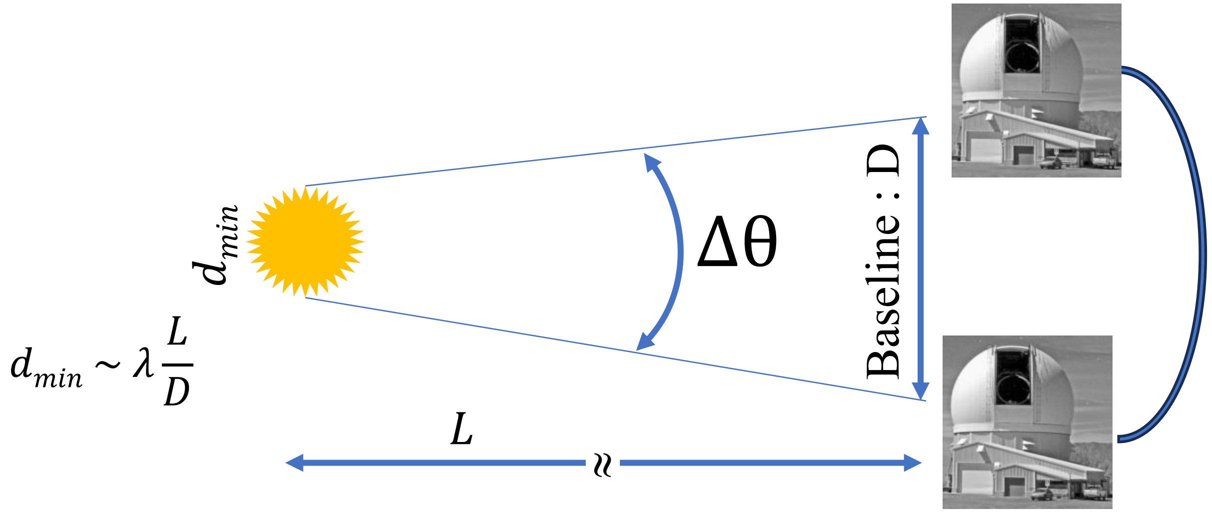






Calern (France) **Paranal (Chili)** **Mt Wilson (USA)**

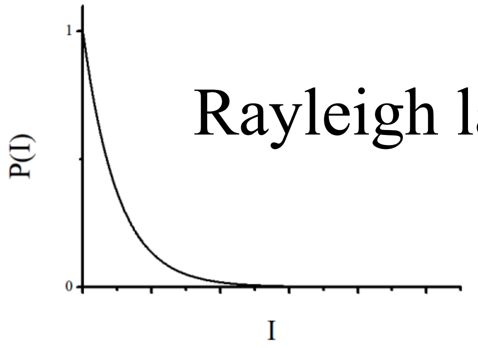
High angular resolution for stars : $\Delta\theta \sim \frac{\lambda}{D}$



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

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

Speckle statistics

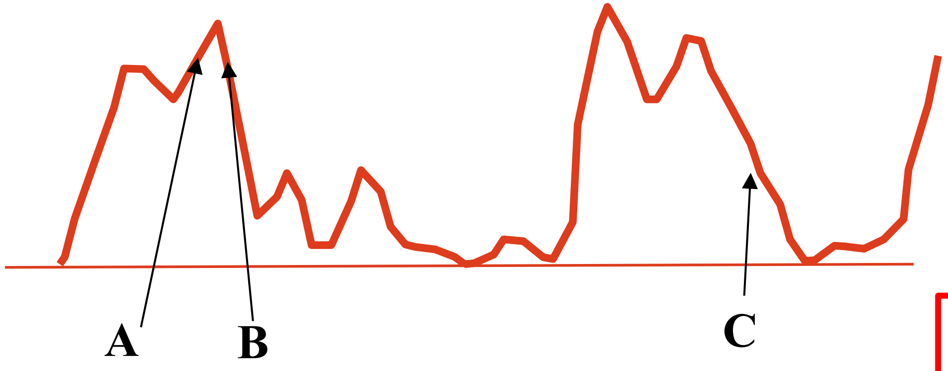


Rayleigh law

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

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

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



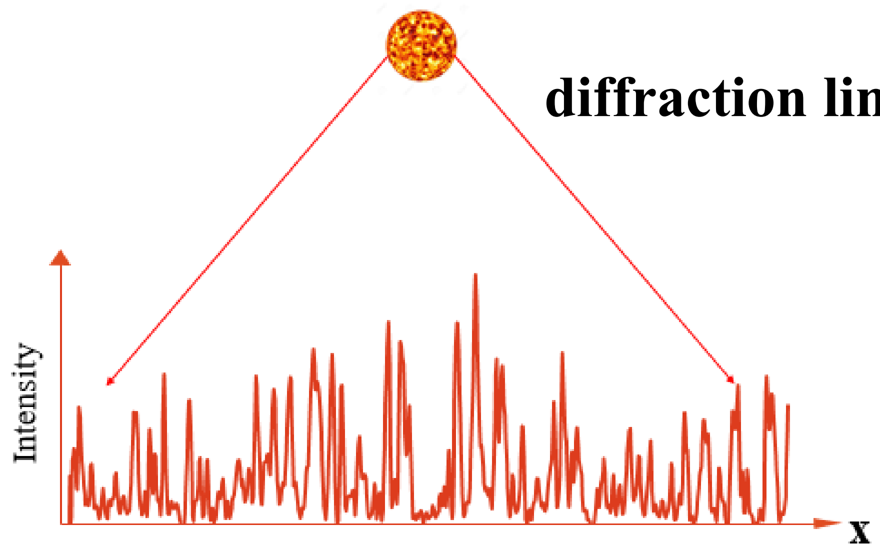
$I_A \sim I_B \neq I_C$

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

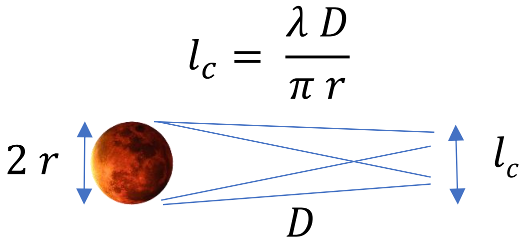
$$g_{AB}(2) = \langle I_A I_B \rangle / \langle I_A \rangle \langle I_B \rangle = 2$$

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

Time and spatial scales



diffraction limit $\theta = \lambda / D$

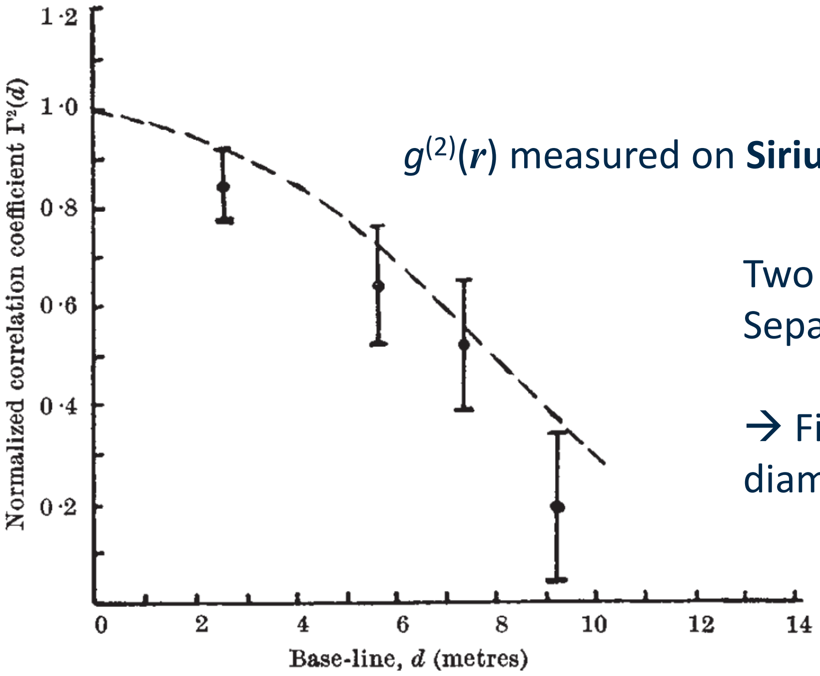


Speckle grain size : $l_c = \theta L \sim \lambda L / D$

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

A TEST OF A NEW TYPE OF STELLAR INTERFEROMETER ON SIRIUS

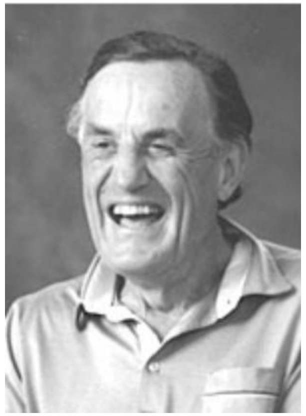
By R. HANBURY BROWN
Jodrell Bank Experimental Station, University of Manchester
AND
DR. R. Q. TWISS
Services Electronics Research Laboratory, Baldock



$g^{(2)}(\boldsymbol{r})$ 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



Robert Hanbury Brown
radio-astronomer

Richard Q. Twiss
applied mathematician

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

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 ☺

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A dynamic advocate for intensity correlations in astrophysics

(with a strong motivation by CTA)

D. Dravins :

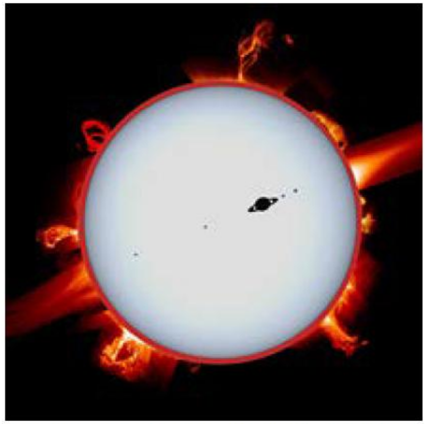
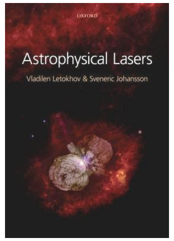


Figure 3. The real meaning of 40 microarcsecond optical resolution: Simulated resolution for an assumed transit of a hypothetical exoplanet across the disk of the relatively nearby star Sirius, using the full Cherenkov Telescope Array as an intensity interferometer. Stellar angular diameter = 6 mas;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

- 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

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



Early attempts for HBT revival with novel fast detectors :

Quanteye : OWL/ELT

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

Aqueye: Asiago (Italy) 182 cm telescope

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

Iqueye : La Silla (Chili) 358cm telescope

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

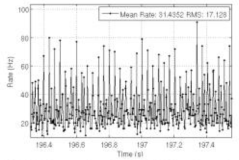
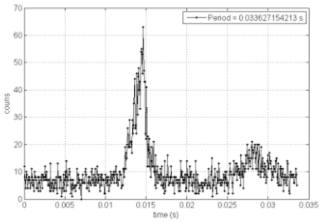
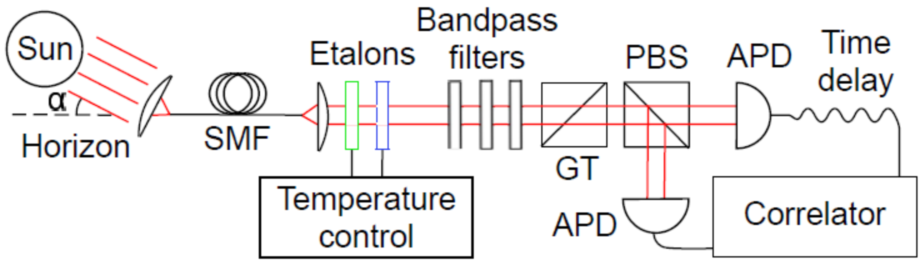


Fig. 9. Individual counts from the Crab Nebula pulsar, with 0.33 ms (1/10 of the period) bin size. The average count rate per time bin is given in the box.



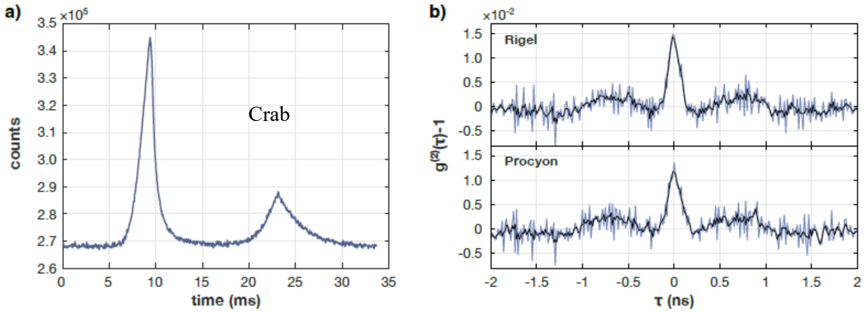
Singapore

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



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

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



SNSPD :

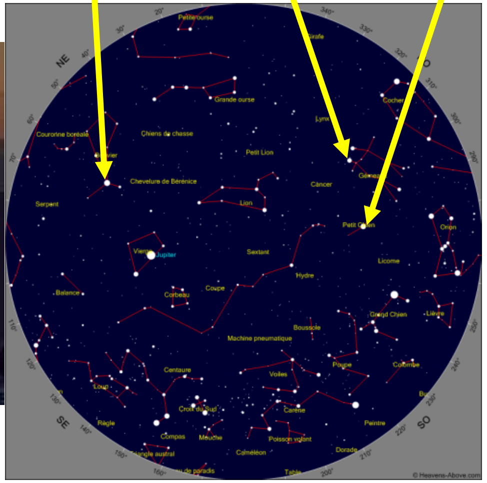
$\Delta t \sim 120$ps

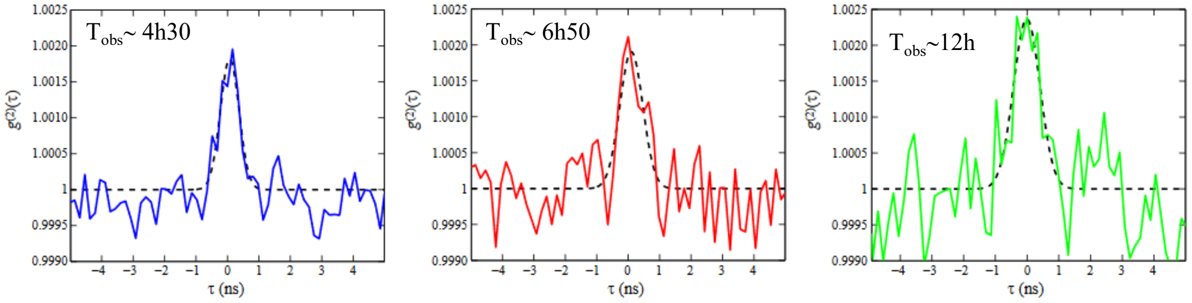
C2PU

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

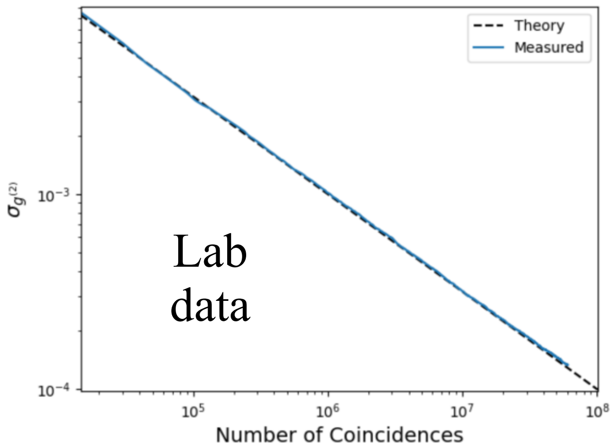
C2PU @ Calern

Arcturus Pollux Procyon

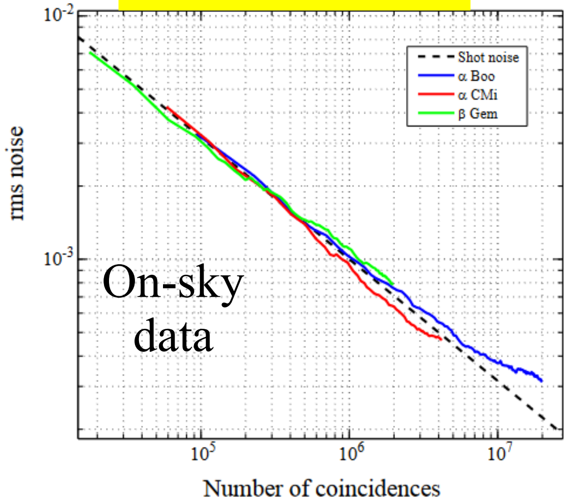




(a) α Boo (Arcturus). (b) α CMi (Procyon). (c) β Gem (Pollux).



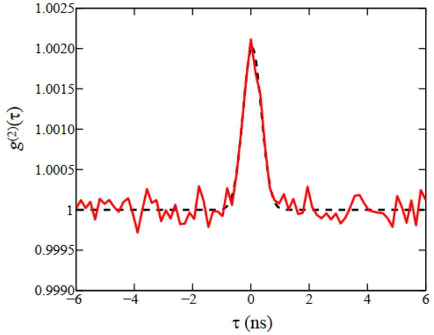
Shot noise limited



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

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

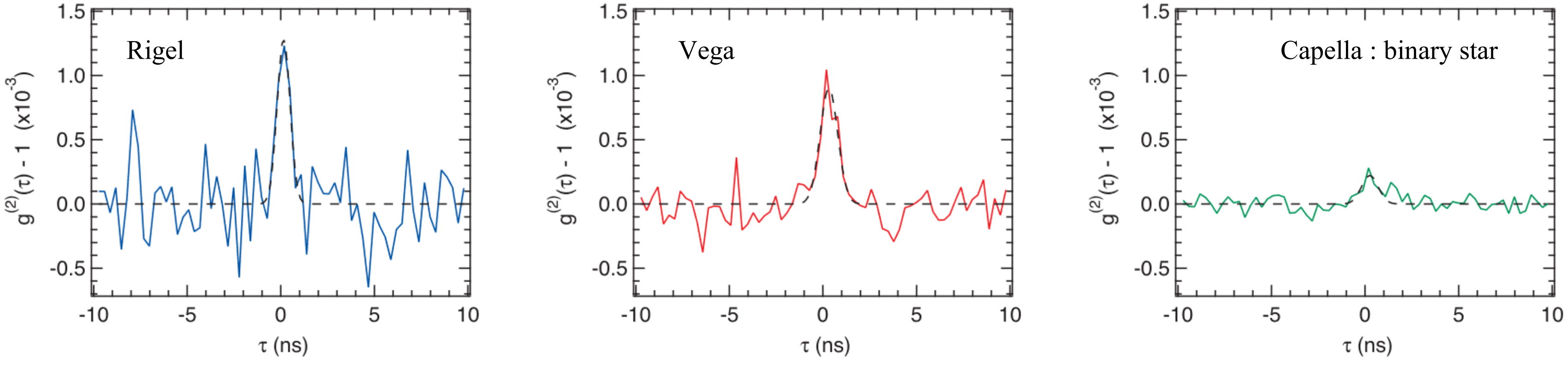
Laboratory calibration:
Convoluted $g^{(2)}(\tau)$



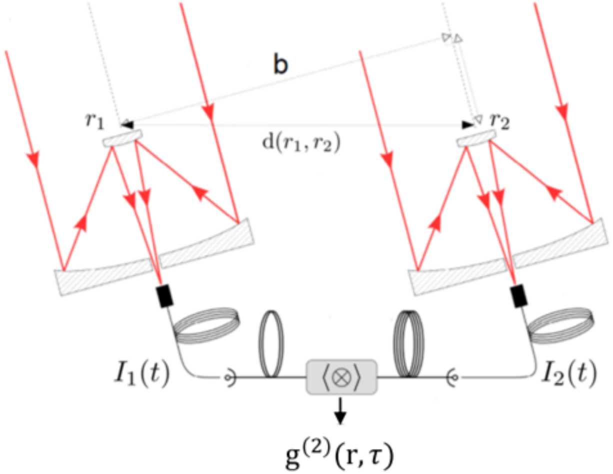
W. Guerin, A. Dussaux, M. Fouche, G. Labeyrie, J.-P. Rivet, D. Vernet, F. Vakili, R. K, Mon. Not. Roy. Astron. Soc. 472, 4126 (2017)

C2PU

Results : fall 2017 : spatial correlation on 3 bright stars



(a) β Ori. (b) α Lyr. (c) α Aur.



First angular measurement of stars with $g^2(r)$ since HBT !!!

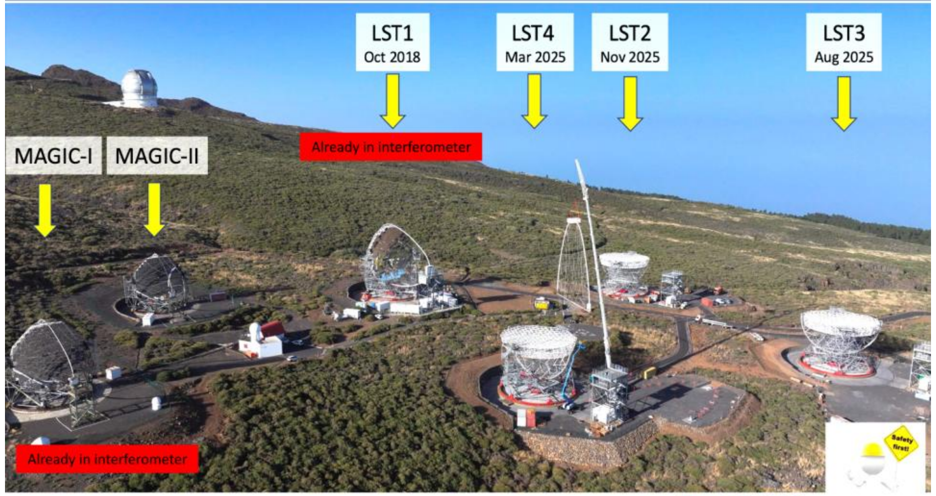
W. Guerin, J.-P. Rivet, M. Fouche, G. Labeyrie, D. Vernet, F. Vakili, R. K., Mon. Not. Roy. Astron. Soc. 480, 245 (2018)

MAGIC

[Juan Cortina](#) & [Alejo Cifuentes](#): *Intensity interferometry observations with MAGIC and the CTAO-North LSTs*

V. Acciari, et al., MNRAS 491, 1540 (2020)

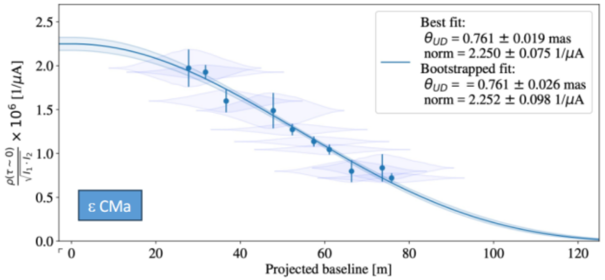
Ongoing deployment of the LSTs in La Palma



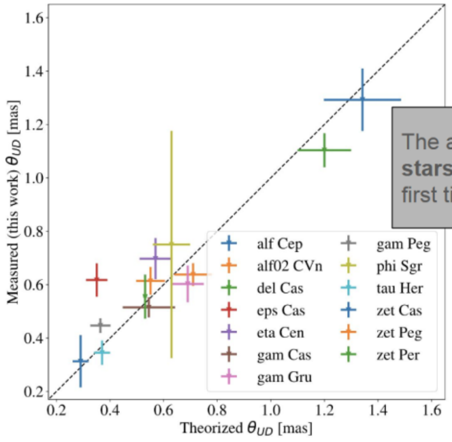
August 22nd, 2024

First science results with MAGIC

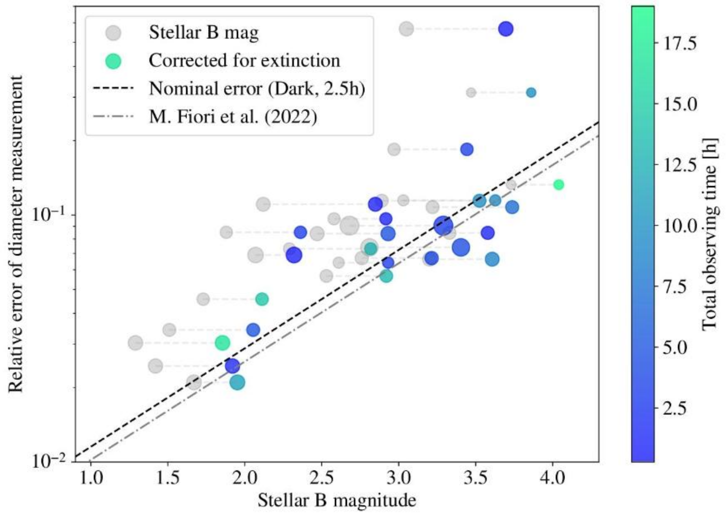
"Performance and first measurements of the MAGIC Stellar Intensity Interferometer", arXiv:2402.04755 and MNRAS 11 March 2024



MAGIC SII: New measurements

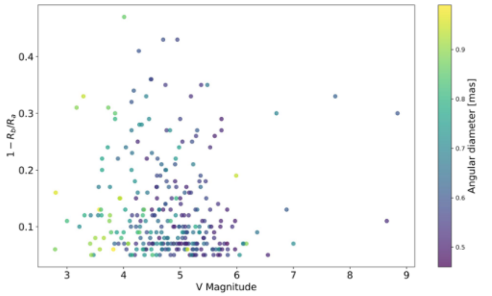


The angular diameter of **13 stars** was measured for the first time in the **B band**.



Science with MAGIC + 4LSTs SII: Fast rotators

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

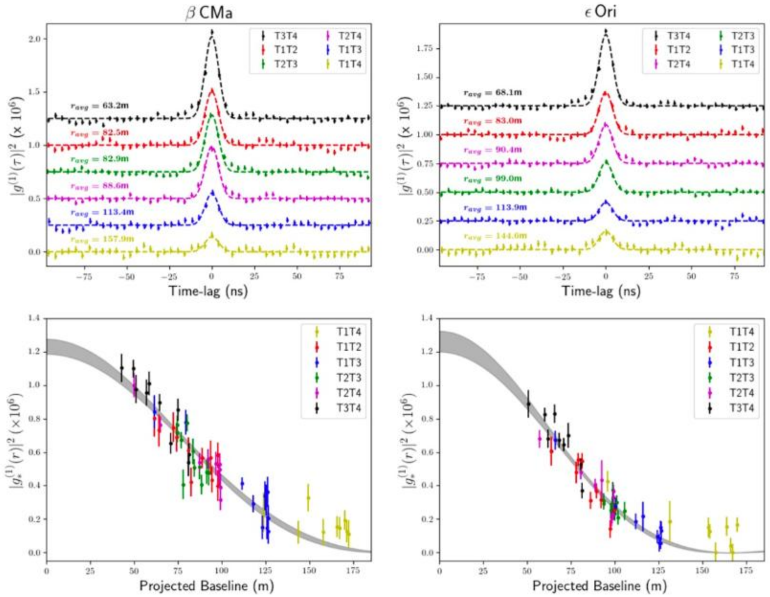


Multiple targets within reach of MAGIC + LST-1, most targets within reach of MAGIC + 4LSTs.

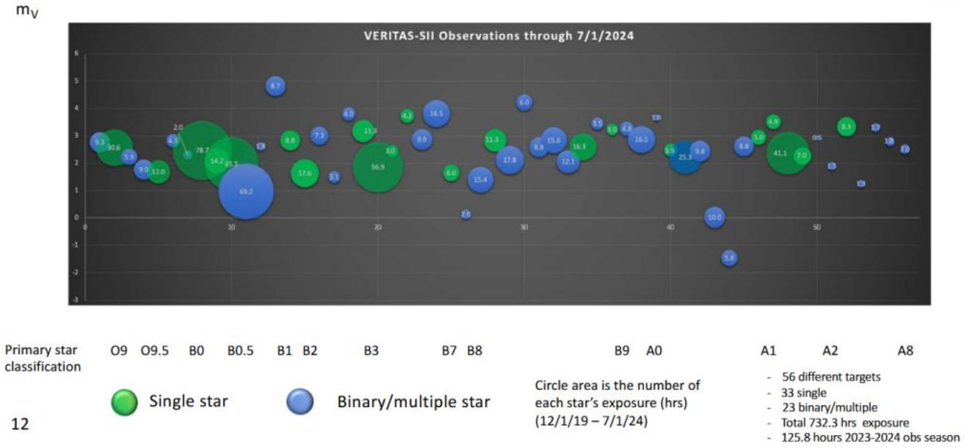
VERITAS

Dave Kieda : *The VERITAS SII Observatory*

Nat. Astronomy 4, 1164 (2020)

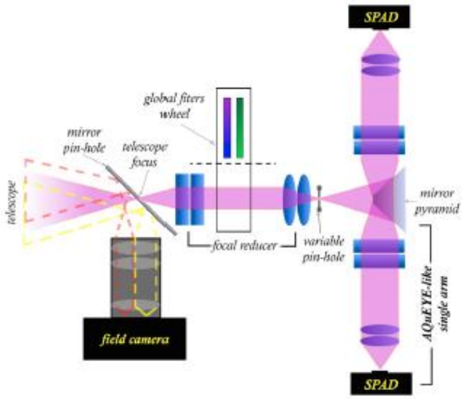


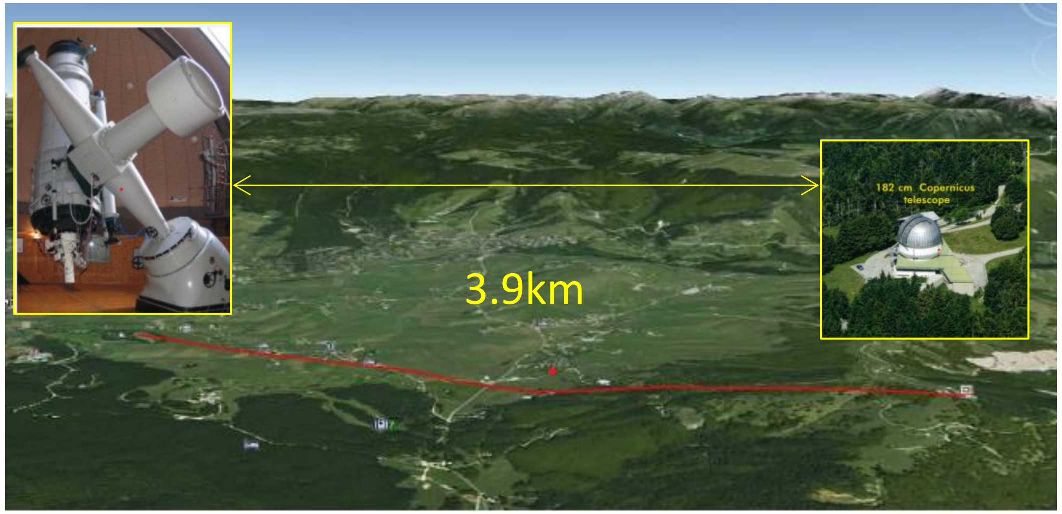
VSII Observations (Jul 1, 2024)

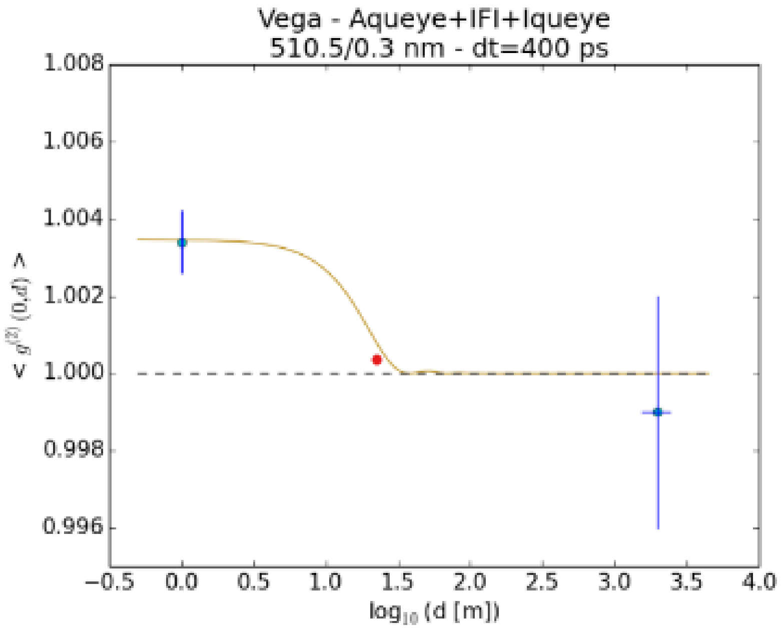


ASIAGO

L. Zampieri et al., MNRAS, 506(2), 1585(2021).

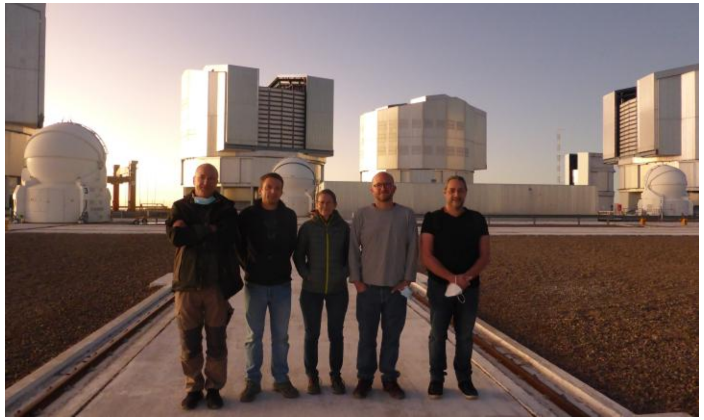


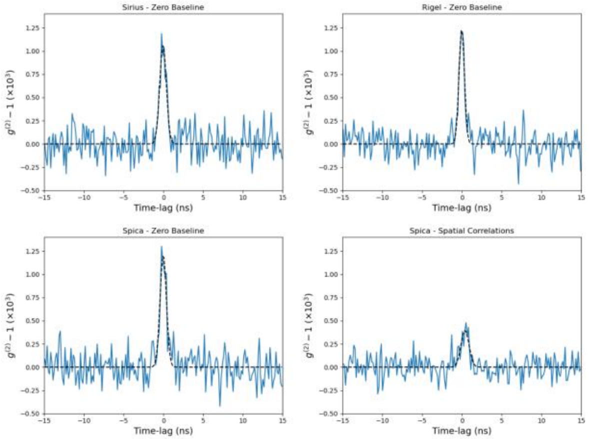




VLT

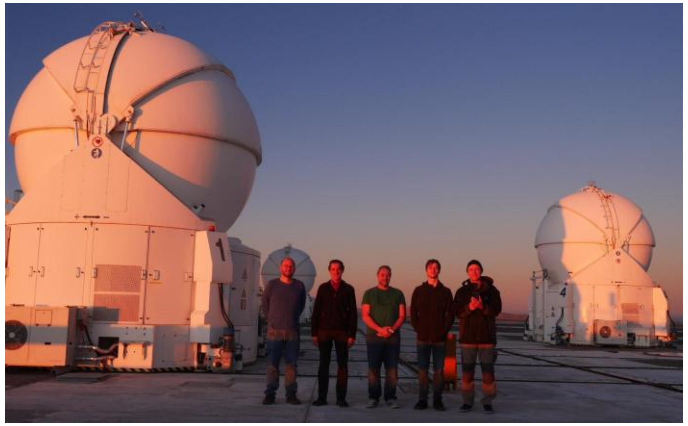
March 2022: Successful interferometric observation with 3 AT at Paranal (VLT)

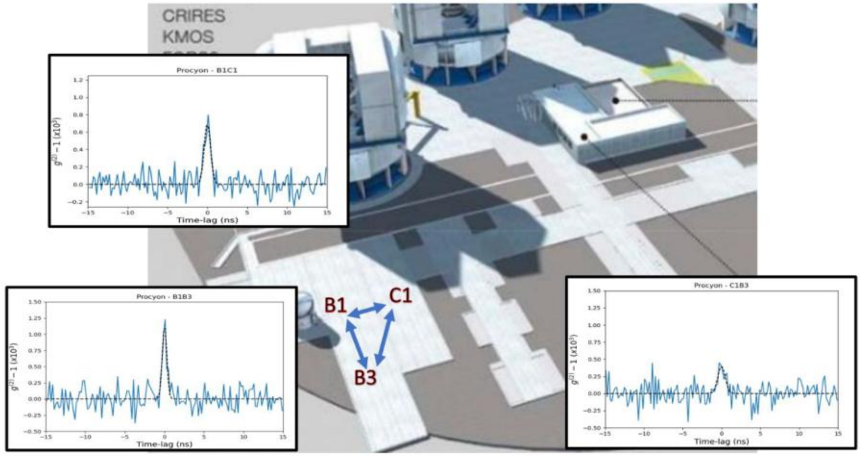




N. Matthews, J.-P. Rivet, M. Hugbart, G. Labeyrie, R. K., O. Lai, F. Vakili, D. Vernet, J. Chabe, C. Courde, N. Schuhler, P. Bourget, W. Guerin, [Proc. SPIE 12183, Optical and Infrared Interferometry and Imaging VIII, 121830G (2022)](),

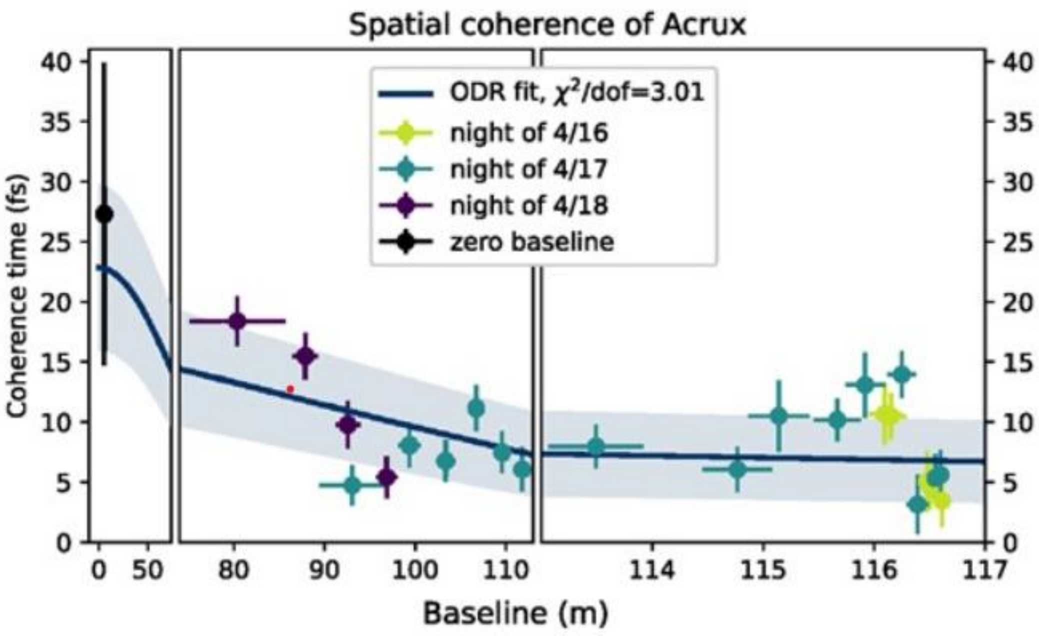
May 2023: Successful interferometric observation with 3 AT telescopes at Paranal

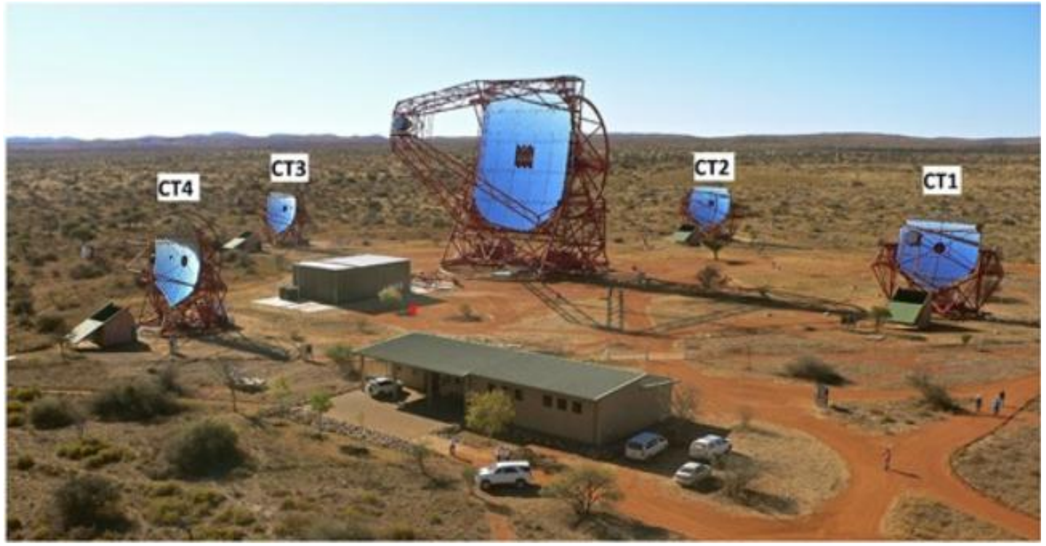


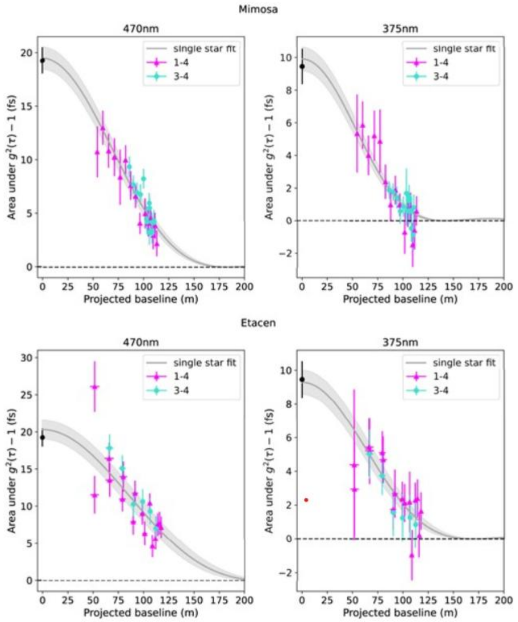


HESS

S. Funk et al MNRAS 527, 12243(2024)



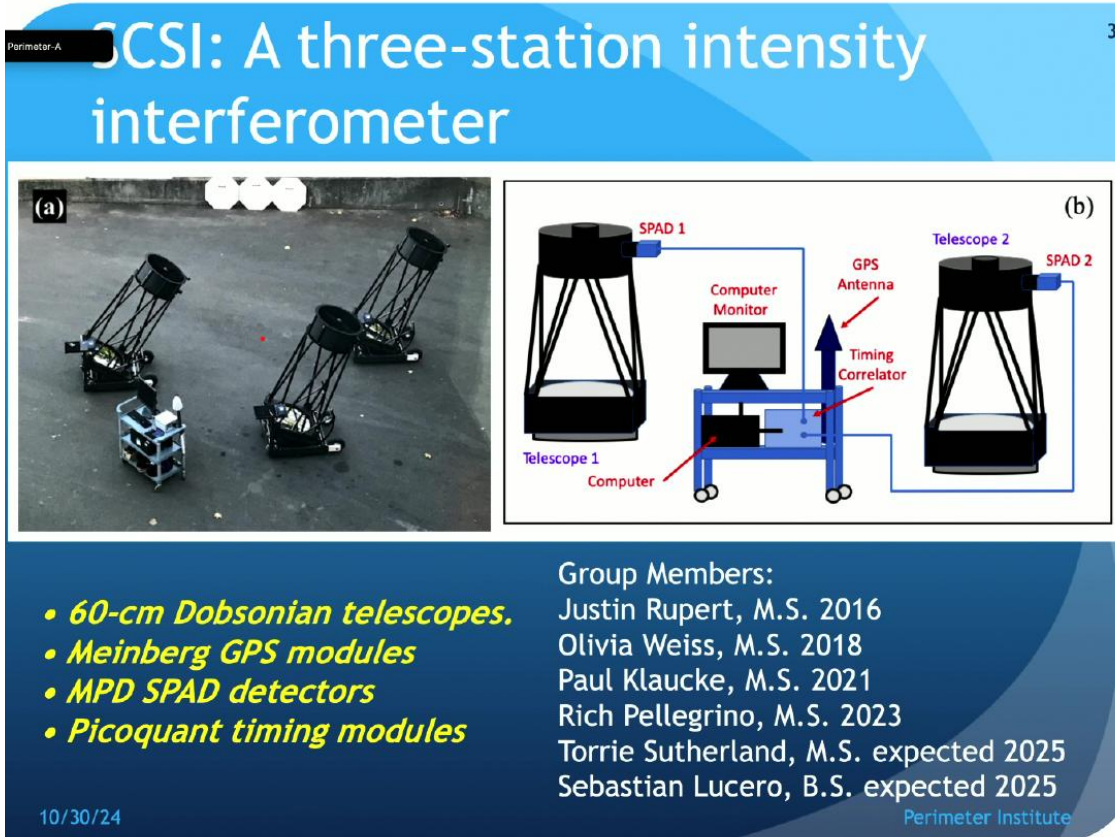


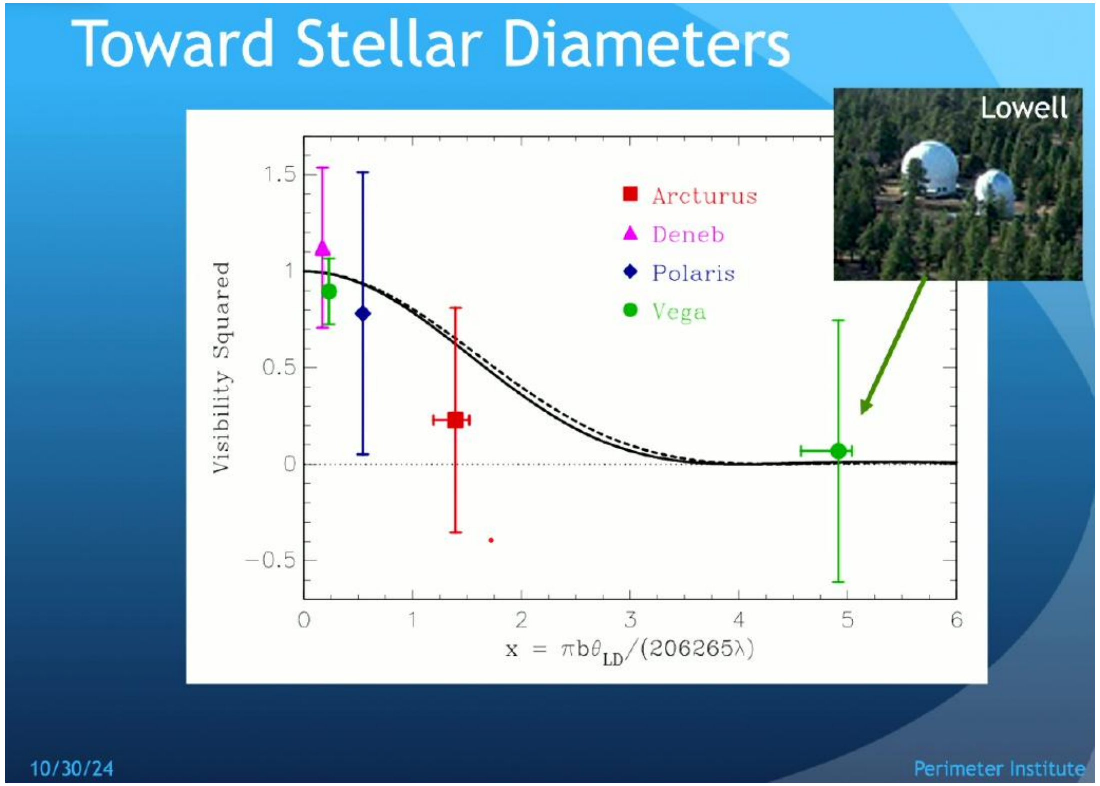


MNRAS 537, 2334, (2025)

Connecticut

E. Horch et al., The Astronomical Journal, 163, 92 (2022)





Ohio

T. Mozdzen et al., MNRAS 537, 2527–2534 (2025)

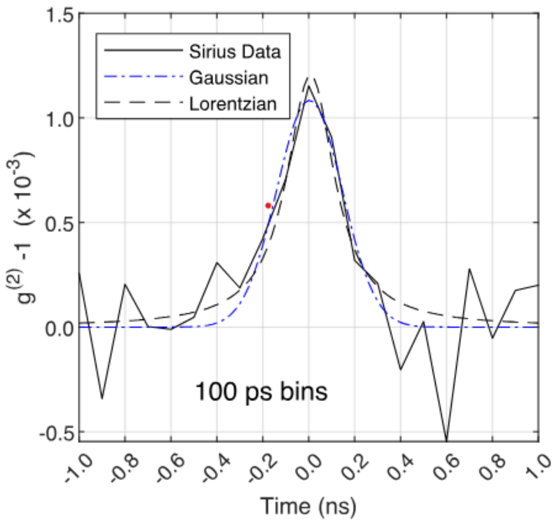


Table 4. Gaussian fitting results on the measured correlation signal of Sirius. The area, height, and sigma of the Gaussian fits are listed in the table.

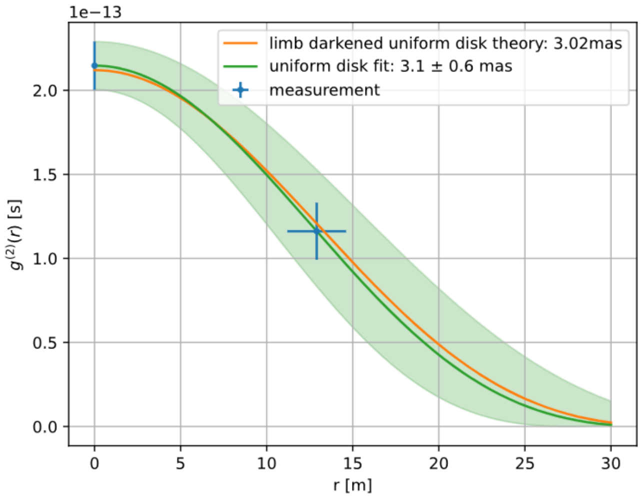
$\tau_{\text{coh-m}}$ (ps)	Fit height (contrast factor) $\times 10^{-3}$	Sigma fit (ps)	τ_{res} derived (ps)	$\lvert V_{12}(3.3\text{ m})\rvert^2$
0.73 ± 0.12	1.07 ± 0.18	136 ± 26	342 ± 65	0.94 ± 0.16

Erlangen

J. V. Zanthier et al.

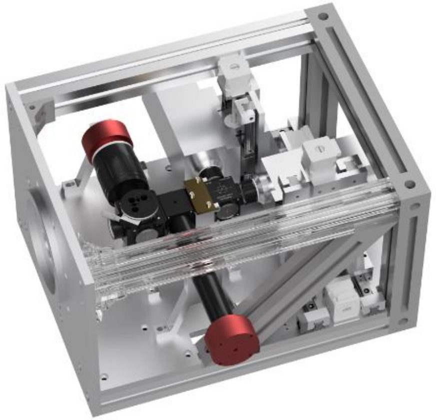
[Sebastian Karl & Verena Leopold]: *Spatial photon correlations using nearly dead time free ultra-high throughput single photon detection*
Stellar Intensity Interferometry Workshop Porquerolles 2024

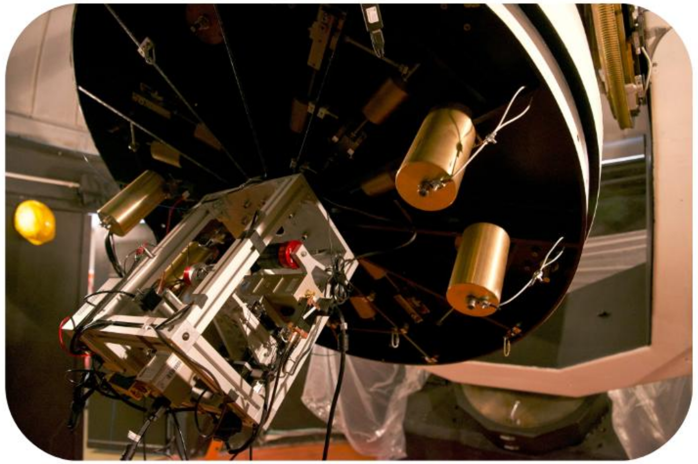
Visibility curve for Vega



Measurement Setup

FAU

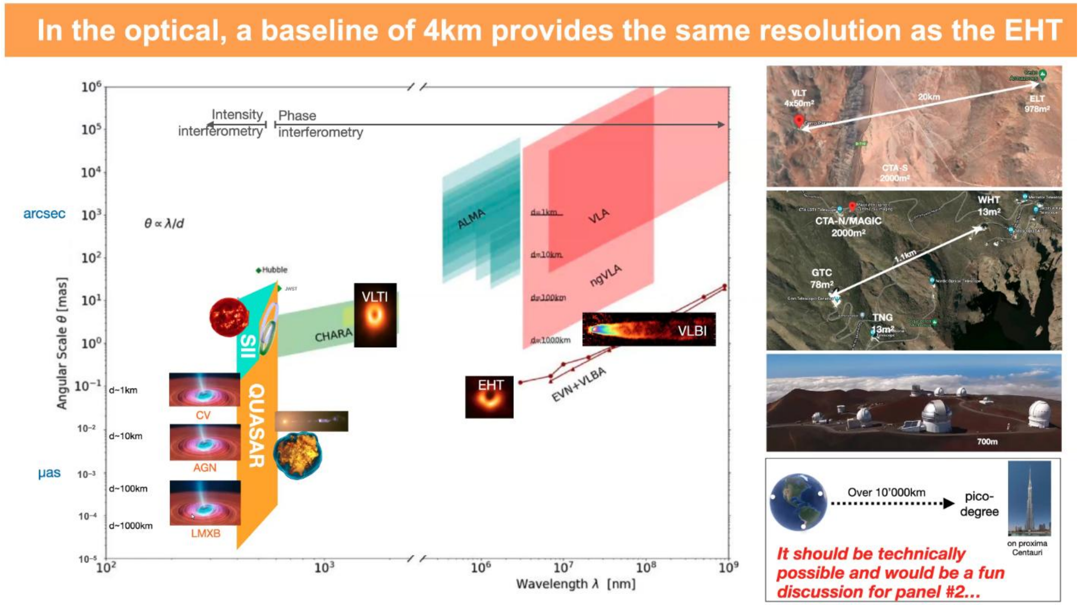


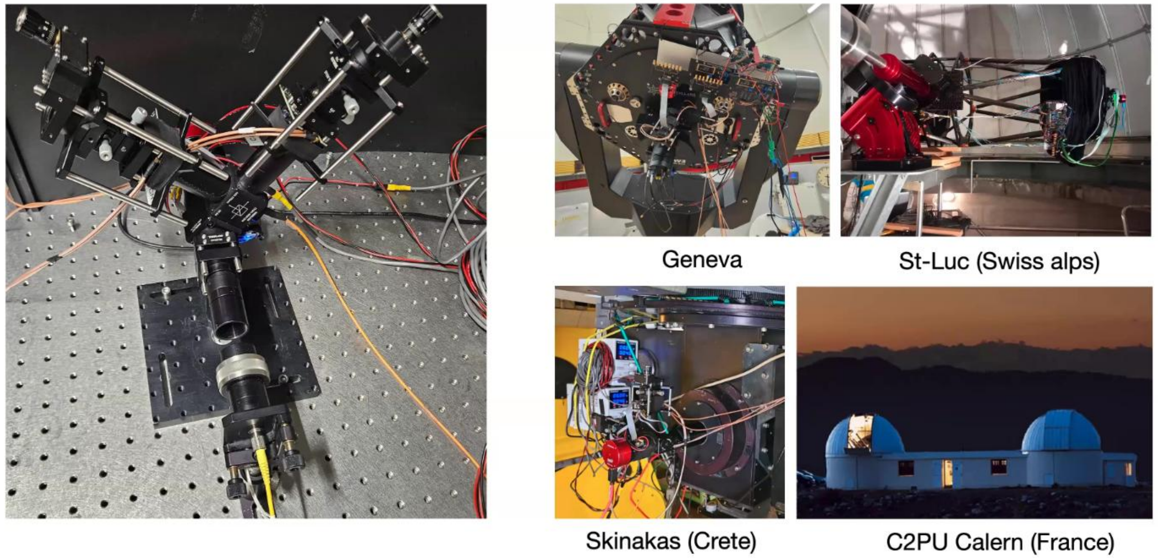


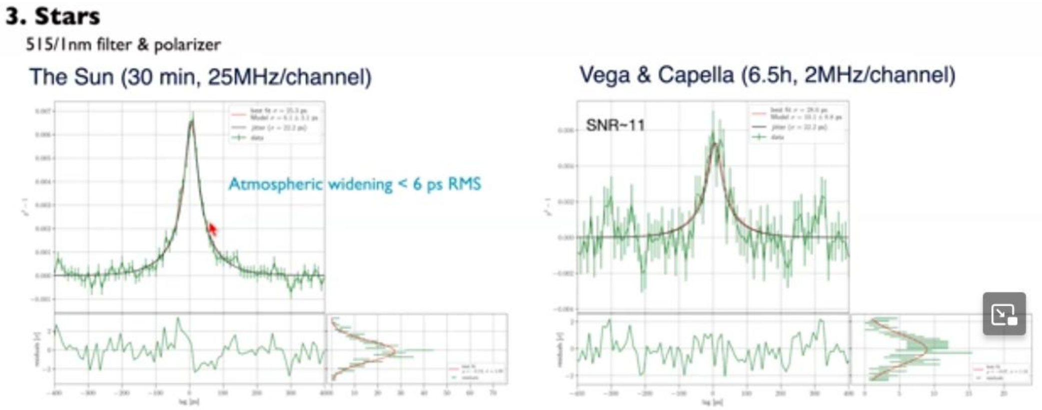
Geneva

R Walter et al.

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



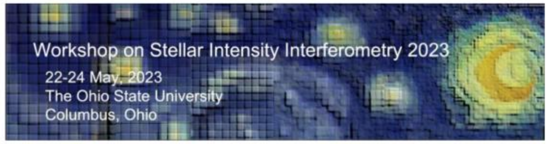




The jitter at the telescope was 22ps rather than 12ps because of a wrong setting of the voltage

Growing community

Stellar Intensity Interferometry



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

Participants in the Workshop on Stellar Intensity Interferometry 2023

Stellar Intensity Interferometry

Workshop 2024

September 9th – 13th, 2024

Porquerolles, France

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

The workshop's focus spans three key objectives:

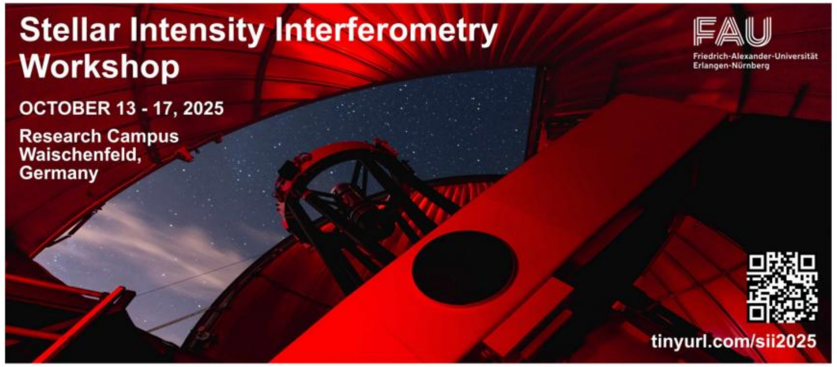
- Develop and disseminate novel ideas concerning science cases unique to intensity interferometry.
- Synthesize insights from observers and photodetector experts concerning the requisite technologies and experimental techniques which will allow for new science with intensity interferometry.
- Initiate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

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

Stellar Intensity Interferometry Workshop 2025

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

Entrer le texte à rechercher



Outline

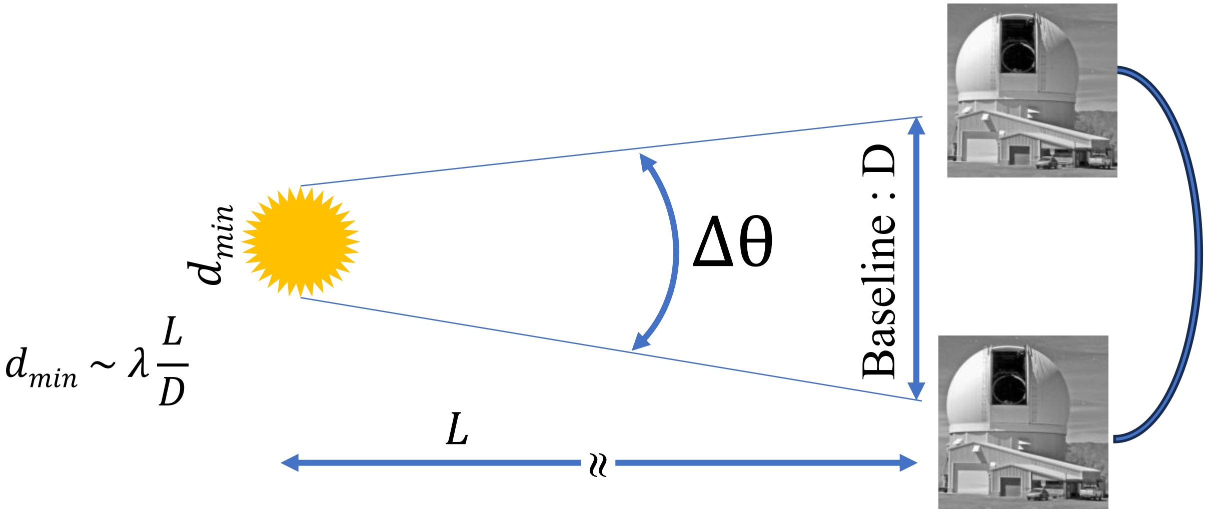
1) Optical astrophysical imaging
   and Hanbury Brown and Twiss experiments

2) Renewal of intensity correlations for astrophysics

3) IC4Star project in Nice :
   4.1 ultrahigh angular resolution
   4.2 quantum optics

Intensity Correlation for Stars (IC4Star)

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



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

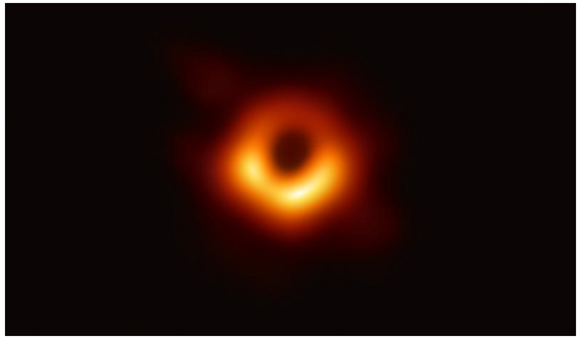
ii. intensity correlations $g^2(r)$
Hanbury Brown & Twiss

- 👍 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

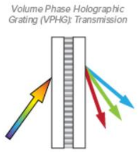
λ~420nm, D ~ km

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

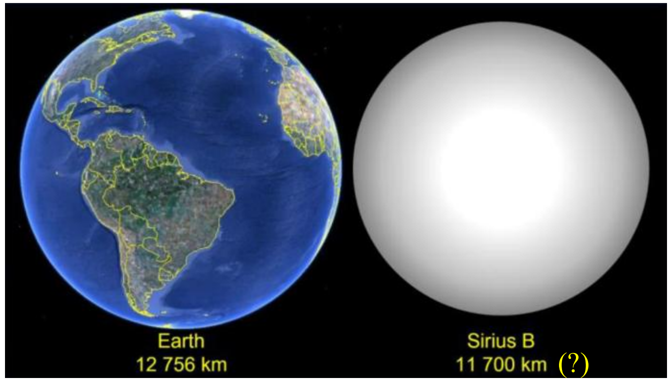
Keck/CFHT
10m/4m

Fast SPD
τ_{el}=20ps

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

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

⇒ **W. Guerin (on thursday)**
⇒ **I. Ellafi (poster)**



Exciting targets for ultrahigh angular resolution in astrophysics :

- Wolf Rayet Stars
  (before Supernovae type II explosion)

WR 124

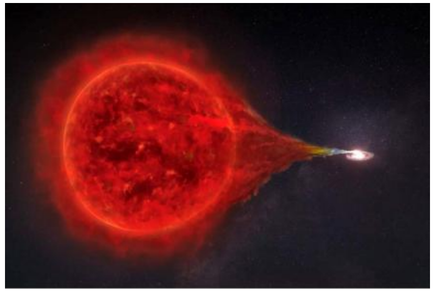
M12 / 20 μ″

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

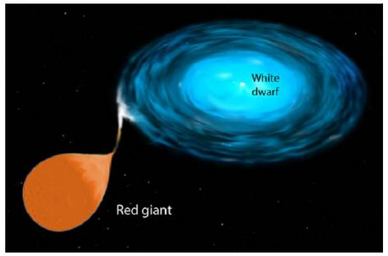
COMPREHENSIVE PHOTOMETRIC HISTORIES OF ALL KNOWN GALACTIC RECURRENT NOVAE

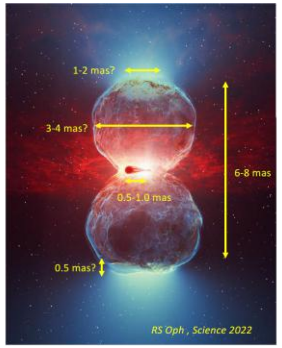
BRADLEY E. SCHAEFER
Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA; schaefer@lsu.edu
Received 2009 April 6; accepted 2010 January 20; published 2010 March 17

- Binary White Dwarfs
  (before Supernovae type I explosion)



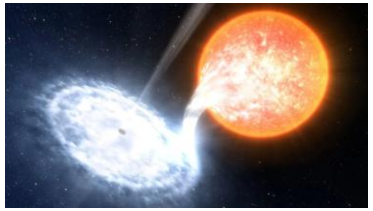
T Cor Bor: recurrent nova?
M10



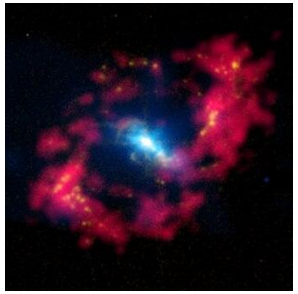


0.55-0.9 mas

- Black hole accretion disks

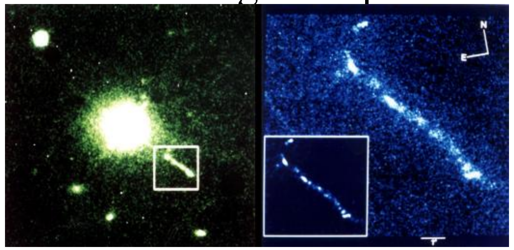


NGC4151



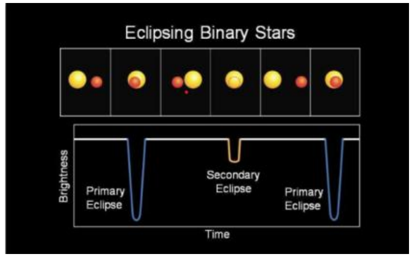
M11.5 / 100 μ″

3C 273 brightest quasar



(supermassive black hole)
M12.9

- Detatched Eclisping Binaries : cosmic distance ladder
  (© A. Kim)



Outline

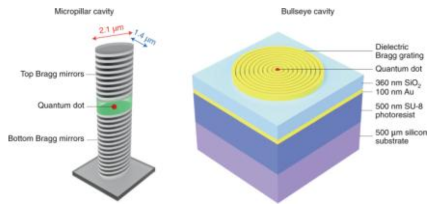
1) Optical astrophysical imaging
   and Hanbury Brown and Twiss experiments

2) 80' : Intensity correlations for quantum physics

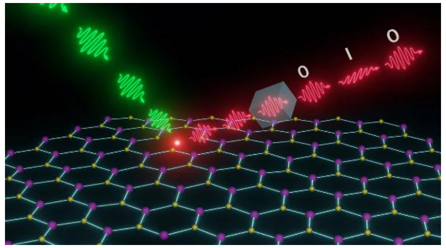
3) Renewal of intensity correlations for astrophysics

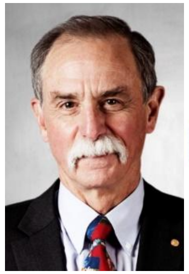
4) **IC4Star project in Nice :**
   4.1 ultrahigh angular resolution
   4.2 quantum optics

Single atoms, ions and photons

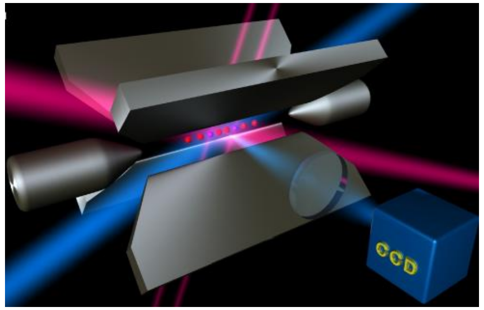


Single photons

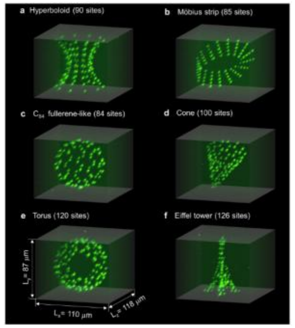




Haroche Wineland 2012



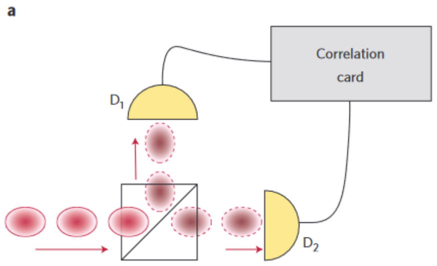
Trapped Ions

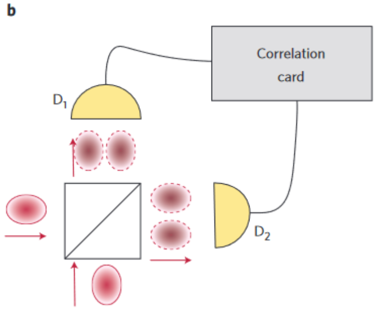


Trapped Atoms

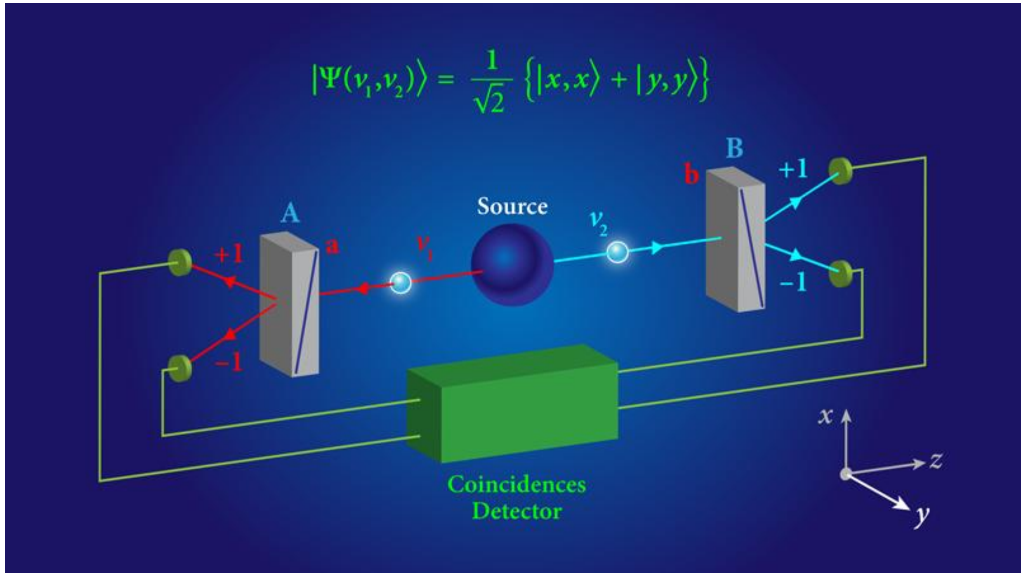
single-photon purity :
HBT

photon indistinguishability:
Hong–Ou–Mandel





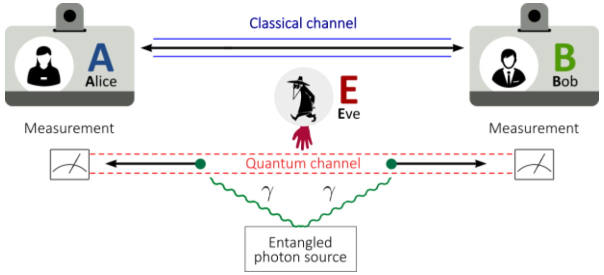
2 particle correlations: classical vs quantum
Philosophical debate until Bell (1964)



2022

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

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

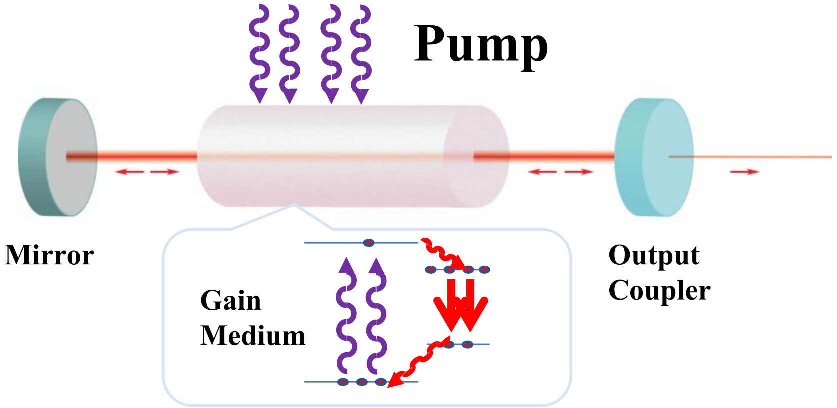


Quantum Optics & Intensity Correlation from space photons

1) **Random lasing**
2) **Gravitational wave background detection**
3) **Hot stars / microwaves**
4) **Pauli Blocking / Non linear optics / squeezing**

1) Random lasing

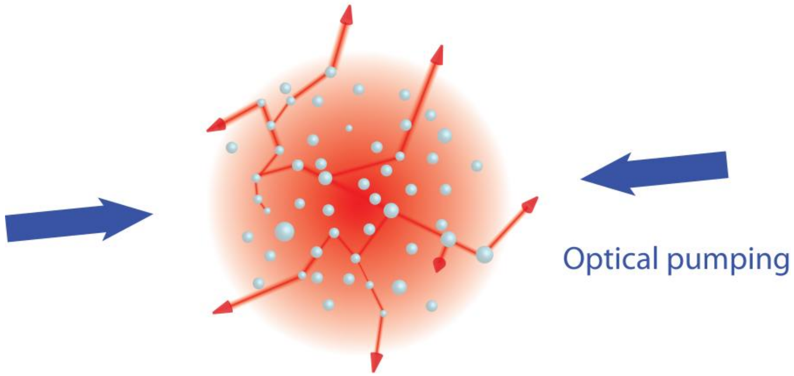
- Cavity Laser



Ingredients:

- Gain Medium
- Cavity
  → Feedback & Mode Selection

- Random Laser



- Gain Medium
- **Multiple scattering**

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

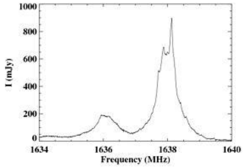
1939–2009

Gain in volume vs **Losses** at surface

⇒ **Critical volume / mass : photonic bomb**

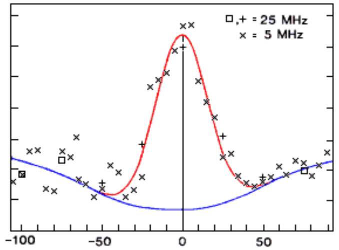
Astrophysics and (random) lasing

Space « masers »: H.Weaver, et al., *Nature*, **208**, 29 (1965):
higher accuracy for red shift measurements



Space « lasers »: M. Mumma, et al., Science, **212**, 45(1981)
atmospheres of Mars and Venus (CO_2 lines)

@Berkeley: ISI project



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

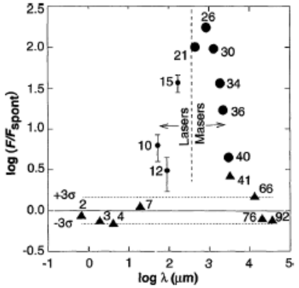


Fig. 8 MWC349A: Log-log plot of the ratio F/F_{spont} where F is the total observed flux in successive hydrogen recombination lines, and F_{spont} the estimated contribution from spontaneous emission. Large dots indicate masing mm and sub-mm lines; small dots are infrared detections. The numbers are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

ALTERNATIVE EXPLANATION FOR THE SPECTRAL LINES OBSERVED IN QUASARS

(*Letter to the Editor*)

Y. P. VARSHNI

Dept. of Physics, University of Ottawa, Ottawa, Canada

(Received 23 June, 1975)

Abstract. It is shown that the emission lines observed in quasars can be satisfactorily explained as being due to laser action in certain atomic species in the expanding envelope of a star. There is no need to assume a redshift.

Publications of the Astronomical Society of Australia (2022), **39**, e011, 4 pages
doi:10.1017/pasa.2022.11

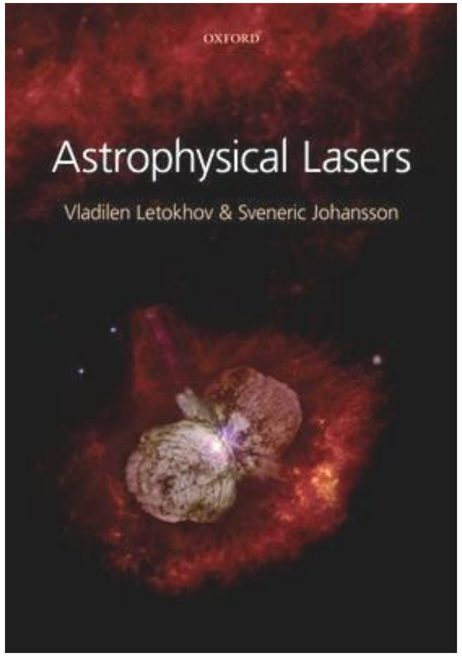
Research Paper

Intensity correlation functions of microwave maser sources

A. V. Shepelev

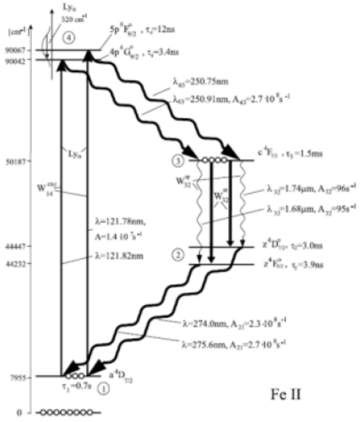
Aurorae on the north pole of Jupiter generate cyclotron masers (Hubble)

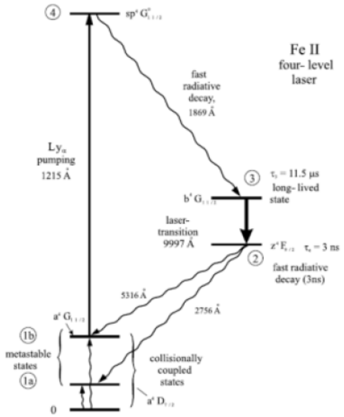
Challenge :
Find **emission lines** with **population inversion**

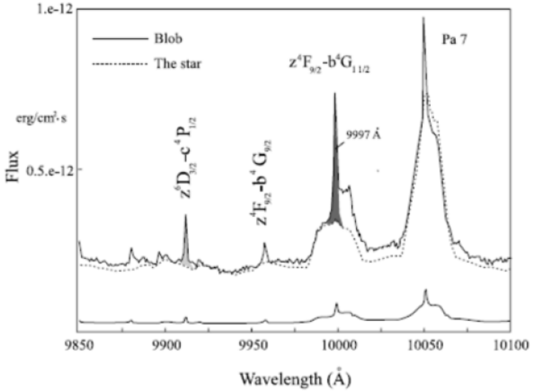


Eta Car : Fe II:

population inversion at
0.99 / 1.6 /1.7 μm







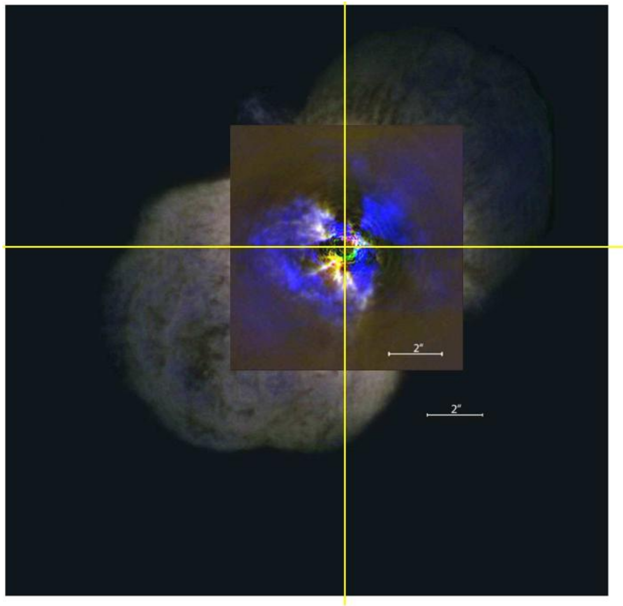
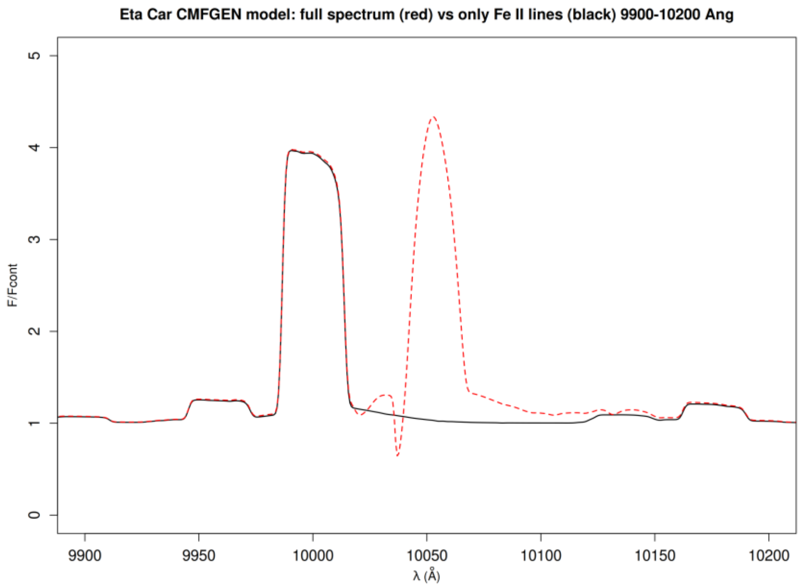
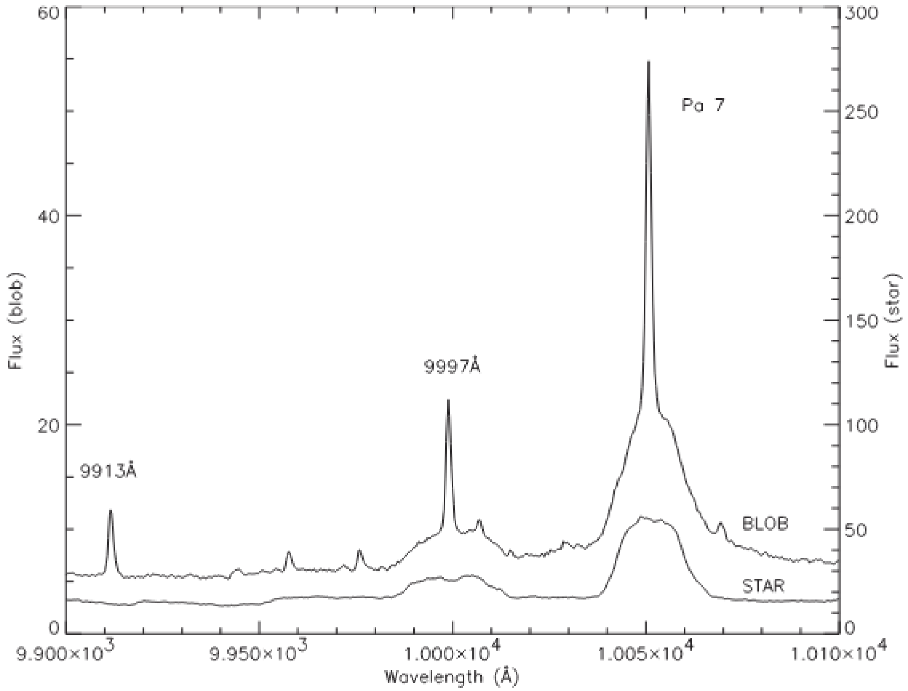


Fig. 2a.— The combined Brγ, H_2, [Fe II] image without the continuum subtraction; Brγ (red), H_2 (green),and [Fe II] (blue). North is up and east is left.

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



E. Almeida ®

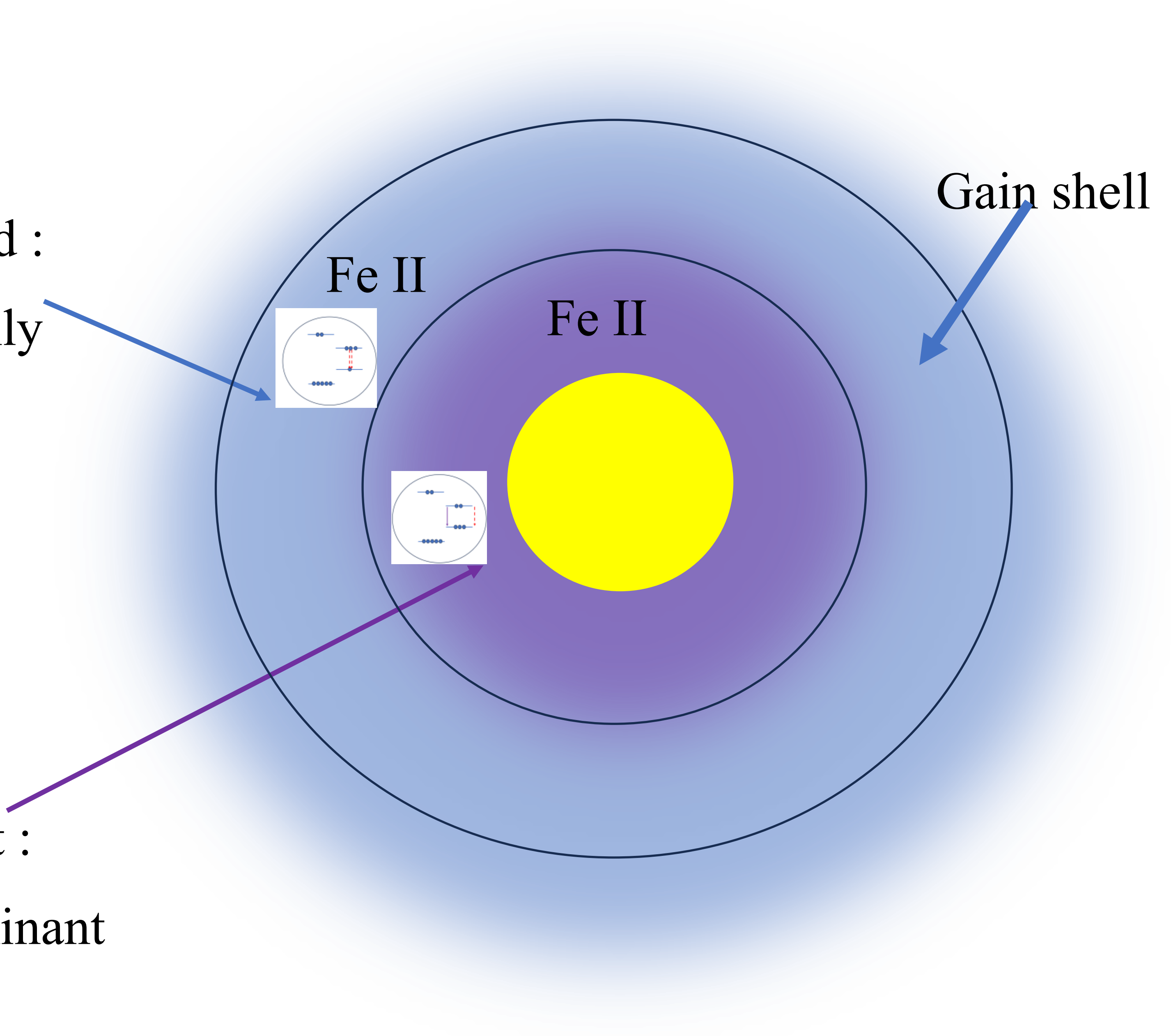


S. Johansson & V. Letokhov, A&A 428, 497 (2004)

Low density & cold :

Radiative decay only

☺



High density & hot :

Collisional decay dominant

☹

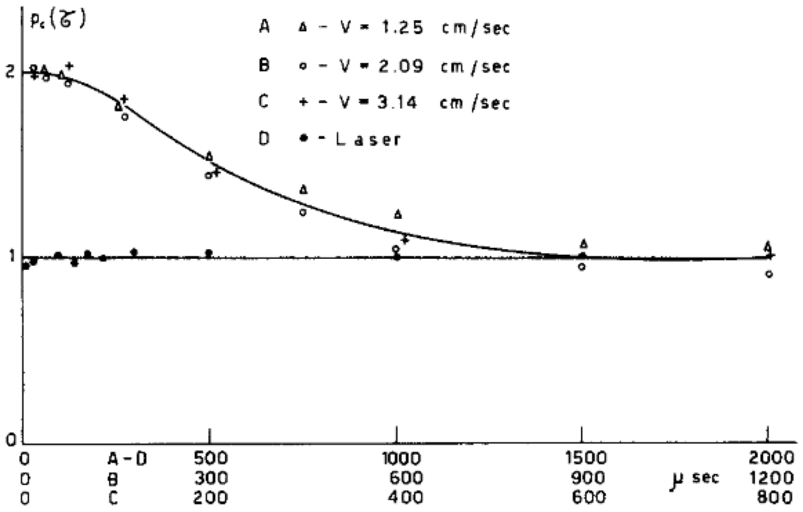
Signatures of random lasing :

second order coherence ≠ first order coherence

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

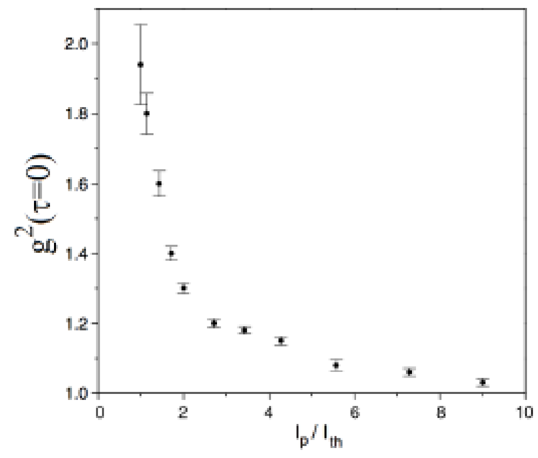
Quasi-Thermal light => $g^{(2)}(\tau=0)=2$

Random lasing



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

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



Quantum theory : R. Glauber

2) Gravitational wave background detection

Feynman *Lectures on Gravitation* (1962)

→ Unavoidable interactions with our gravitational environment could be at the origin of the classical behavior of macroscopic systems.

B. Lamine (LPNHE.pdf)

nature communications

Article https://doi.org/10.1038/s41467-023-43348-2

Gravitationally induced decoherence vs space-time diffusion: testing the quantum nature of gravity

Received: 12 July 2023

Accepted: 8 November 2023

Jonathan Oppenheim[1], Carlo Sparaciari[1], Barbara Šoda[1,2,3] & Zachary Weller-Davies[1,3]

Gravitational waves, diffusion and decoherence

Authors	S. Reynaud, B. Lamine, M.-T. Jaekel
Pages	219 - 239
DOI	10.3254/978-1-58603-990-5-219
Series	Proceedings of the International School of Physics "Enrico Fermi"
Ebook	Volume 168: Atom Optics and Space Physics (2009)

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

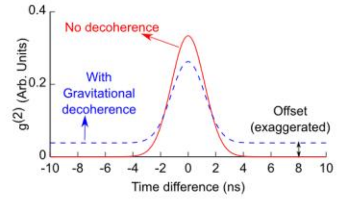


Figure 3. Illustration of the gravitational decoherence effect. Consider a temporal cross correlation histogram $g^{(2)}$ between the arrival times of photons at the OGS and on the ISS. The area of the peak represents the number of photon pairs while the number of singles events is obtained from the 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).

Science

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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

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Review | Published: 24 April 2019

The new frontier of gravitational waves

M. Coleman Miller & Nicolás Yunes

Nature **568**, 469–476 (2019) | Cite this article

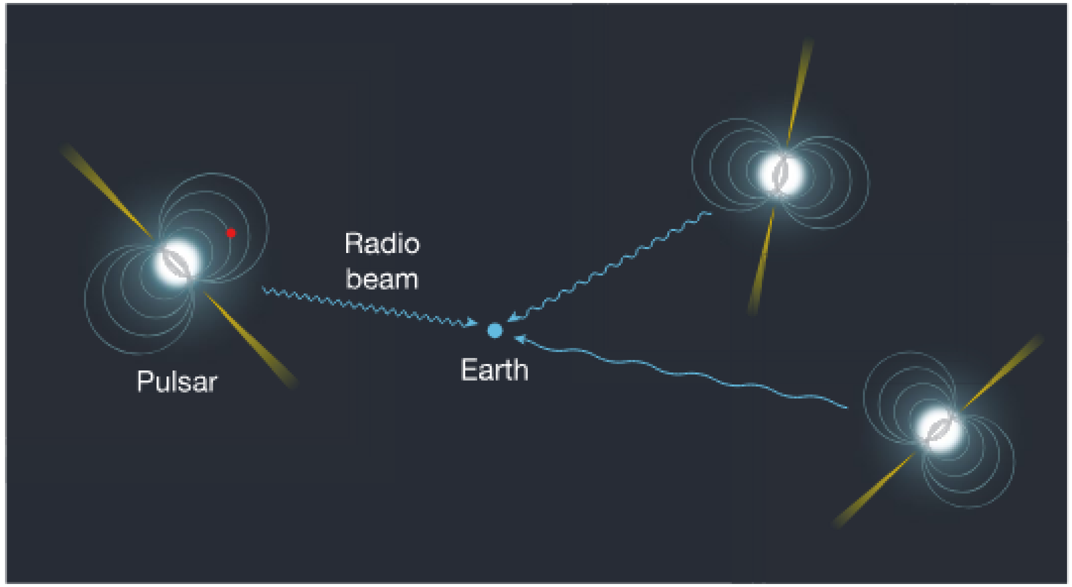


Fig. 5 | Operation of a pulsar timing array for the detection of low-frequency gravitational waves. The signals from the pulsars travel through spacetime that is dynamically warped by gravitational waves, which changes the timing of the pulsars in a correlated way. Figure adapted from ref. [93] (Springer Nature).

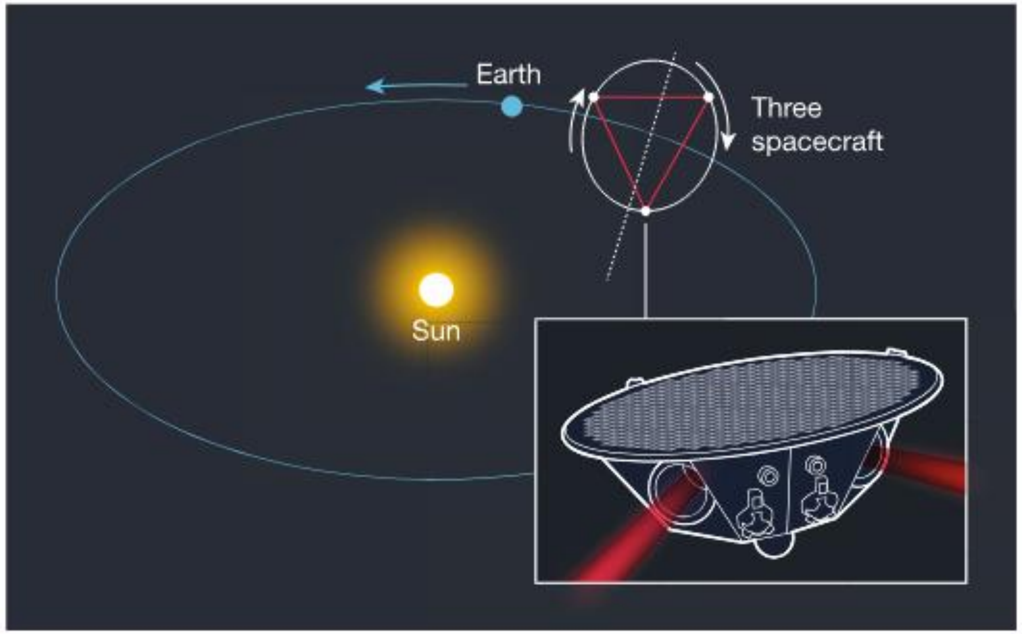
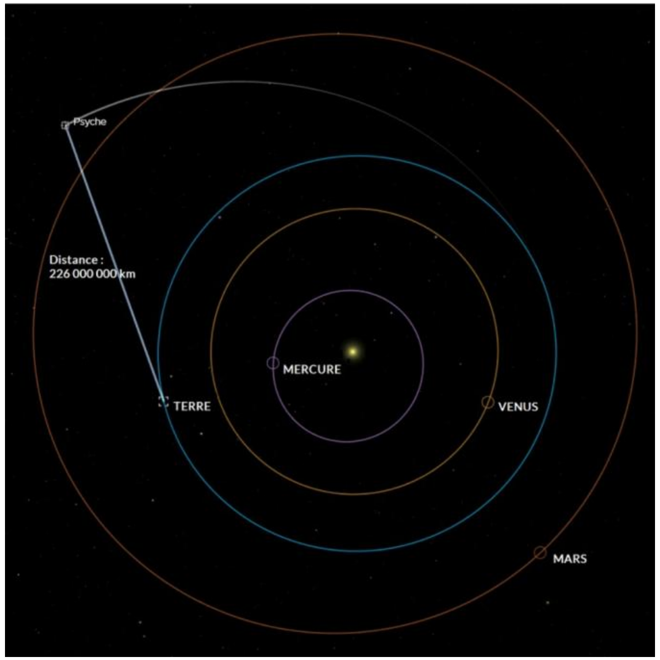
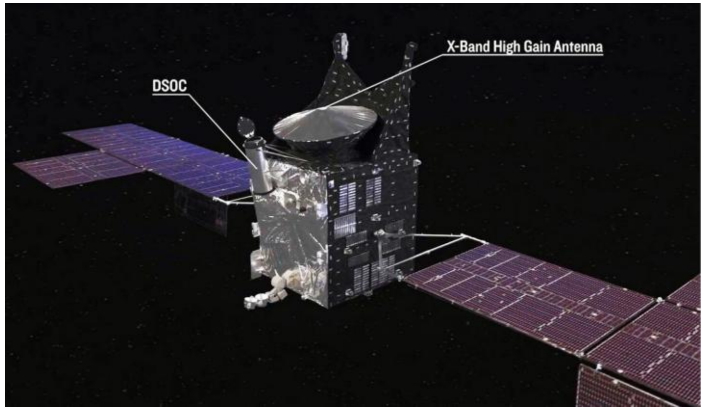


Fig. 6 | Representation of the upcoming space-based LISA gravitational-wave detector. Unlike ground-based detectors, such as LIGO and Virgo, in LISA the stations are free-floating test masses in orbit around the Sun. Figure adapted from ref. [93] (Springer Nature).

Intensity correlations for gravitational wave detection

NASA : DSOC





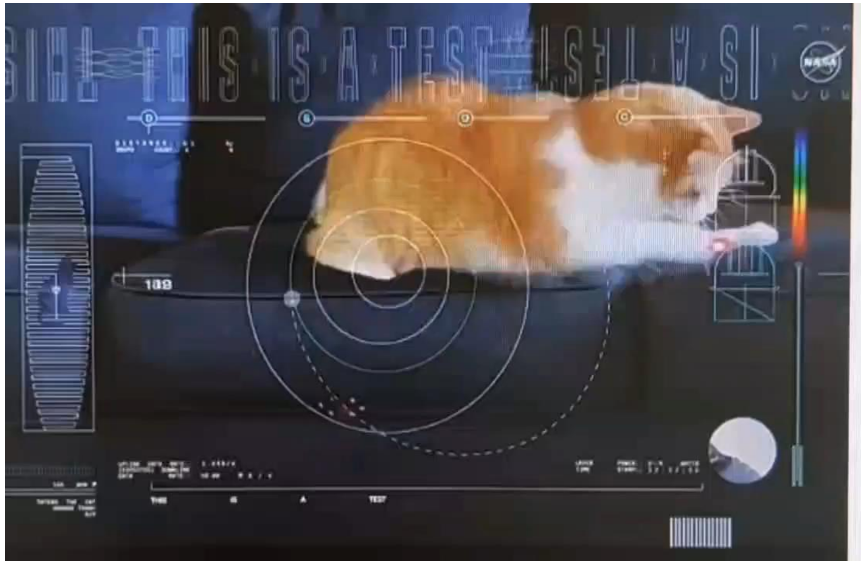
Research Article Vol. 32, No. 27 / 30 Dec 2024 / *Optics Express* 48185

Optics EXPRESS

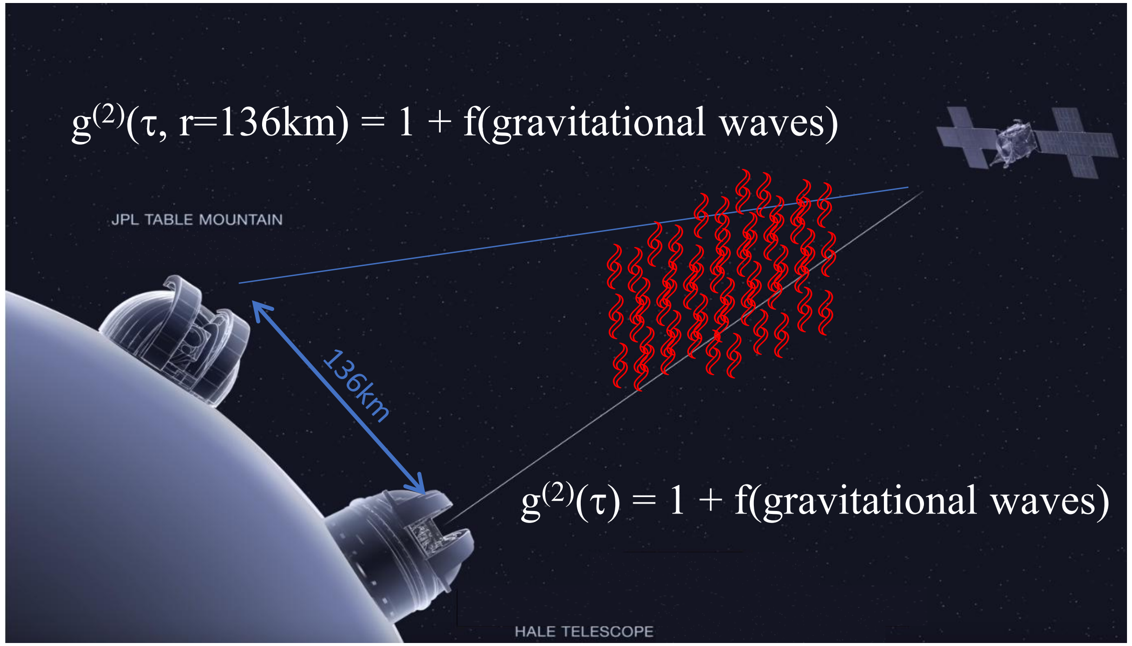
SNSPD-based detector system for NASA's Deep Space Optical Communications project

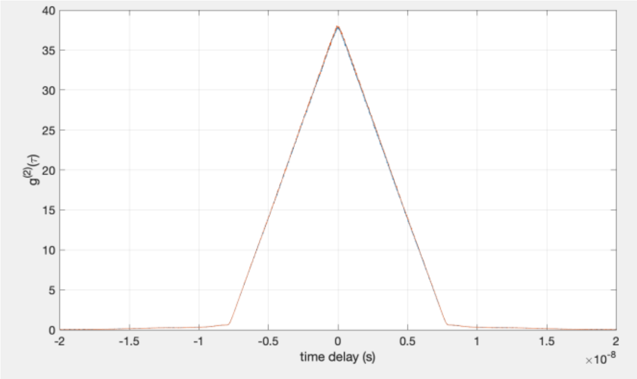
EMMA E. WOLLMAN,[1,*] JASON P. ALLMARAS,[1] ANDREW D. BEYER,[1] BORIS KORZH,[1] MARC C. RUNYAN,[1,2] LAUTARO NARVÁEZ,[3] WILLIAM H. FARR,[1] FRANCESCO MARSILI,[1] RYAN M. BRIGGS,[1] GREGORY J. MILES,[1] AND MATTHEW D. SHAW[1]

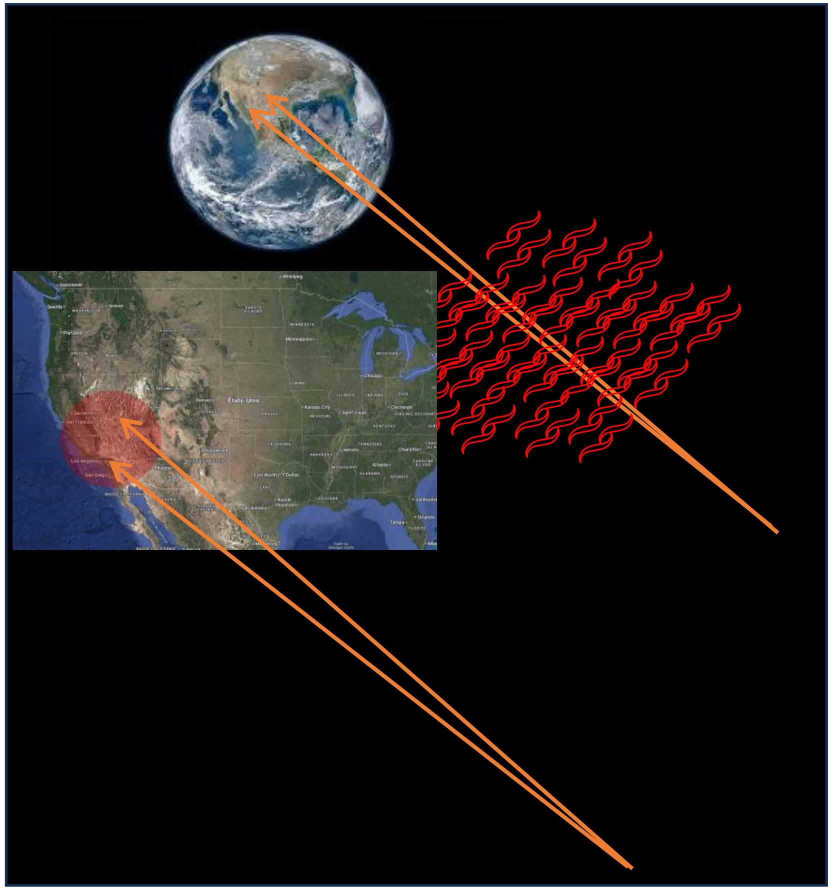
[1] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109, USA*
[2] *Current affiliation: AWS Center for Quantum Computing, Pasadena, CA 91125, USA*
[3] *Division of Physics, Mathematics and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA*



Coherent light sources at 300 million km !



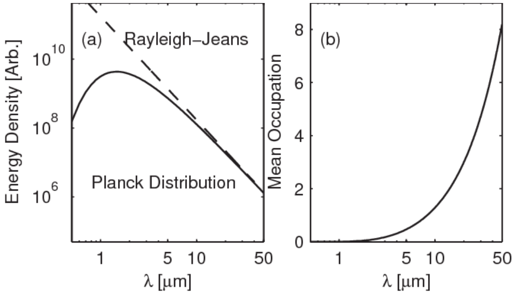




3) Hot stars / microwaves : modified photon statistics?

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

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



T=2500K

Intensity correlations modified for hot stars / low energy photons

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

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

Mandel&Wolf, 1995

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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,*]

Abstract: The photon statistics and bunching of a semiconductor laser with external optical feedback are investigated experimentally and theoretically. In a chaotic regime, the photon number distribution is measured and undergoes a transition from Bose-Einstein distribution to Poisson distribution with increasing the mean photon number. The second order degree of coherence decreases gradually from 2 to 1. Based on Hanbury Brown-Twiss scheme, pronounced photon bunching is observed experimentally for various injection currents and feedback strengths, which indicates the randomness of the associated emission light. Near-threshold injection currents and strong feedback strengths modify exactly the laser performance to be more bunched. The macroscopic chaotic dynamics is confirmed simultaneously by high-speed analog detection. The theoretical results qualitatively agree with the experimental results. It is potentially useful to extract randomness and achieve desired entropy source for random number generator and imaging science by quantifying the control parameters.

PHYSICAL REVIEW RESEARCH **6**, L032025 (2024)
Letter

Silent white light: Reduction of the second-order intensity correlation coefficient

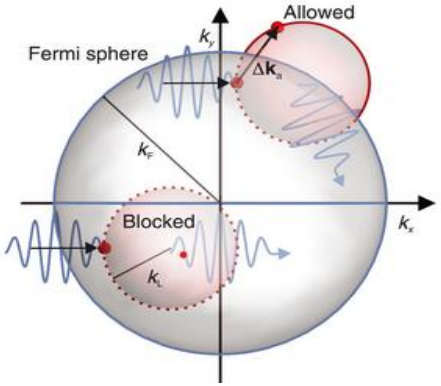
Kai Niklas Hansmann,[1,*] Franziska Dommermuth,[1] Wolfgang Elsäßer,[1,2,3] and Reinhold Walser[1]

Novel correlations functions

to be explored ?

(I. Mazets, N. Mauser)

4) Pauli Blocking / Non linear optics / squeezing

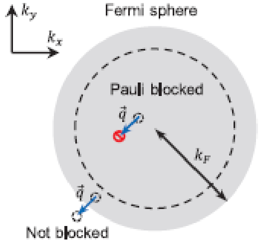


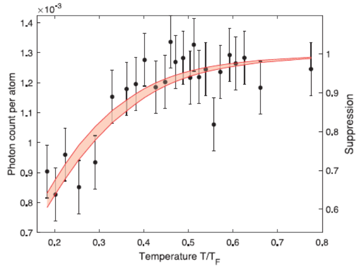
QUANTUM GASES

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)

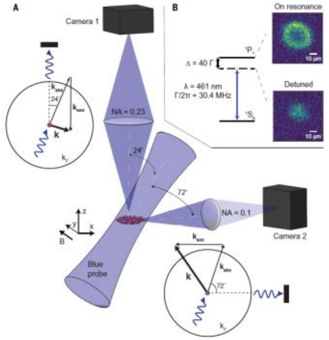


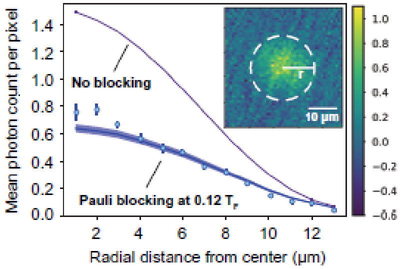


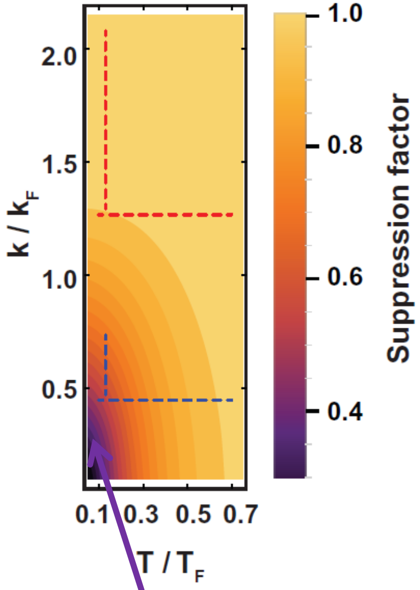
QUANTUM GASES

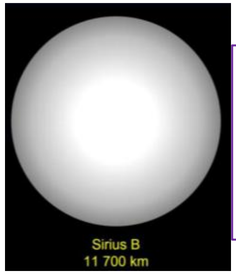
Pauli blocking of atom-light scattering

Sanner *et al.*, *Science* **374**, 979–983 (2021) , Lingfeng Yan, William R. Milner, Jun Ye*









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

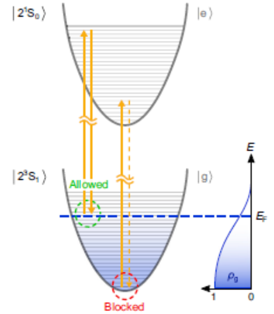
nature communications

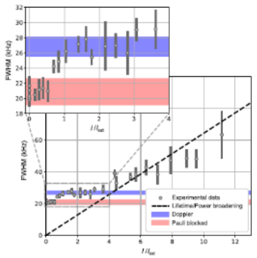
Article https://doi.org/10.1038/s41467-022-34135-6

Pauli blocking of stimulated emission in a degenerate Fermi gas

Received: 24 March 2022
Accepted: 14 October 2022

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





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


Thank you for your attention