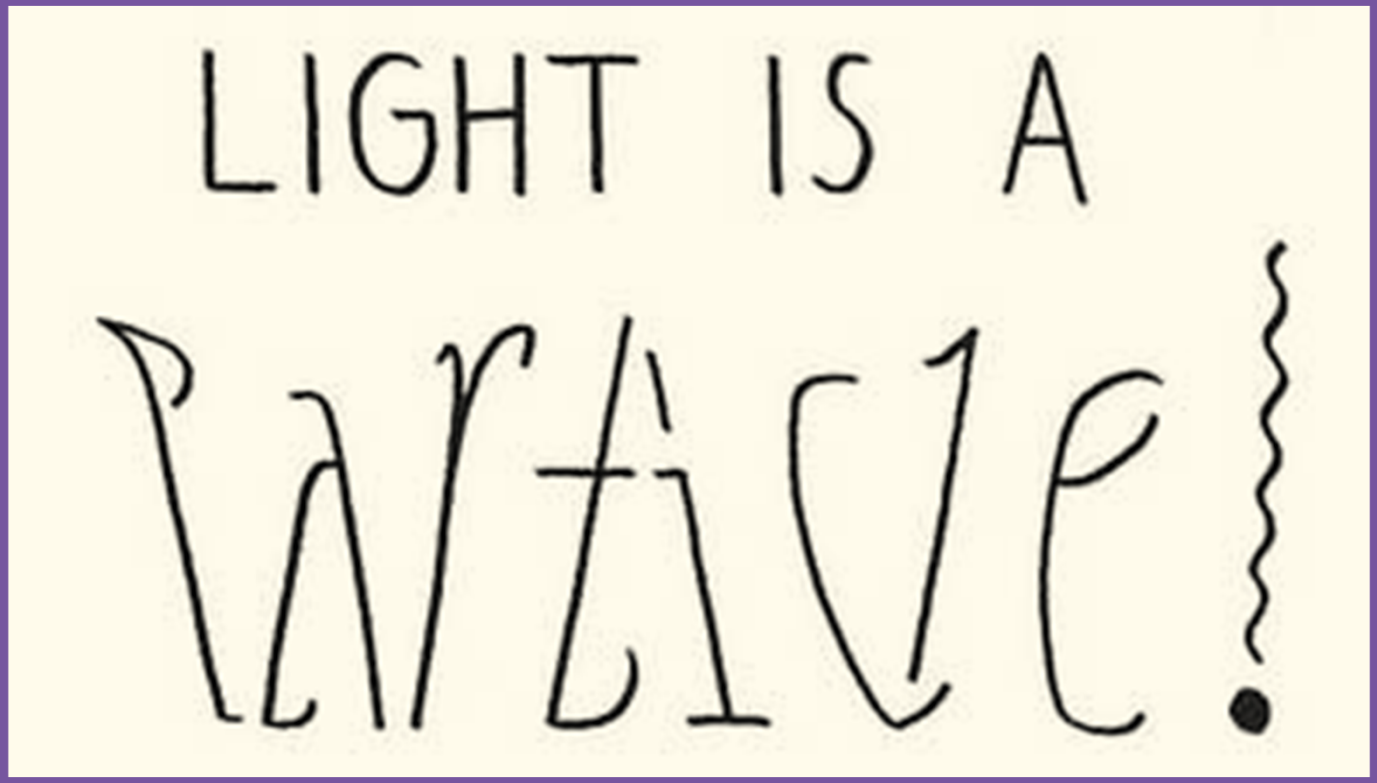
WAVE

or

PARTICLE

?

(what do you recognize, which do you exploit?)



INTENSITY INTERFEROMETRY

ITS PAST AND ITS FUTURE

Dainis Dravins — Lund Observatory, Sweden

www.astro.lu.se/~dainis

First astronomical interferometry

COMPTES RENDUS

HEBDOMADAIRES

DES SÉANCES

DE L'ACADÉMIE DES SCIENCES.

PRIX BORDIN.

QUESTION PROPOSÉE EN 1865 POUR 1867.

(Commissaires : MM. Duhamel, Pouillet, Regnault, Bertrand, Edmond Becquerel, Fizeau rapporteur.)

Rapport sur le Concours de l'année 1867.

« *Le prix sera décerné au savant qui aura exécuté ou proposé une expérience* » *décisive permettant de trancher définitivement la question déjà plusieurs fois* » *étudiée de la direction des vibrations de l'éther dans les rayons polarisés.* »

Il existe en effet pour la plupart des phénomènes d'interférence, tels que les franges d'Yung, celles des miroirs de Fresnel et celles qui donnent lieu à la scintillation des étoiles d'après Arago, une relation remarquable et nécessaire entre la dimension des franges et celle de la source lumineuse, en sorte que des franges d'une ténuité extrême ne peuvent prendre naissance que lorsque la source de lumière n'a plus que des dimensions angulaires presque insensibles; d'où, pour le dire en passant, il est peut-être permis d'espérer qu'en s'appuyant sur ce principe et en formant par exemple, au moyen de deux larges fentes très-écartées, des franges d'interférence au foyer des grands instruments destinés à observer les étoiles, il deviendra possible d'obtenir quelques données nouvelles sur les diamètres angulaires de ces astres.



Hippolyte Fizeau:
Prix Bordin
Compt.Rend.Acad.Sci. Paris **66**, 932 (1868)

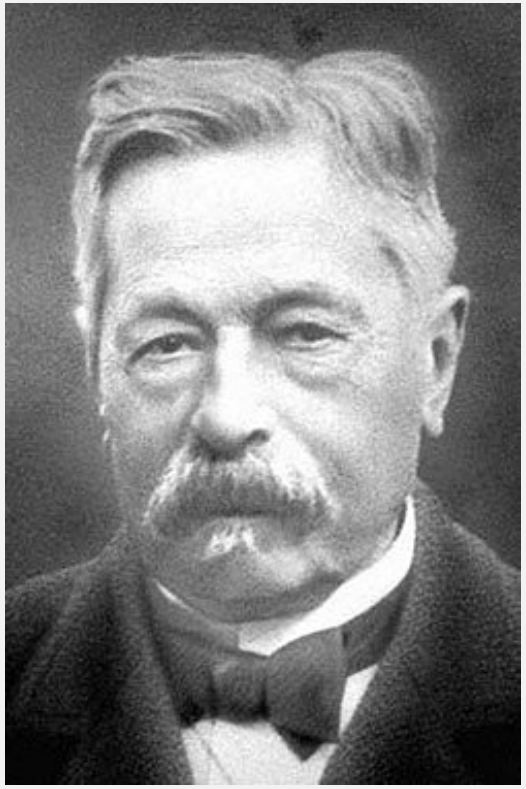
Photo in 1883 by Eugène Pirou; Gallica Digital Library

COMPTES RENDUS

HEBDOMADAIRES

DES SÉANCES

DE L'ACADÉMIE DES SCIENCES.



MÉMOIRES LUS.

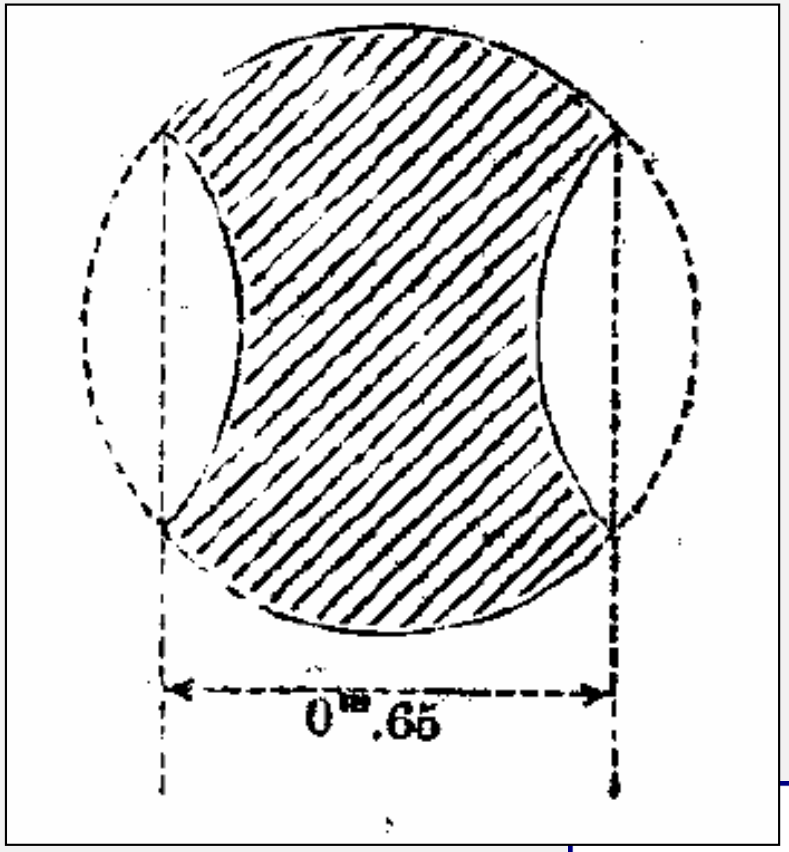
ASTRONOMIE PHYSIQUE. — *Sur l'extrême petitesse du diamètre apparent des étoiles fixes*. Note de M. STÉPHAN.

(Commissaires : MM. Le Verrier, Fizeau, Janssen.)

« Dans une Communication précédente (*Comptes rendus*, t. LXXVI, p. 1008), j'ai eu l'honneur de rappeler à l'Académie une idée anciennement émise par M. Fizeau sous forme de simple aperçu et qui, jusque-là, semblait être restée dans l'oubli, bien que renfermant le germe de conséquences fort importantes. Cette idée peut se formuler comme il suit : Dans plusieurs cas, en donnant naissance à certains phénomènes d'interférence, on peut augmenter la sensibilité des instruments d'optique ordinaires.

» Guidé par l'illustre physicien, j'ai cherché à déduire de cette conception originale quelques notions précises sur le diamètre apparent des étoiles fixes, et, dans la Note citée plus haut, j'ai fait connaître à l'Académie le résultat de quelques expériences préliminaires dont il convient de rappeler le principe général.

Édouard Stéphan:
Sur l'extrême petitesse du diamètre apparent des étoiles fixes
Compt.Rend.Acad.Sci. Paris **78**, 108 (1874)



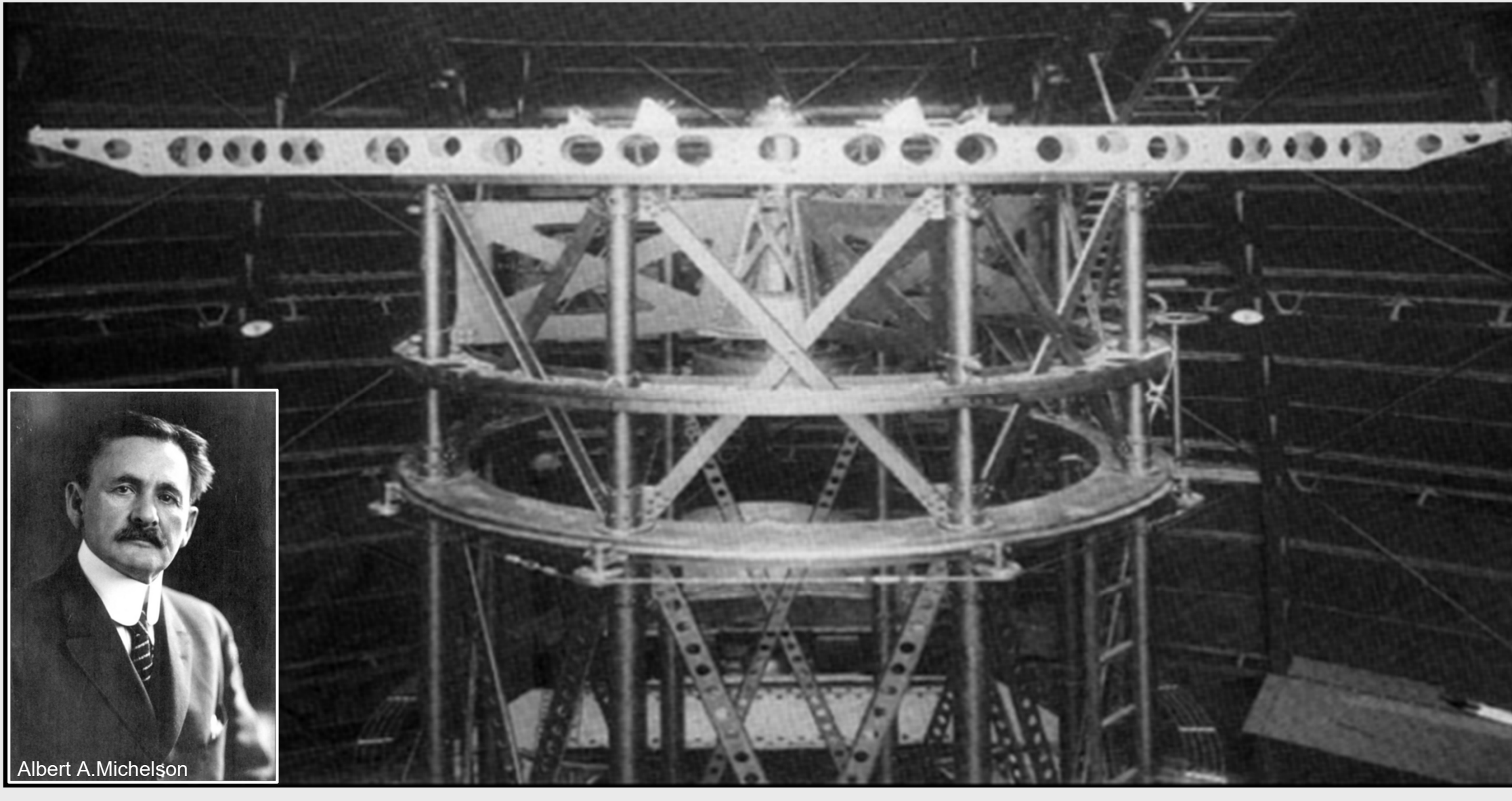
» L'instrument dont j'ai fait usage à Marseille est le grand télescope Foucault, de 80 centimètres de diamètre, muni d'un écran lunulaire; les lunules sont limitées par des cercles égaux de 80 centimètres; leurs grands axes sont parallèles et distants de 65 centimètres.

En d'autres termes, les expériences citées ne prouvent pas seulement que le diamètre apparent des étoiles examinées est inférieur à o",158, elles montrent encore que ce diamètre est une très-faible fraction du nombre précédent. »

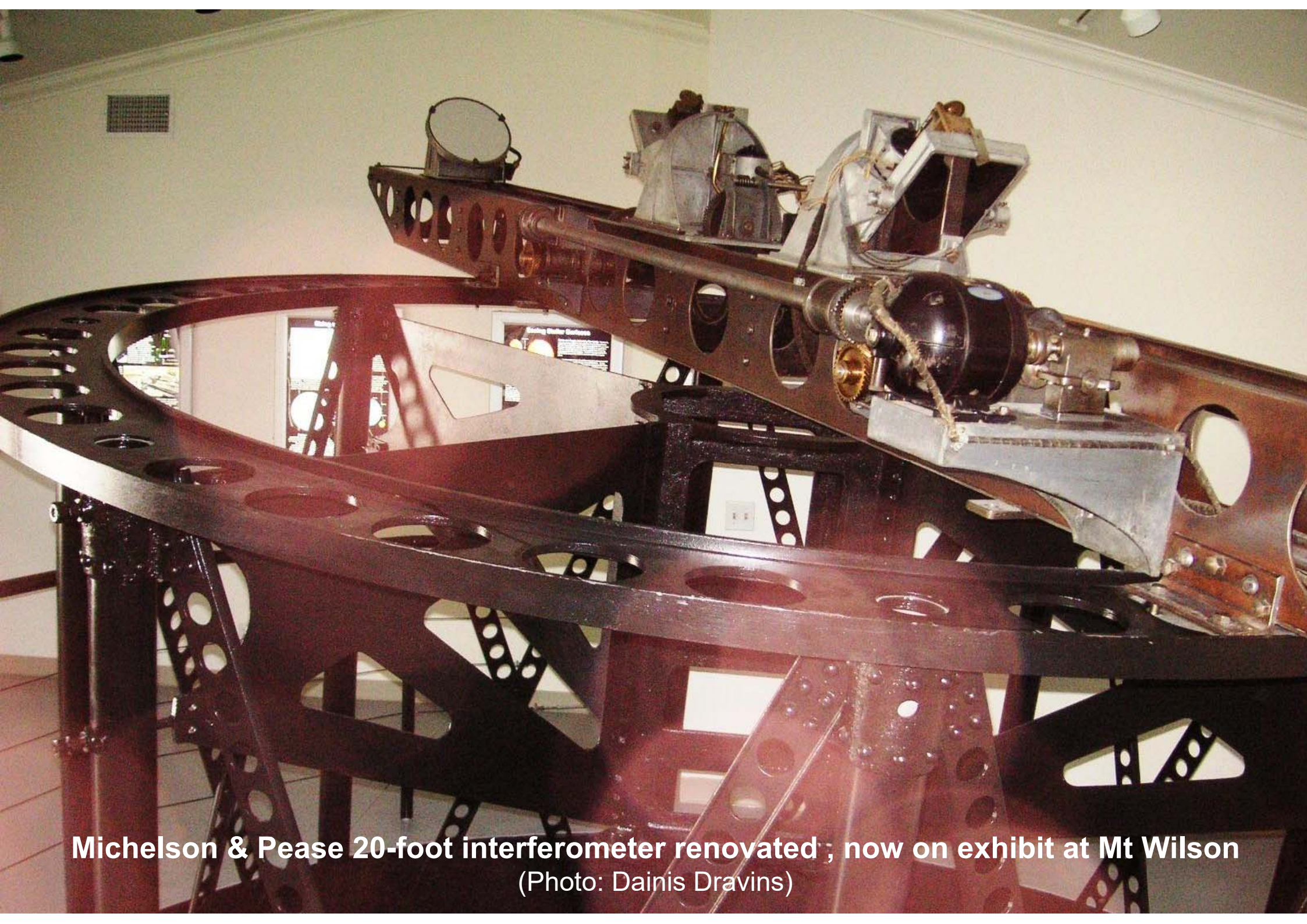
Édouard Stéphan:
Sur l'extrême petitesse du diamètre apparent des étoiles fixes
Compt.Rend.Acad.Sci. Paris **78**, 108 (1874)

50 years hence …

FIRST SUCCESSFUL STELLAR INTERFEROMETER



20-foot Michelson Stellar Interferometer circa 1919



Michelson & Pease 20-foot interferometer renovated , now on exhibit at Mt Wilson
(Photo: Dainis Dravins)

50-foot Pease interferometer on Mt.Wilson circa 1930



Images courtesy of the Observatories of the Carnegie Institution for Science Collection at the Huntington Library, San Marino, CA

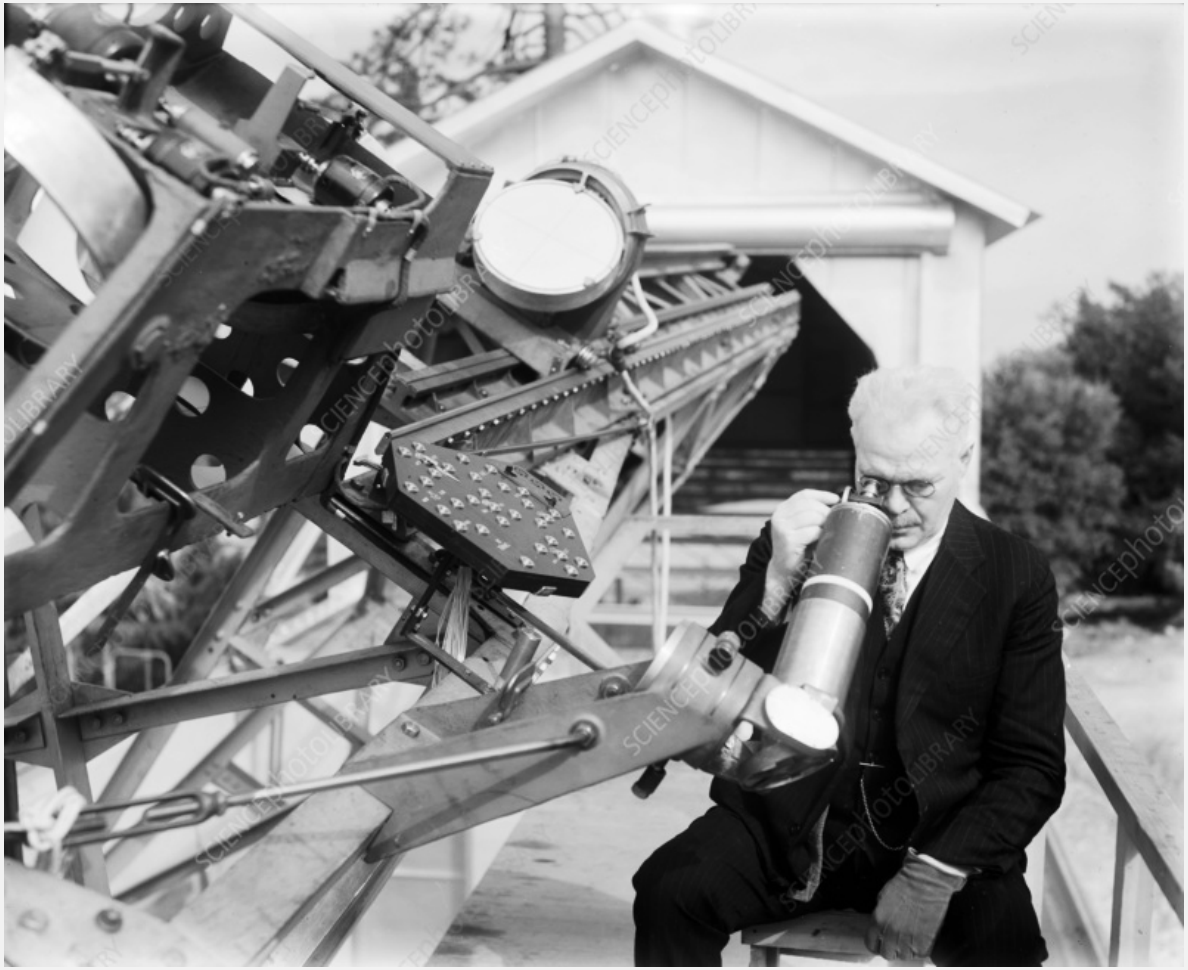


F.G.Pease: *The New Fifty-foot Stellar Interferometer*, Scientific American **143**, issue 4, pp 290-293 (October 1930)

F.G.Pease: *Interferometer Methods in Astronomy*, Ergebnisse der Exakten Naturwissenschaften **10**, 84 (1931)

50-foot Pease interferometer on Mt.Wilson circa 1930





Francis Pease at the eyepiece of the 50-foot interferometer

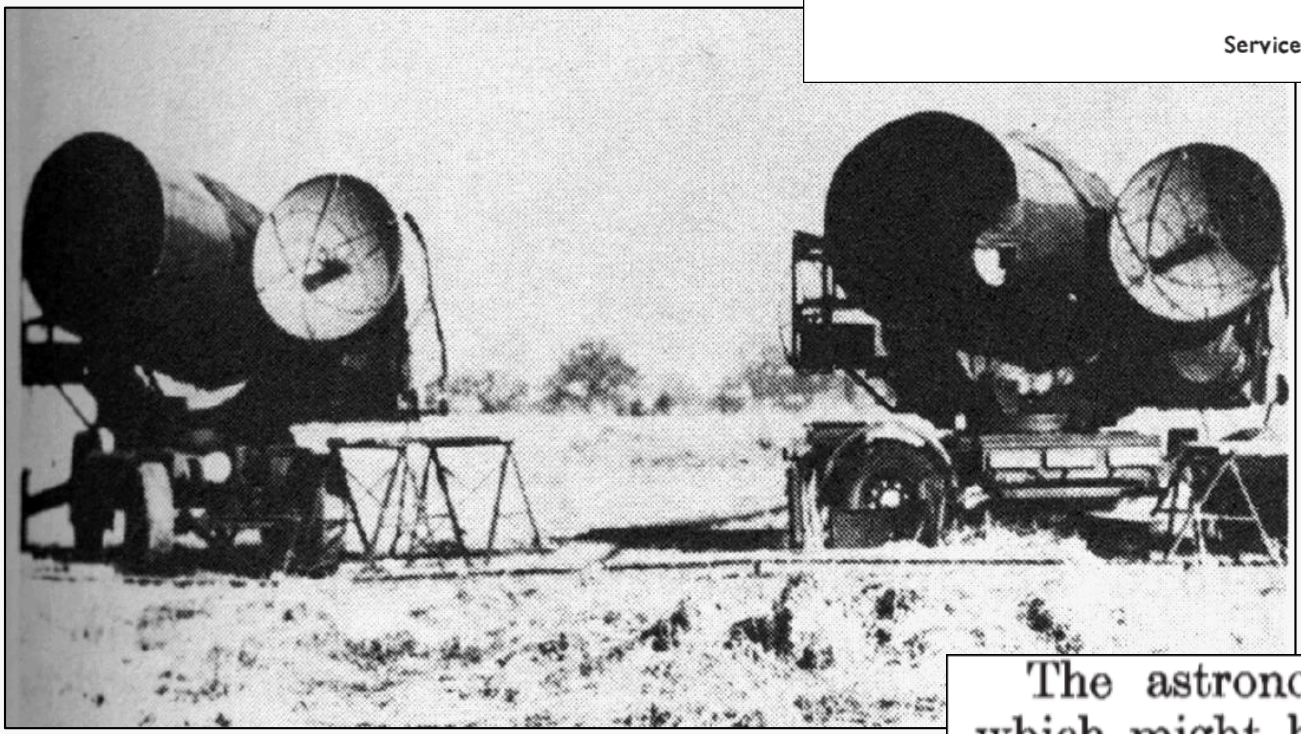
Left image: Courtesy of the Observatories of the Carnegie Institution for Science Collection at the Huntington Library, San Marino, CA.
Right image: Science Source/Science Photo Library

Photon correlations measured

Intensity interferometry … the earliest days

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





Two 5-foot army surplus searchlights installed at Jodrell Bank provided first measurements ever of the angular diameter of a main-sequence star (*Nature* **178**, 1046, 1956)

The astronomical value of such an instrument, which might be called an 'intensity' interferometer, lies in its great potential resolving power, the maximum usable base-line being governed by the limitations of electronic rather than of optical technique. In particular, it should be possible to use it with base-lines of hundreds, if not thousands of feet,

Intensity interferometry … the earliest days



Robert Hanbury Brown leads a blackboard discussion at the first *Rochester Conference on Coherence and Quantum Optics* (June 1960)

From left: A.T.Forrester, R.Q.Twiss, E.M.Purcell, R.Hanbury Brown

Image from: Svetlana G. Lukishova & William J. Tango:
First Observation of Photon Correlations (Bunching) with Beamsplitter and Photomultipliers (Robert Hanbury Brown and Richard Quintin Twiss)
In: R.W. Boyd et al. (eds.), *Quantum Photonics: Pioneering Advances and Emerging Applications*, Springer Series in Optical Sciences 217 (2019)

Intensity interferometry … the earliest days



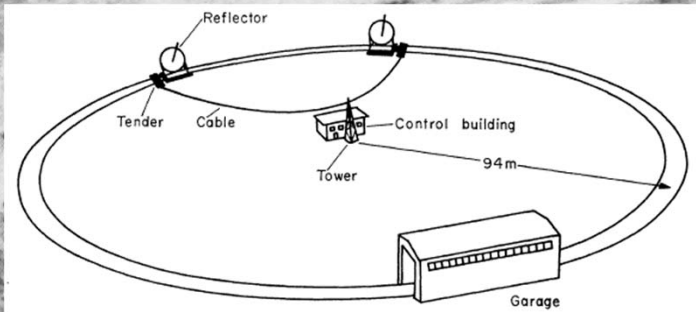
Richard Quintin Twiss and Robert Hanbury Brown at the first *Rochester Conference on Coherence and Quantum Optics* (June 1960)

Image from: Svetlana G. Lukishova & William J. Tango:
First Observation of Photon Correlations (Bunching) with Beamsplitter and Photomultipliers (Robert Hanbury Brown and Richard Quintin Twiss)
In: R.W. Boyd et al. (eds.), *Quantum Photonics: Pioneering Advances and Emerging Applications*, Springer Series in Optical Sciences 217 (2019)

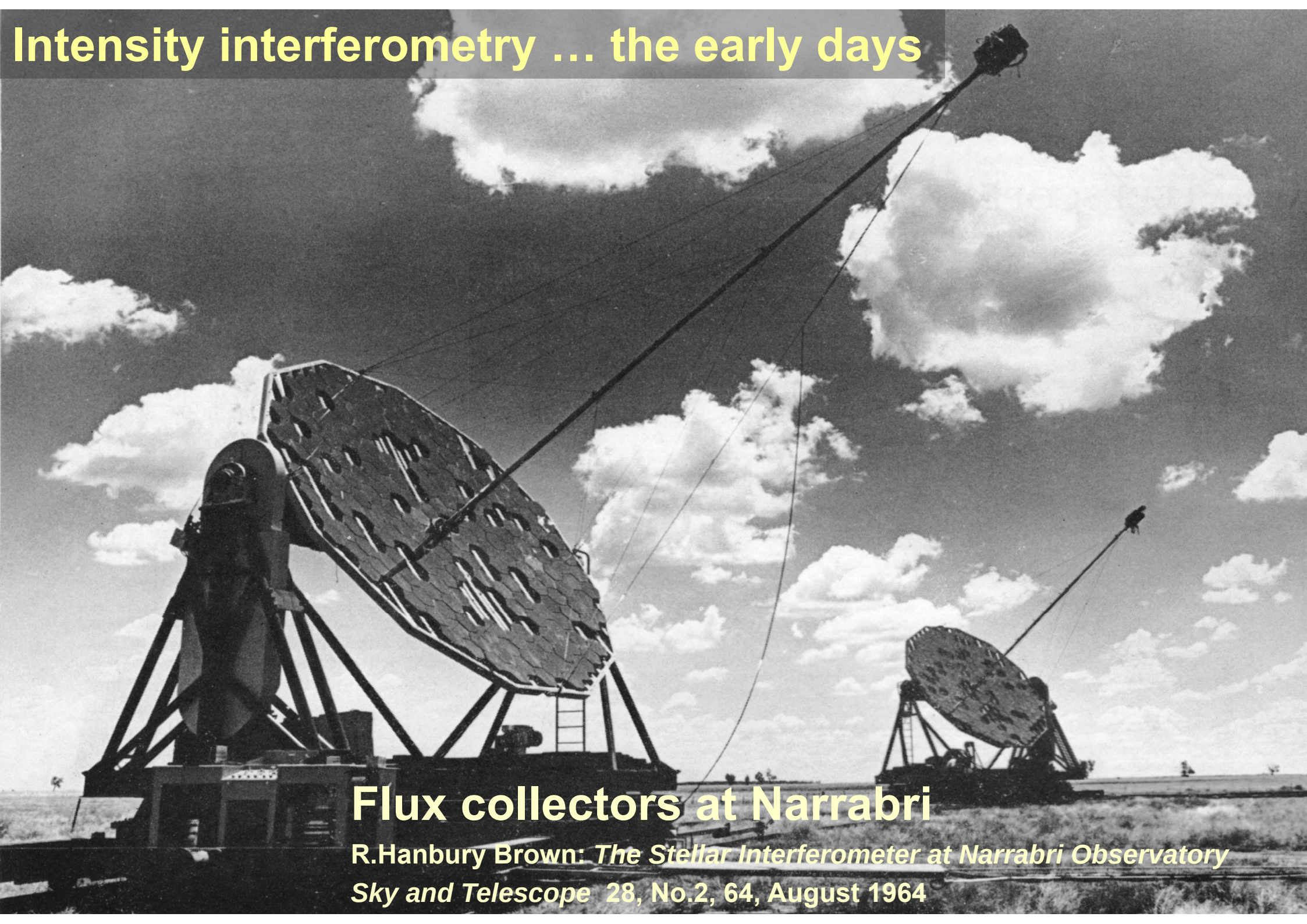
Intensity interferometry … the early days

Narrabri observatory
with its circular railway track

R.Hanbury Brown: *BOFFIN. A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics* (1991)



Intensity interferometry … the early days

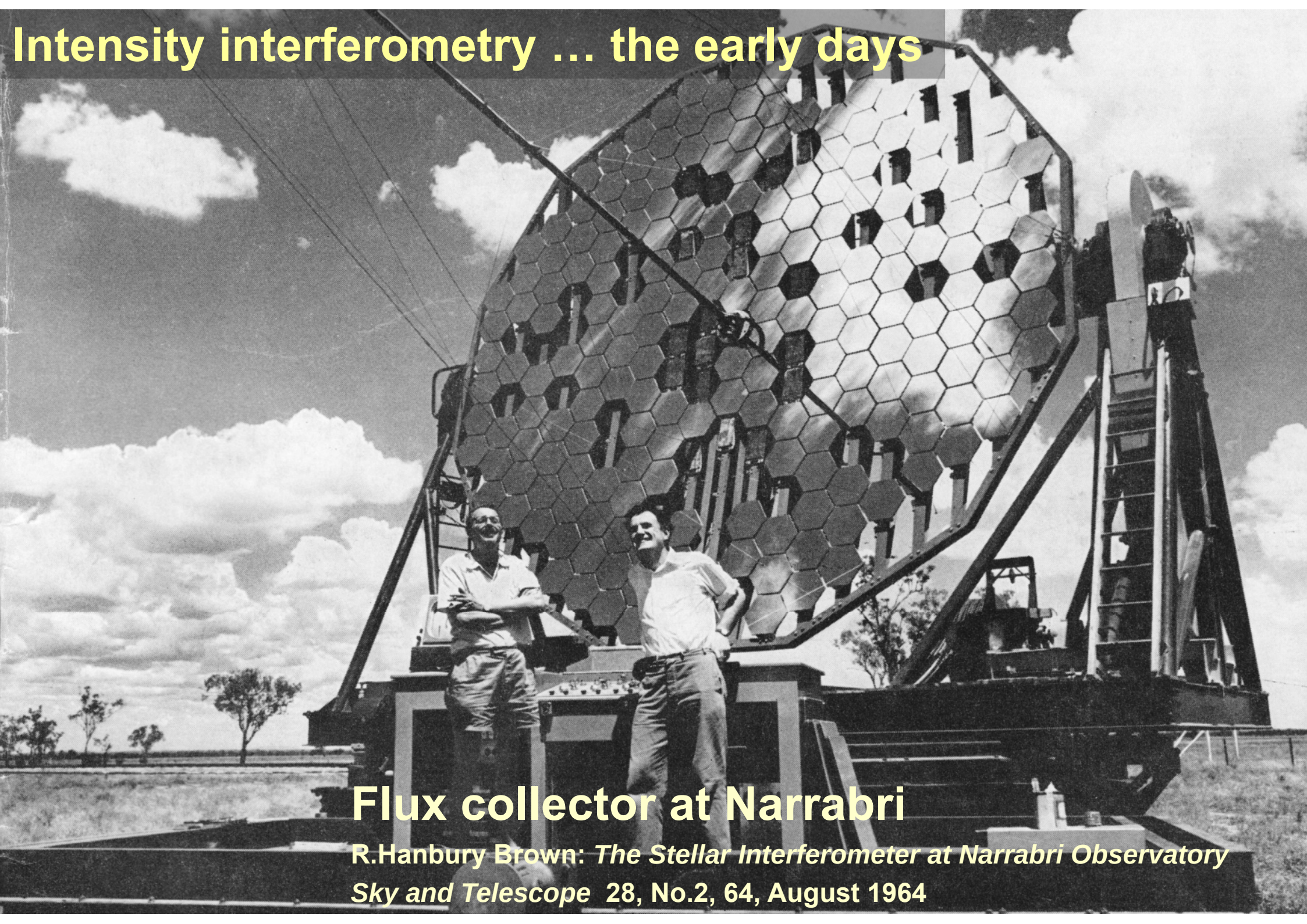


Flux collectors at Narrabri

R.Hanbury Brown: *The Stellar Interferometer at Narrabri Observatory*

Sky and Telescope 28, No.2, 64, August 1964

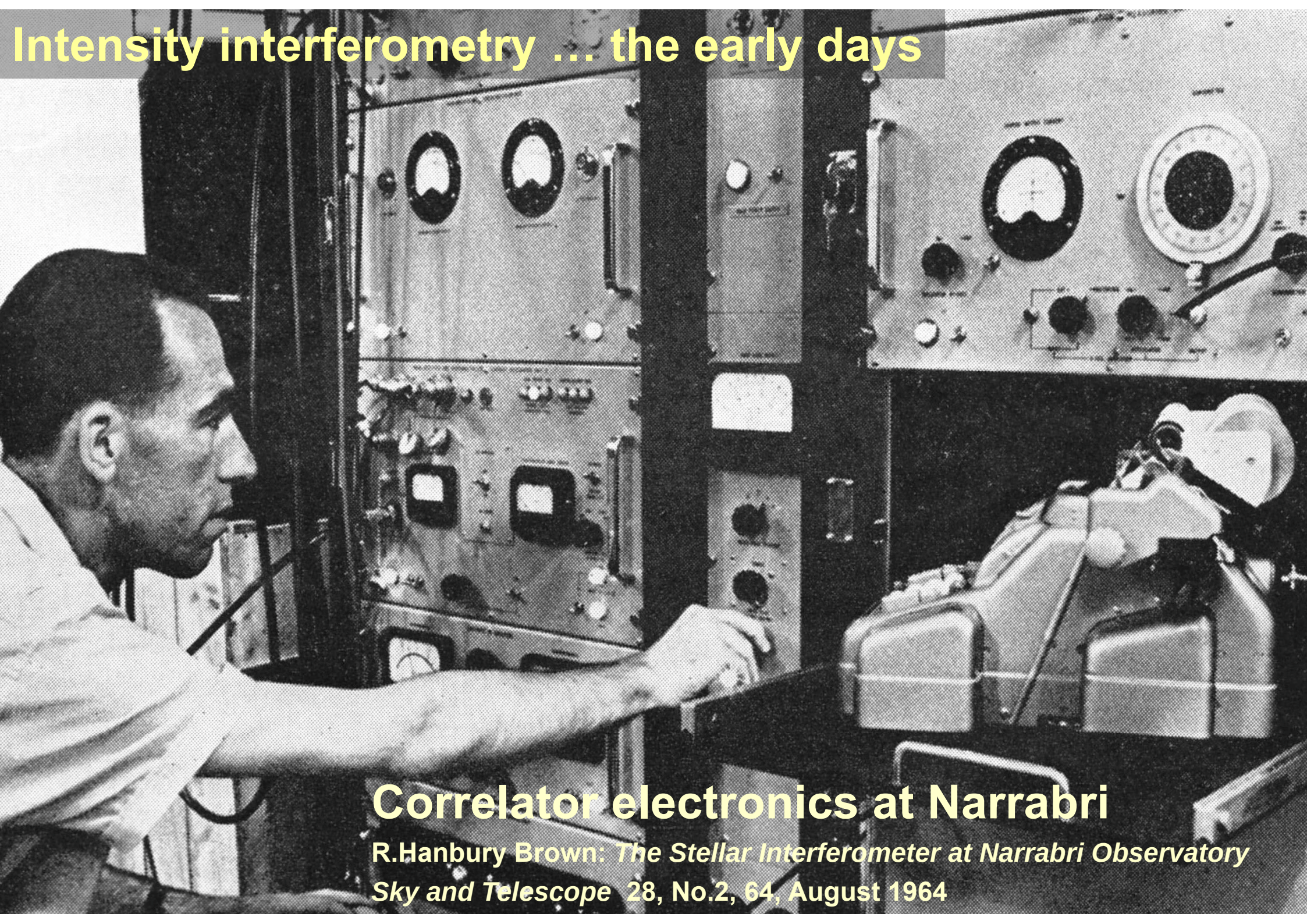
Intensity interferometry … the early days



Flux collector at Narrabri

R.Hanbury Brown: *The Stellar Interferometer at Narrabri Observatory*
Sky and Telescope 28, No.2, 64, August 1964

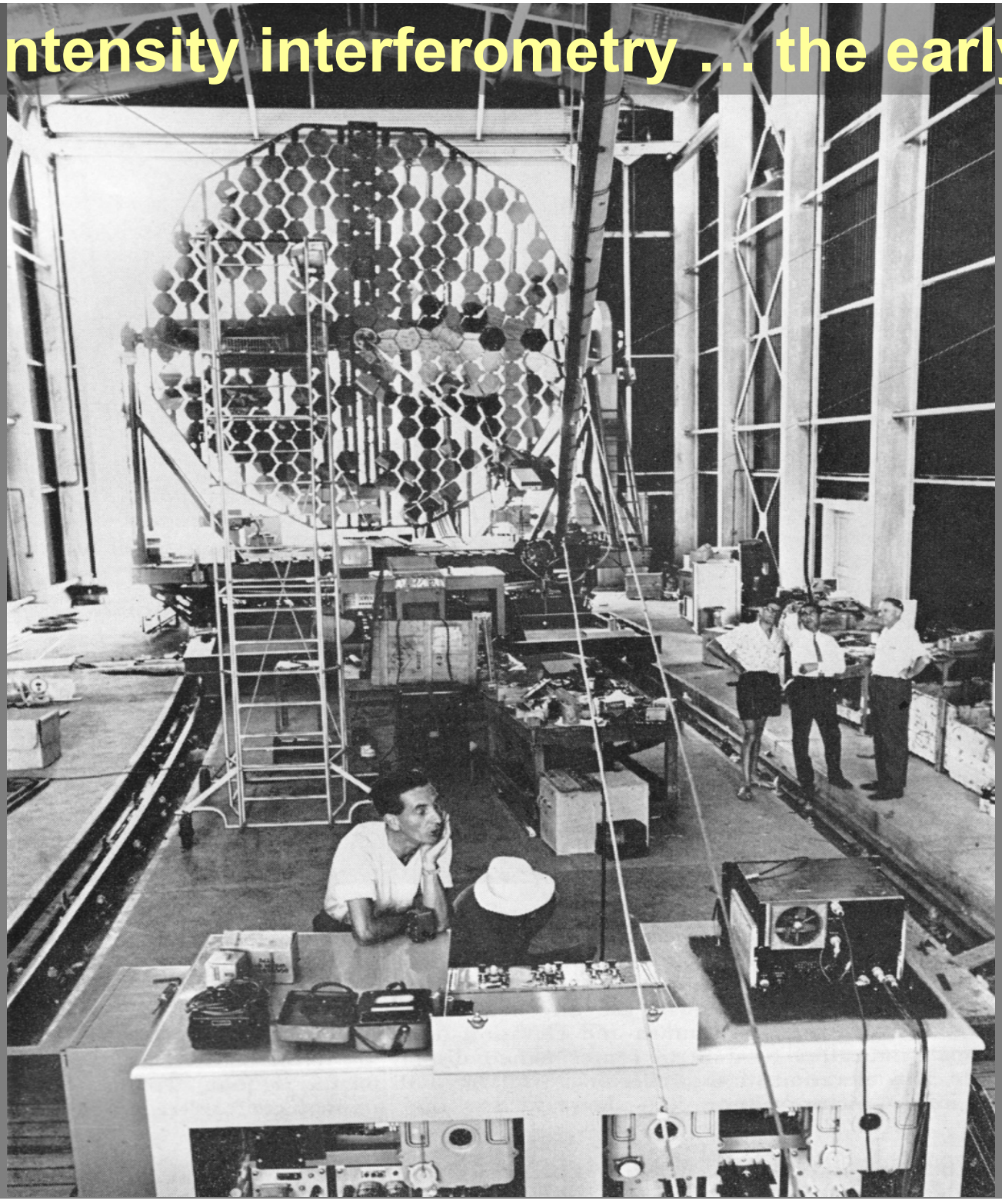
Intensity interferometry … the early days



Correlator electronics at Narrabri

R.Hanbury Brown: *The Stellar Interferometer at Narrabri Observatory*
Sky and Telescope 28, No.2, 64, August 1964

Intensity interferometry … the early days



Narrabri flux collector inside its garage

R.Hanbury Brown:

The Stellar Interferonmeter at Narrabri Observatory

Sky and Telescope **28**, No.2, 64, August 1964

Intensity interferometry … the early days



Flux collectors at Narrabri
(University of Sydney)

Intensity interferometry … the early days



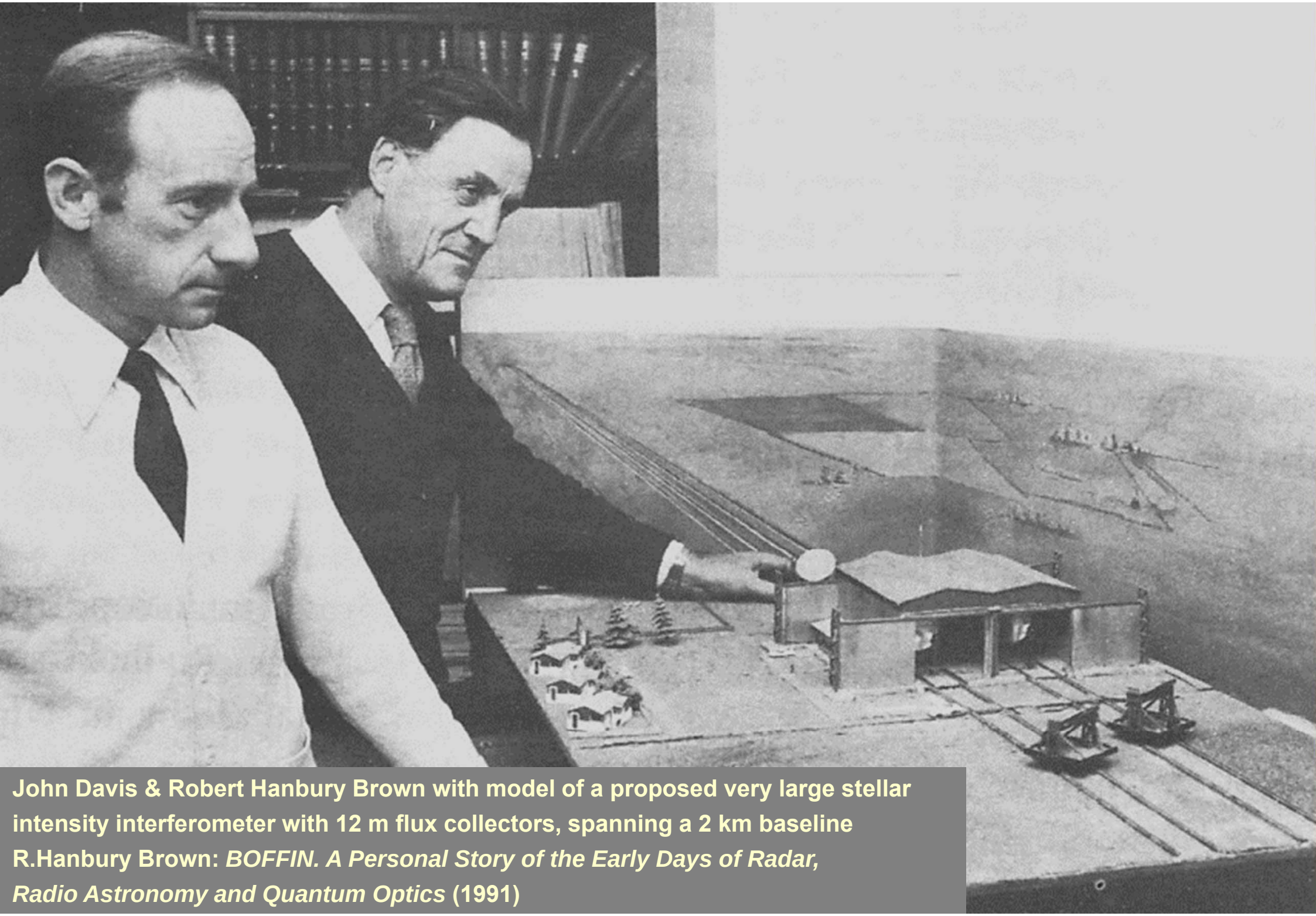
One flux collector at Narrabri

(after the intensity interferometry program had been finished)

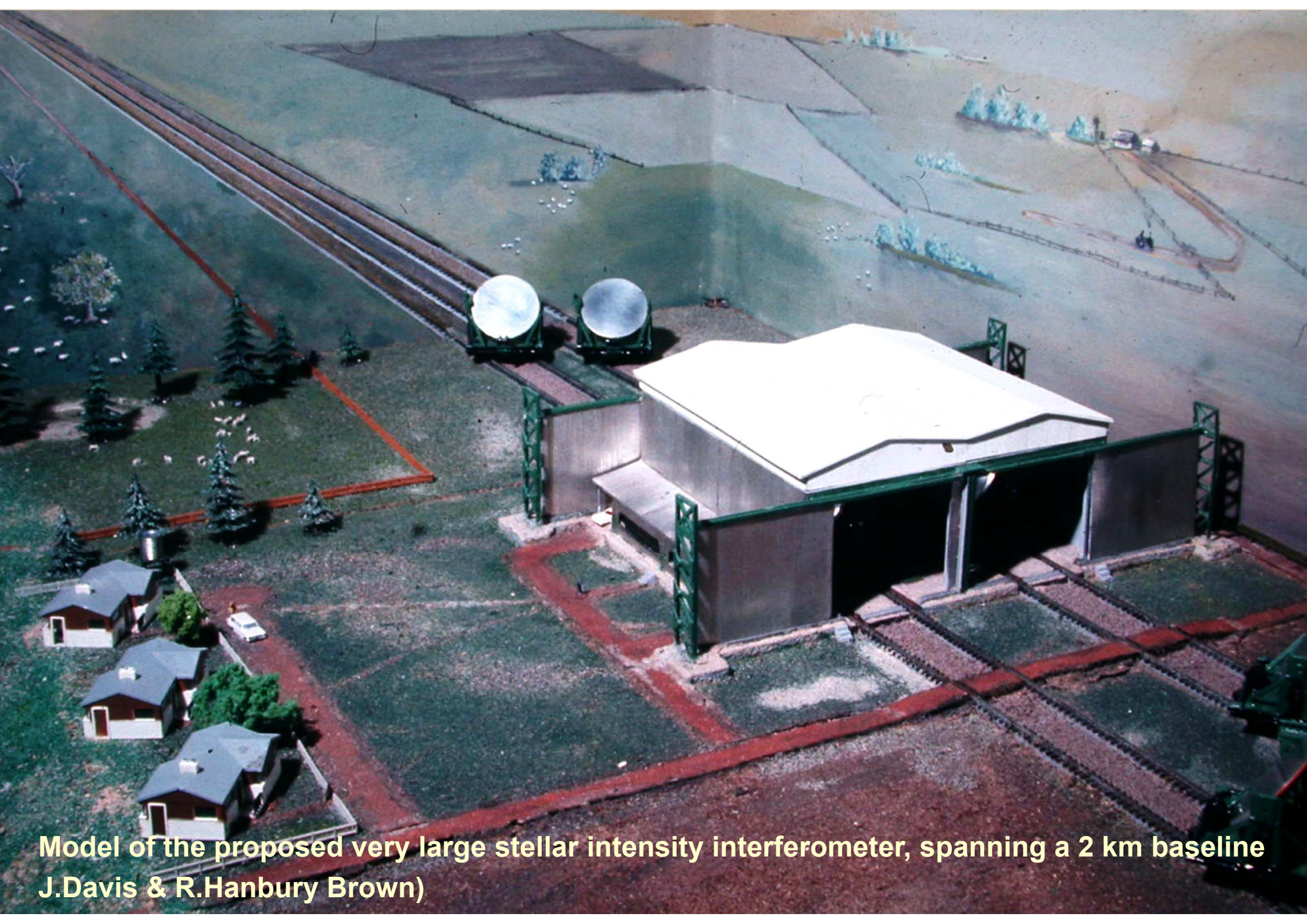
R.Hanbury Brown:
"This must be the most incomprehensible instrument in all of astronomy"

Photo: Dainis Dravins

Narrabri,
2nd generation plans



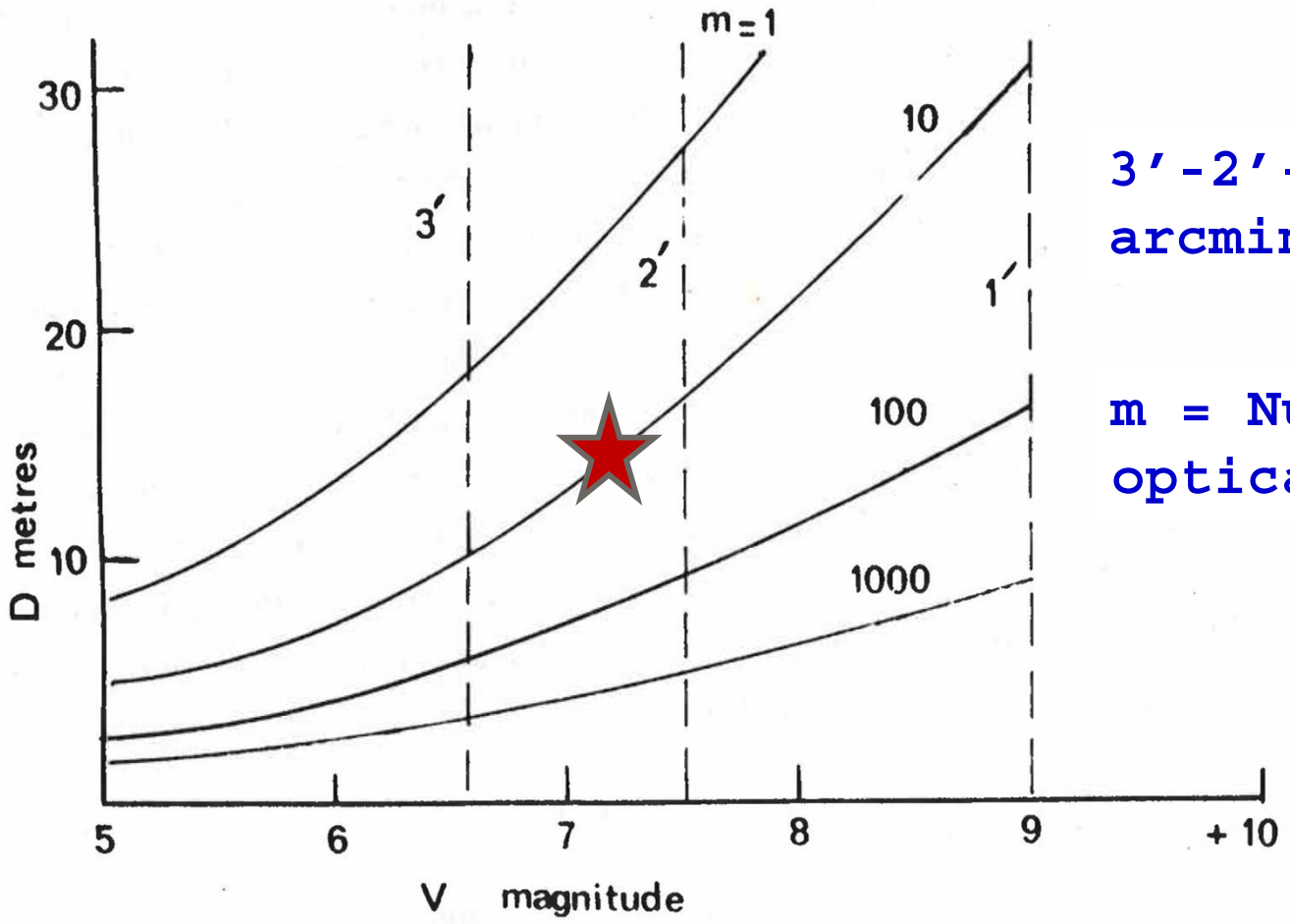
John Davis & Robert Hanbury Brown with model of a proposed very large stellar intensity interferometer with 12 m flux collectors, spanning a 2 km baseline
R.Hanbury Brown: *BOFFIN. A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics* (1991)



Model of the proposed very large stellar intensity interferometer, spanning a 2 km baseline
J.Davis & R.Hanbury Brown)

Narrabri, 2nd generation plans

m_v = 7.3
4 × 12 m ∅
10 channels



3′-2′-1′
arcmin FOV

m = Number of
optical channels

The limiting magnitude (V) of an intensity interferometer with two circular flux-collectors of diameter D. The curves are shown for four different numbers (m) of optical channels. (b_v = 1000 MHz, exposure 100 h, uncertainty in final result ±5%).

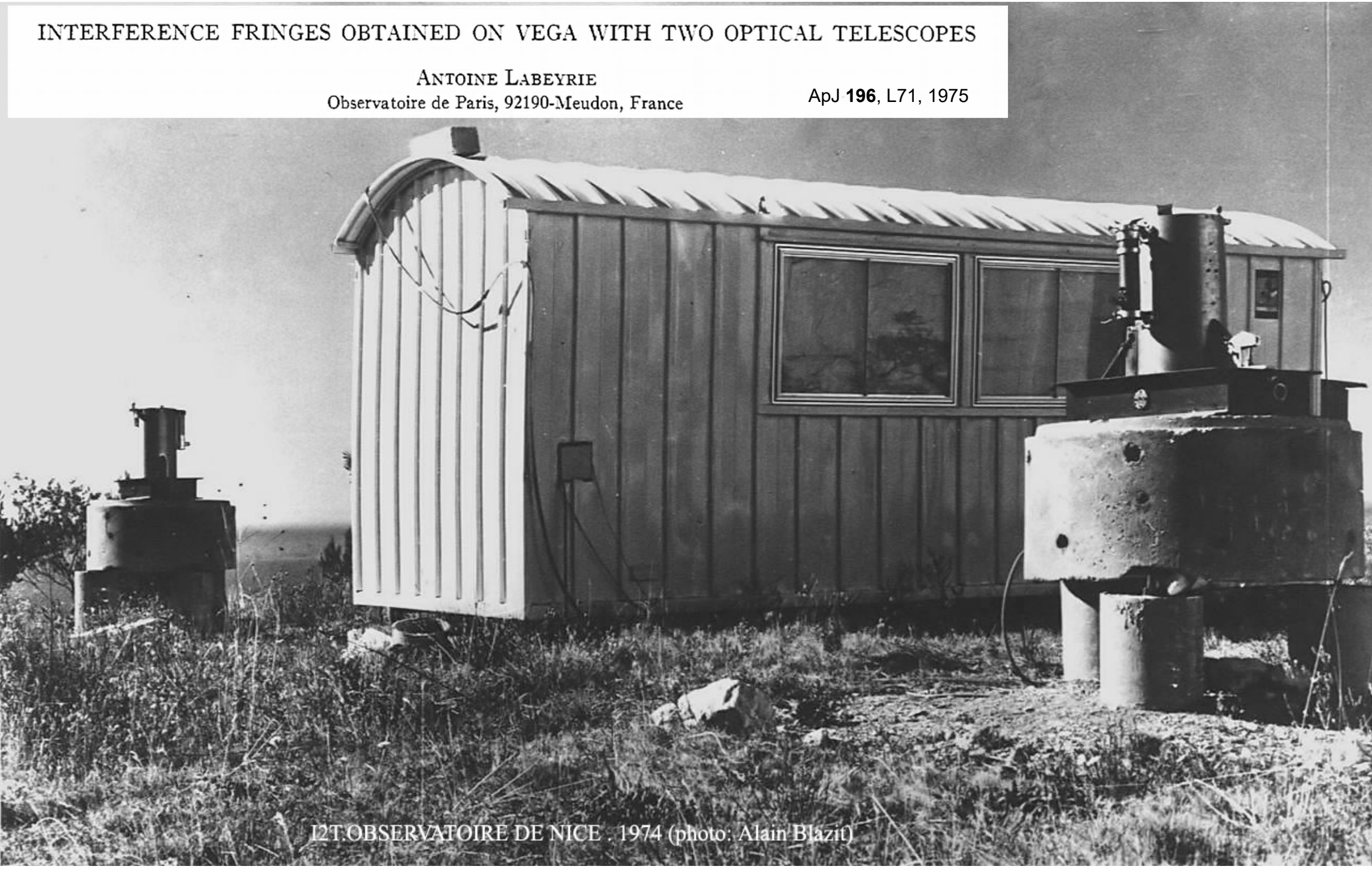
R.Hanbury Brown: *A review of the achievements and potential of intensity interferometry*
In: High angular resolution stellar interferometry; Proc. IAU Coll. 50, College Park, MD, Aug./Sept. 1978; University of Sydney, p. 11-1 -- 11-17 (1979)

What happened?

INTERFERENCE FRINGES OBTAINED ON VEGA WITH TWO OPTICAL TELESCOPES

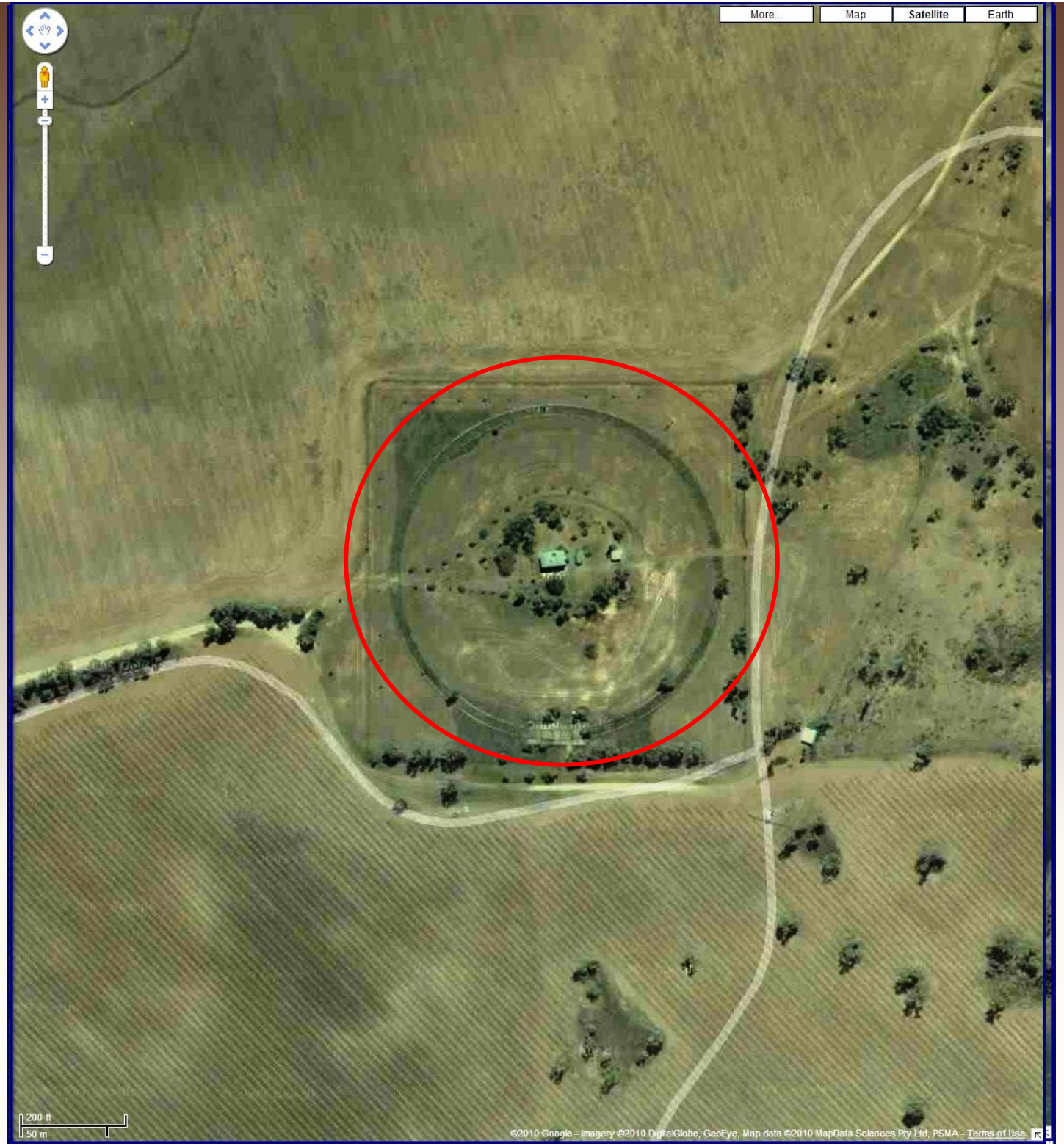
ANTOINE LABEYRIE
Observatoire de Paris, 92190-Meudon, France

ApJ **196**, L71, 1975



FIRST SUCCESSFUL OPTICAL PHASE INTERFEROMETER OF THE MODERN ERA (1974)
I2T, ***Interféromètre à 2 Télescopes*** (Observatoire de CERGA, France)

What happened to the Narrabri interferometer?



Google Earth

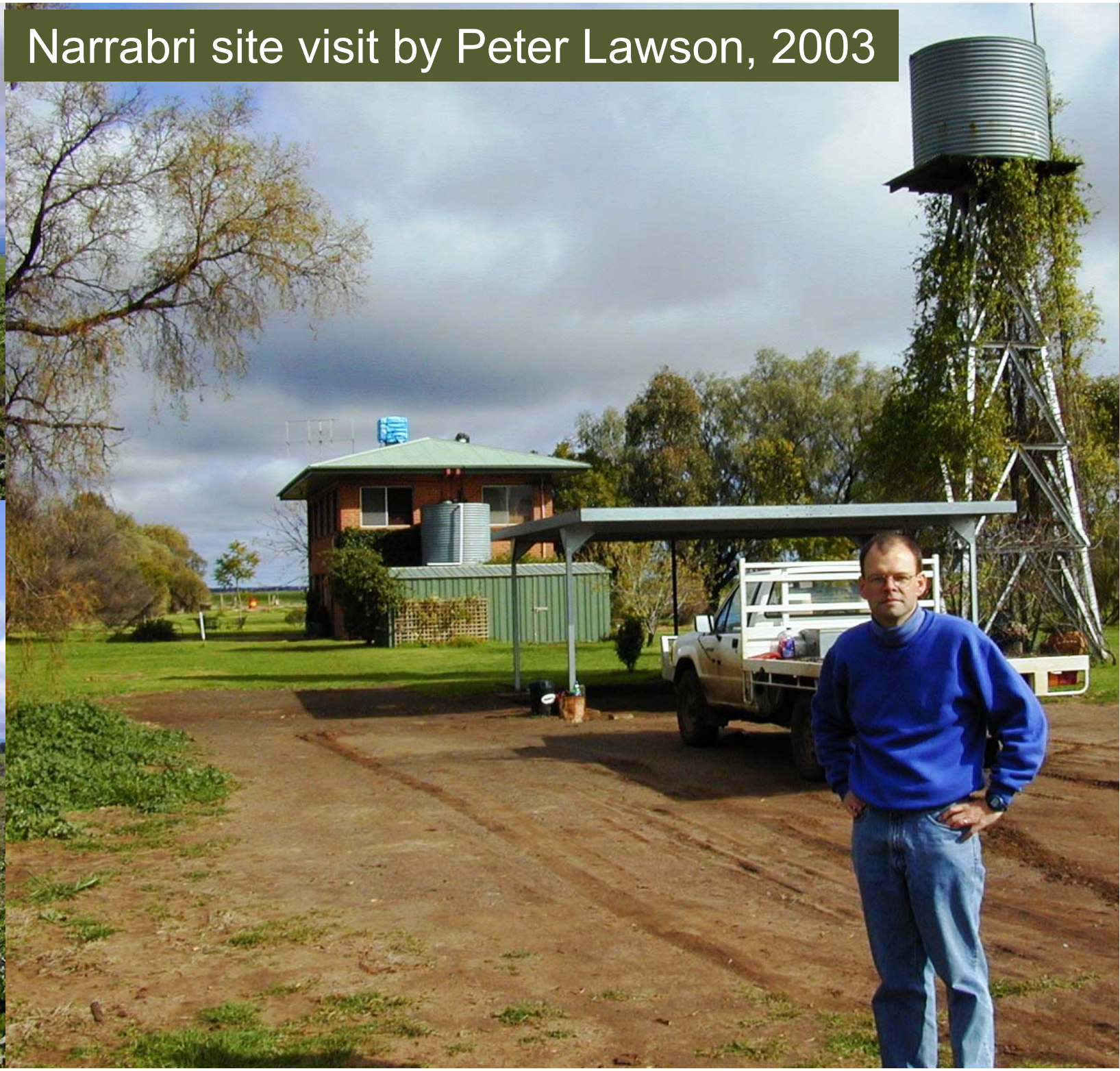


Google Earth (2023): –30.209262, 149.751061

Narrabri site visit by Peter Lawson, 2003







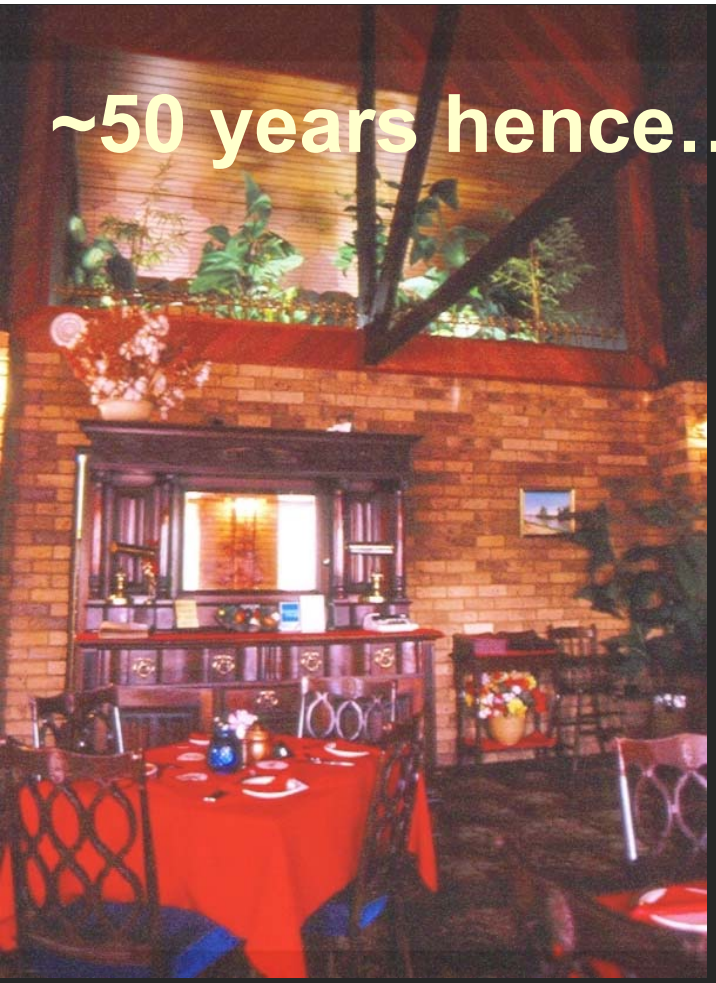






Narrabri site visit by Peter Lawson, 2003


Narrabri site visit by Peter Lawson, 2003







Sic transit gloria mundi...

Motel restaurant and bar in Narrabri, its wall covered with mirrors from the former observatory.

Photos: Dainis Dravins (left); Peter Lawson (right)

Postscripts

Robert Hanbury Brown after Narrabri

- SUSI project taken over by John Davis
- Major role in Australian astronomy (e.g., AAO)
- President of IAU 1982-1985
- Eventually moved back to the U.K.
- Passed away January 2002

Richard Quentin Twiss after Narrabri

- Started a project on a Michelson interferometer on Monte Porzio Catone (Rome)
- Gradually left the academic world
- Eventually returned to Australia, visited arts festivals in Sydney
- Passed away May 2005

Astronomy out … particle physics in

Particle physics

PHYSICAL REVIEW VOLUME 120, NUMBER 1 OCTOBER 1, 1960

Influence of Bose-Einstein Statistics on the Antiproton-Proton Annihilation Process*

GERSON GOLDHABER, SULAMITH GOLDHABER, WONYONG LEE, AND ABRAHAM PAIS†
Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California

Abstract: Recent observations of angular distributions of π mesons in $\overline{p}-p$ annihilation indicate a deviation from the predictions of the usual Fermi statistical model. …

Deviation caused by the Bose-Einstein statistics for identical integer-spin particles (bosons)

It was the discovery of the particle physics equivalent of the optical HBT effect

Now widely used to measure size and expansion of quark-gluon plasma and nuclear matter

Brazilian Journal of Physics, vol. 35, no. 1, March, 2005

HBT Interferometry: Historical Perspective

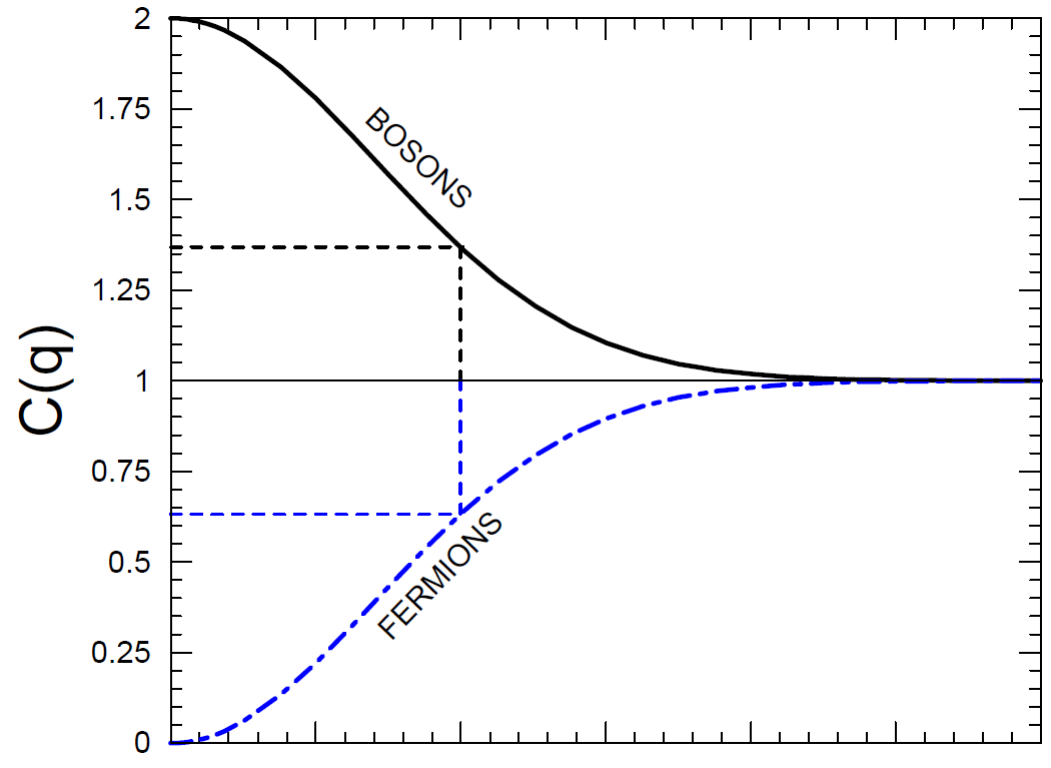
Sandra S. Padula

Instituto de Física Teórica - UNESP, Rua Pamplona 145, 01405-900 São Paulo, Brazil

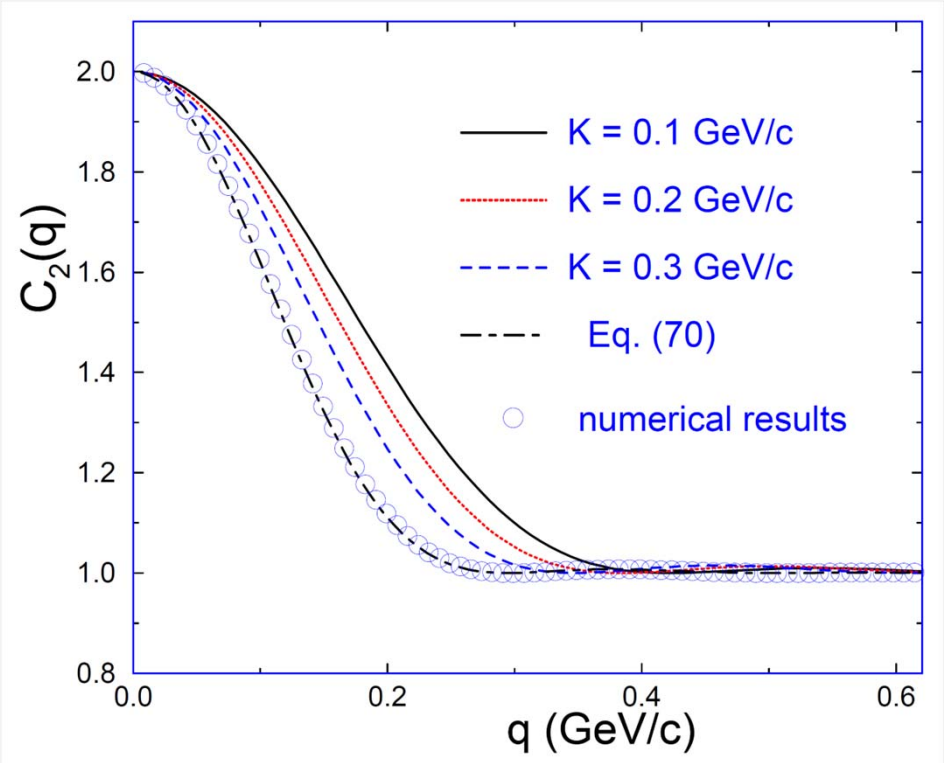
Received on 15 December, 2004

I review the history of HBT interferometry, since its discovery in the mid 1950's, up to the recent developments and results from BNL/RHIC experiments. I focus the discussion on the contributions to the subject given by members of our Brazilian group.

Particle physics



Ideal Gaussian sources.
Coherence as function of emitting region radius



R

Pions confined in a sphere.
Correlation shrinks for increasing average momentum, showing a progressively smaller emission region.

Intensity interferometry in subatomic physics

David H. Boal

Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6

Claus-Konrad Gelbke

Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824

Byron K. Jennings

TRIUMF, 4000 Wesbrook Mall, Vancouver, Britis

INSTITUTE OF PHYSICS PUBLISHING REPO

Rep. Prog. Phys. 66 (2003) 481–522 P

Bose–Einstein and Fermi–Dirac interfero particle physics

Gideon Alexander

Annu. Rev. Nucl. Part. Sci. 1992. 42:77–100
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Br

HBT Interferometry: Histo

Sandra S. Padul

Instituto de Física Teórica - UNESP, Rua Pamplona ,

Received on 15 December

iew the history of HBT interferometry, since its discovery in

Review of HBT or Bose-Einstein correlations in high energy heavy ion collisions

T. Csörgő

MTA KFKI RMKI, H - 1525 Budapest 114, P.O.Box 49, Hungary

Abstract. A brief review is given on the discovery and the first five decades of the Hanbury Brown - Twiss effect and its generalized applications in high energy nuclear and particle physics that includes a meta-review. Interesting and inspiring new directions are also highlighted including for example source imaging, lepton and photon interferometry, non-Gaussia pe analysis as well as many other new directions. Existing models are com d p correlation measurements and the so-called RHIC HBT puzzle is resolv vic for (directional) Hubble flow is presented and the conclusion is confirmed by a suc ful d iption of the pseudorapidity dependence of the elliptic flow as measured Au isions by th PHOBOS Collaboration.

HADRONIC INTERFEROMETRY IN HEAVY-ION COLLISIONS

Wolfgang Bauer and Claus-Konrad Gelbke

National Superconducting Cyclotron Laboratory and Department o and Astronomy, Michigan State University, East Lansing, Michigan 1321

Scott Pratt

Department of Physics, University of Wisconsin, Madison, Wiscon

KEY WORDS: intensity interferometry, Hanbury Brown and Twiss effect, two-particle correlation functions, transport theory

THE PH SI S O HANBURY BROWN–TWISS IN EN Y INTERFEROMETRY: ROM ST RS TO NUCLEAR COLLISIONS *

GORDON BAYM

Department of Physics, University of Illinois at Urbana-Champaign
1110 W. Green St., Urbana, IL 61801, USA

(Received April 14, 1998)

In the 1950's Hanbury Brown and Twiss showed that one could measure the angular sizes of astronomical radio sources and stars from correla- tions of s Their su ing of ph quantum has beco providing effect is depends the basi in high e matter a

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ELSEVIER

25 May 1995

PHYSICS LETTERS B

Physics Letters B 351 (1995) 293–301

Bose–Einstein effects and W mass determinations

Leif Lönnblad, Torbjörn Sjöstrand [1]

Theory Division, CERN, CH–1211 Geneva 23, Switzerland

Received 30 January 1995
Editor: R. Gatto

Abstract

In $e^+e^- \to W^+W^- \to q_1\bar{q}_2\,q_3\bar{q}_4$ events at LEP 2, the two W decay vertices are much closer to each other than typical hadronization distances. Therefore the Bose–Einstein effects, associated with the production of identical bosons (mainly pions), may provide a 'cross-talk' between the W^+ and the W^- decay products. If so, the observable W masses are likely to be affected. We develop algorithms for the inclusion of Bose–Einstein effects in multi-hadronic events. In this way we can study potential uncertainties in the W mass determination. In some scenarios the effects are significant, so that this source of uncertainty cannot be neglected.

Annu. Rev. Nucl. Part. Sci. 1999. 49:529–79
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TWO-PARTICLE CORRELATIONS IN RELATIVISTIC HEAVY-ION COLLISIONS

Ulrich Heinz

Theory Division, CERN, CH-1211 Geneva 23, Switzerland;
e-mail: ulrich.heinz@c n.ch nd Institut für Theoretische Physik, Universität Regensb g, D- Regensb g, Germany

Barbar V. c k

D arment Physics, State University of New York at Stony Brook, Stony Brook, Ne ork 1794; e-mail: jacak@skipper.physics.sunysb.edu

Key Words Hanbury Brown–Twiss interferometry, Bose-Einstein correlations, collective expansion, source size/lifetimes

■ **Abstract** Two-particle momentum correlations between pairs of identical particles produced in re of th ased lision for t

Annu. Rev. Nucl. Part. Sci. 2005. 55:357–402
doi: 10.1146/annurev.nucl.55.090704.151533
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FEMTOSCOPY IN RELATIVISTIC HEAVY ION COLLISIONS: Two Decades of Progress

Michael Annan Lisa

Department of Physics, The Ohio State University, Columbus, Ohio 43210; email: lisa@mps.ohio-state.edu

Scott Pratt

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Ron Soltz

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Urs Wiedemann

Theory Division, CERN, Geneva, Switzerland; email: urs.wiedemann@cern.ch

Key Words HBT, intensity interferometry, heavy ion collisions, femtoscopy

■ **Abstract** Analyses of two-particle correlations have provided the chief means for determining spatio-temporal characteristics of relativistic heavy ion collisions. We discuss the theoretical formalism behind these studies and the experimental methods used in carrying them out. Recent results from RHIC are put into context in a systematic review of correlation measurements performed over the past two decades. The current understanding of these results is discussed in terms of model comparisons and overall trends.

Particle physics

Nobel prize to Glauber

PHOTON CORRELATIONS*

Roy J. Glauber
Lyman Laboratory, Harvard University, Cambridge, Massachusetts
(Received 27 December 1962)

In 1956 Hanbury Brown and Twiss[1] reported that the photons of a light beam of narrow spectral width have a tendency to arrive in correlated pairs. We have developed general quantum mechanical methods for the investigation of such correlation effects and shall present here results for the distribution of the number of photons counted in an incoherent beam. The fact that photon correlations are enhanced by narrowing the spectral bandwidth has led to a prediction[2] of large-scale correlations to be observed in the beam of an optical maser. We shall indicate that this prediction is misleading and follows from an inappropriate model of the maser beam. In considering these problems we shall outline a method of describing the photon field which appears particularly well suited to the discussion of experiments performed with light beams, whether coherent or incoherent.

The correlations observed in the photoionization processes induced by a light beam were given a simple semiclassical explanation by Purcell,[3] who made use of the methods of microwave noise theory. More recently, a number of papers have been written examining the correlations in considerably greater detail. These papers[2,4-6] retain the assumption that the electric field in a light beam can be described as a classical Gaussian stochastic process. In actuality, the behavior of the photon field is considerably more

Pioneering paper by Roy Glauber explaining the functioning of the intensity interferometer

THE

PRINCIPLES

OF

QUANTUM MECHANICS

BY

P. A. M. DIRAC

LUCASIAN PROFESSOR OF MATHEMATICS
IN THE UNIVERSITY OF CAMBRIDGE

THIRD EDITION

Some time before the discovery of quantum mechanics people realized that the connexion between light waves and photons must be of a statistical character. What they did not clearly realize, however, was that the wave function gives information about the probability of *one* photon being in a particular place and not the probable number of photons in that place. The importance of the distinction can be made clear in the following way. Suppose we have a beam of light consisting of a large number of photons split up into two components of equal intensity. On the assumption that the intensity of a beam is connected with the probable number of photons in it, we should have half the total number of photons going into each component. If the two components are now made to interfere, we should require a photon in one component to be able to interfere with one in the other. Sometimes these two photons would have to annihilate one another and other times they would have to produce four photons. This would contradict the conservation of energy. The new theory, which connects the wave function with probabilities for one photon, gets over the difficulty by making each photon go partly into each of the two components. Each photon then interferes only with itself. Interference between two different photons never occurs.

The association of particles with waves discussed above is not restricted to the case of light, but is, according to modern theory, of universal applicability. All kinds of particles are associated with waves in this way and conversely all wave motion is associated with

Slide from presentation by Roy Glauber

Roy Glauber in Lund, December 2005







Photos: Sune Svanberg

Roy Glauber

Nobel prize in physics

Stockholm, December 2005



“For his contribution to the quantum theory of optical coherence"



Meanwhile in physics: Photon correlations

Laurie M. Brown, Abraham Pais, A. B. Pippard
Twentieth Century Physics
CRC Press, 1995

EARLY PHOTON-CORRELATION SPECTROSCOPY

1960's: Laser invented, photon-counting statistics explored. Correlation spectroscopy at Royal Radar Establishment in Malvern, U.K., electronically computing Glauber's $g^{(2)}$.

1970: First photon correlator measures size of the molecule haemocyanin. Autocorrelation function from a monodisperse suspension is an exponential with decay rate providing the hydrodynamic size of the molecule.

1980's: Commercial digital photon correlators evolve, with applications to macromolecular suspensions (proteins, enzymes, viruses, polymers, etc.), thermal diffusion, air and fluid velocity flows and turbulence, etc.

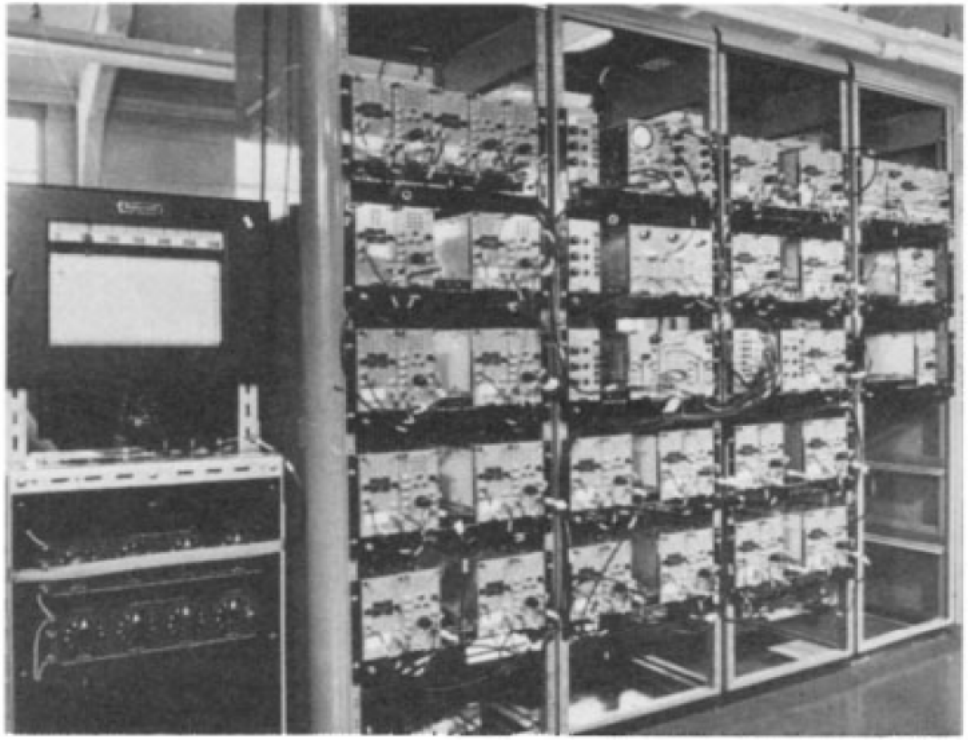


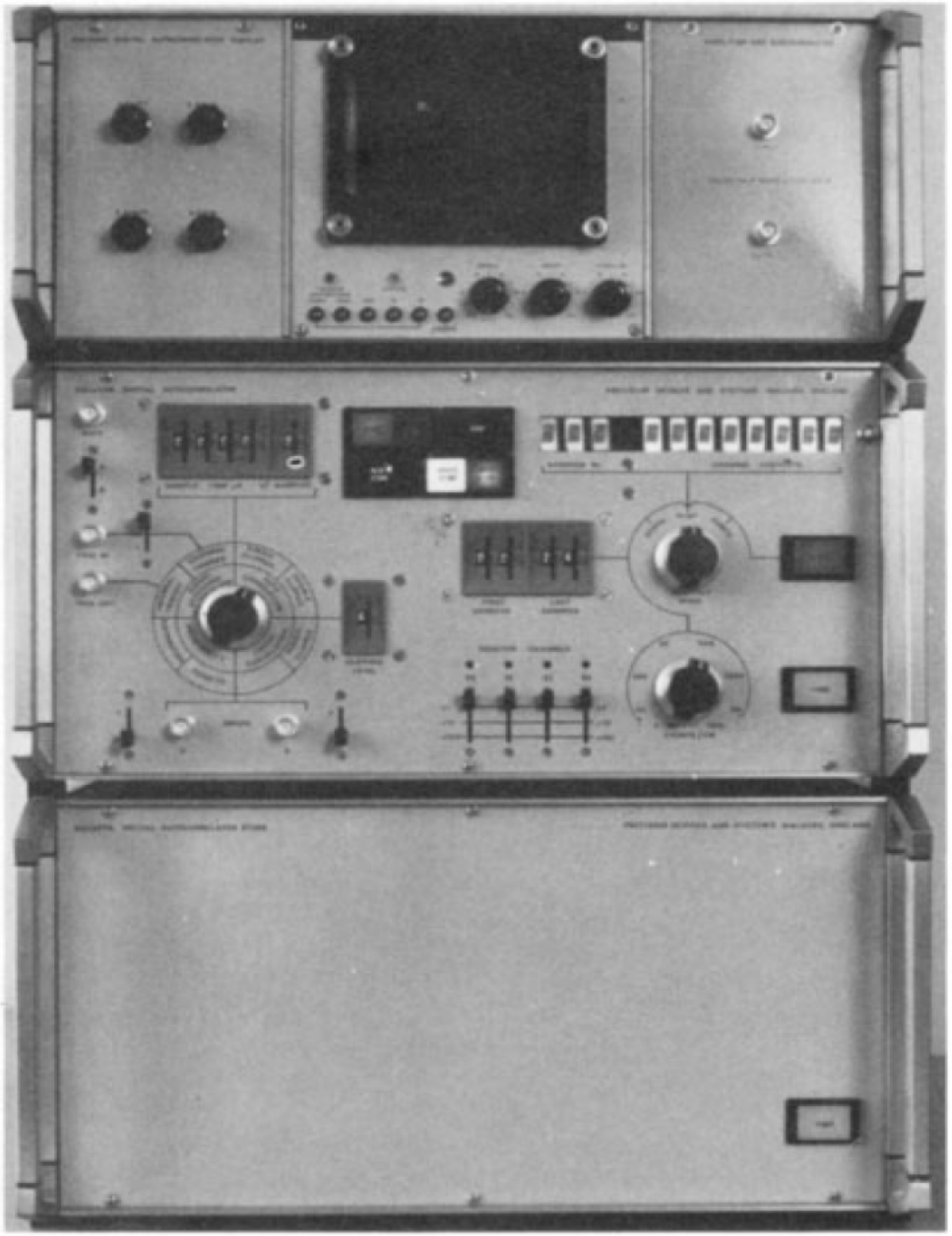
Radar and WW2

March 1942: More that 1,500 scientists and technical staff moved from secret establishments for telecommunications and radar from the British south coast to Malvern



Malvern Radar And Technology History Society (2016)
https://mraths.org.uk/





(Above) The original correlator at Harwell, 1969. It had 18 stores which were derived from fast nuclear counting systems, and occupied a great deal of space. Advances in integrated-circuit technology led to a 24-channel version which could be accomodated in a standard 19 in rack module (right). The version shown is the first commercial model of the Malvern Correlator made (under NRDC licence) by Precision Devices and Systems Ltd, which later became Malvern Instruments

E.R.Pike
The Malvern Correlator: Case study in development
Phys.Technol. **10**, 104 (1979)

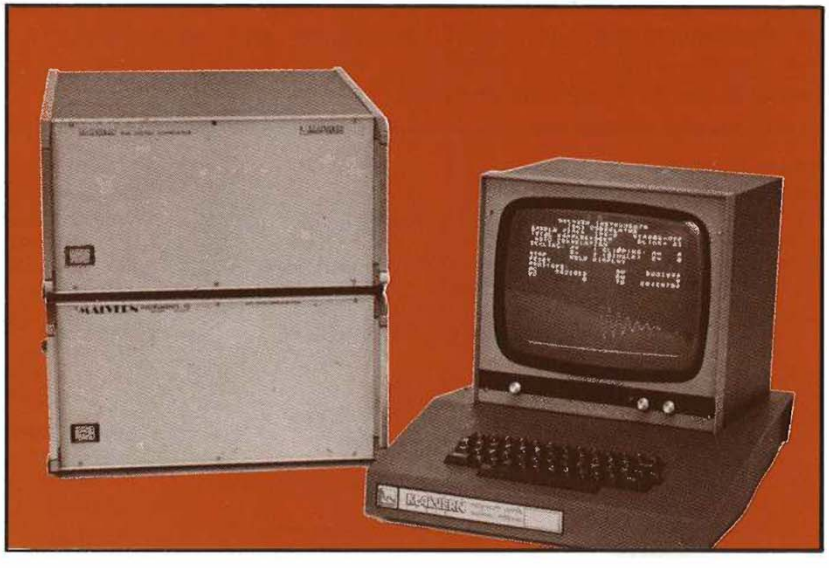
Early 1980's: First commercial photon correlators

MALVERN

TYPE K7026

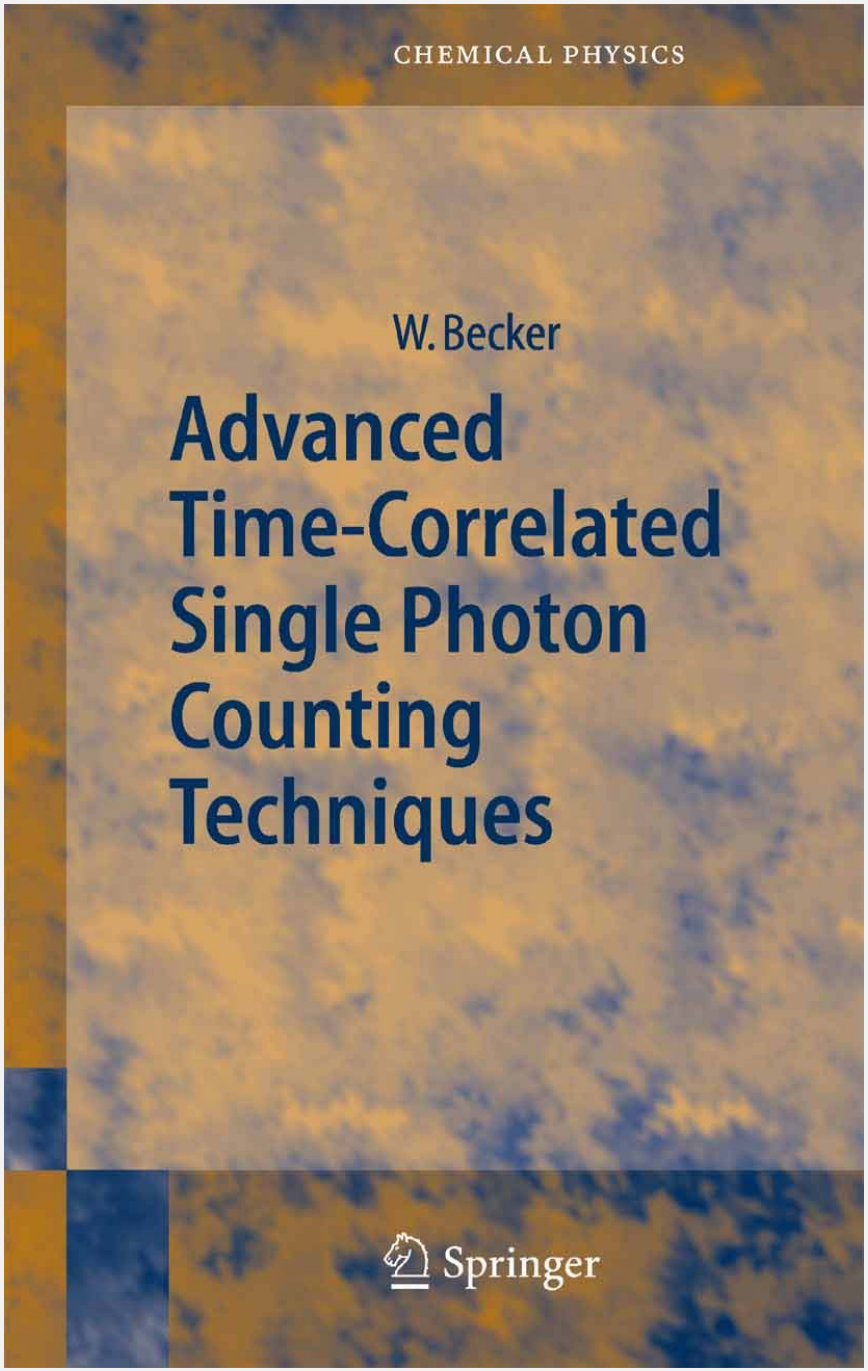
20 Nanosecond "Burst Correlator"
Laser Velocimeter Signal Processor

The development of the new 20 nanosecond "Burst Correlator" Laser Anemometer Signal Processor introduces to research and engineering a powerful new analytical tool for the analysis of a wide range of flows. These include gaseous and liquid flows, flames, combustion, turbulence studies, and internal combustion engine analysis.



Main Performance Details and Features

* Sample time resolution variable, 20 nanoseconds to 9.98 seconds. ①
* 64 channels extendable to 120 channels.
* Fast data readout: 32u sec for 64 8 bit channels.
* Maximum signal input rate 100MHz.
* Microprocessor controlled. Full ASCII keyboard. Single key operation for most frequently used functions.
* Self programmable string and loop facility.
* Large CRT display with graphics and alpha numerics.
* Remote control by external computer.
* Full correlation with 100% efficient signal processing on all ranges. Far superior performance, in difficult flow conditions, than "Batch Processing" correlators.
* Suitable for Fringe or Two Spot Anemometry.
* Ultimate sensitivity able to detect single photon events.
* Minimum laser power and seeding requirements.
* Full range of compatible detectors and optical systems available. Both for two spot and fringe velocimetry.
* Widest possible velocity range, microns per minute up to many 1000's of metres per second.



5 Application of Modern TCSPC Techniques

5.1 Classic Fluorescence Lifetime Experiments

5.2 Multispectral Fluorescence Lifetime Experiments

5.3 Excitation-Wavelength Multiplexing

5.4 Transient Fluorescence Lifetime Phenomena

5.5 Diffuse Optical Tomography and Photon Migration

5.6 Autofluorescence of Biological Tissue

5.7 TCSPC Laser Scanning Microscopy

5.8 Other TCSPC Microscopy Techniques

5.9 Picosecond Photon Correlation

5.10 Fluorescence Correlation Spectroscopy

5.11 Combinations of Correlation Techniques

5.12 The Photon Counting Histogram

5.13 Time-Resolved Single Molecule Spectroscopy

5.14 Miscellaneous TCSPC Applications

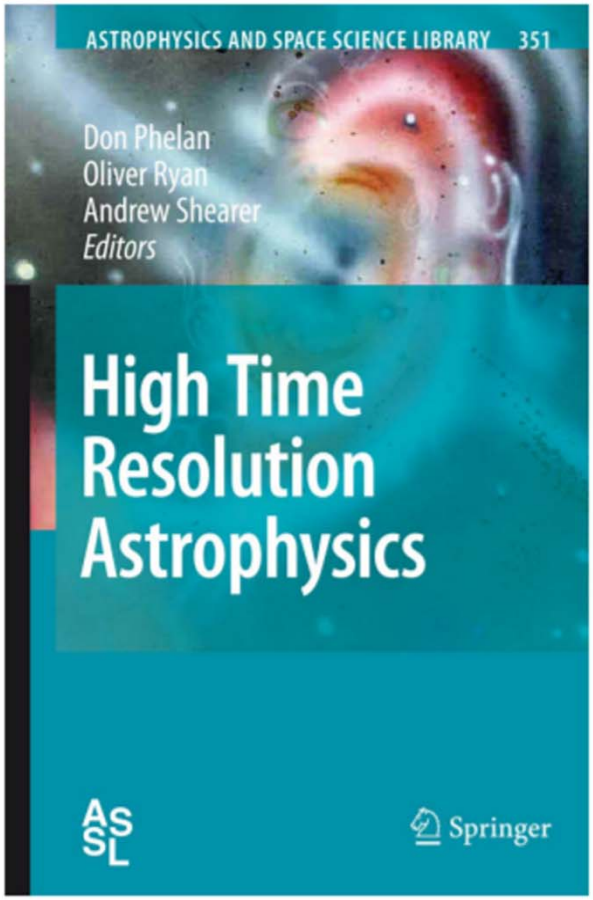
(Springer 2005)

Meanwhile in astronomy: High time resolution astrophysics

European networks within HTRA

Springer

springer.com



2008, X, 350 p.

Don Phelan, Oliver Ryan, Andrew Shearer (Eds.)

High Time Resolution Astrophysics

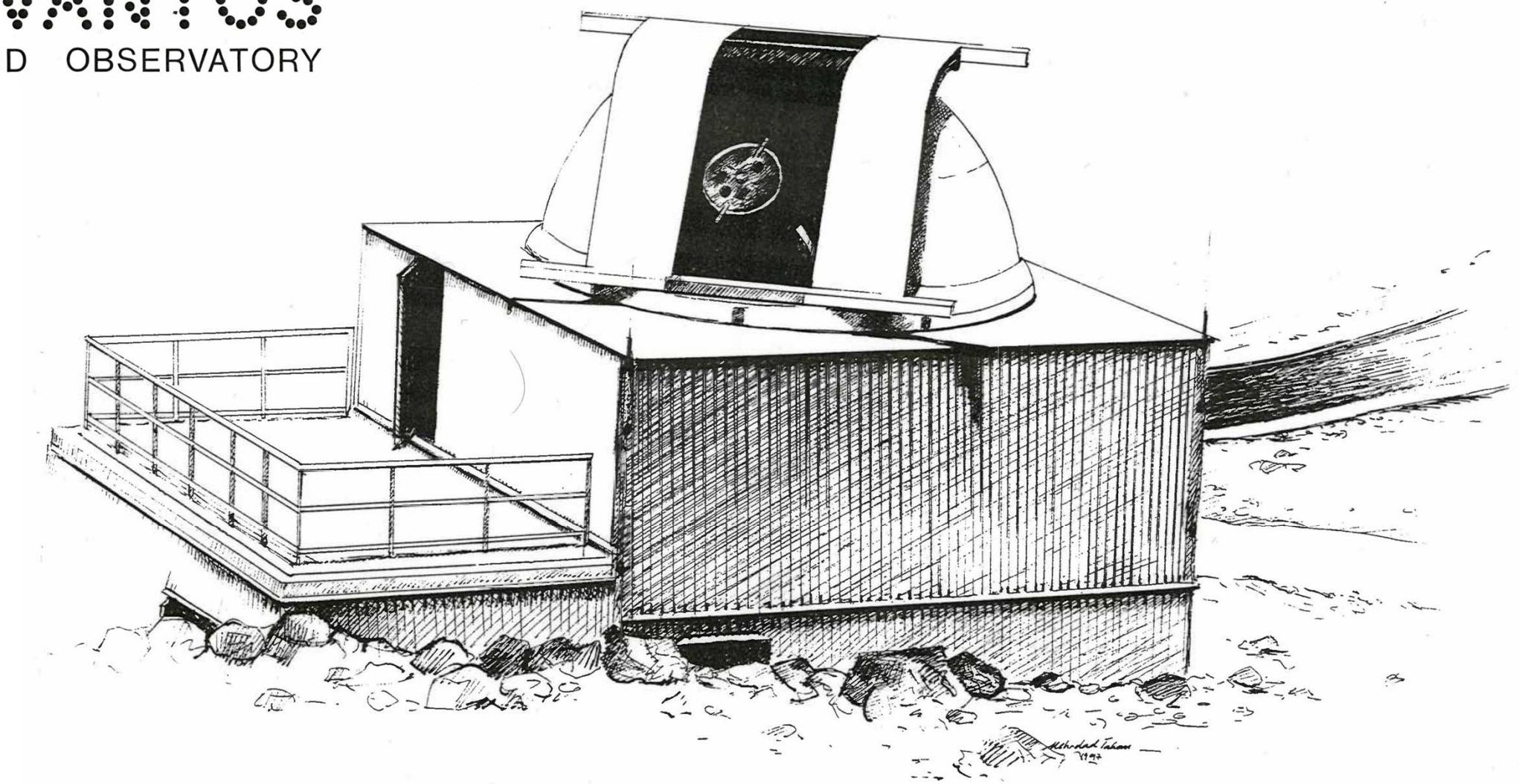
Series: Astrophysics and Space Science Library

- First volume of its kind dedicated to the area of high time resolution astrophysics

High Time Resolution Astrophysics (HTRA) is an important new window to the universe and a vital tool in understanding a range of phenomena from diverse objects and radiative processes. This importance is demonstrated in this volume with the description of a number of topics in astrophysics, including quantum optics, cataclysmic variables, pulsars, X-ray binaries and stellar pulsations to name a few. Underlining this science foundation, technological developments in both instrumentation and detectors are described. These instruments and detectors combined cover a wide range of timescales and can measure fluxes, spectra and polarisation. These advances make it possible for HTRA to make a big contribution to our understanding of the Universe in the next decade.

Atmospheric intensity scintillation

QUANTOS
LUND OBSERVATORY



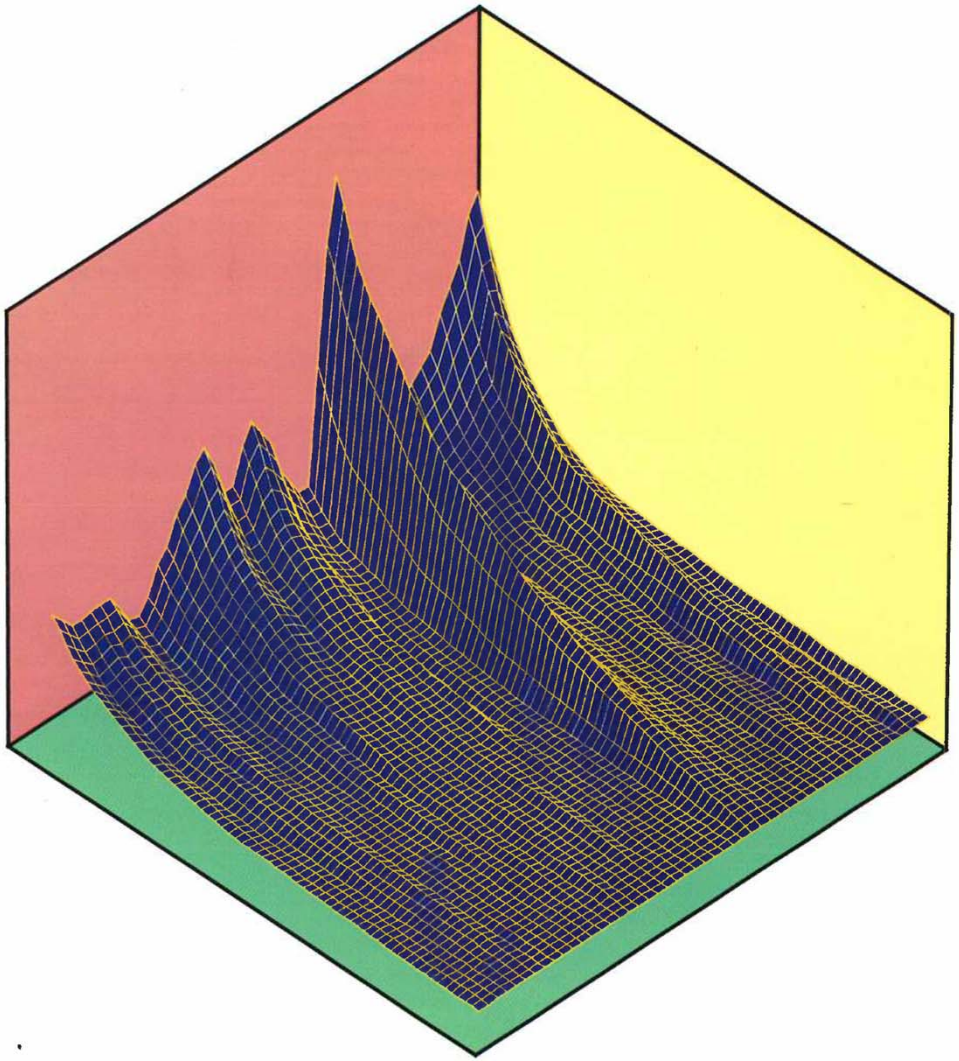
Swedish 60-cm telescope on La Palma (dismantled 2024)

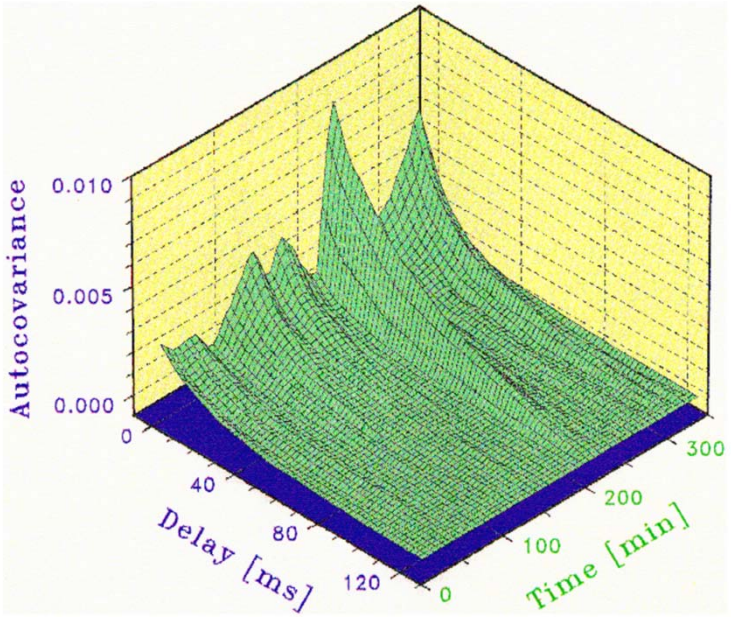
Here covered with a two-hole mask for measurements of spatial correlations in atmospheric scintillation

Publications of the Astronomical Society of the Pacific

Volume 109
Number 732
1997 February

Founded 1889





Publications of the Astronomical Society of the Pacific
109: 173–207, 1997 February

Atmospheric Intensity Scintillation of Stars. I. Statistical Distributions and Temporal Properties

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Publications of the Astronomical Society of the Pacific
109: 725–737, 1997 June

Atmospheric Intensity Scintillation of Stars. II. Dependence on Optical Wavelength

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PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, **110**:610–633, 1998 May

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Atmospheric Intensity Scintillation of Stars. III. Effects for Different Telescope Apertures

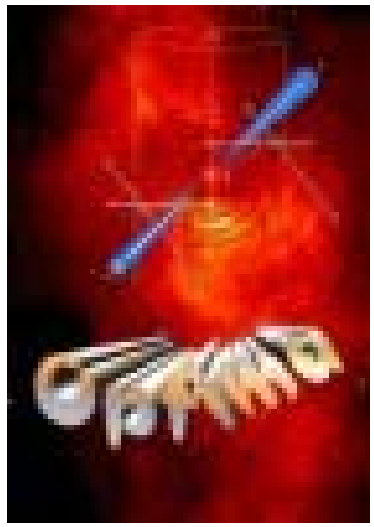
DAINIS DRAVINS, LENNART LINDEGREN, AND EVA MEZEY

Lund Observatory, Box 43, SE-22100 Lund, Sweden; dainis@astro.lu.se, lennart@astro.lu.se, evam@astro.lu.se

AND

ANDREW T. YOUNG

Department of Astronomy, San Diego State University, San Diego, CA 92182-1221; aty@mintaka.sdsu.edu

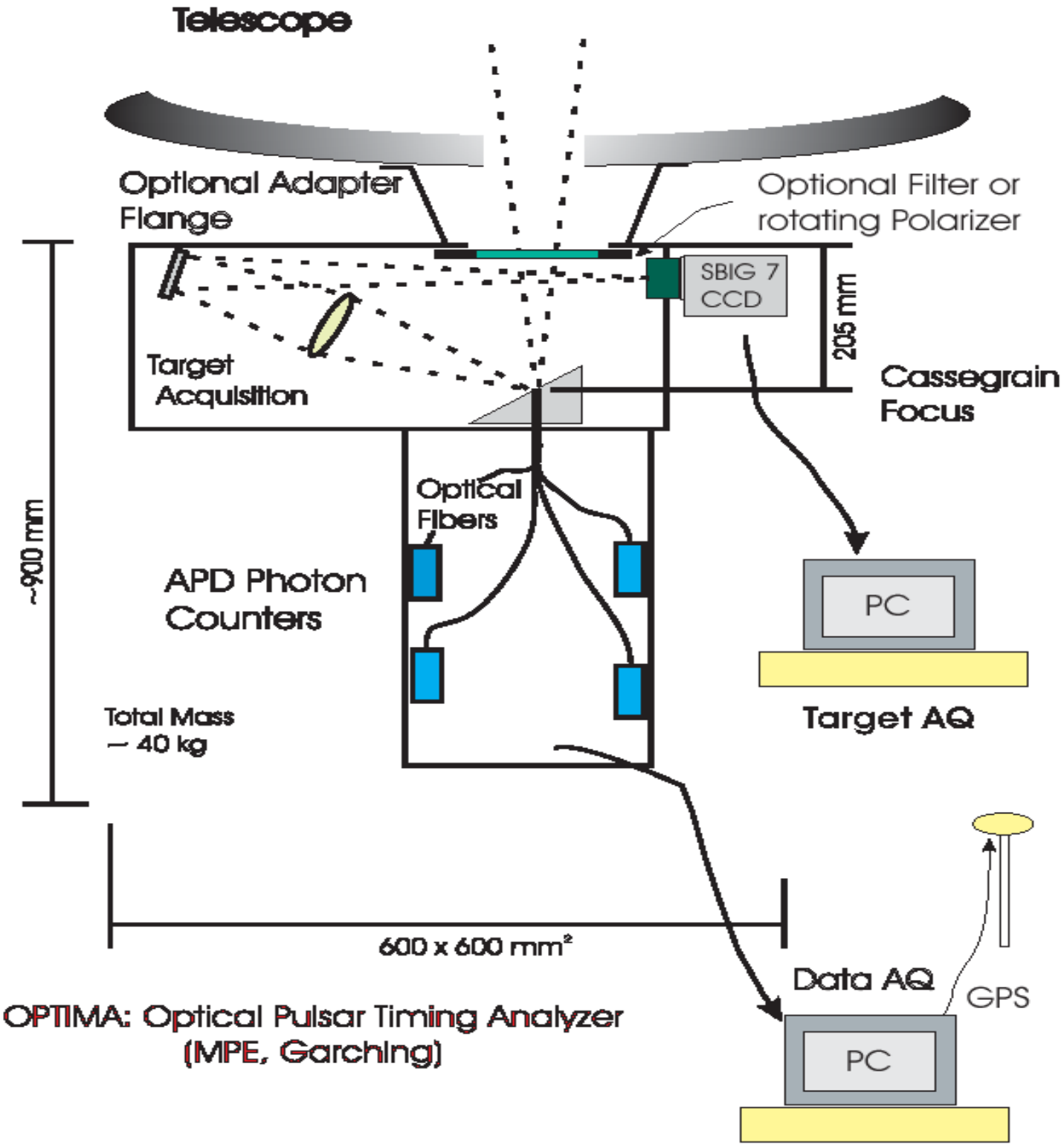


OPTIMA

Optical Pulsar Timing Analyzer

Max-Planck Institute for Extraterrestrial Physics, Garching

P.I.: Gottfried Kanbach





Skinakas
Observatory
October 2004:

Operating
QVANTOS (Lund)
& OPTIMA (Garching):

Alexander Stefanescu
(MPE)

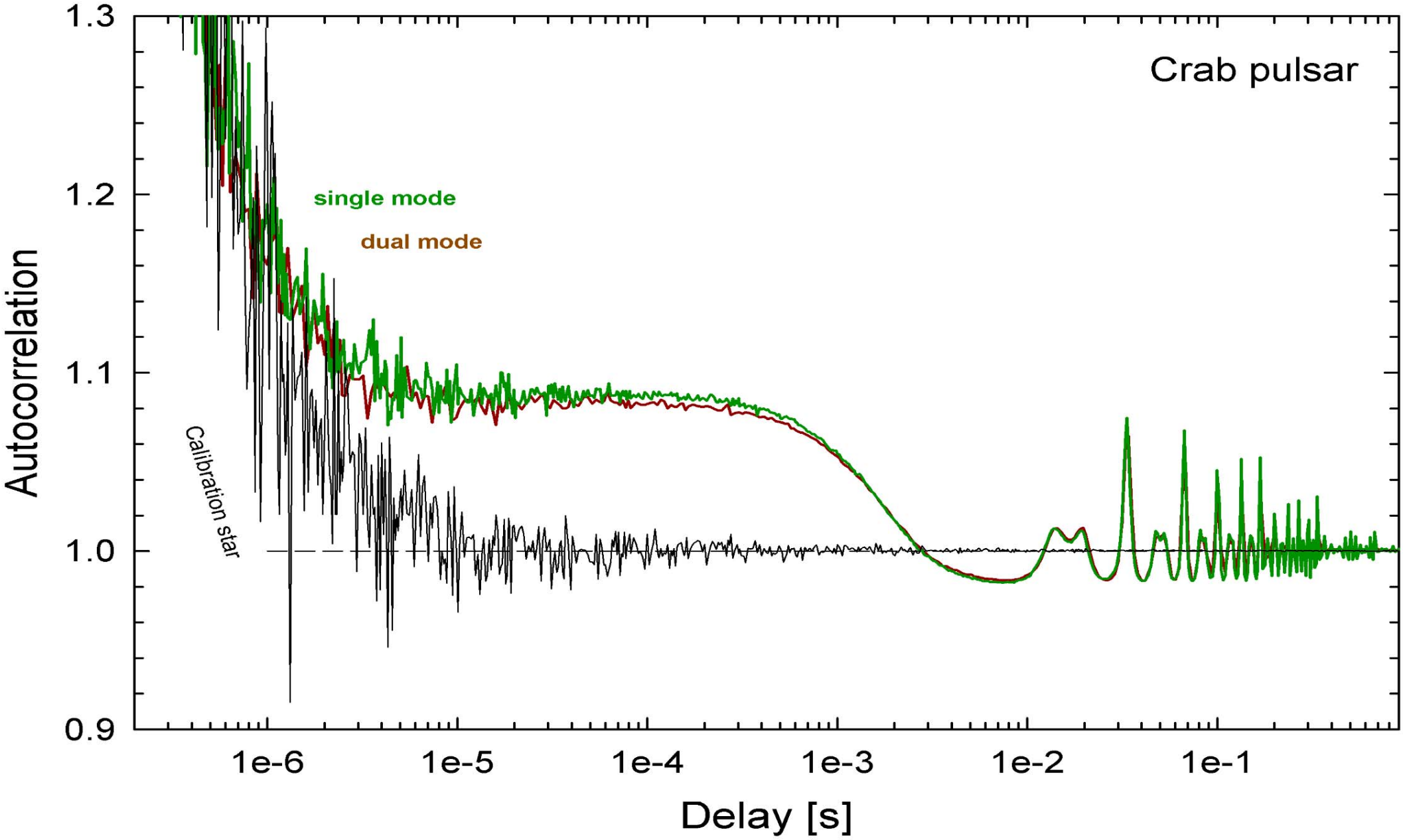
Tasos Kougentakis
(Heraklion)

Helena Uthas
(Lund)

Gottfried Kanbach
(MPE)

Crab pulsar autocorrelation functions (period = 33 ms)

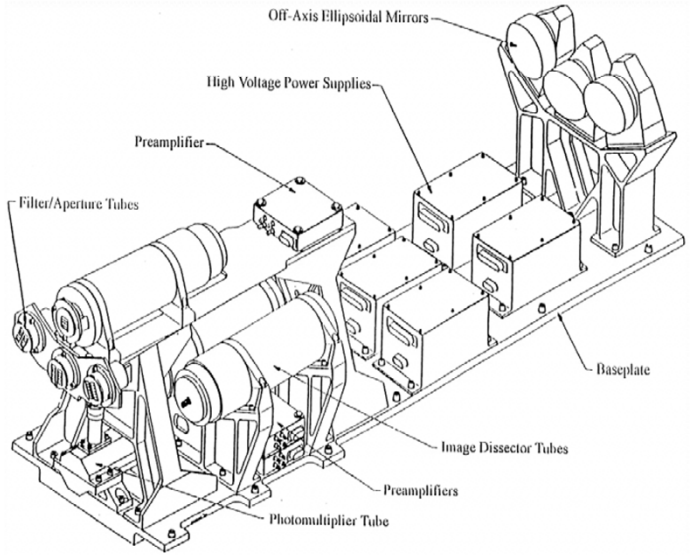
Skinakas Observatory 1.3 m telescope, Oct. 2004; OPTIMA (MPE) + QVANTOS Mark II (Lund)

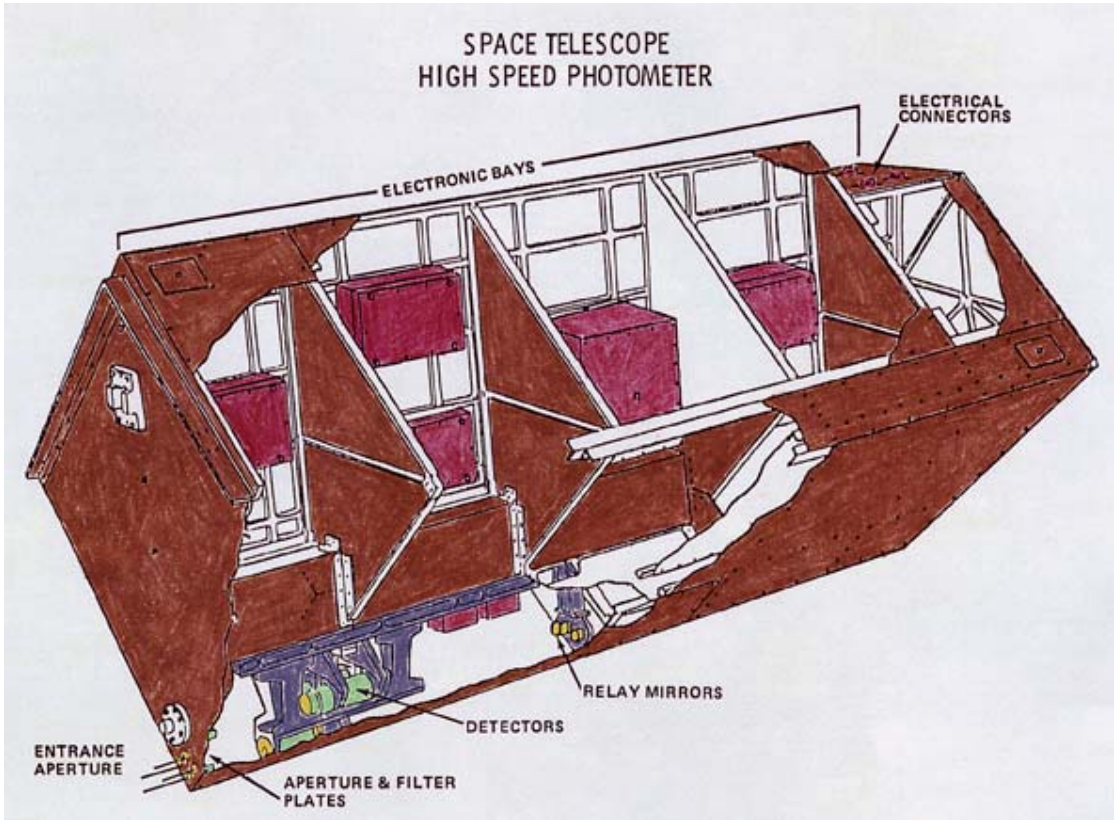


HSP, High Speed Photometer on Hubble Space Telescope

A3.1. HSP on Hubble Space Telescope

The High Speed Photometer (HSP) was one of the four original axial instruments on the Hubble Space Telescope (HST). The HSP on HST was designed to make very rapid photometric observations of astrophysical sources in a variety of filters and passbands from the near ultraviolet to the visible. The simplest of the original scientific instruments on HST, the High Speed Photometer had no moving parts. Its five detectors measured the brightness of celestial objects in several different spectral bands in the ultraviolet, as well as in visible.
The High Speed Photometer (HSP) was designed and built at the University of Wisconsin by a group led by principal investigator Robert C. Bless. Pre-and post-launch overviews are given by Bless (1982, 1997).

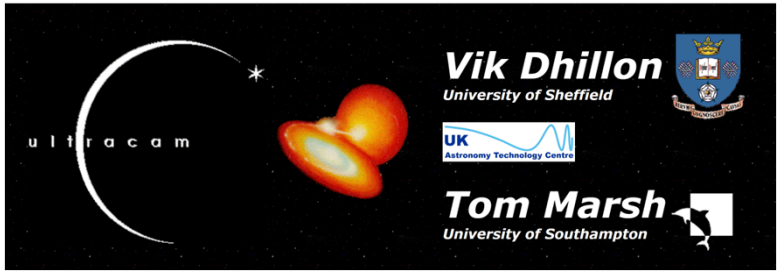


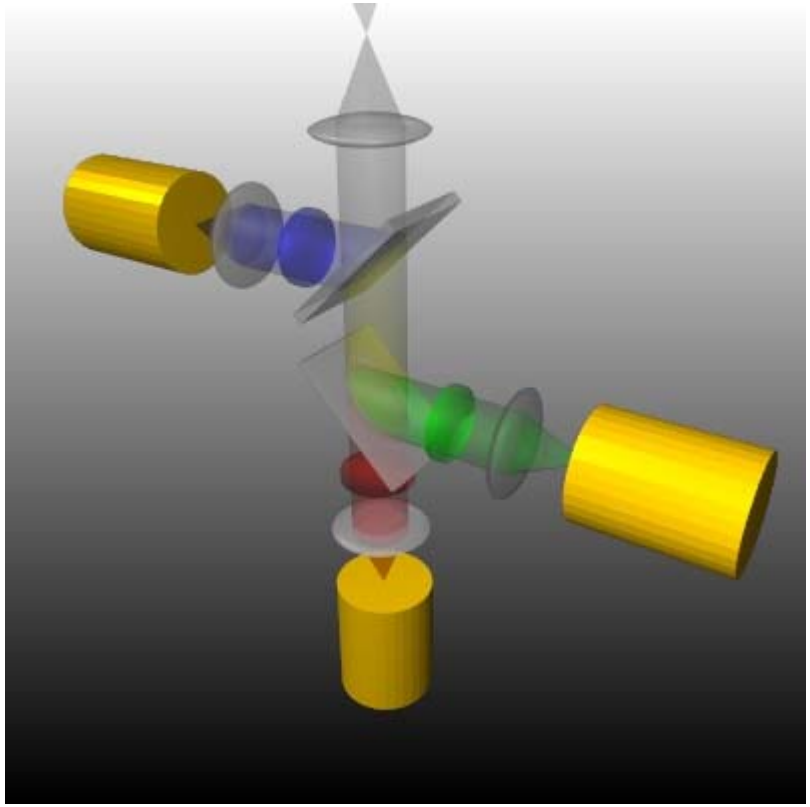


HSP was on the Hubble Space Telescope (HST) when it was launched on 25 April 1990

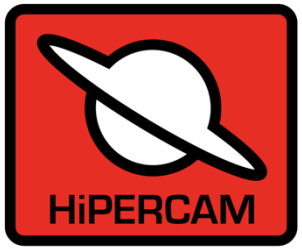
The HSP was replaced early in the mission with COSTAR (Corrective Optics Space Telescope Axial Replacement) in order to correct an aberration in the primary mirror for the remaining instruments.

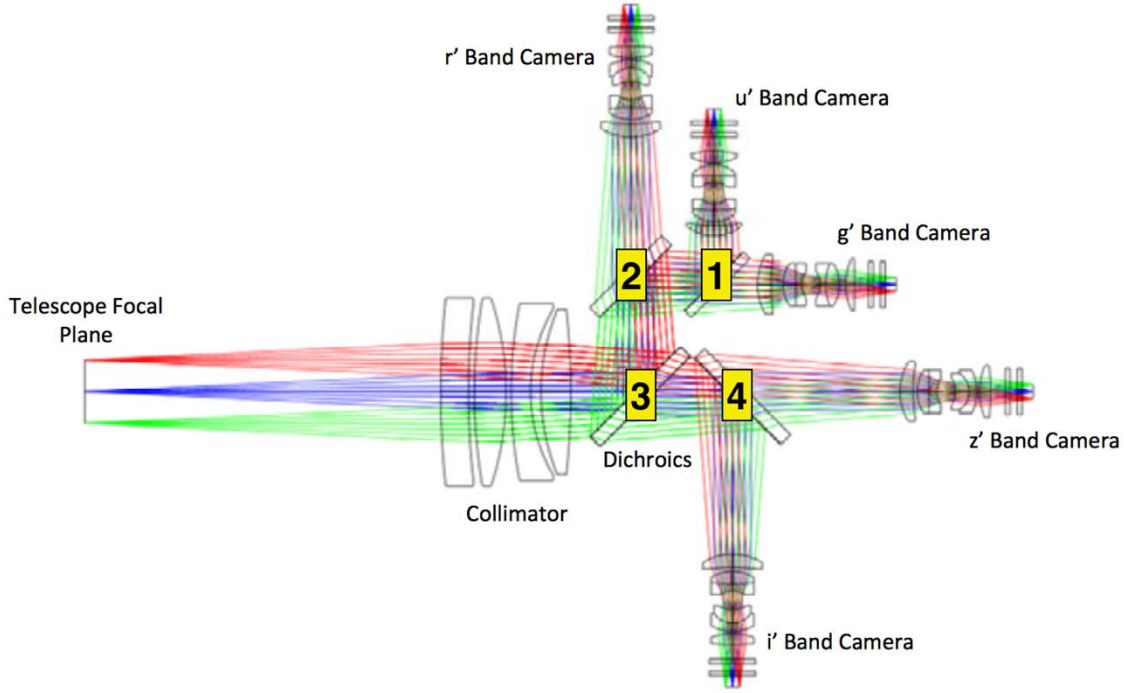
ULTRACAM & HiPERCAM





ULTRACAM is a triple-beam CCD camera for high-speed imaging in three colors. First light 2002 on the William Herschel Telescope on La Palma, later also at the VLT *Melipal* visitor focus.

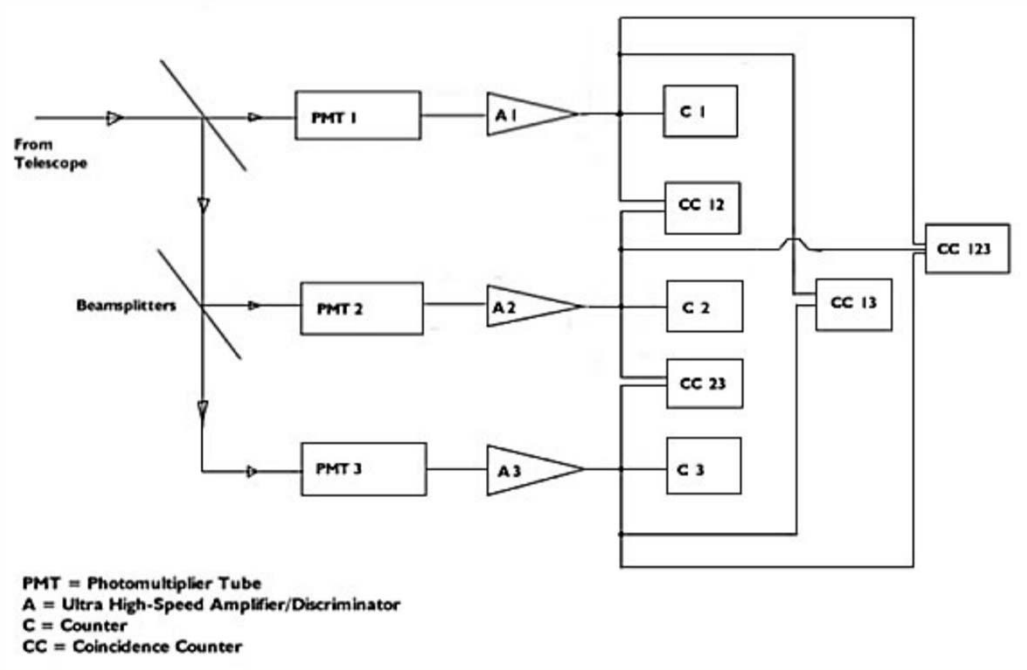




HiPERCAM uses 5 frame-transfer CCDs, allowing both standard and high-speed imaging at over 1000 frames per second. Telescopes used include the GranTelCan.

Optical SETI

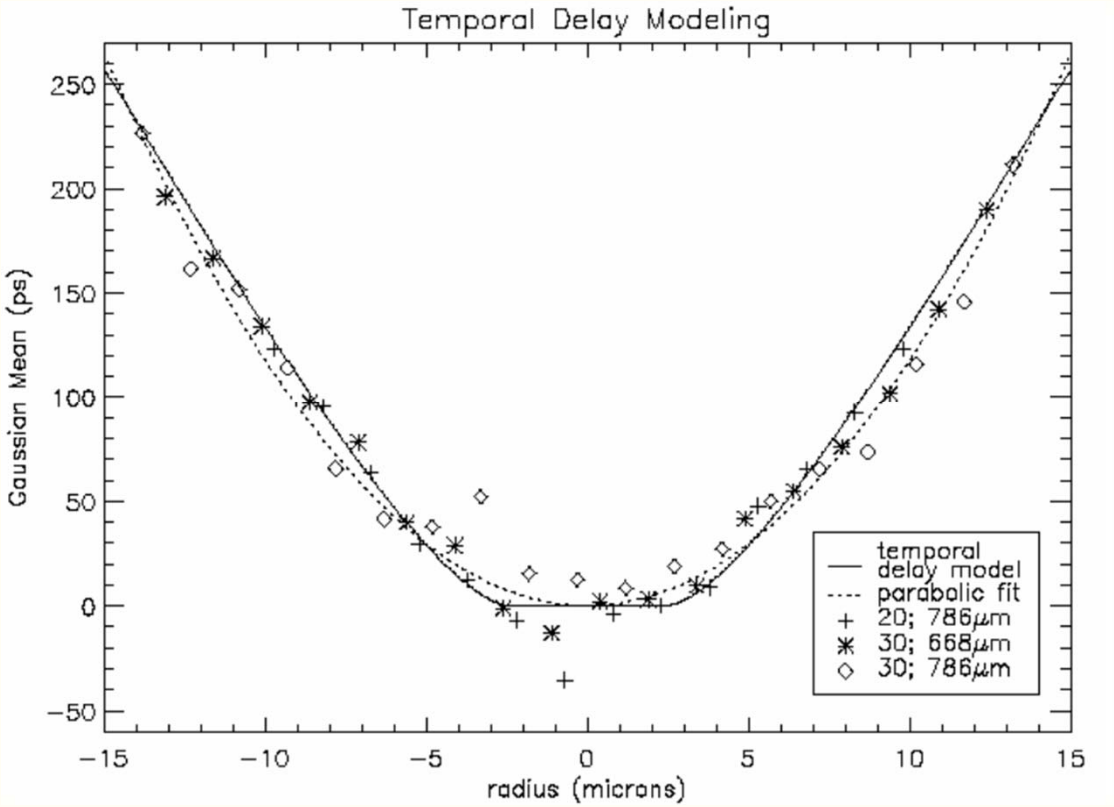




Harvard SETI photometer; first light in 1998; a second system began observations at Princeton in 2001 (Howard et al. 2004).

Wright et al. (2001) noted that two-detector optical SETI experienced "surprisingly" many false positives. To alleviate this, a three-detector system is now used at Lick Observatory.

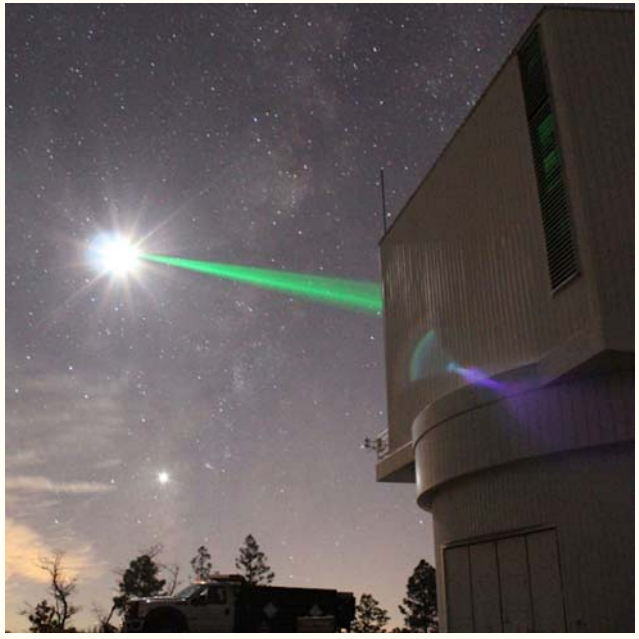
Lunar laser ranging



AVALANCHE INITIATION LOCATION: For extreme precision, the evolution of the electron avalanche inside the detector pixel needs to be understood.

Spatial scans of avalanche initiation delay for two detectors. Model based on linear spread of the avalanche front inside the diode (Murphy et al. 2004).

Avalanches initiated at the center of the pixel reach saturation sooner than if initiated at its edges. Measured with laser pulses focused to a few μm.



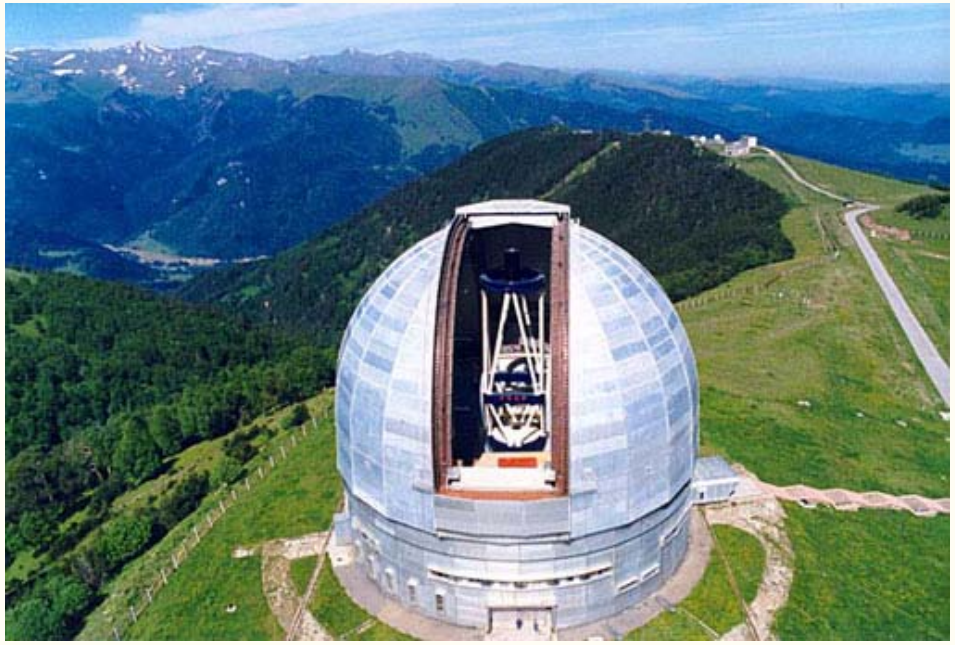
***APOLLO* (Apache Lunar Laser-ranging Operation) uses a 3.5 m telescope at Apache Point in New Mexico.**

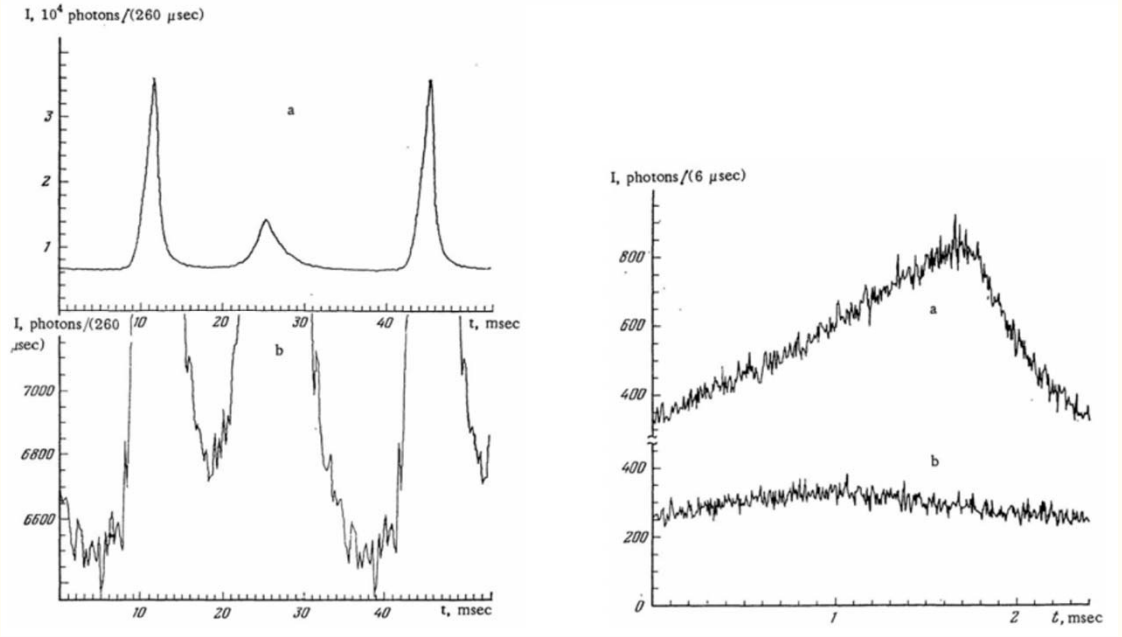
Return travel time is measured within a few picoseconds, corresponding to ~1 mm in range to the Moon.

MANIA experiment

Started at 6-m BTA observatory in Northern Caucasus around 1972, initially led by Viktorij Shvartsman. Visionary project with hard- and software to study optical variations on timescales down to 100 ns.

After tests on smaller telescopes, first BTA measurements in 1977. Initial driver was search for instabilities in magnetized plasma accreting onto stellar-mass black holes, with no periodicity expected; later also exploding black holes. In 1991, the instrumentation was brought to the 2.15 m telescope at *El Leoncito* in Argentina.





Crab pulsar in R-band, observed with the 6-m BTA telescope at 6 μs resolution (Beskin et al. 1983)

«MANIA» – "Multichannel Analysis of Nanosecond Intensity Alterations"
«МАНИЯ» – "Многоканальный Анализ Наносекундных Изменений Яркости"

MANIA experiment

Statistical analysis of time interval distribution between photon arrival times

Astronomical and Astrophysical Transactions, 1997, Vol. 13, pp. 13–17
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Printed in India

SUPERFAST PHOTOMETRY WITH THE MANIA COMPLEX

V. F. SHVARTSMAN, I. N. BERNSTEIN, G. M. BESKIN, V. N. KOMAROVA, S. I. NEIZVESTNY, V. L. PLOKHOTNICHENKO, M. Yu. POPOVA, and A. V. ZHURAVKOV

Special Astrophysical Observatory, Nizhniy Arkhyz, Karachai-Circassia, 357147, Russia

(Received December 19, 1995)

We describe the hard/software MANIA complex for carrying out superfast photometry. A new type of time-code converter Quantochron allows us to measure arrival times of photons registered by a photodetector with time resolution up to 20 ns in 2^{16} channels (space, colours, polarization, etc.) simultaneously. Special software was developed to investigate variability on a time-scale of 2×10^{-8}–10^{3} s by statistical analysis of the time inverval distribution between detected photons and classical light curves. The results of some observations are presented.

KEY WORDS Superfast photometry

A.1. The y_2 functions

The method of the y_2 function is designed for the search and analysis of variabilities with timescales τ_ν in the range $\tau_\nu \approx 10^{-7} - 10^{-2}$ sec. It is based on the statistical analysis of time intervals between successive photon detections (in contrast to the typic analysis of amounts of photons at fixed intervals).

If we define the interval duration as the time interval in which a prefixed number of photons are registered, then y_2 function is the relative difference between fractions of intervals duration for the object and the reference star

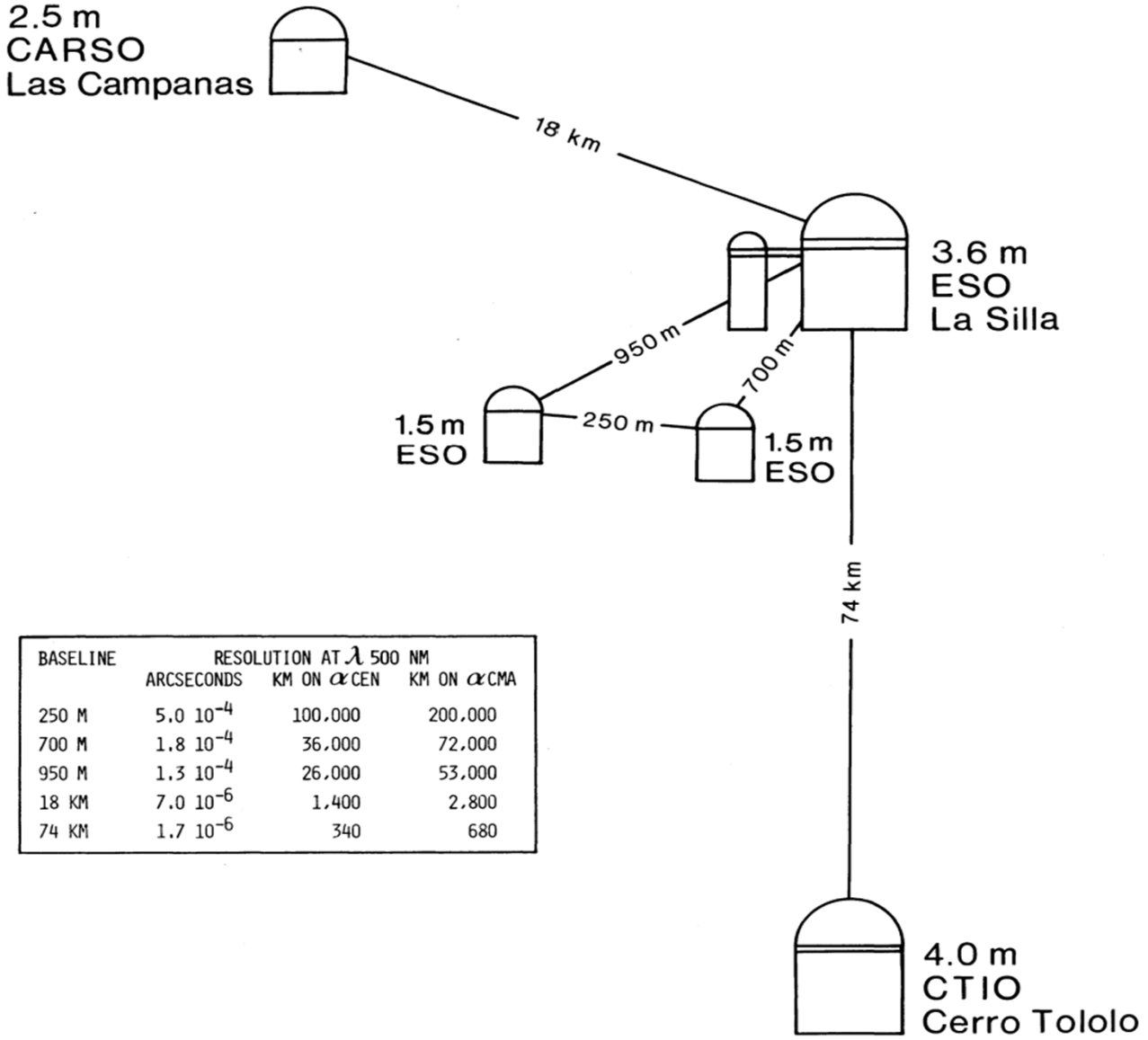
$$y_{2i}(\tau_i, \tau_{i+1}) = (p_o(\tau_i, \tau_{i+1}) - p_r(\tau_i, \tau_{i+1})) / p_r(\tau_i, \tau_{i+1}) \quad \text{(A1)}$$

where $p_o(\tau_i, \tau_{i+1})$ and $p_r(\tau_i, \tau_{i+1})$ are the fraction of intervals of duration from τ_i to τ_{i+1} for the object and the reference star respectively.

G.Beskin et al.: *Optical study of LMXBs with high temporal resolution: Evidence for non-thermal flares from MXB 1735-44*, Astron.Astrophys. **289**, 141, 1994

Nanoseconds enable intensity interferometry

Early thinking about long baselines



BASELINE	RESOLUTION AT λ 500 NM		
	ARCSECONDS	KM ON αCEN	KM ON αCMA
250 M	$5.0\ 10^{-4}$	100,000	200,000
700 M	$1.8\ 10^{-4}$	36,000	72,000
950 M	$1.3\ 10^{-4}$	26,000	53,000
18 KM	$7.0\ 10^{-6}$	1,400	2,800
74 KM	$1.7\ 10^{-6}$	340	680

D.Dravins: *Possible Applications of Long-Baseline Intensity Interferometry*
In Proc. ESO conf. *Scientific importance of high angular resolution at infrared and optical wavelengths* (Garching, West Germany, March 1981), p. 295

Nanosecond Resolution Observations: Quatum-Optical Spectrosocpy and Intensity Interferometry
In Proc. *Solar Instrumentation: What's Next?* (Sunspot, NM, October 1980), Sacramento Peak National Obs., p. 253 (1981)

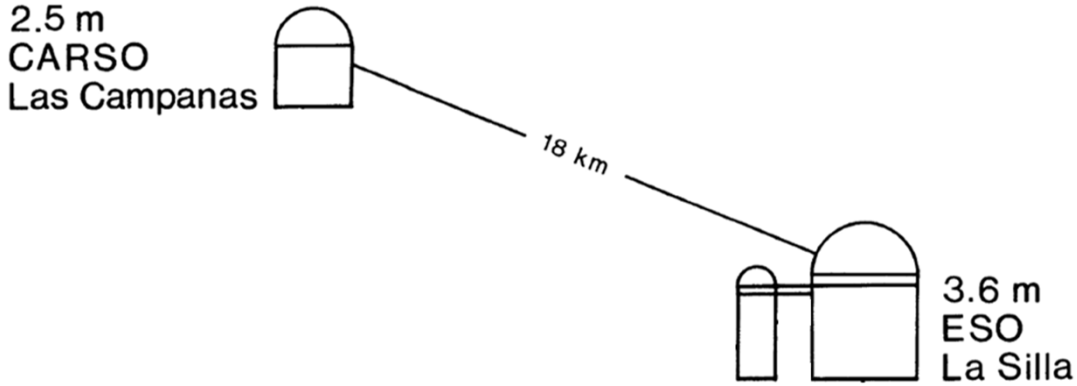
Early thinking about long baselines



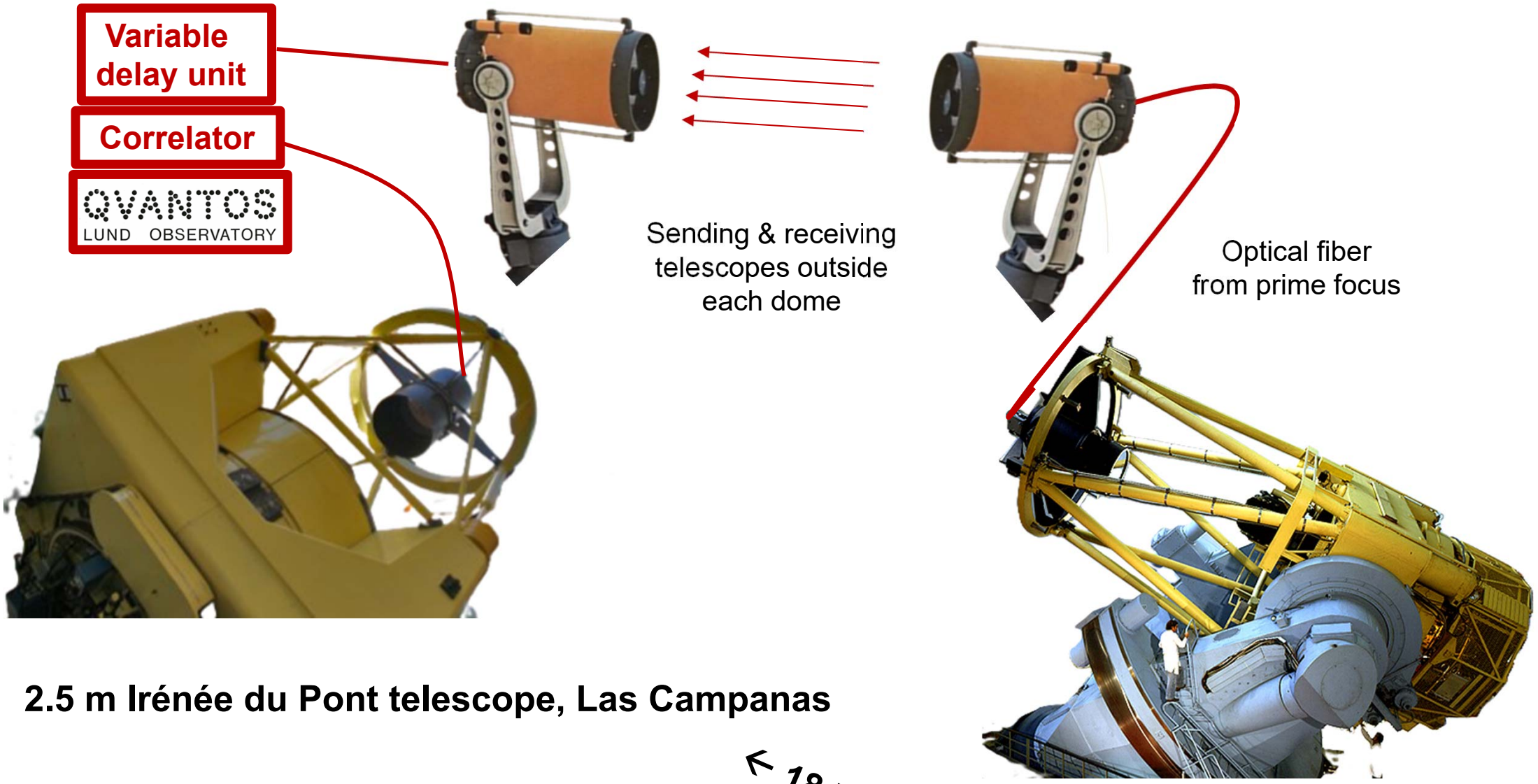
Las Campanas seen from La Silla



La Silla seen from Las Campanas



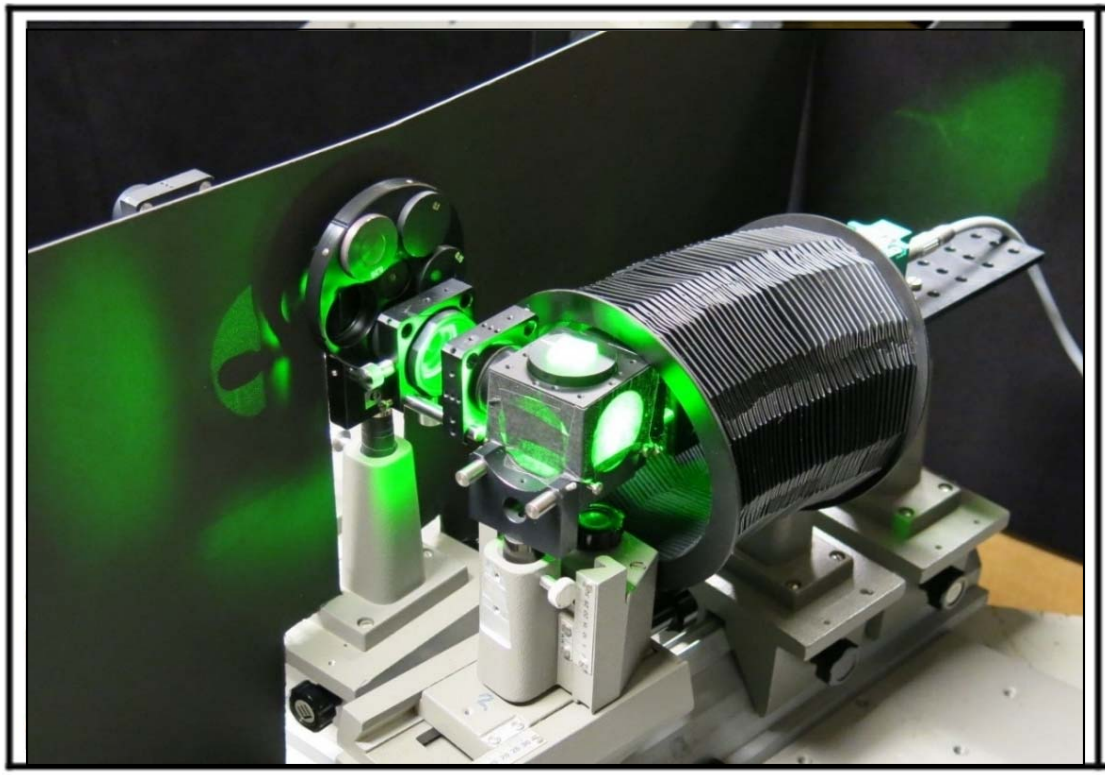
Early thinking about long baselines

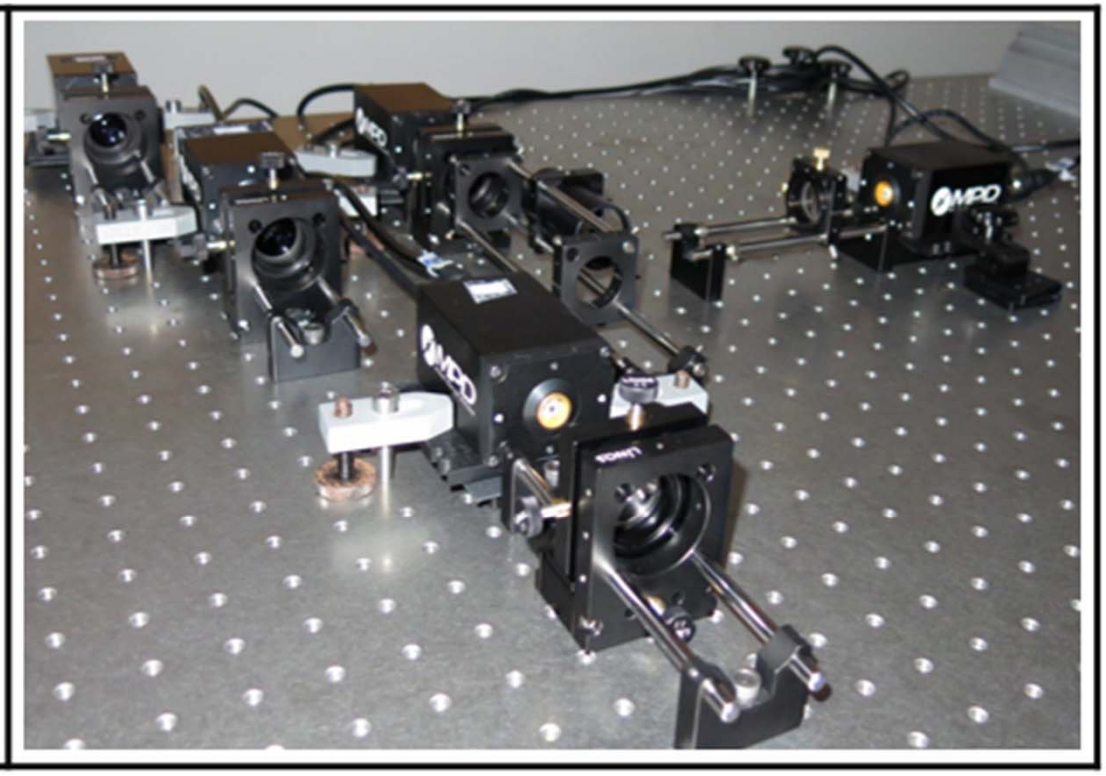


Laboratory Intensity Interferometer

(Lund Observatory)



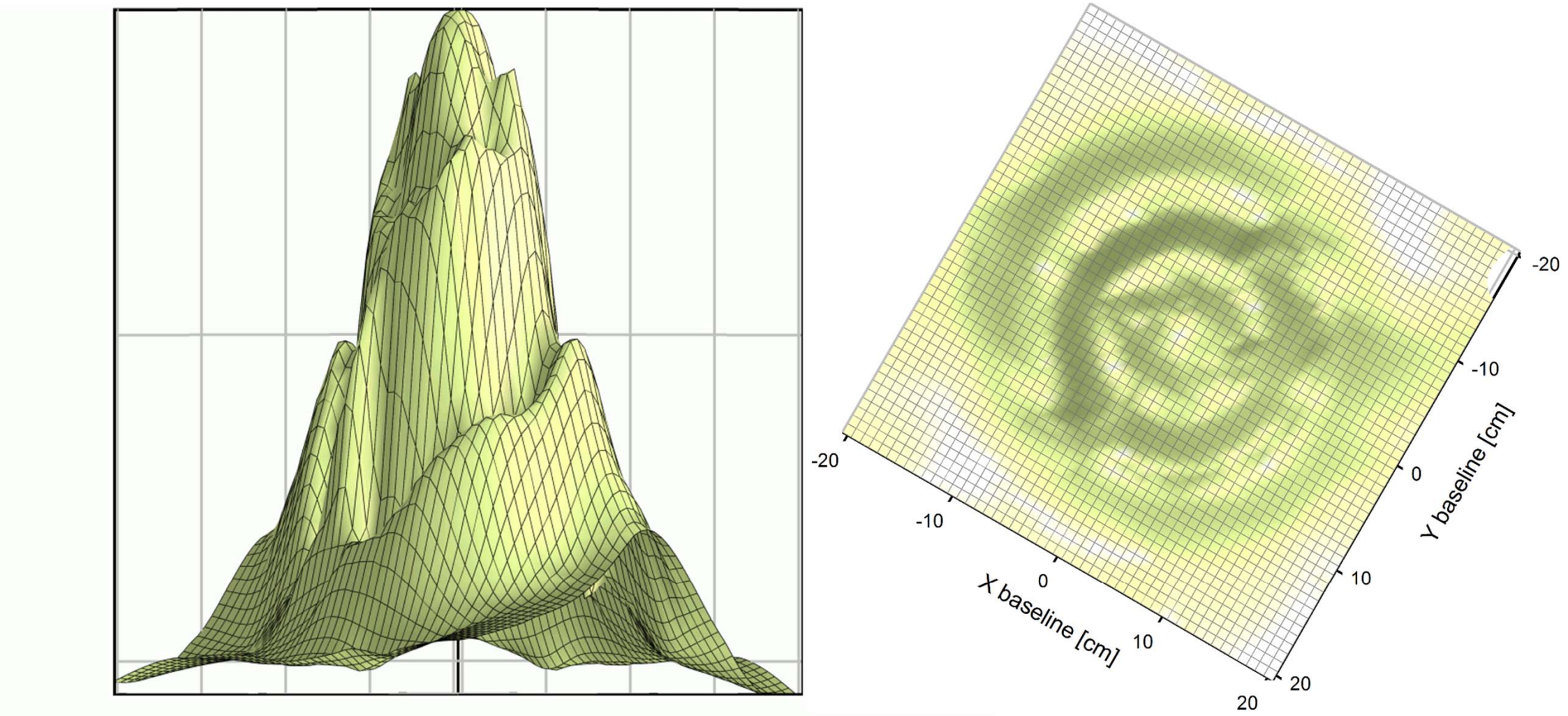




Left: Light from a 300 mW λ 532 nm laser is randomized through scattering against microscopic particles in a square-top cuvette and focused by a condenser onto artificial 'stars', being apertures in a rotatable holder.
Right: The 'stars' are observed by an array of small telescopes, each with a photon-counting SPAD detector. 2-D coverage is achieved by rotating the asymmetric source relative to the plane of the telescopes.

(D.Dravins, T.Lagadec, P.D.Nuñez: *Long-baseline optical intensity interferometry. Laboratory demonstration of diffraction-limited imaging,* Astron.Astrophys. **580**, A99, 2015)

Laboratory intensity interferometry with 100 baselines

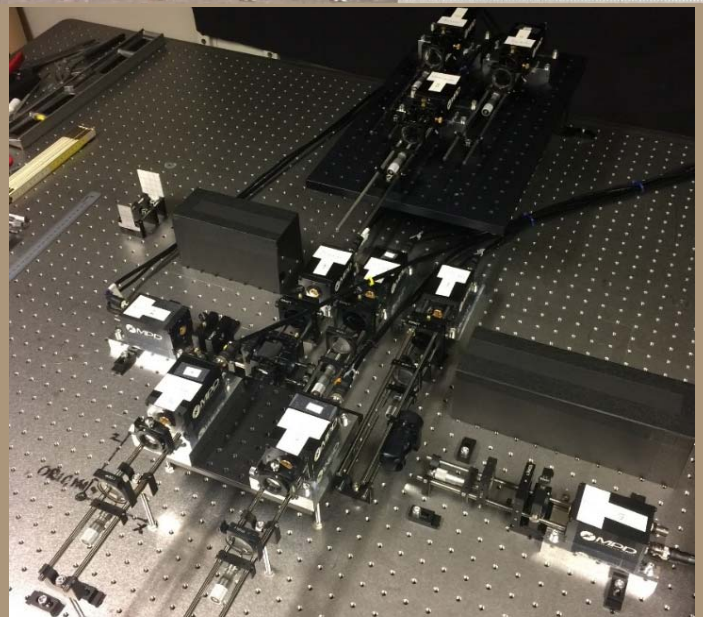


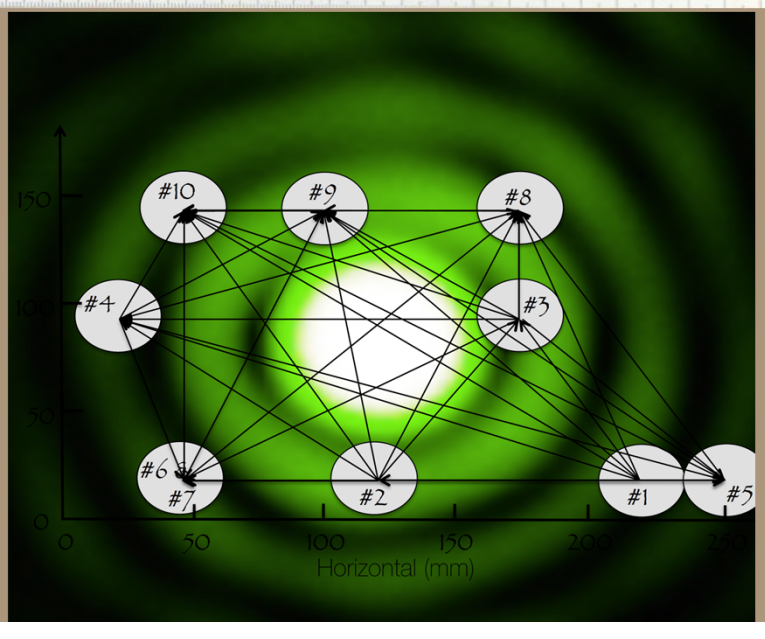
Intensity interferometry measurements with 100 different telescopic baselines. The data largely fill the interferometric (u,v)-plane of the second-order coherence g(2) for an artificial star, somewhat irregular and elliptic, with angular extent just below 1 arcsecond. At right, the projection of the 3-D mesh is oriented straight down, showing [the modulus of] the source's Fourier transform ('diffraction pattern').

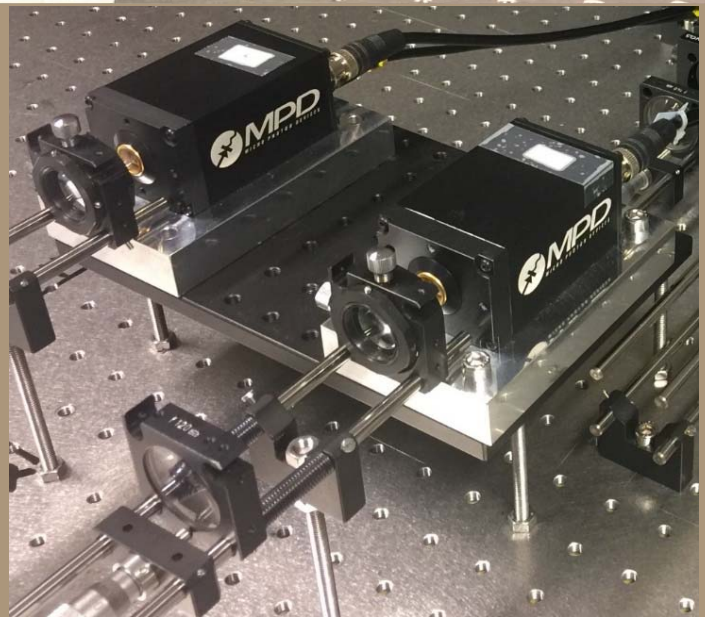
(D.Dravins & T.Lagadec: *Stellar intensity interferometry over kilometer baselines: laboratory simulation of observations with the Cherenkov Telescope Array*, Proc. SPIE **9146**, Optical and Infrared Interferometry IV, 91460Z (2014)

Ten telescopes in a 2-dimensional array

Colin Carlile: *Seeing Stars - Intensity Interferometry in the Laboratory and on the Ground*
Lund University, 2021







OWL 100-m
Overwhelmingly Large Telescope
project & planning 1998-2006

OWL Phase A Review - Garching - 2nd to 4th Nov 2005

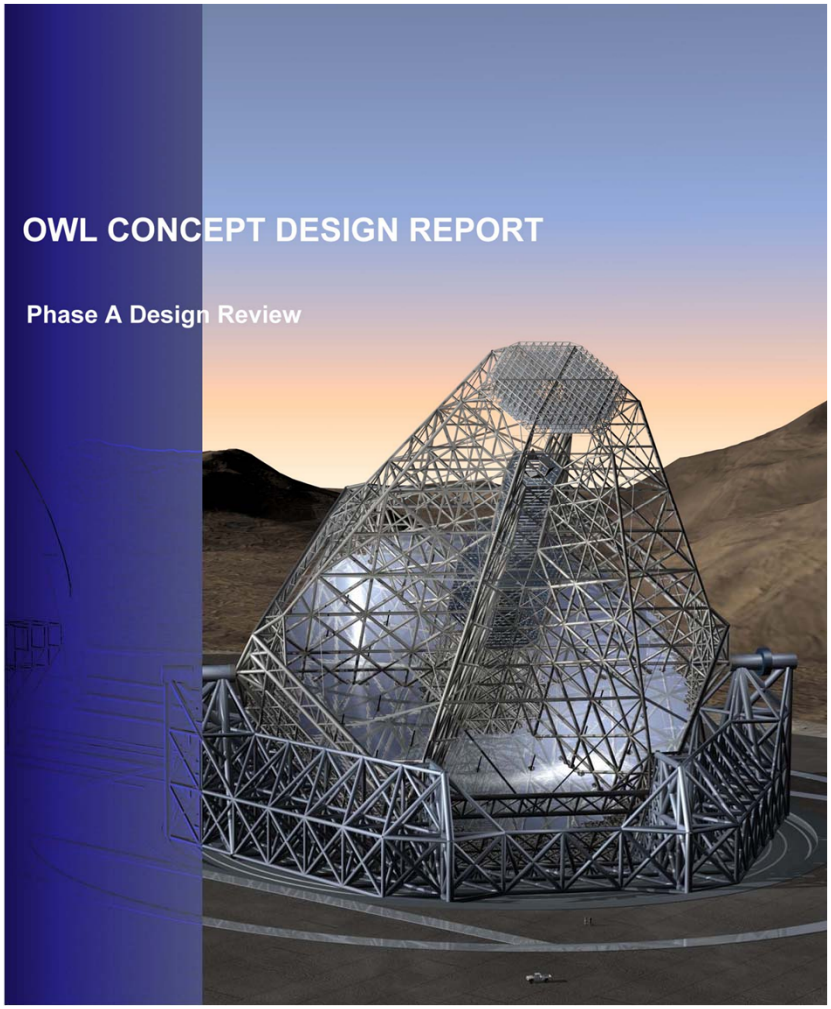
Overview

(Presented by R. Gilmozzi)

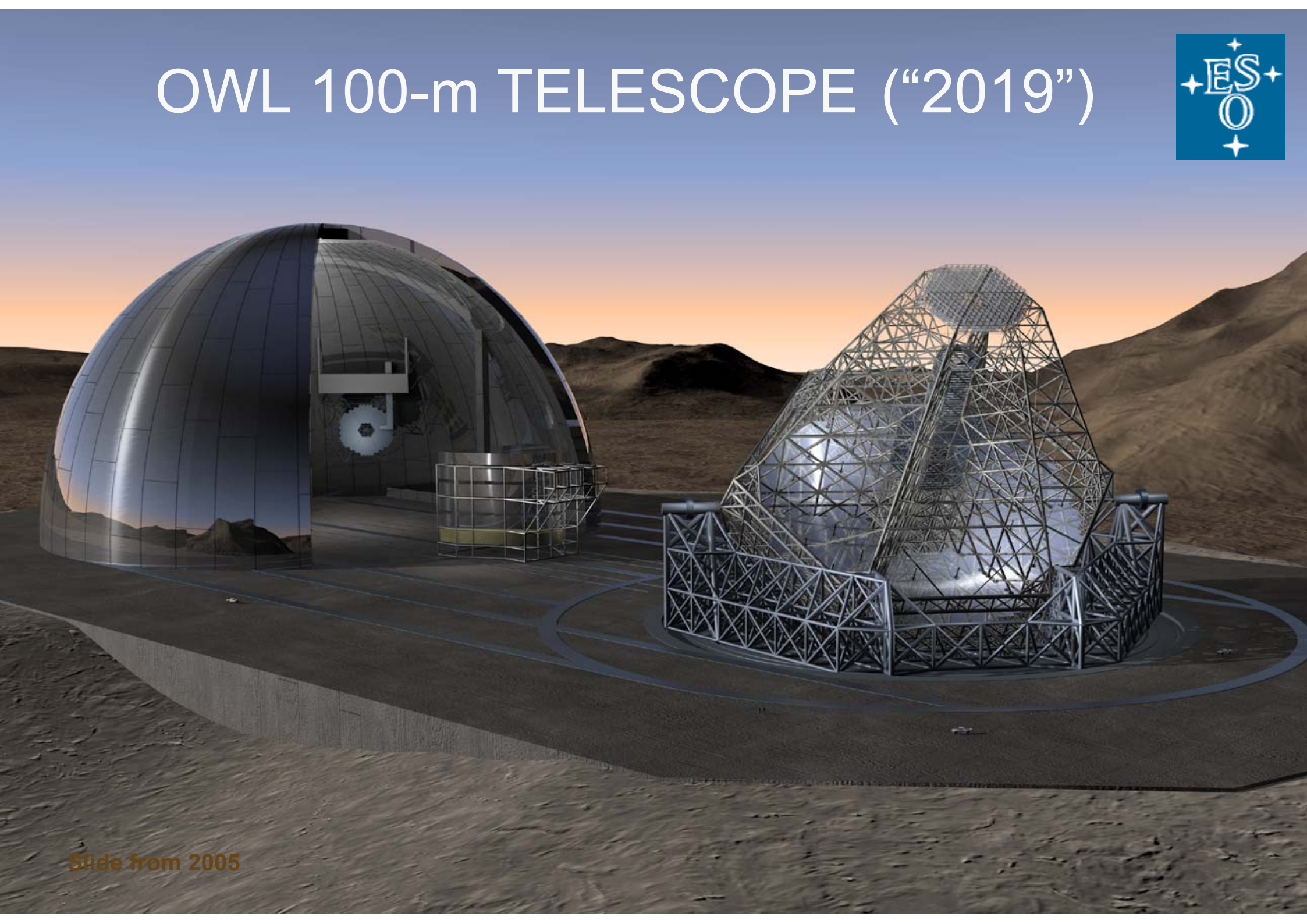


OWL

European Southern Observatory



OWL 100-m TELESCOPE (“2019”)



Slide from 2005

OWL 100-m TELESCOPE (“2019”)



Despite its size and apparent complexity, OWL has a rather clean aperture

QuantEYE
& offspring instruments

OWL Instrument Concept Studies

OWL Conceptual Study Report

OWL Telescope-Instruments Interface
Control Document

- ICD-



OWL-ICD-ESO-00000-0139

Issue: 1.0
5 October 2004

EUROPEAN SOUTHERN OBSERVATORY
Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

FRAMEWORK OF OWL INSTRUMENT
CONCEPT DESIGN STUDIES



Document Number : OWL-CSR-ESO-00000-0147

Issue : 1
Date of Issue : 24/9/2004

EUROPEAN SOUTHERN OBSERVATORY
Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

OWL Instrument Concept Study



QUANTUM OPTICS INSTRUMENTATION FOR ASTRONOMY

D. Dravins[1], C. Barbieri[2], V. Da Deppo[3], D. Faria[1], S. Fornasier[2], R. A. E. Fosbury[4], L. Lindegren[1], G. Naletto[3], R. Nilsson[1], T. Occhipinti[3], F. Tamburini[2], H. Uthas[1], L. Zampieri[5]

(**1**) Lund Observatory, Box 43, SE-22100 Lund, Sweden

(**2**) Department of Astronomy, University of Padova, Vicolo dell'Osservatorio 2, IT-35122 Padova, Italy

(**3**) Dept. of Information Engineering, University of Padova, Via Gradenigo, 6/B, IT-35131 Padova, Italy

(**4**) Space Telescope-European Coordinating Facility & European Southern Observatory, Karl-Schwarzschild-Straße 2, DE-85748 Garching bei München, Germany

(**5**) INAF – Astronomical Observatory of Padova, Vicolo dell'Osservatorio 5, IT-35122 Padova, Italy

OWL-CSR-ESO-00000-0162 — Version 1.0, October 2005

SECONDS & MILLISECONDS

- Lunar & planetary-ring occultations
- Rotation of cometary nuclei
- Pulsations from X-ray pulsars
- Cataclysmic variable stars
- Pulsating white dwarfs
- Optical variability around black holes
- Flickering of high-luminosity stars
- X-ray binaries
- Optical pulsars
- Gamma-ray burst afterglows

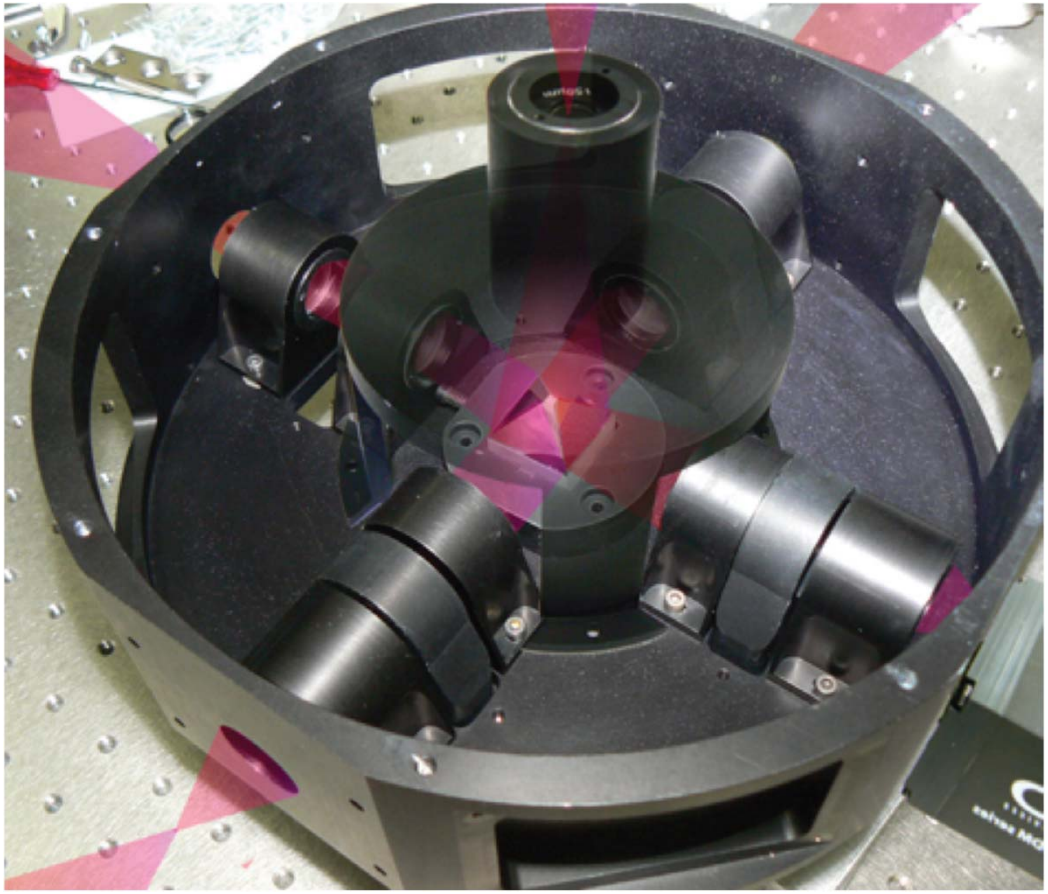
MILLI-, MICRO- & NANOSECONDS

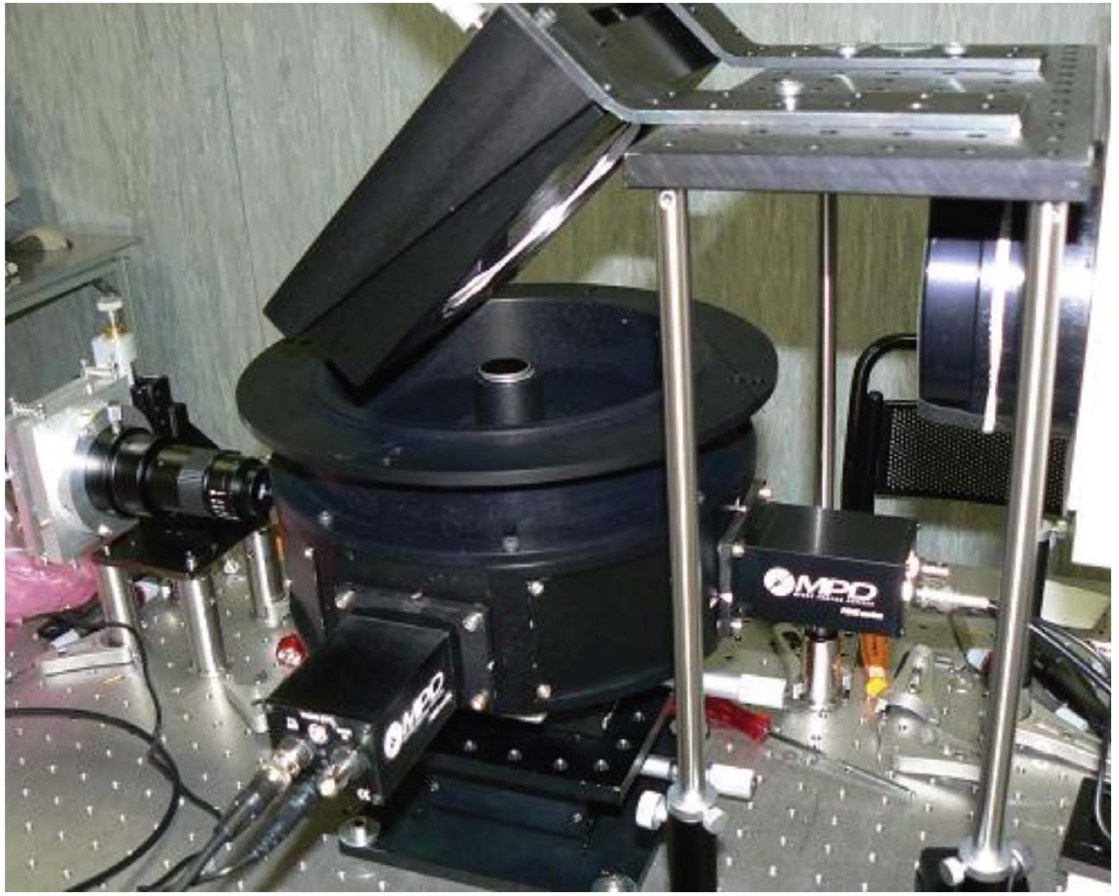
- Millisecond pulsars ?
- Variability near black holes ?
- Surface convection on white dwarfs ?
- Non-radial oscillations in neutron stars ?
- Surface structures on neutron-stars ?
- Photon bubbles in accretion flows ?
- Free-electron lasers around magnetars ?
- Astrophysical laser-line emission ?
- Spectral resolutions reaching R = 100 million ?
- Quantum statistics of photon arrival times ?

https://www.eso.org/sci/facilities/eelt/owl/Files/publications/OWL-CSR-ESO-00000-0162_iss1.pdf , 278 pages (2005)

AQuEYE
Asiago

The AquEYE (*Asiago Quantum Eye*) instrument for high time-resolution astronomy uses single-photon avalanche photodiode detectors to achieve sub-nanosecond precision in photon arrival times; enabling intensity interferometry.





C.Barbieri; G. Naletto; T.Occhipinti; C.Facchinetti; E.Verroi; E.Giro; A.Di Paola, S.Billotta; P.Zoccarato; P.Bolli, et al.: *AquEYE, a single photon counting photometer for astronomy,* J.Mod.Optics **56**, 261 (2009)

AQUEYE+ | IQUEYE

UNIVERSITY OF PADOVA
INAF-ASTRONOMICAL OBSERVATORY OF PADOVA



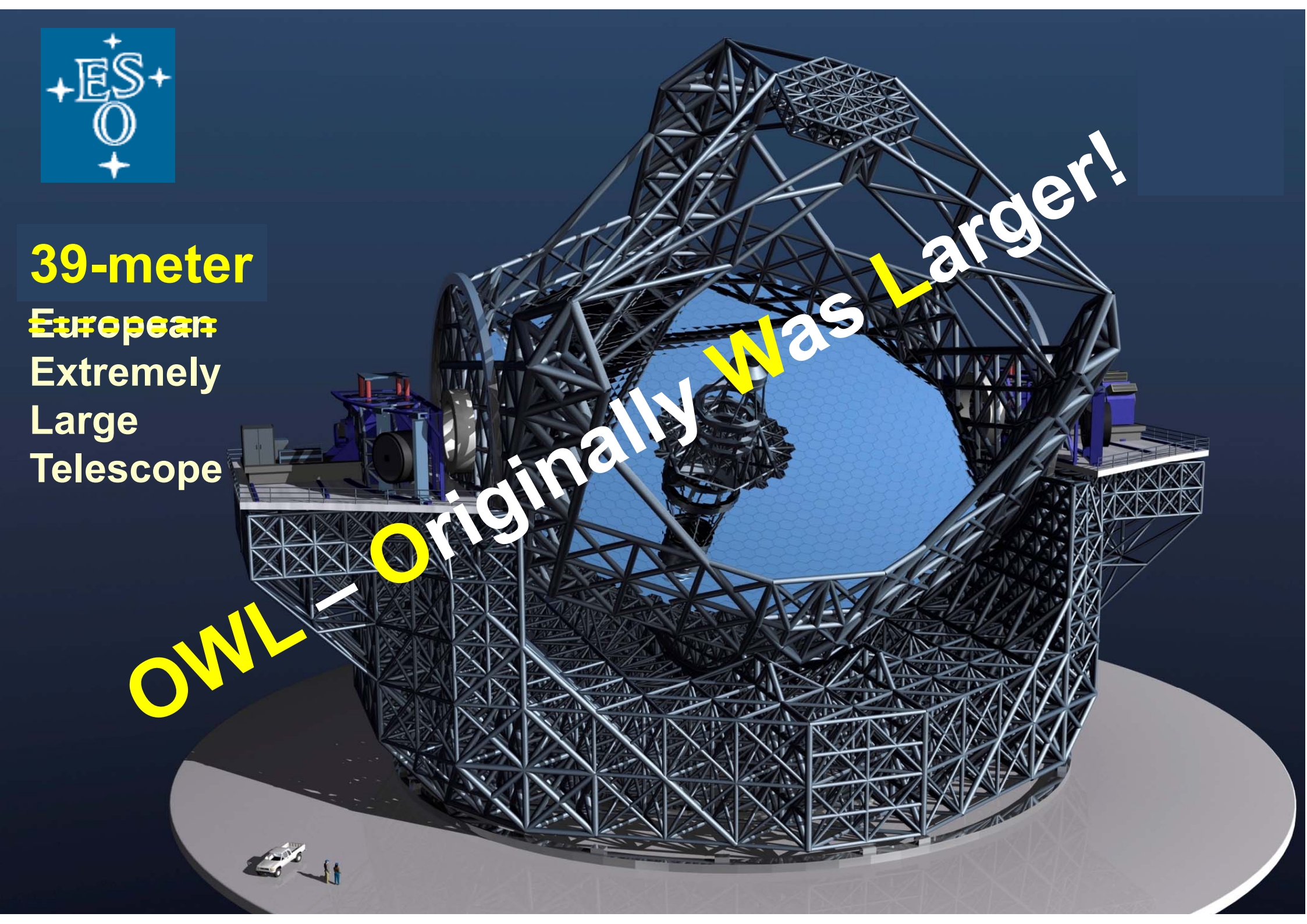
***Iqueye* instrument @ NTT on La Silla, January 2009**

Padova team: Ivan Capraro, Paolo Zoccarato, Andrea di Paola, Cesare Barbieri, Enrico Verroi, Tommaso Occhipinti, Giampiero Naletto

Iqueye – *Italian Quantum Eye*

G. Naletto et al.: *Iqueye, a single photon-counting photometer applied to the ESO new technology telescope,* Astron.Astrophys. **508**, 531, 2009

What happened to OWL?


39-meter
~~European~~
Extremely
Large
Telescope
OWL – Originally Was Larger!

Air Cherenkov Telescopes

Cherenkov telescopes for intensity interferometry?

S.Le Bohec & J.Holder
Optical Intensity Interferometry with Atmospheric Cerenkov Telescope Arrays
Astrophys.J. 649, 299, 2006

CHARACTERISTICS OF ACT ARRAYS AND CORRESPONDING CAPABILITIES AS INTENSITY INTERFEROMETERS

Array	N	A	n	$d_{\min} - d_{\max}$ (m)	$\theta_{\min} - \theta_{\max}$ (mas)	$V_{\max}$ (mag)	$T_{V=5}$ (hr)
MAGIC-II	2	227	1	85	1.2	4.7 (6.0)	0.16
CANGAROO	4	57	6	100–184	0.5–1.0	4.2 (5.5)	2.61
HESS-4	4	108	6	120–170	0.6–0.8	4.9 (6.1)	0.73
VERITAS-4	4	113	6	80–140	0.7–1.2	4.9 (6.2)	0.66
VERITAS-7[a]	7	113	21	80–160	0.6–1.2	5.6 (6.9)	0.66
HESS-16[a]	16	108	120	120–510	0.2–0.8	6.5 (7.8)	0.73
Next-Generation[b]	50	100	1225	80–1000	0.1–1.2	7.7 (9.0)	0.85
Narrabri	2	30	1	10 → 188	0.5–10	2.5 (3.8)	9.4

Increasing community engagement

Toward a revival of Stellar Intensity Interferometry

Stephan LeBohec[1], Cesare Barbieri[2], Willem-Jan de Wit[3], Dainis Dravins[4], Philippe Feautrier[5], Cédric Foellmi[5], Andreas Glindemann[6], Jeter Hall[7], Jamie Holder[8], Richard Holmes[9], Pierre Kervella[10], David Kieda[1], Etienne Le Coarer[5], Stephan Lipson[12], Fabien Malbet[5], Sébastien Morel[6], Paul Nuñez[1], Aviv Ofir[11], Erez Ribak[12], Swapan Saha[13], Markus Schoeller[6], Boris Zhilyaev[14] and Hans Zinnecker[15]

[1] Department. of Physics, University of Utah, 115 S 1400 E, Salt Lake City, UT 84112-0830, USA
[2] Department of Astronomy, University of Padova, 35122 Padova, Italy
[3] School of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT,UK
[4] Lund Observatory, Box 43, SE-22100 Lund, Sweden
[5] Laboratoire d'Astro. de Grenoble, 414 rue de la Piscine, 38400 Saint-Martin d'Hères, France
[6] ESO, Karl-Schwarzschild Str.-2, 85748, Garching-bei-Mnchen, Germany
[7] Fermilab, PO Box 500 Batavia, IL 60510, USA
[8] Department of Physics and Astronomy, University of Delaware, Newark, Delaware, USA
[9] Nutronics Inc., 3357 Chasen Drive, Cameron Park, CA 95682, USA
[10] LESIA, Observatoire de Paris-Meudon, 5, place Jules Janssen, 92195 Meudon, France
[11] Dept. of Astronomy and Astrophys., Tel-Aviv University, P.O. Box 39040, Tel-Aviv 69978, Israel
[12] Department of Physics, Technion - Israel Institute of Technology, Haifa 32000, Israel
[13] Indian Institute of Astrophysics II Block, Koramangala, Bangalore 560 034, India
[14] Main Astronomical Obs., NAS of Ukraine, 27 Akademika Zabolotnoho St., 03680 Kyiv, Ukraine
[15] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany

SPIE Astronomical Telescopes +Instrumentation, Marseille
SPIE Proc. **7013**, Optical and Infrared Interferometry; 70132E (2008)

CTA	*Task A output*	Ref : PHYS-WP Date : April 6, 2009 Author : PHYS-WP

Internal Note

Distribution list: PHYS-WP

Enabling CTA for intensity interferometry
and high time-resolution astrophysics

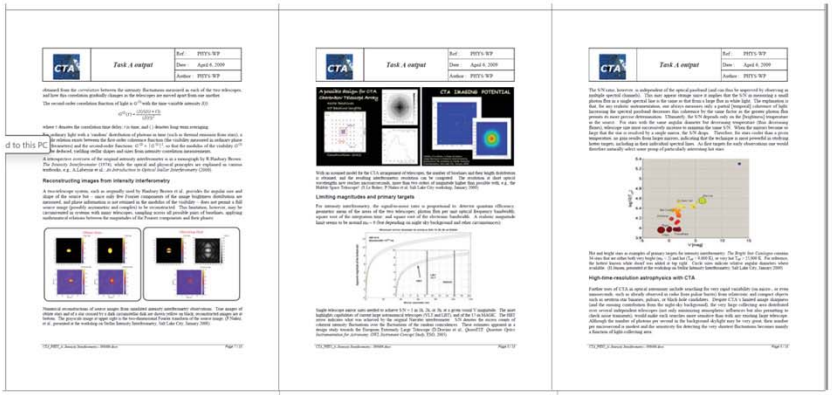
Task leader: **Dainis Dravins, Lund Observatory, Sweden** <dainis@astro.lu.se>

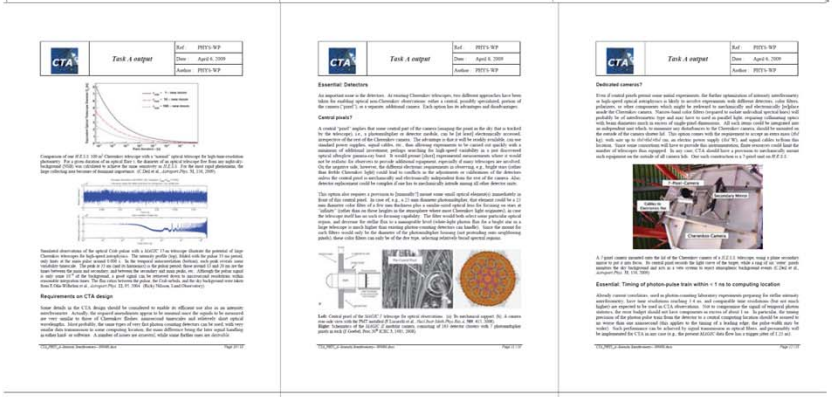
Task contributors: Michael Andersen, Cesare Barbieri, Hugues Castarede, Michael Daniel, Okkie de Jager, Francesco De Sabata, Willem-Jan de Wit, Wilfried Domainko, Cédric Foellmi, Werner Hofmann, Richard Holmes, Hannes Jensen, David Kieda, Antoine Labeyrie, Stephan Le Bohec, Hans-Günter Ludwig, Giampiero Naletto, Paul Nuñez, Aviv Ofir, Guy Perrin, Andreas Quirrenbach, Erez Ribak, Stephen Ridgway, Markus Schöller, Diego F. Torres, Gerard van Belle, Luca Zampieri, and participants at the *Stellar Intensity Interferometry* workshop, Salt Lake City, January 2009.

Enabling CTA for intensity interferometry

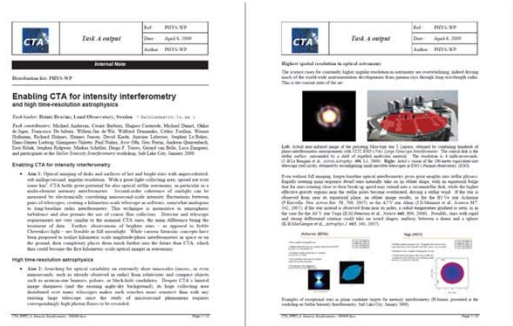
- **Aim 1:** Optical imaging of disks and surfaces of hot and bright stars with unprecedented, sub-milliarcsecond, angular resolution. With a great light-collecting area, spread out over some km^2, CTA holds great potential for also optical stellar astronomy, in particular as a

CTA Physics Work-Package report April 2009











CTA special issue of *Astroparticle Physics*

Astroparticle Physics 43 (2013) 331–347

Contents lists available at SciVerse ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

Optical intensity interferometry with the Cherenkov Telescope Array

Dainis Dravins [a,*], Stephan LeBohec [b], Hannes Jensen [a,c,1], Paul D. Nuñez [b], for the CTA Consortium

[a] Lund Observatory, Box 43, SE-22100 Lund, Sweden
[b] Department of Physics and Astronomy, The University of Utah, 115 South 1400 East, Salt Lake City, UT 84112-0830, USA
[c] Department of Astronomy, Stockholm University, AlbaNova University Center, SE-10691 Stockholm, Sweden

ARTICLE INFO

Article history:
Available online 20 June 2012

Keywords:
Cherenkov telescopes
Intensity interferometry
Hanbury Brown–Twiss
Optical interferometry
Stars: individual
Photon statistics

ABSTRACT

With its unprecedented light-collecting area for night-sky observations, the Cherenkov Telescope Array (CTA) holds great potential for also optical stellar astronomy, in particular as a multi-element intensity interferometer for realizing imaging with sub-milliarcsecond angular resolution. Such an order-of-magnitude increase of the spatial resolution achieved in optical astronomy will reveal the surfaces of rotationally flattened stars with structures in their circumstellar disks and winds, or the gas flows between close binaries. Image reconstruction is feasible from the second-order coherence of light, measured as the temporal correlations of arrival times between photons recorded in different telescopes. This technique (once pioneered by Hanbury Brown and Twiss) connects telescopes only with electronic signals and is practically insensitive to atmospheric turbulence and to imperfections in telescope optics. Detector and telescope requirements are very similar to those for imaging air Cherenkov observatories, the main difference being the signal processing (calculating cross correlations between single camera pixels in pairs of telescopes). Observations of brighter stars are not limited by sky brightness, permitting efficient CTA use during also bright-Moon periods. While other concepts have been proposed to realize kilometer-scale optical interferometers of conventional amplitude (phase-) type, both in space and on the ground, their complexity places them much further into the future than CTA, which thus could become the first kilometer-scale optical imager in astronomy.

New Astronomy Reviews 56 (2012) 143–167

Contents lists available at SciVerse ScienceDirect

New Astronomy Reviews

journal homepage: www.elsevier.com/locate/newastrev

Stellar intensity interferometry: Prospects for sub-milliarcsecond optical imaging

Dainis Dravins [a,*], Stephan LeBohec [b], Hannes Jensen [a,1], Paul D. Nuñez [b]

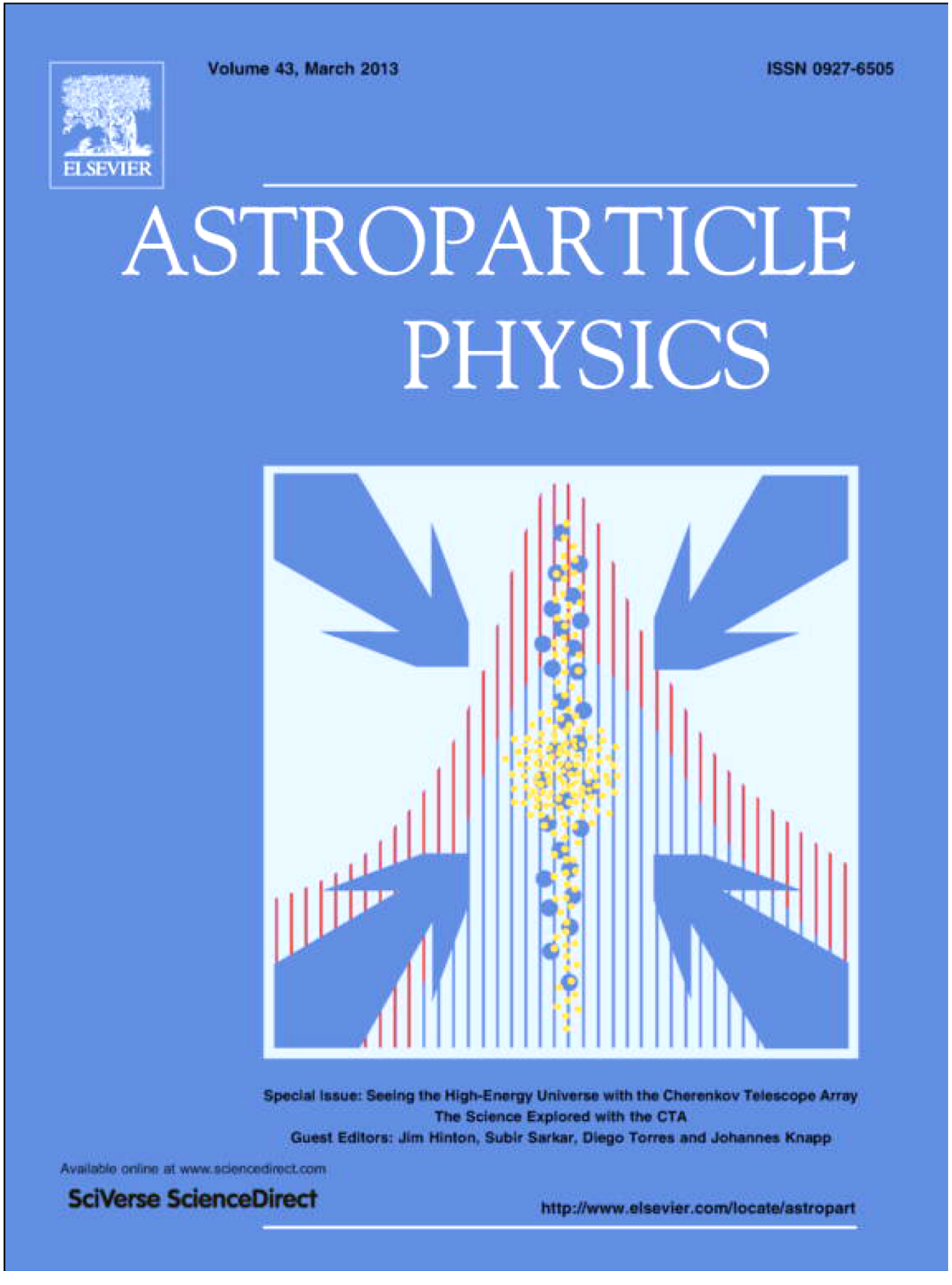
[a] Lund Observatory, Box 43, SE-22100 Lund, Sweden
[b] Department of Physics and Astronomy, The University of Utah, 115 South 1400 East, Salt Lake City, UT 84112-0830, USA

ARTICLE INFO

Article history:
Accepted 28 June 2012
Available online 20 July 2012

ABSTRACT

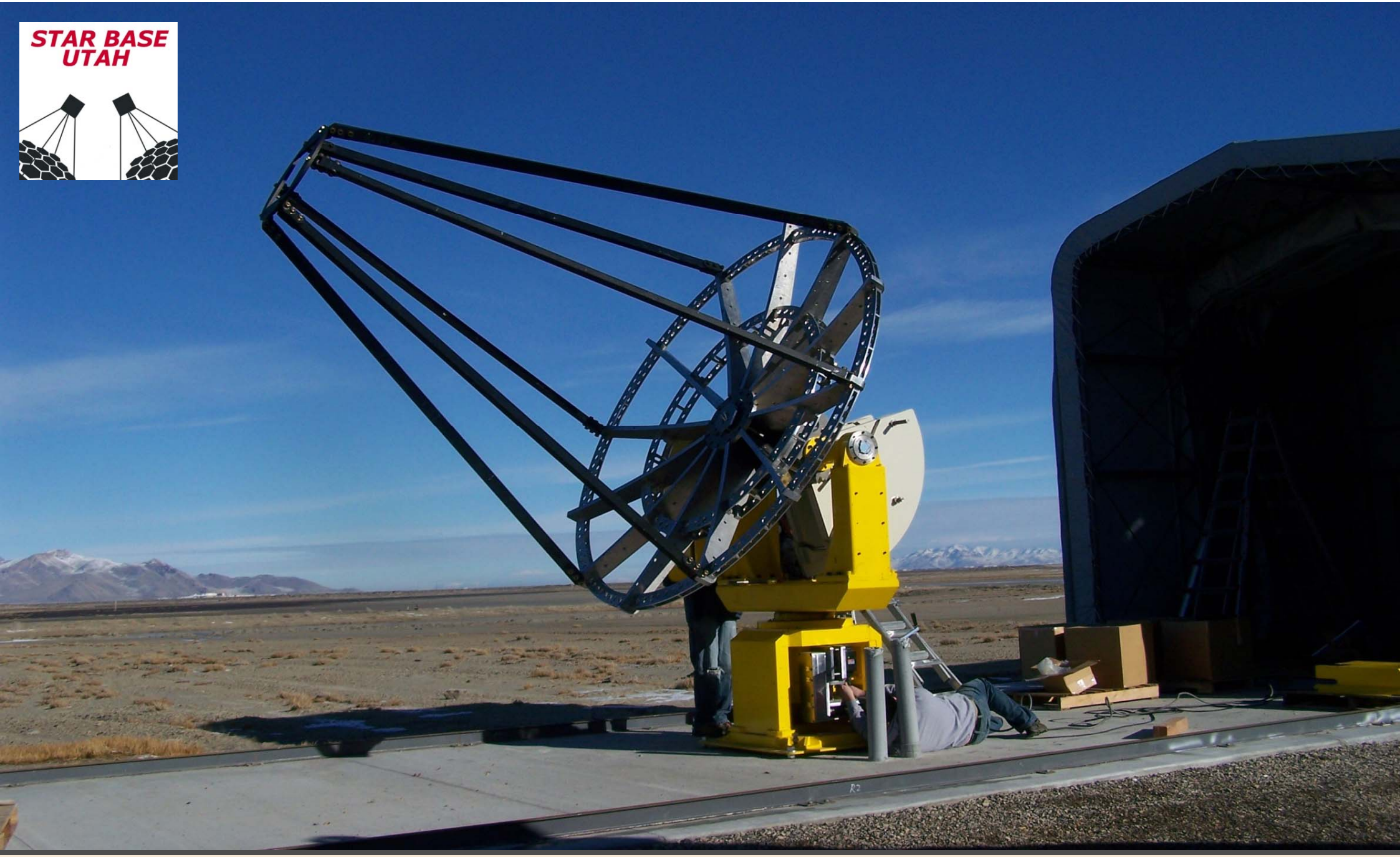
Using kilometric arrays of air Cherenkov telescopes at short wavelengths, intensity interferometry may increase the spatial resolution achieved in optical astronomy by an order of magnitude, enabling images of rapidly rotating hot stars with structures in their circumstellar disks and winds, or mapping out patterns of nonradial pulsations across stellar surfaces. Intensity interferometry (once pioneered by Hanbury Brown and Twiss) connects telescopes only electronically, and is practically insensitive to atmospheric turbulence and optical imperfections, permitting observations over long baselines and through large air-masses, also at short optical wavelengths. The required large telescopes (~10 m) with very fast detectors (~ns) are becoming available as the arrays primarily erected to measure Cherenkov light emitted in air by particle cascades initiated by energetic gamma rays. Planned facilities (e.g., CTA, *Cherenkov Telescope Array*) envision many tens of telescopes distributed over a few square km. Digital signal handling enables very many baselines (from tens of meters to over a kilometer) to be simultaneously synthesized between





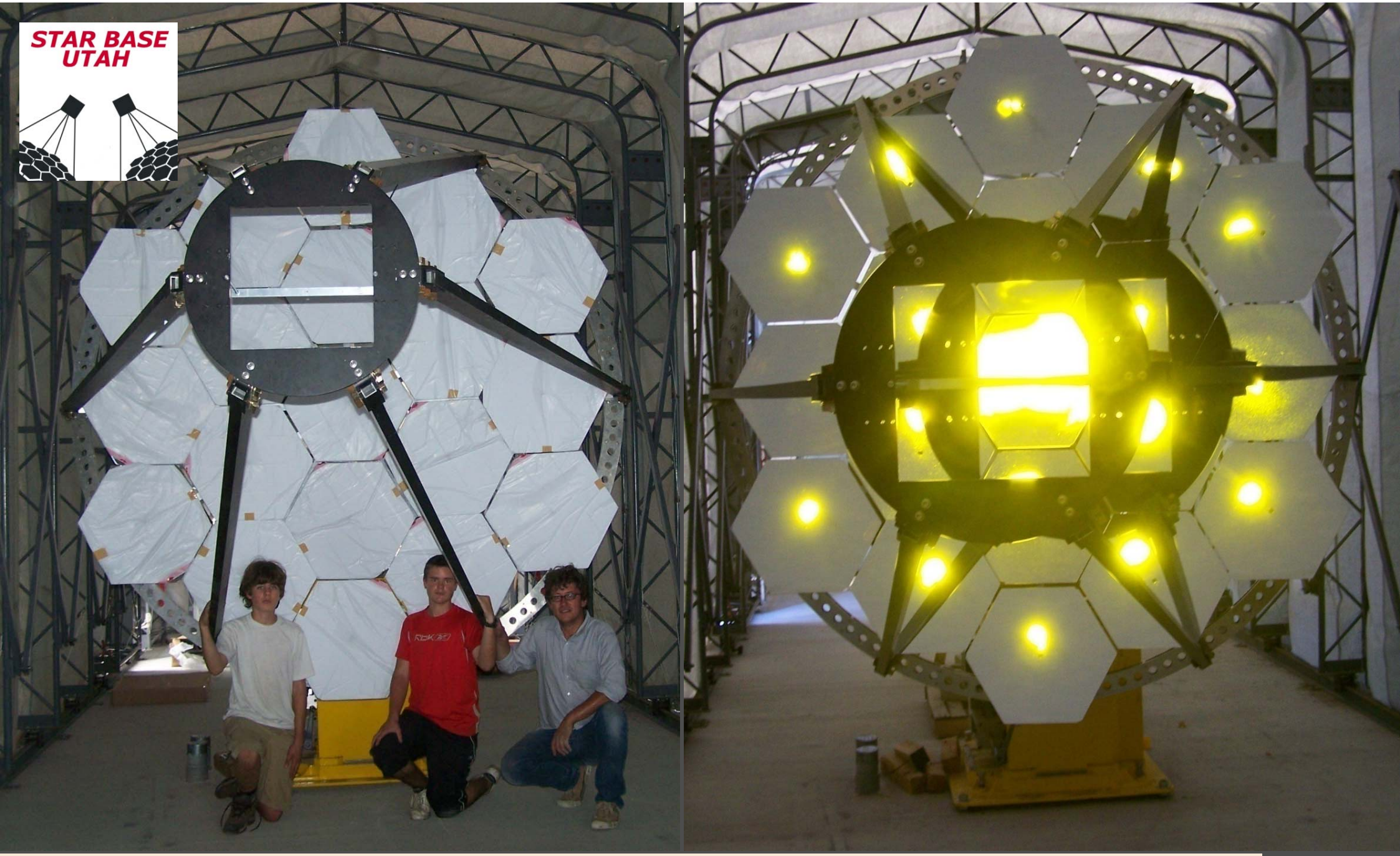
STAR BASE UTAH, A testbed for Air Cherenkov Telescope instrumentation and intensity interferometry. (Stephan [Tugdual] LeBohec et al., University of Utah)

November 2007: Mount for first f/1 Davis-Cotton 3-m telescope is installed in the western building



STAR BASE UTAH, A testbed for Air Cherenkov Telescope instrumentation and intensity interferometry Location is next to Bonneville SeaBase, some 80 km from Salt Lake City (Stephan [Tugdual] LeBohec et al., University of Utah)

January 2008: Setting up mounts for f/1 Davis-Cotton 3-m telescopes.



STAR BASE UTAH, A testbed for Air Cherenkov Telescope instrumentation and intensity interferometry (Stephan [Tugdual] LeBohec et al., University of Utah)

August 2008: Mounting and aligning f/1 Davis-Cotton 3-m telescopes.

STAR BASE UTAH (near Salt Lake City)

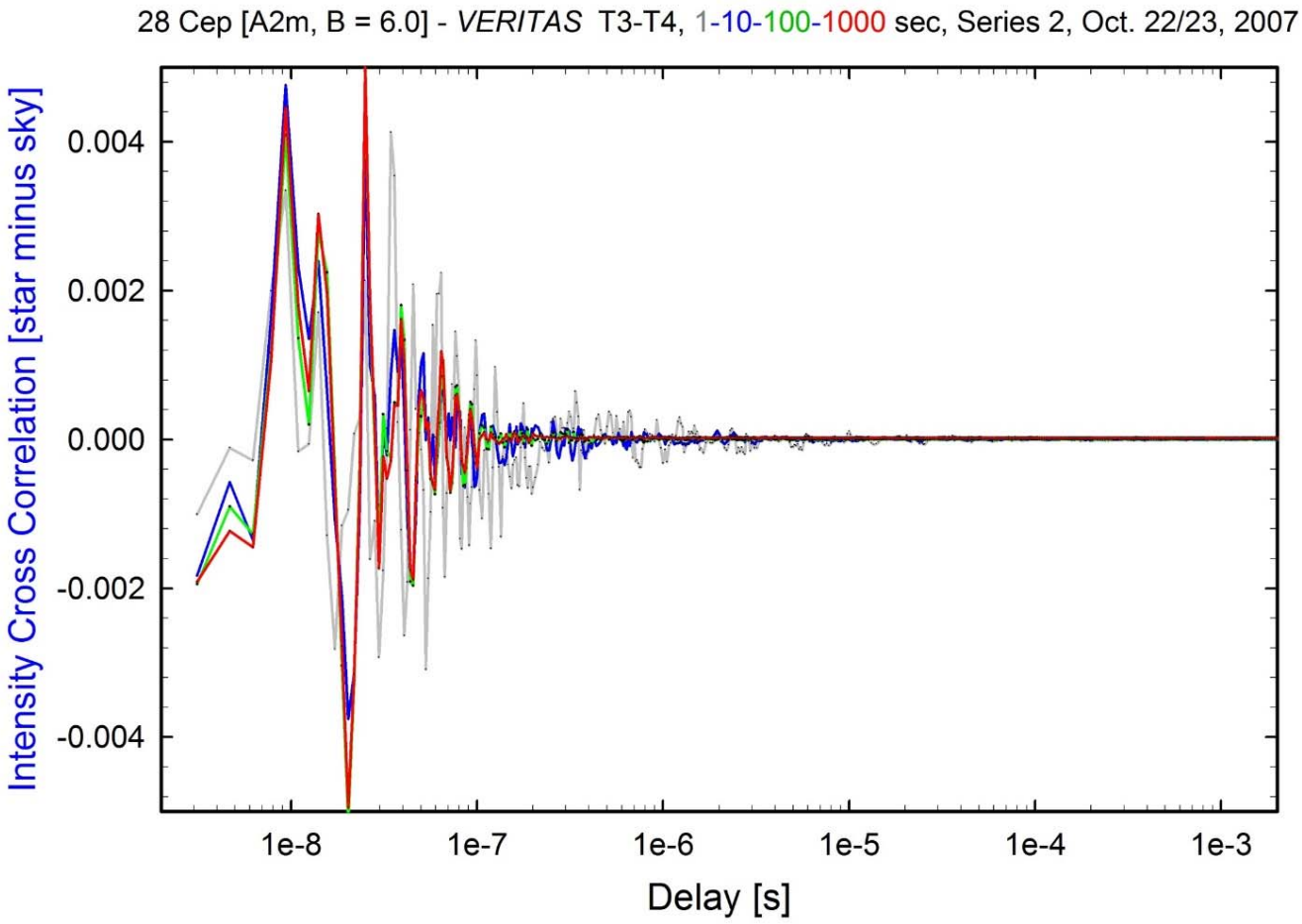
Testbed for intensity interferometry & Cherenkov telescope instrumentation



The StarBase 3 m Cherenkov telescopes are protected by buildings which can be rolled open for observation. The control room is located between the two telescopes.

D.Dravins, S.LeBohec, H.Jensen, P.D.Nuñez:
Stellar Intensity Interferometry: Prospects for sub-milliarcsecond optical imaging, New Astron. Rev. **56**, 143 (2012)

First attempted intensity interferometry with VERITAS, October 2007



Participants:
Michael Daniel (University of Leeds)
Dainis Dravins (Lund Observarory)
Stephan [Tugdual] LeBohec (Univ. of Utah)

* Digitally correlated 12-m telescopes

* Photon rates >30 MHz per telescope

* Real-time cross correlation, Δt = 1.6 ns

D.Dravins, S.LeBohec
Toward a diffraction-limited square-kilometer optical telescope: Digital revival of intensity interferometry
Proc. SPIE **6986**, *Extremely Large Telescopes: Which Wavelengths?*, 698609 (2008)

First conference in the modern era: Salt Lake City 2009

Workshop on Stellar Intensity Interferometry
The University of Utah, January 2009



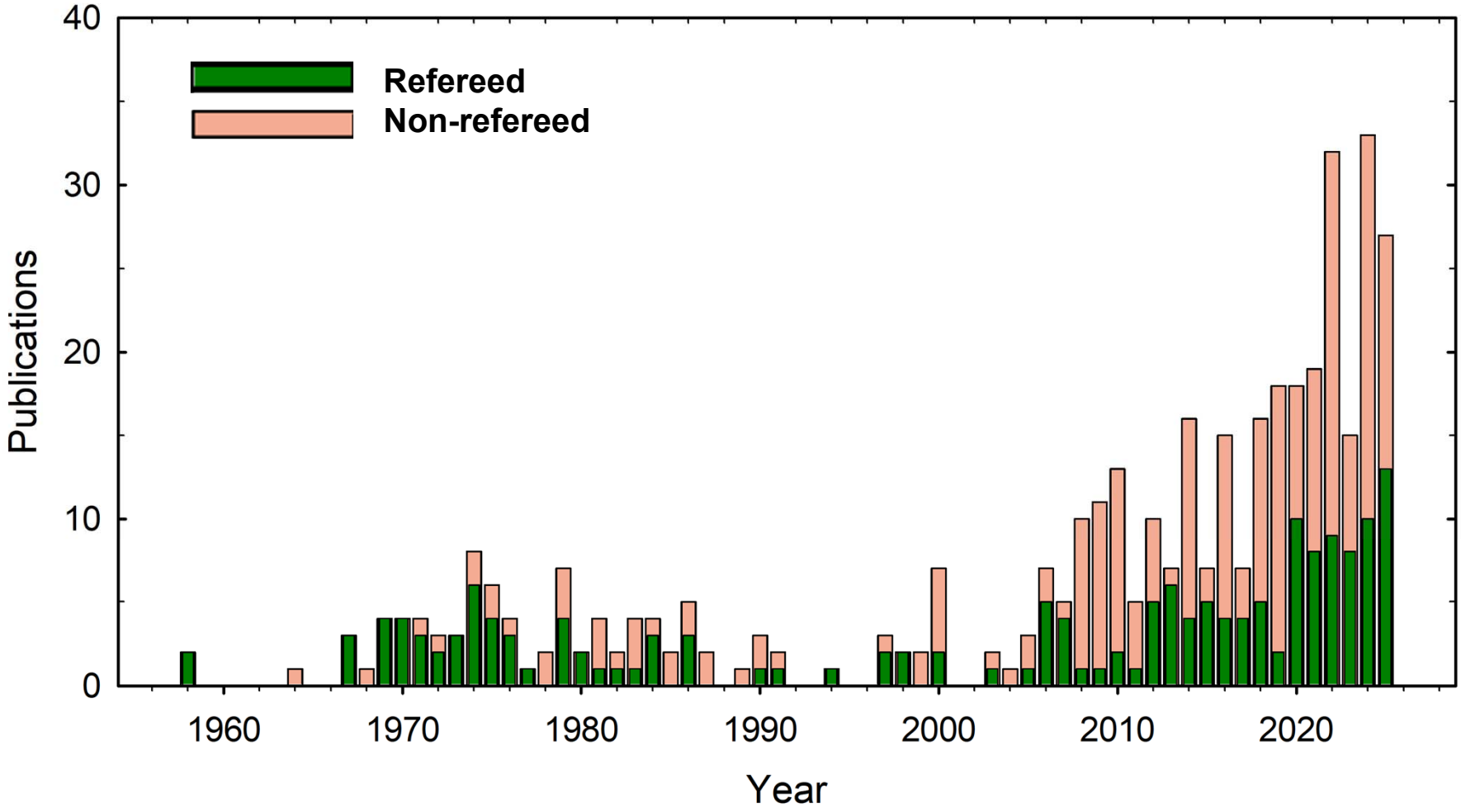


A group from the *Workshop on Stellar Intensity Interferometry*, at *StarBase Utah*, Grantsville, January 2009

The present

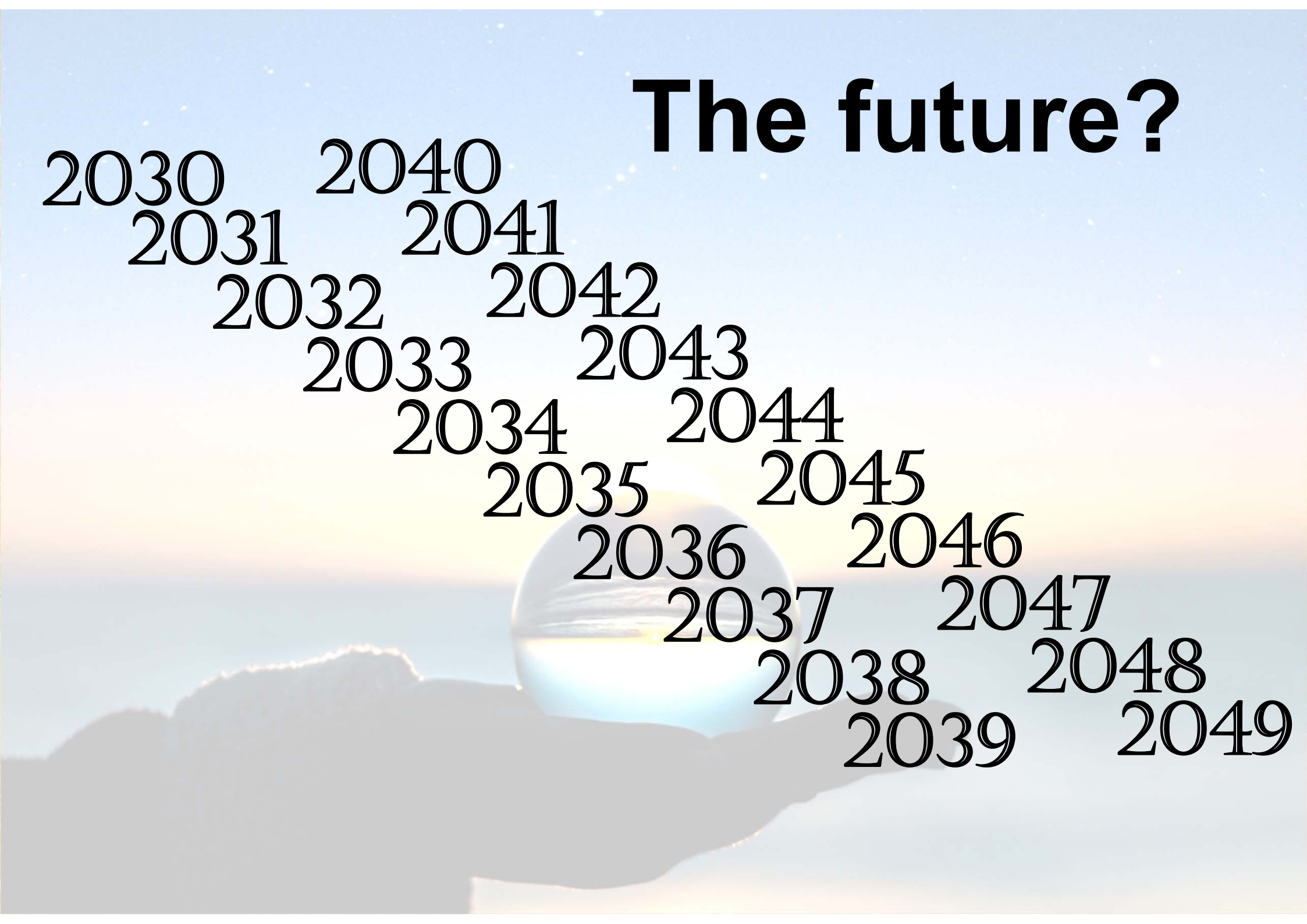

2010
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Astronomical Intensity Interferometry



***Astronomical* publications 1958-2025 with "*intensity interferometry*" in the title or abstract**
Data from SciX by ADS

A greater number of publications exists in physics, often with "HBT-interferometry", "femtoscopy", "Bose-Einstein correlations", etc.


The future?
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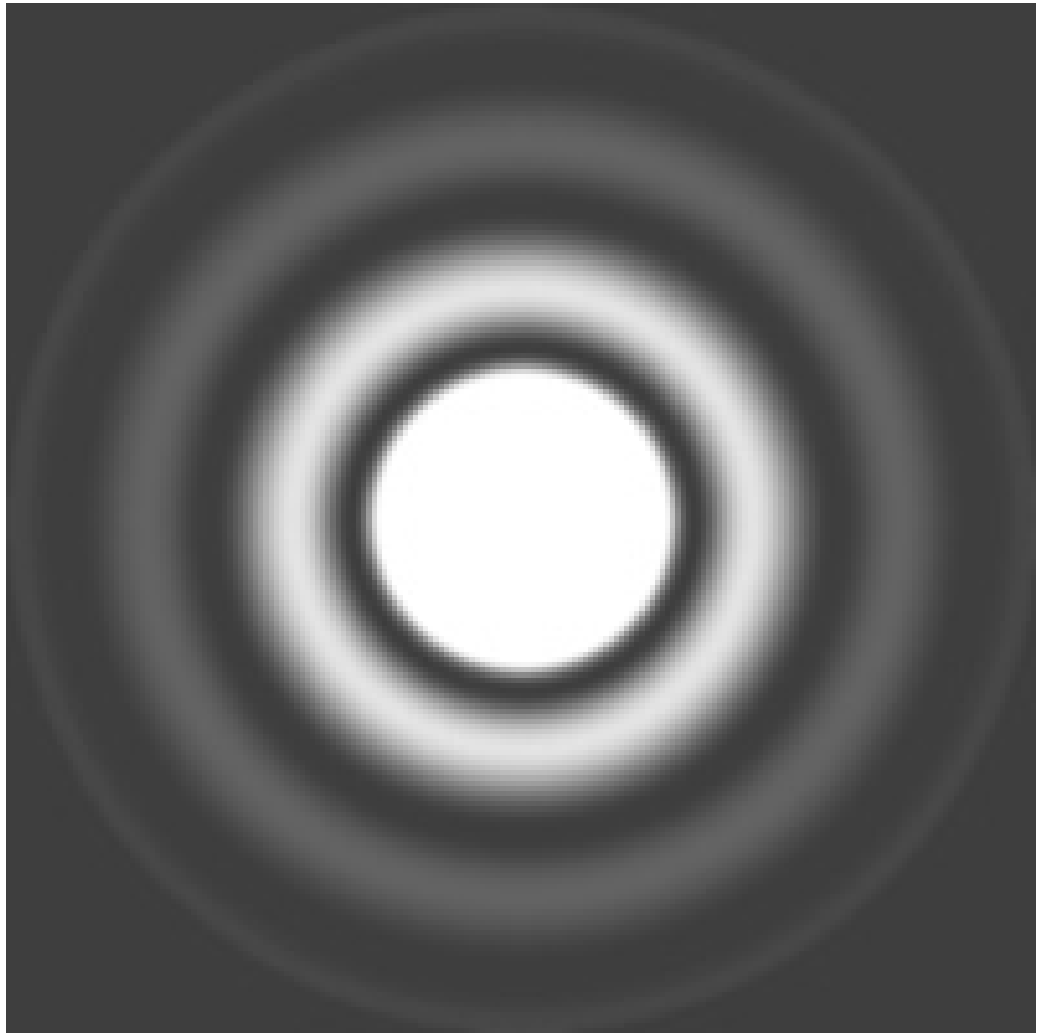
EXPLOITING II STRENGTHS:

- Very long baselines
- Very many baselines
- Very good (u,v)-coverage
- Full 2-D image reconstruction

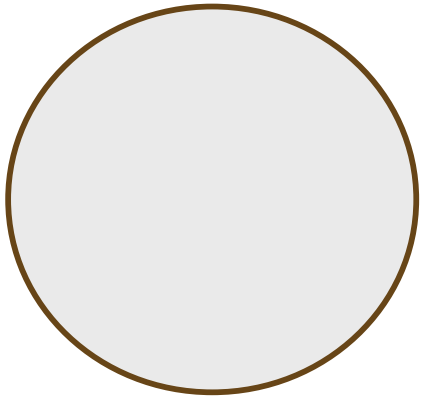
CIRCUMVENTING II WEAKNESSES:

- Low sensitivity
- Limited community

2-D image reconstruction



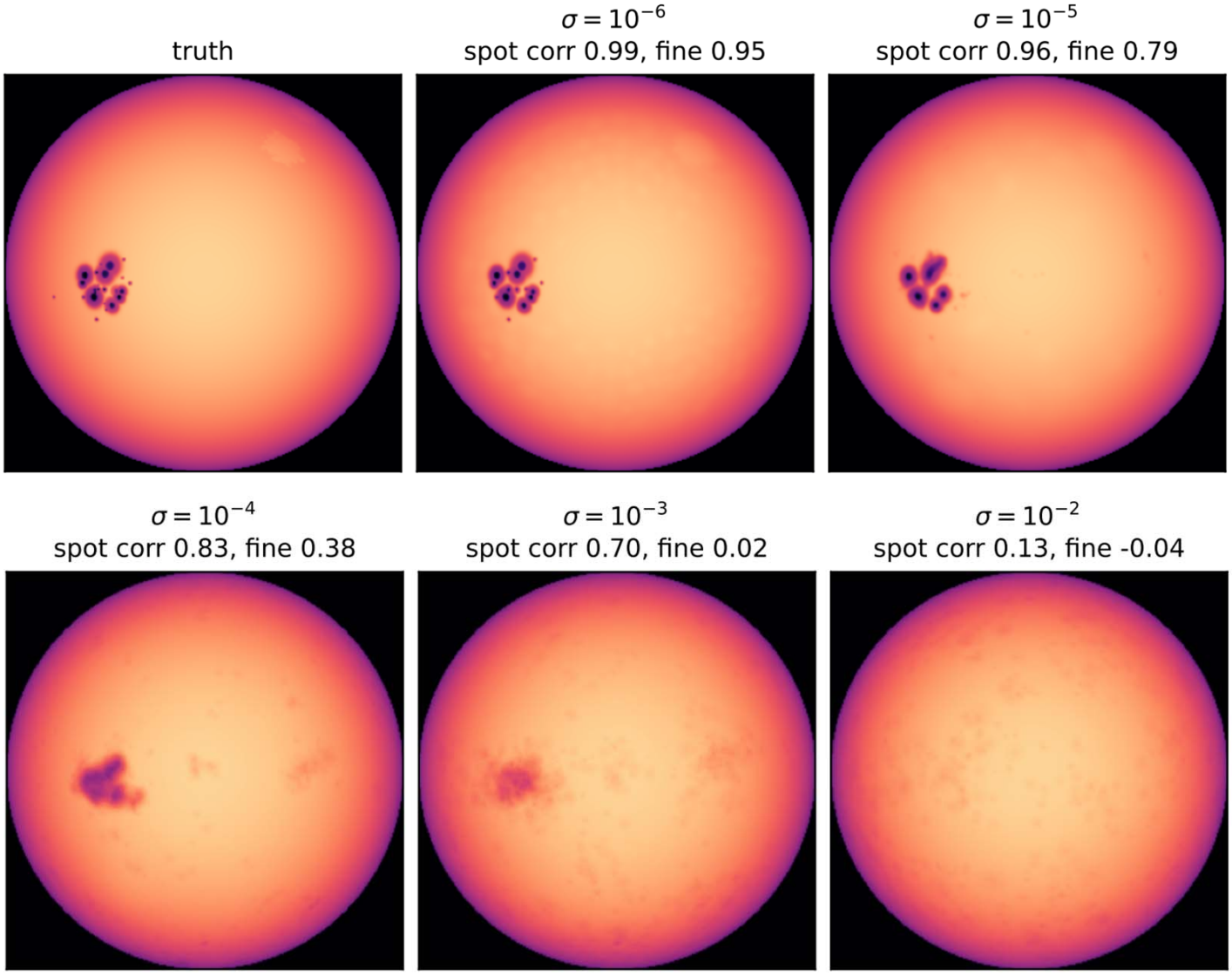
This Airy-disk diffraction pattern is immediately recognized as originating in a circular aperture, although only intensities are recorded.



Two-dimensional images can be reconstructed without phase information, provided two-dimensional coverage of the (u,v)-plane is available

2-D image reconstruction

Information recovery as function of S/N



True surface and images for squared-visibility noise $\sigma|\nu|^2$ 10^{-6} to 10^{-2}

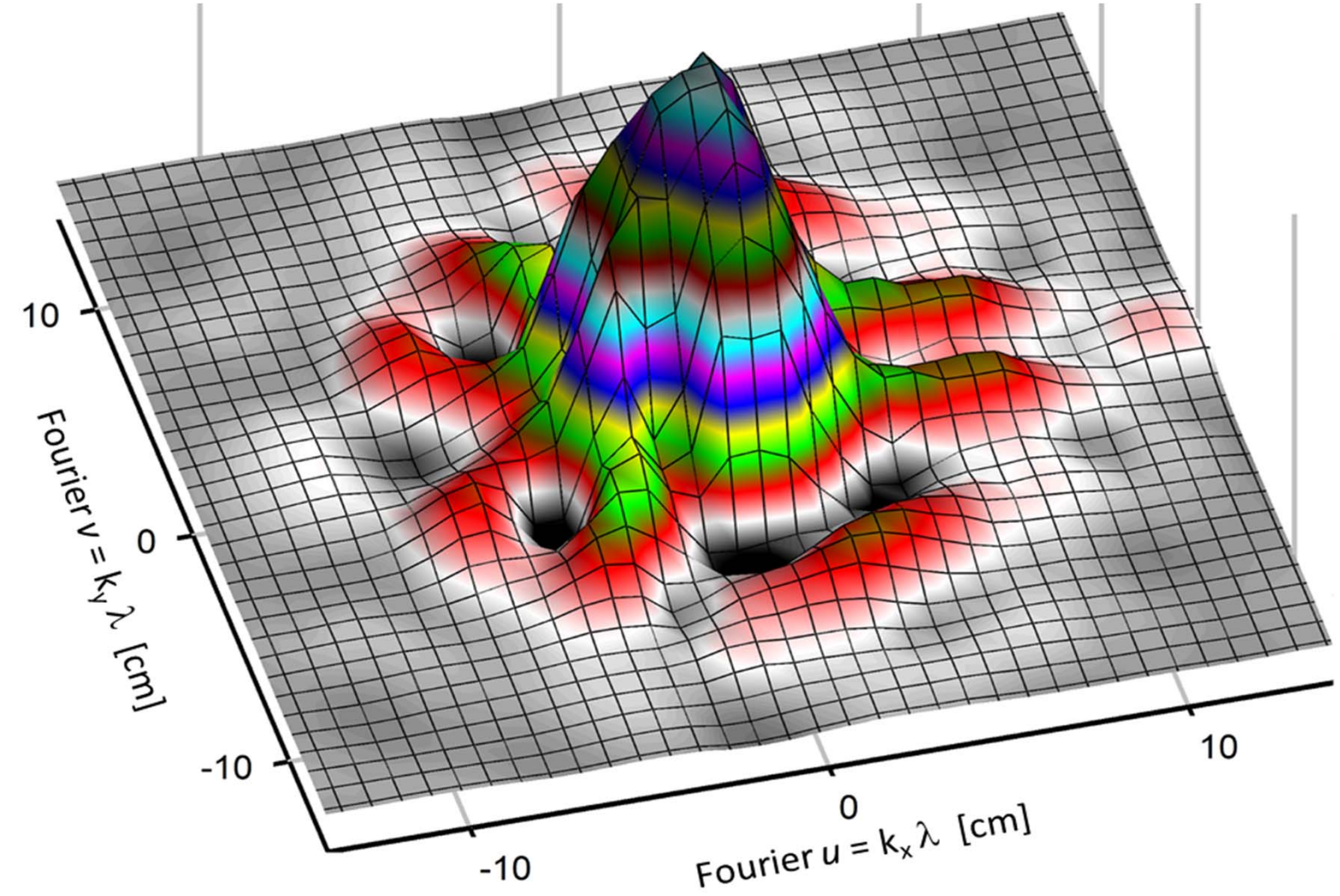
Also spot correlation and its "fine" high-pass component

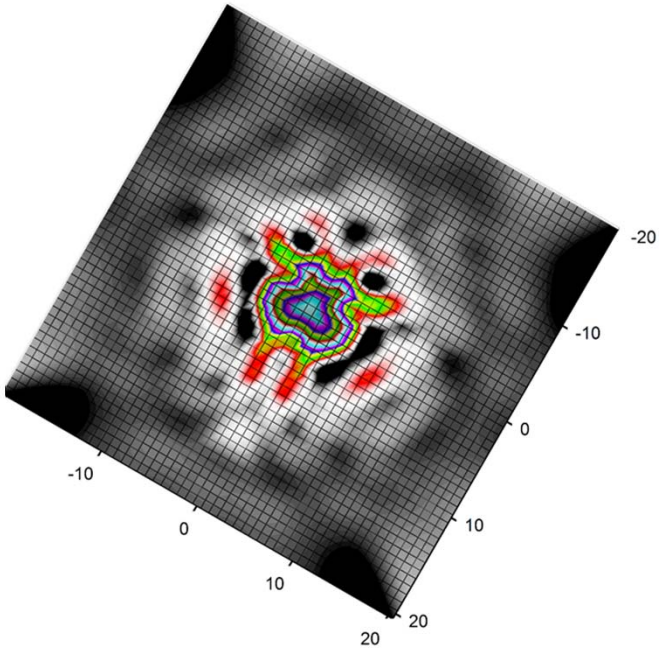
Spot complex arrives by $\sigma|\nu|^2 = 10^{-4}$, fine structure only at lowest noise

At $\sigma|\nu|^2 \geq 10^{-3}$, correct location is found but ghost reflections on opposite side of the disk

N.Dalal, B.Dai, M.K.Browning: *The Information Content of Optical Intensity Interferometry,* arXiv:2609.05602 (2026)

Laboratory intensity interferometry with 180 baselines

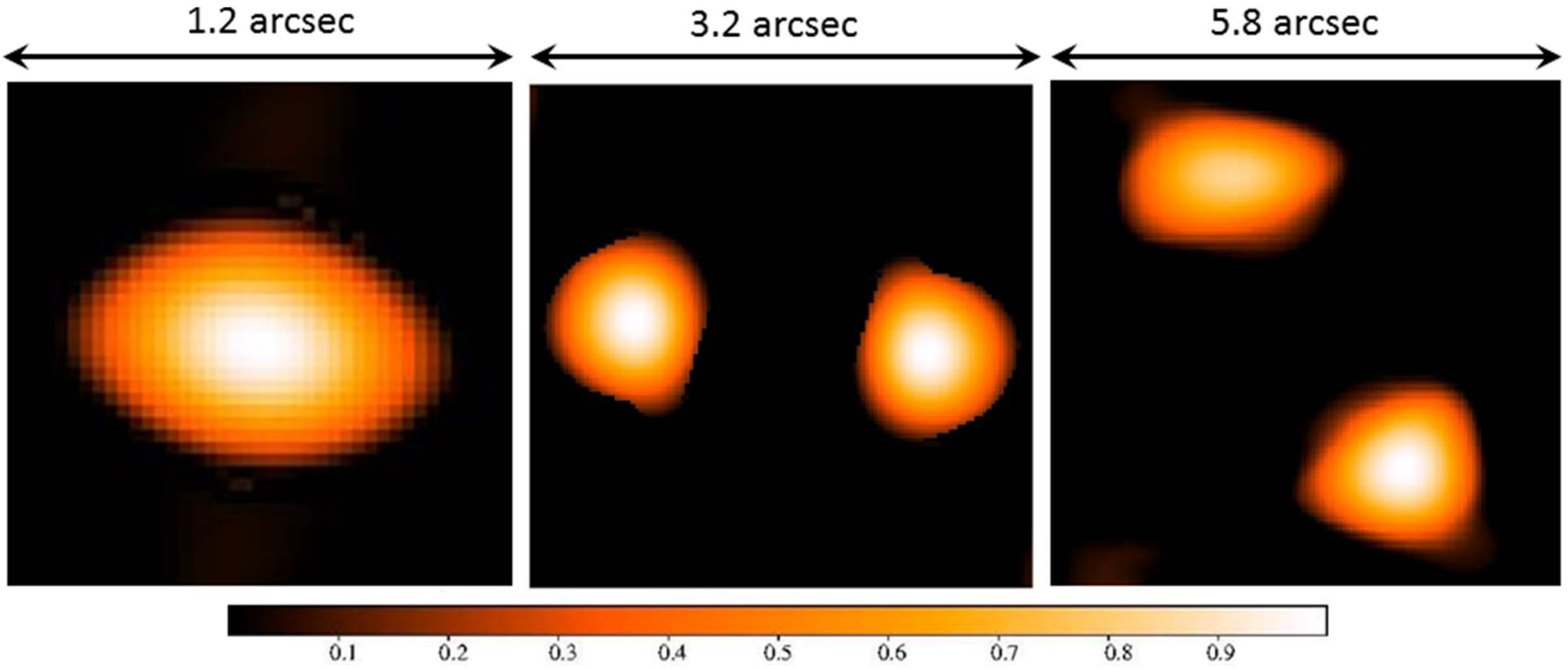




Measured second-order spatial coherence $g^{(2)}$ from intensity interferometry over 180 telescopic baselines. The source is an artificial binary star with differently large components. The structure corresponds to the pattern that would be produced by coherent light undergoing diffraction in a corresponding aperture.

(D.Dravins, T.Lagadec, P.Nuñez, *Nature Commun.* **6**, 6852, 2015; *Astron.Astrophys.* **580**, A99, 2015)

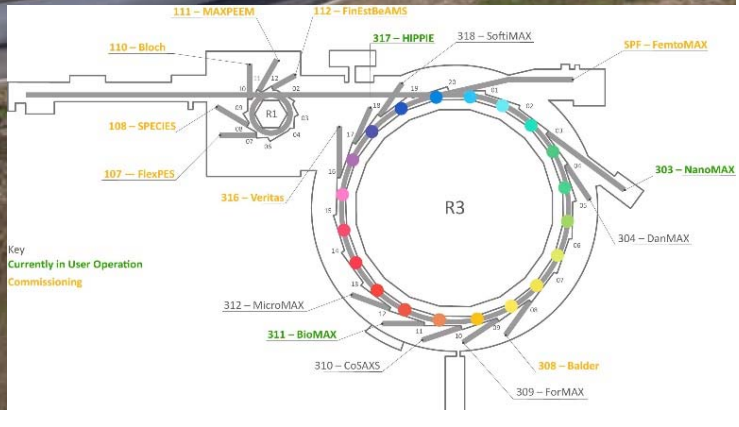
Image reconstructions from intensity interferometry



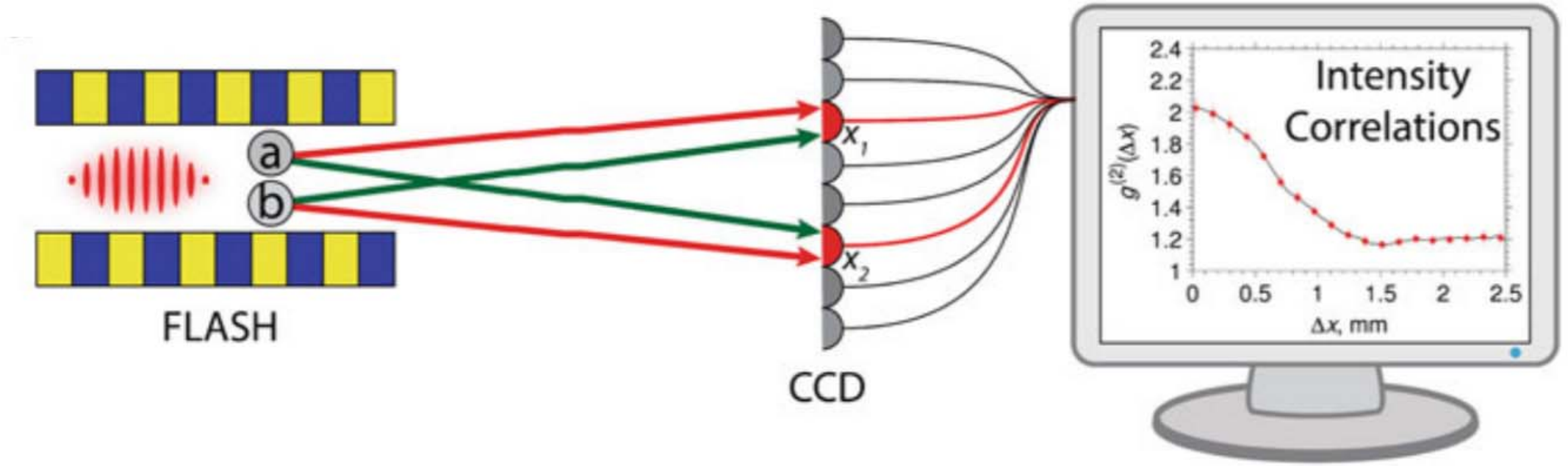
Optical images reconstructed from intensity interferometry measurements in the laboratory.
Data covered 100, 60, and 180 baselines, respectively, of a single elliptical ‘star’, a binary with equal components, and an asymmetric one with flux ratio 1:4. Scale show linear intensities.
In principle, the images are unique, except for their possible mirrored reflections.

(D.Dravins, T.Lagadec, P.Nuñez, *Nature Commun.* **6**, 6852, 2015; *Astron.Astrophys.* **580**, A99, 2015)

MAX-IV synchrotron X-ray radiation facility at Lund University, Sweden



X-ray Intensity Interferometry at Free-Electron Lasers



Principle of intensity-intensity correlation (HBT) experiments at X-ray Free-Electron Lasers

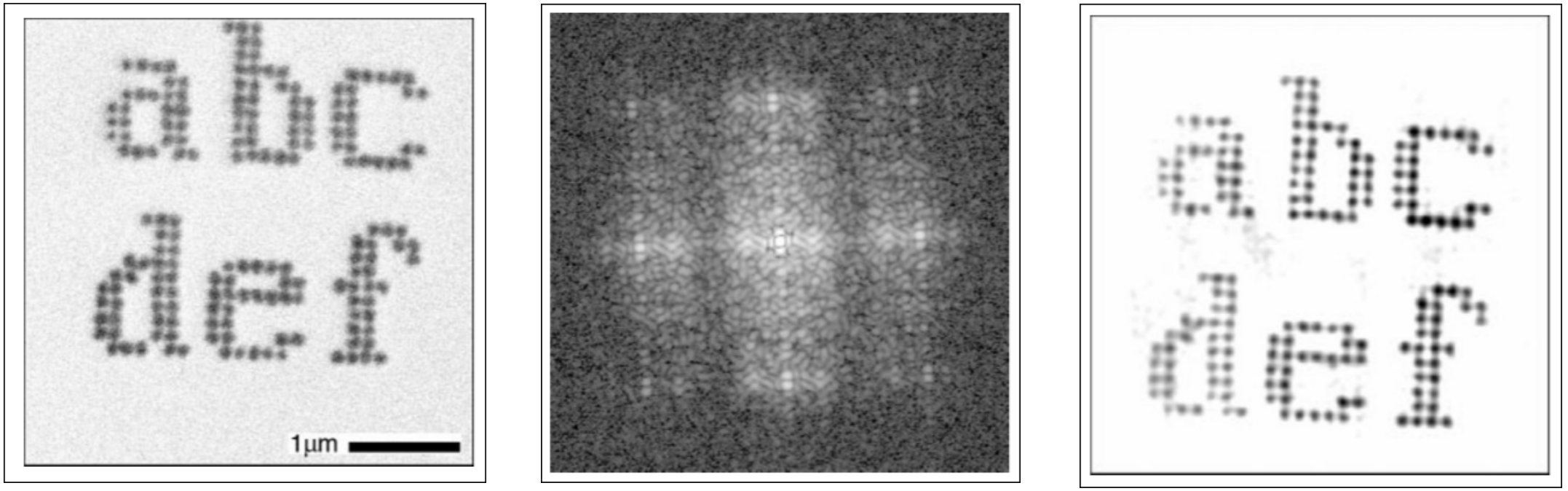
Radiation from the undulator is diffracted by the sample and recorded on a multi-pixel detector.

Different pixels are measured simultaneously and correlated.

Intensity correlation measurements are gated by the short pulse duration of tens of femtoseconds.

Ivan A. Vartanyants & Andrej Singer: *Coherence Properties of Third-Generation Synchrotron Sources and Free-Electron Lasers,*
in Synchrotron Light Sources and Free-Electron Lasers, Springer (2017)

Image reconstruction from X-ray intensity interferometry



Left: **Scanning electron microscope image of the specimen (gold dots on membrane)**

Center: **Diffraction pattern (logarithmic intensity scale)**

Right: **Image reconstructed from this diffraction pattern**

J. Miao et al.: *Extending the methodology of X-ray crystallography to allow imaging of micrometre-sized non-crystalline specimens*, Nature **400**, 342 (1999)

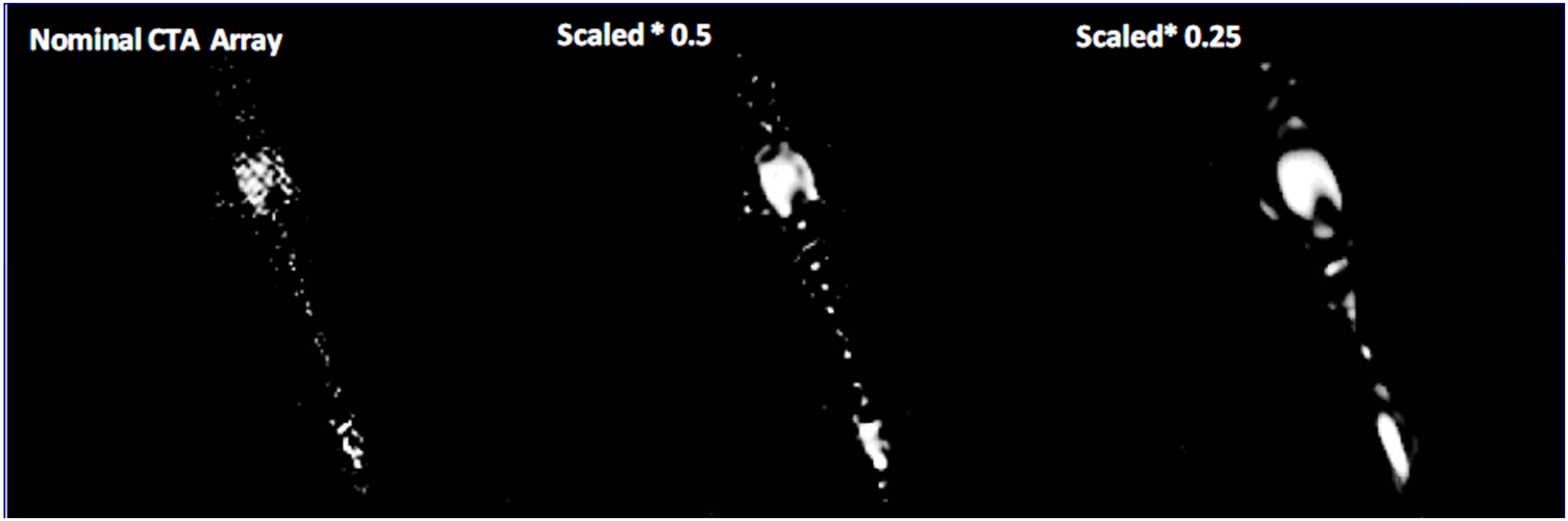


Image reconstruction of a geostationary satellite using a nominal CTA layout, and scaled versions

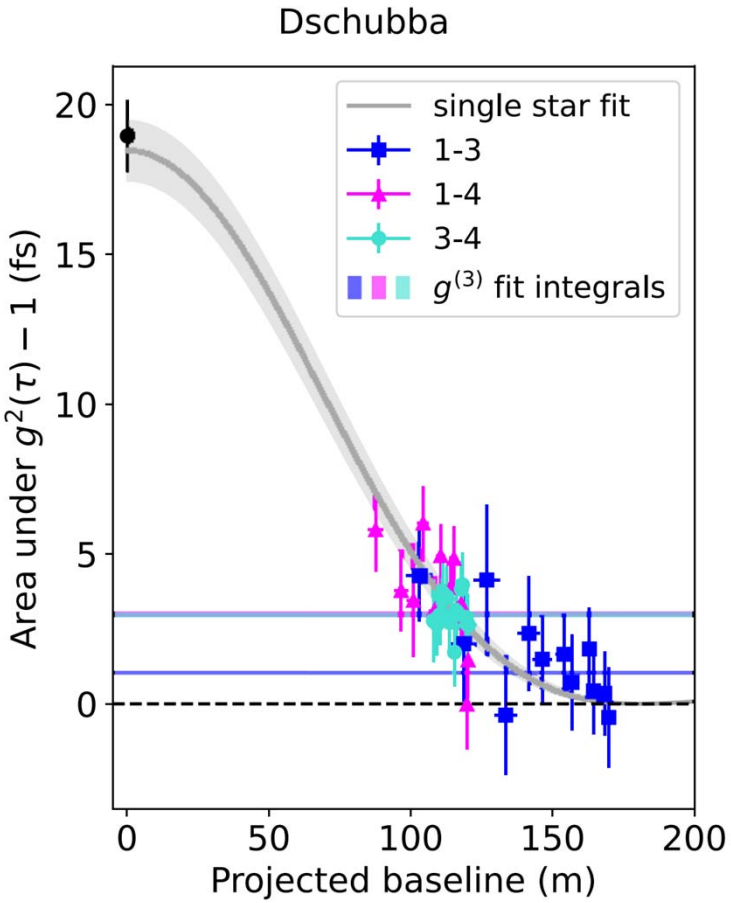
Image Reconstruction from Sparse Irregular Intensity Interferometry Measurements of Fourier Magnitude

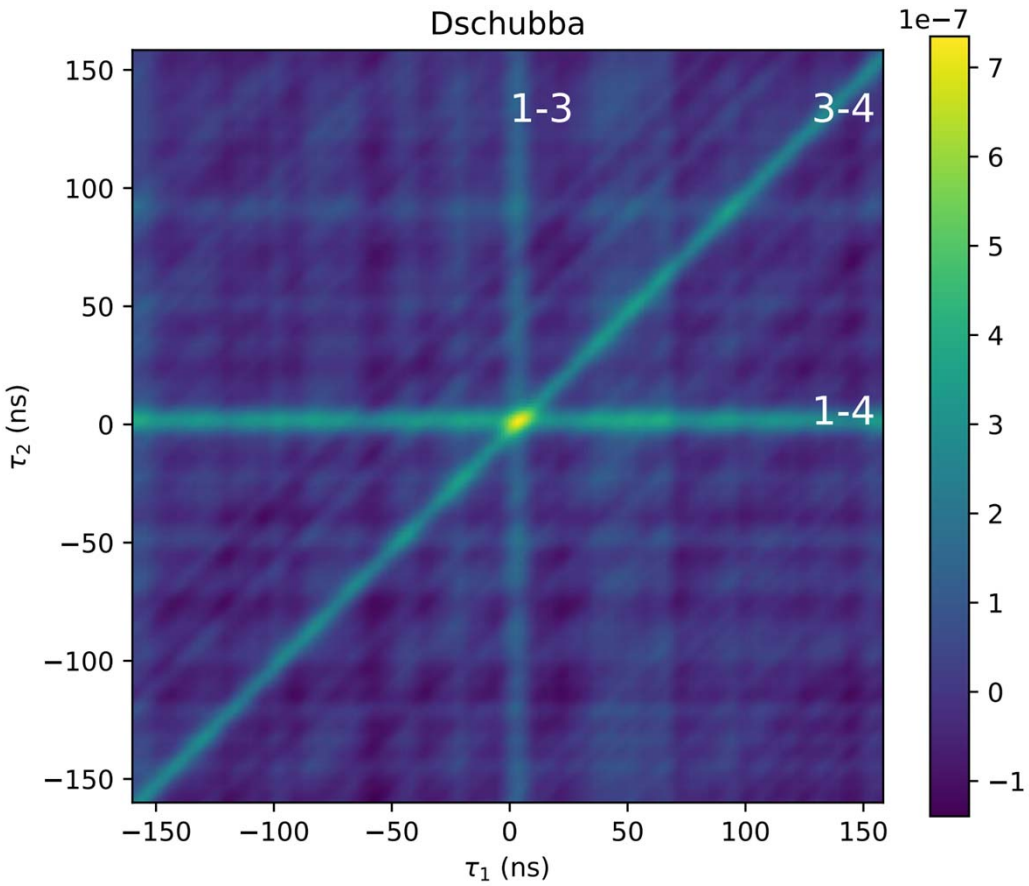
David R. Gerwe, J. J. Dolne
Boeing Phantomworks Space & Intelligence Systems
Peter N. Crabtree
United States Air Force Research Labs
Richard B. Holmes, Brandoch Calef
Boeing Laser and Technical Services

Triple correlations
& Phase closure function

Higher order correlations

Three-photon correlation from triplets of telescopes





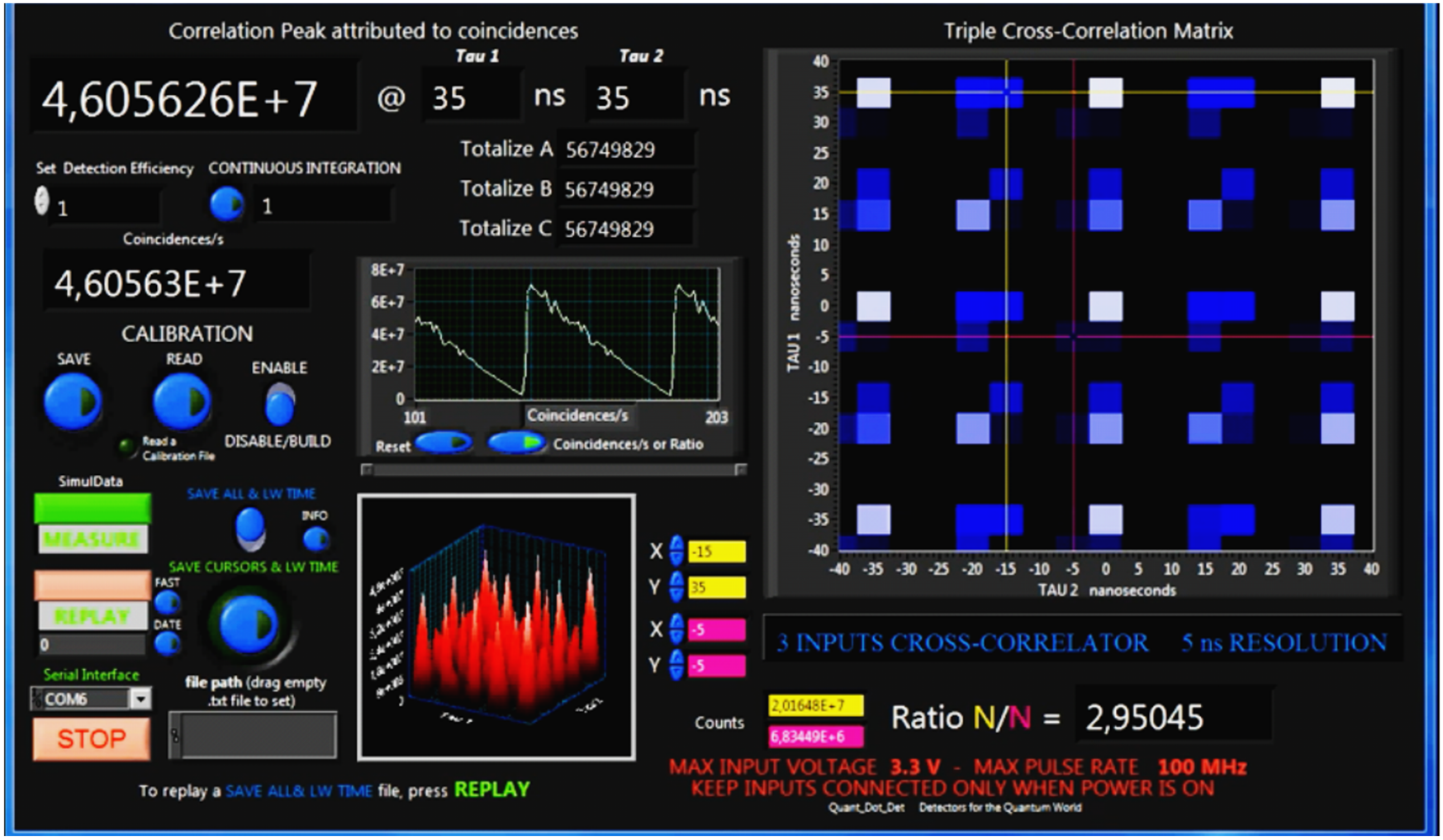
Left: Second-order temporal correlation measurement of the star Dschuba (δ Sco) at 470 nm

Right: Scheme for third-order temporal correlation measurement with telescopes #1, #3, #4

A.Zmija, G.Anton, C.Ingenhuett, A.Mitchell, P.Saha, P.Silva Batista, N.Vogel, A.Zink, R.Kaiser, S.Funk:
Towards measuring astrophysical third order correlation functions with the H.E.S.S. optical intensity interferometer
Mon.Not.Roy.Astron.Soc. **546**, 1 (2026)

Higher order correlations

Three-photon correlator for triplets of telescopes



QUANT.DET
Digital Real-Time Triple Cross-Correlator
Developed at the University of Trento, Italy
https://www.youtube.com/watch?v=DVjQLP5Nrbg

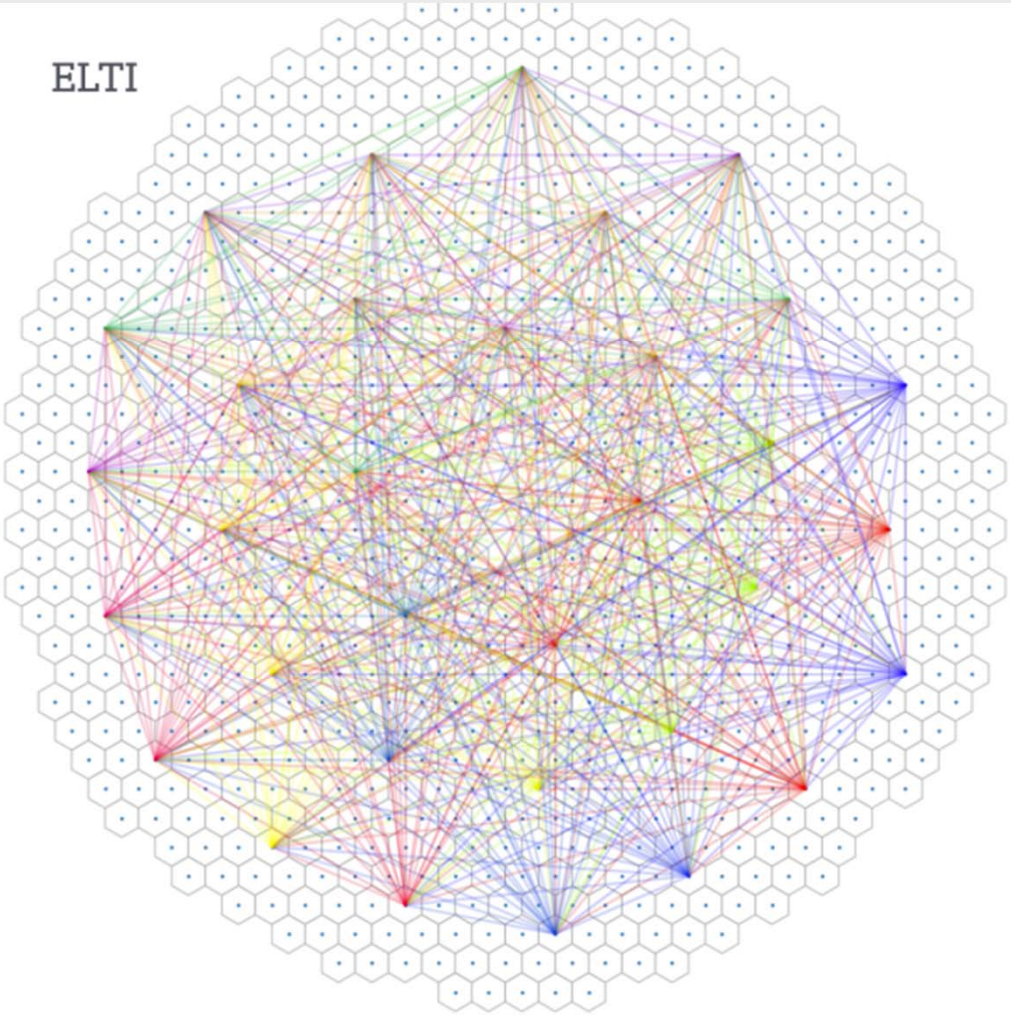
ELT as an intensity interferometer?

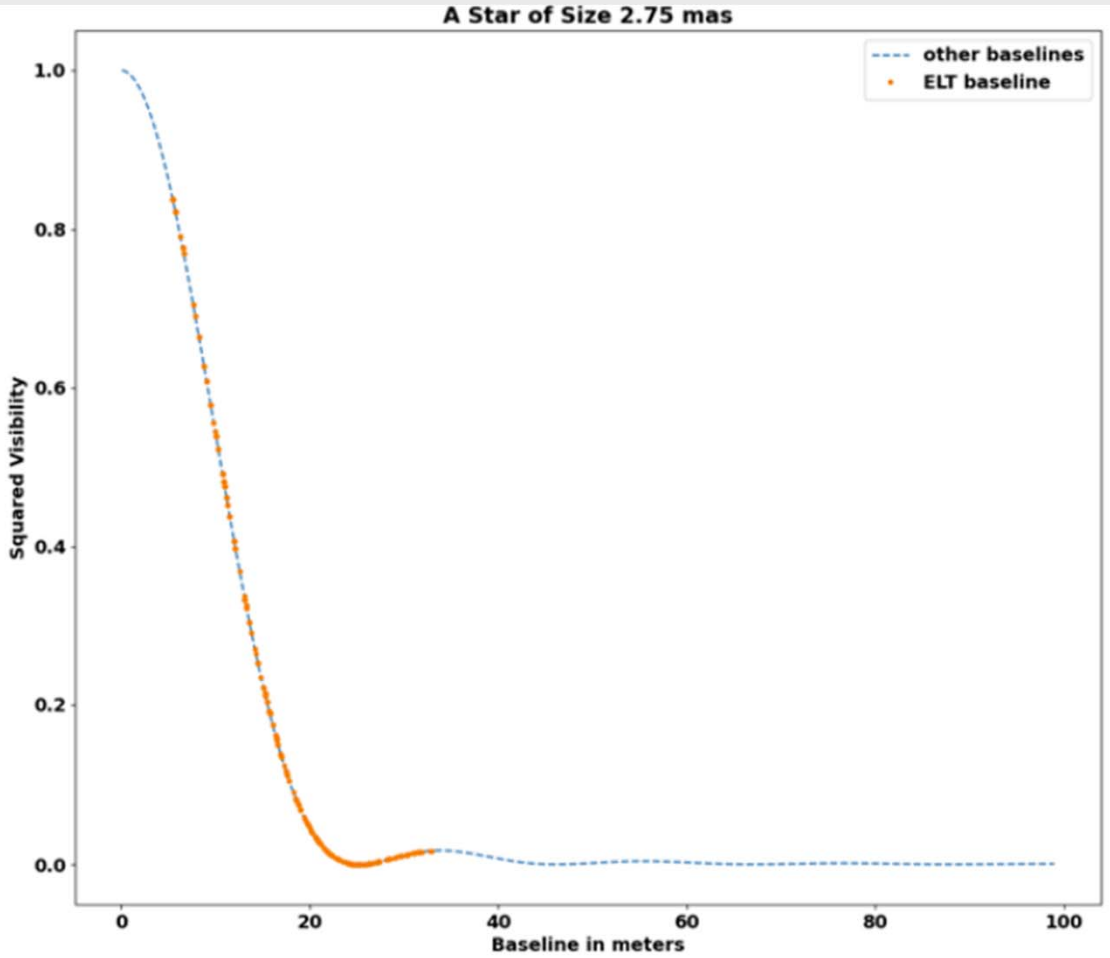


Mock-up of E-ELT 39.3 m main mirror with 798 hexagons, each 1.4 m wide

(ESO's Open House Day in Garching bei München)

ELT as an intensity interferometer?



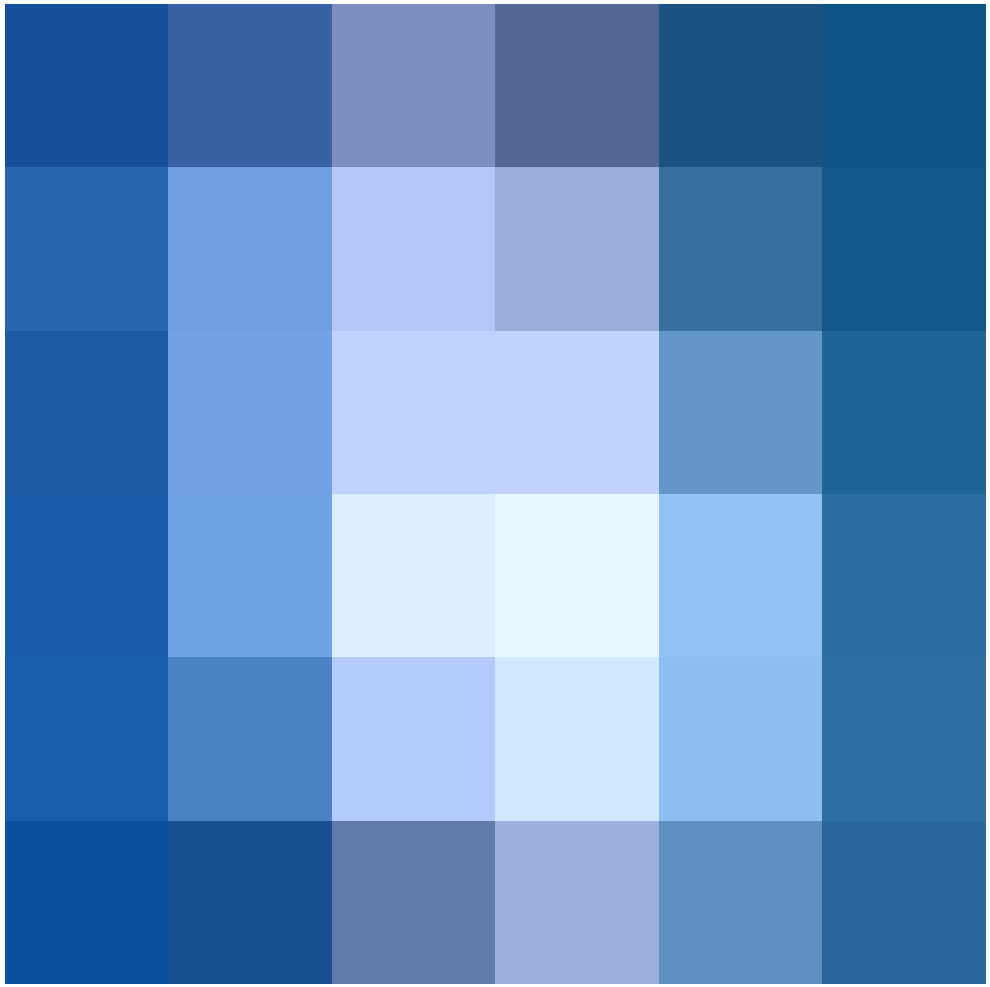


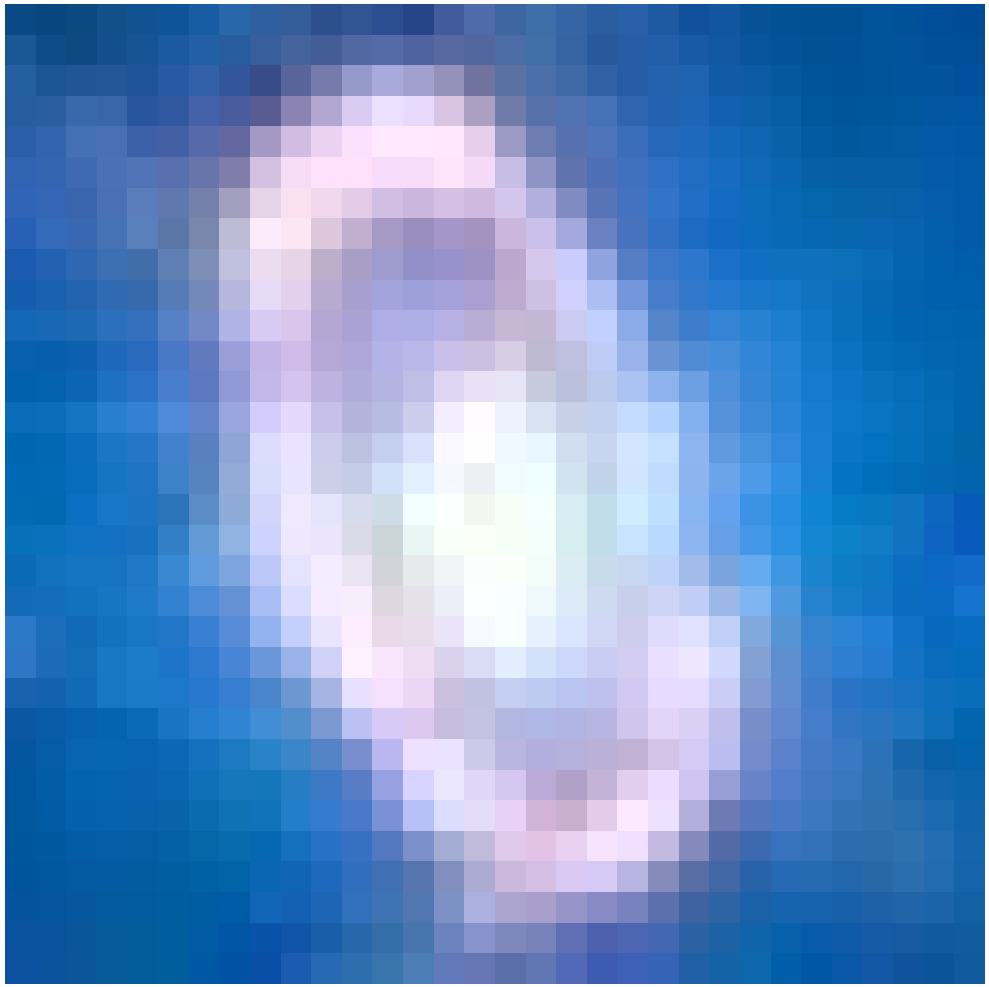
ELTI (u,v)-plane coverage:
528 baselines between 33 sub-pupils

Visibility for a uniform disk with
2.75 mas diameter at 450 nm

F.Prada, E.Perez, S.Fernandez-Acosta, K.Nitu Rai, J.Sanchez-Bermudez:
The Extremely Large Telescope Interferometer, arXiv:2603.05589 (2026)

ELT as an intensity interferometer?





SN1987A - Artist's vision image from ESO press release eso1032

ELT

Adaptive optics @ 2 μm vs. Intensity interferometry @ 400 nm

EXPLOITING II STRENGTHS:

- Very long baselines
- Very many baselines
- Very good (u,v)-coverage
- Full 2-D image reconstruction

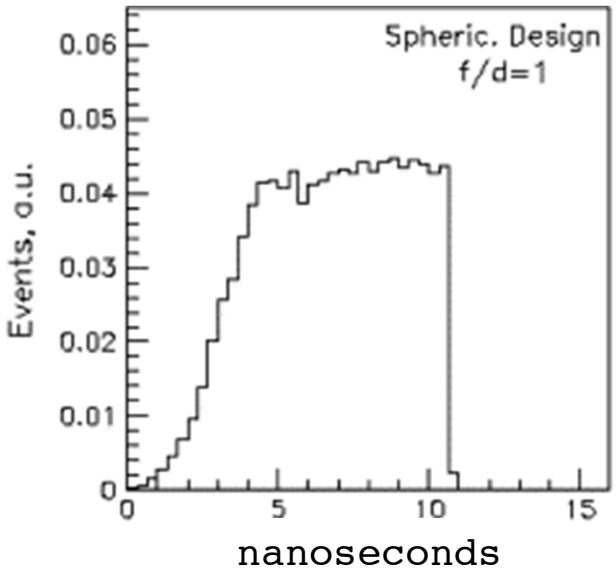
CIRCUMVENTING II WEAKNESSES:

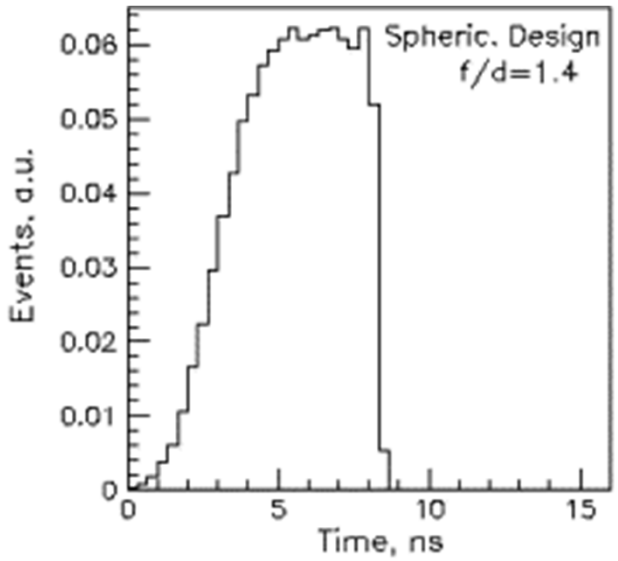
- Low sensitivity
- Limited community

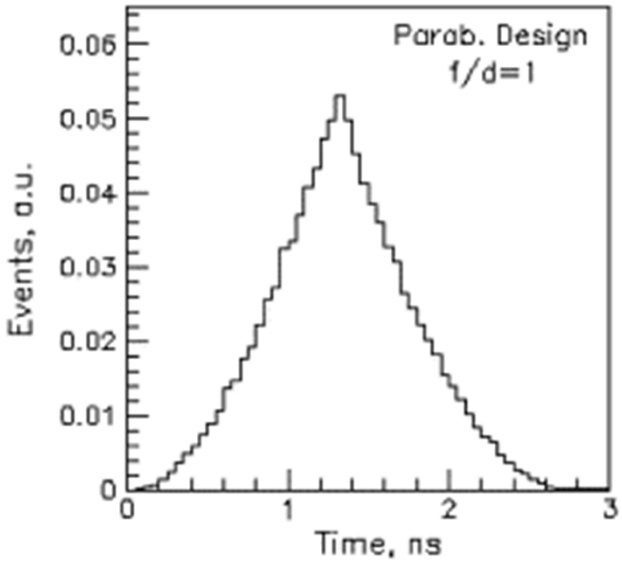
Image quality & Telescopic time spread

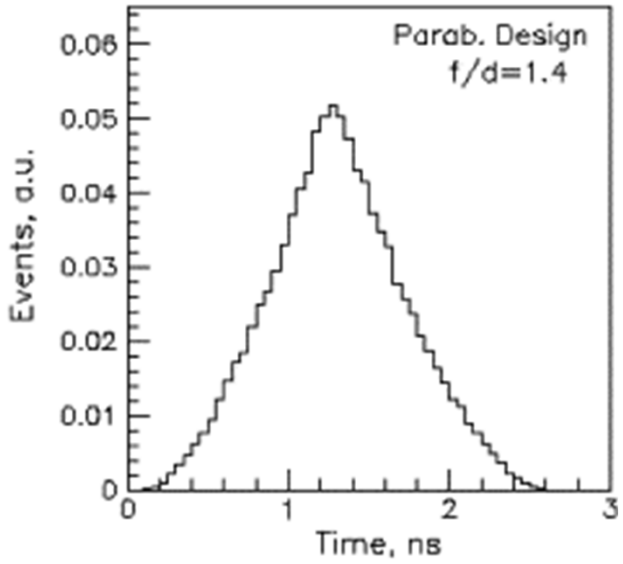
Schwarzschild-Couder, parabolic, or Schmidt better than Davies-Cotton

Time spread in 20 m∅ Cherenkov telescopes









Top: Spherical (Davies–Cotton)

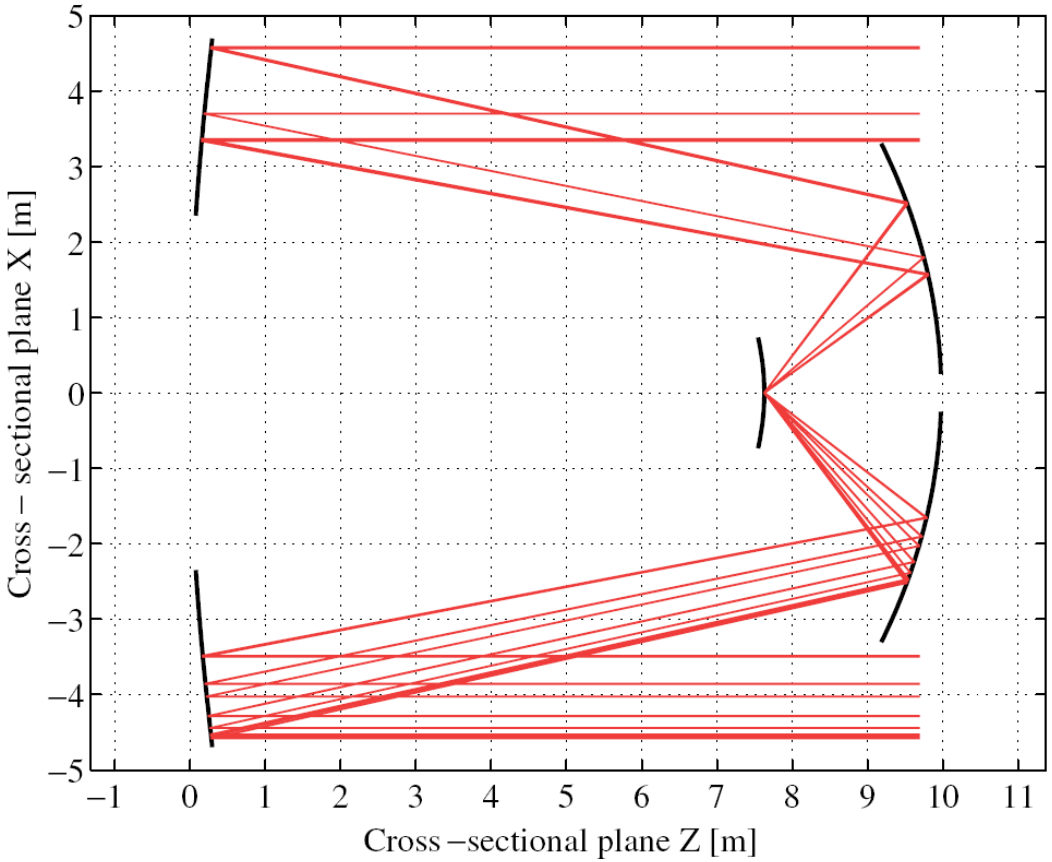
A spherical reflector substantially widens the photon pulse.

Angles of incidence = 2°

Bottom: Parabolic

Isochronous on axis, for zero angle of incidence

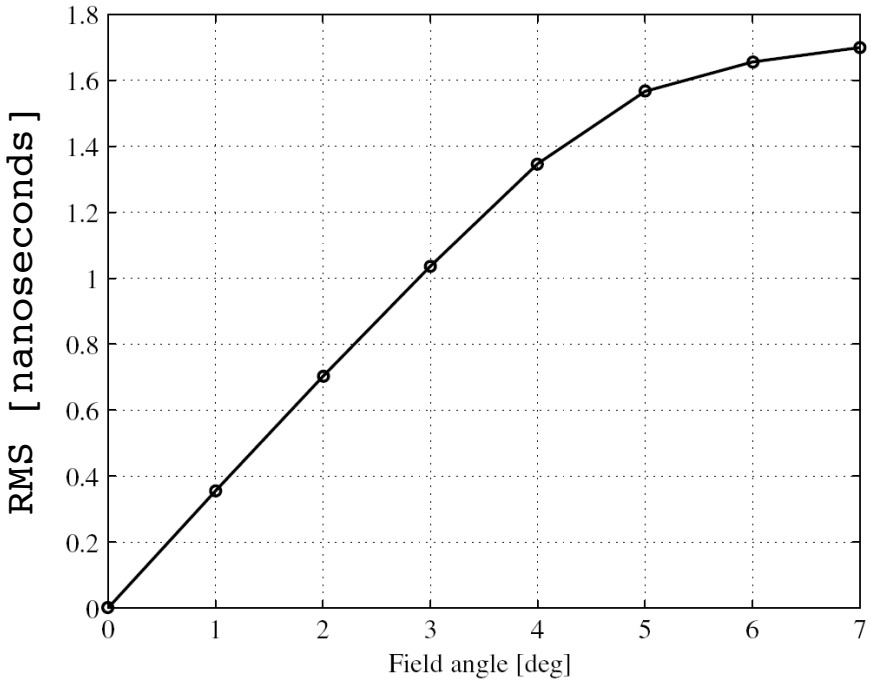
A.Akhperjanian & V.Sahakian
Performance of a 20 m diameter Cherenkov imaging telescope
Astropart.Phys. **21**, 149 (2004)



Schwarzschild-Couder two-mirror IACT telescope

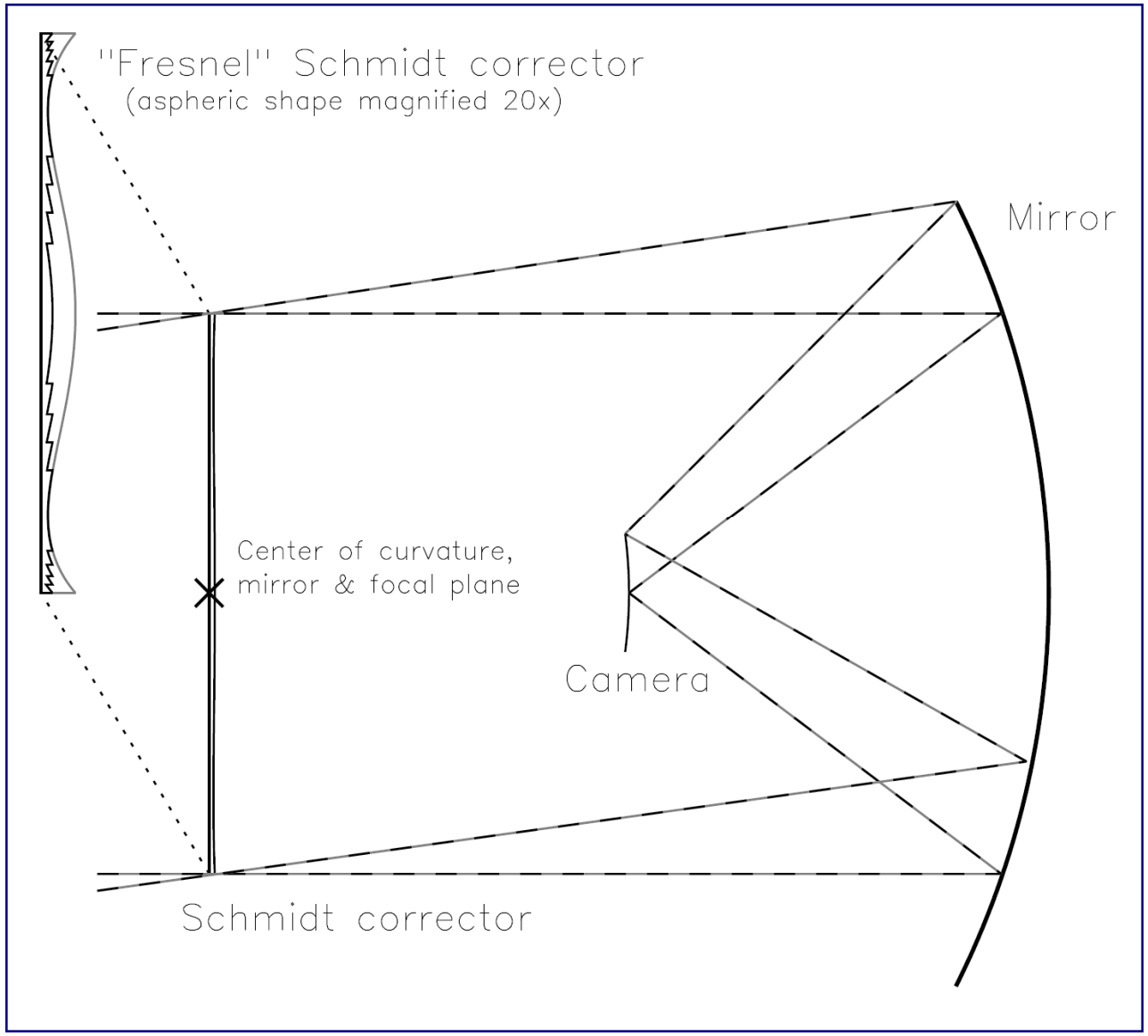
RMS spread in arrival time of rays at focal plane as a function of field angle.

Design is isochronous on optical axis.



V.Vassiliev, S.Fegan, P.Brousseau:
Wide field aplanatic two-mirror telescopes for ground-based γ-ray astronomy
Astropart.Phys. **28**, 10 (2007)

Best isochronicity



IACT Schmidt telescope

Diameter 7.0 m

F-ratio 0.8

Focal length 5.6 m

Field of View 15°

Resolution (RMS) < 1′

Non-isochronicity ≤ 30 ps

The mirror and the focal plane have centers of curvature at center of the corrector plate

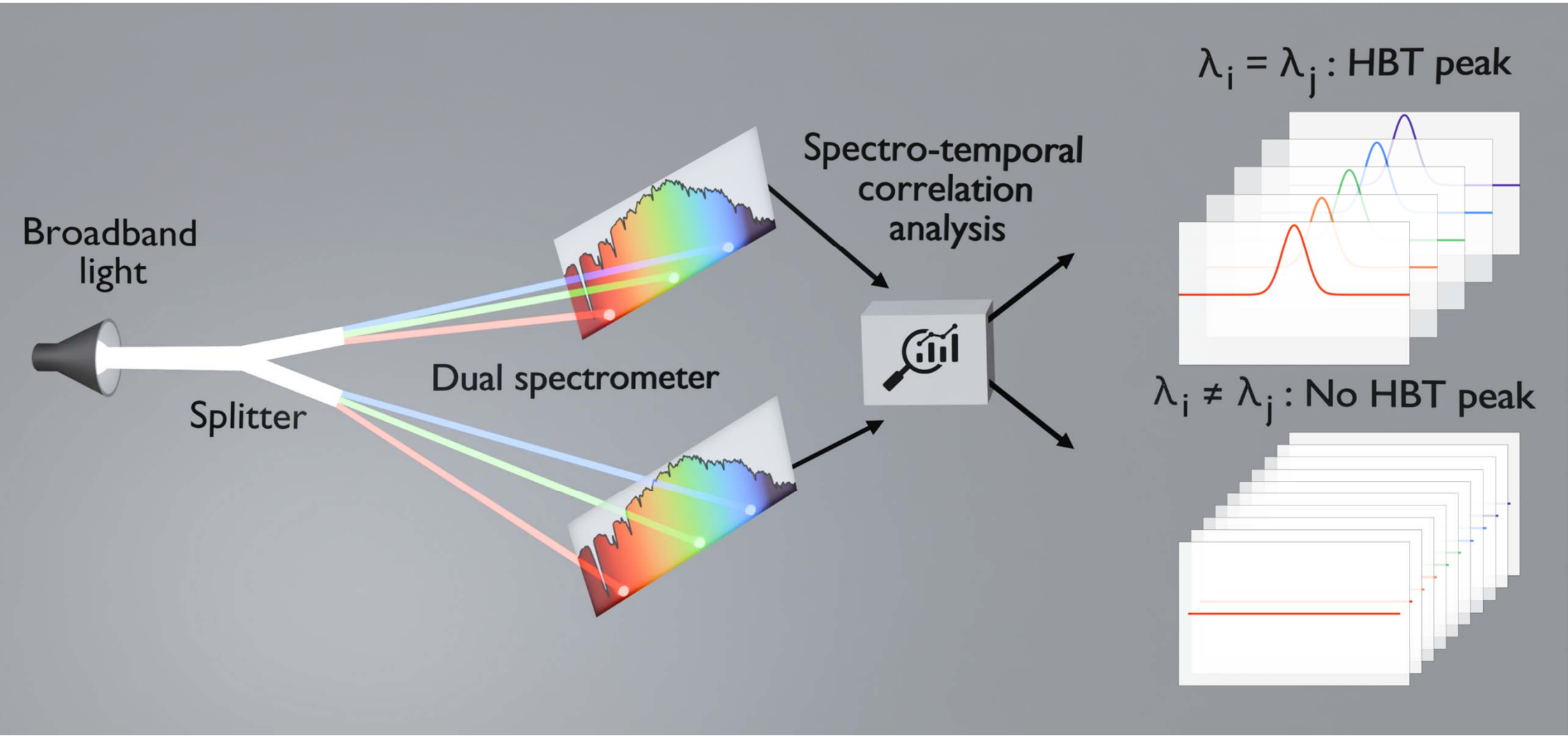
Schmidt corrector is shown with its aspheric shape magnified by a factor of 20

Both the nominal corrector and a Fresnel version is shown

R. Mirzoyan, M.I. Andersen
A 15 deg Wide Field of View Imaging Air Cherenkov Telescope
Astropart.Phys. **31**, 1, 2009

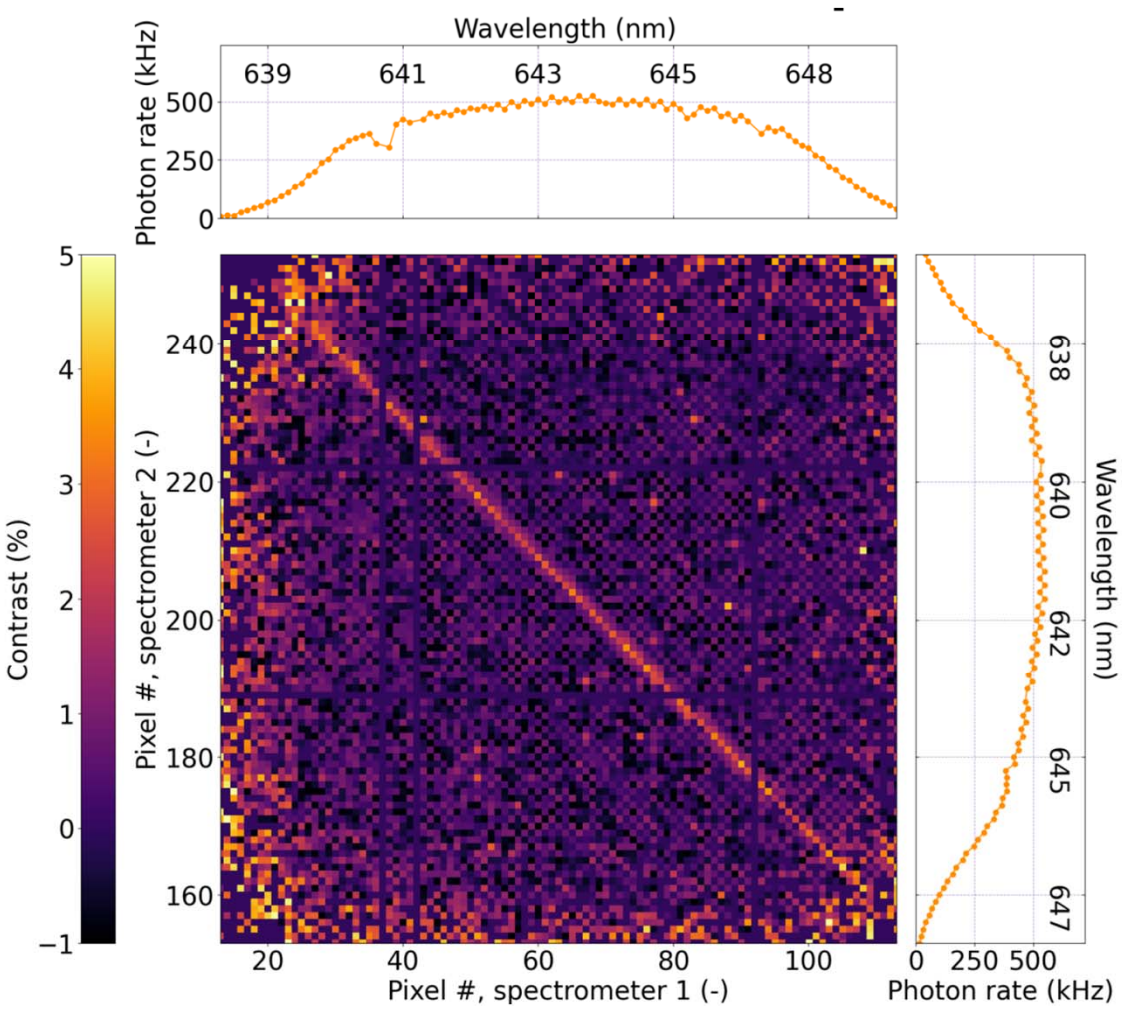
Spectral resolution
(& polarization?)

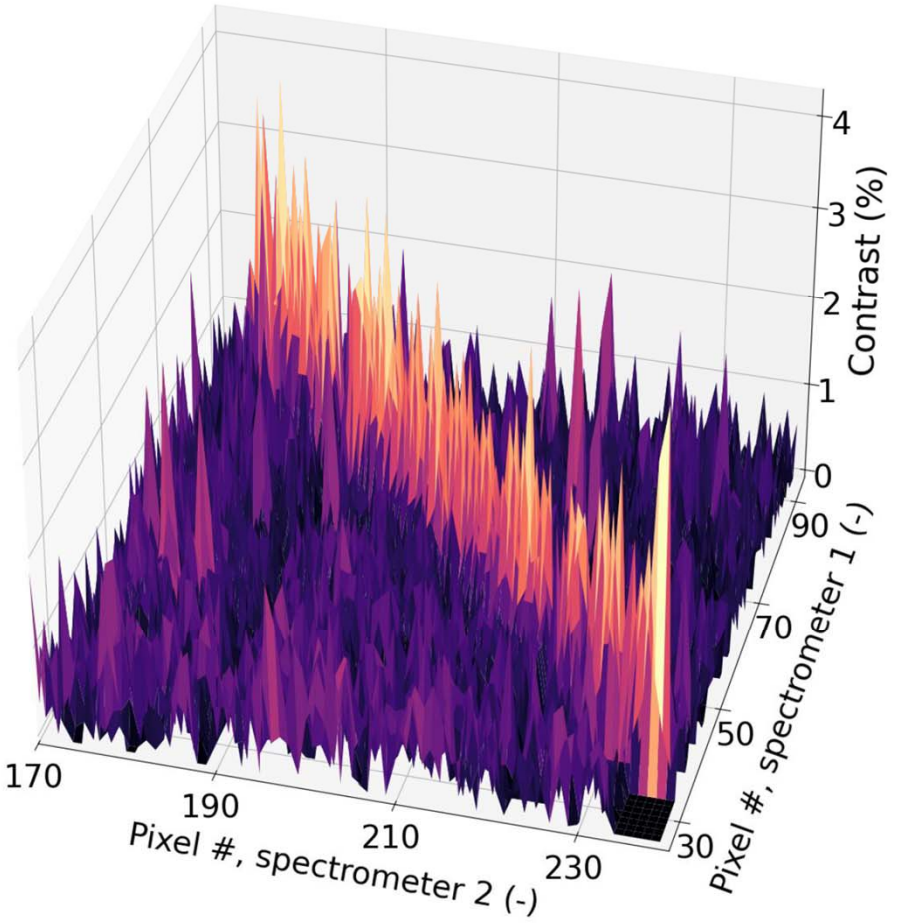
Multiple spectral channels



S.Kulkov et al.: *Hanbury Brown-Twiss interference with massively parallel spectral multiplexing for broadband light,* arXiv:2509.05649

Multiple spectral channels





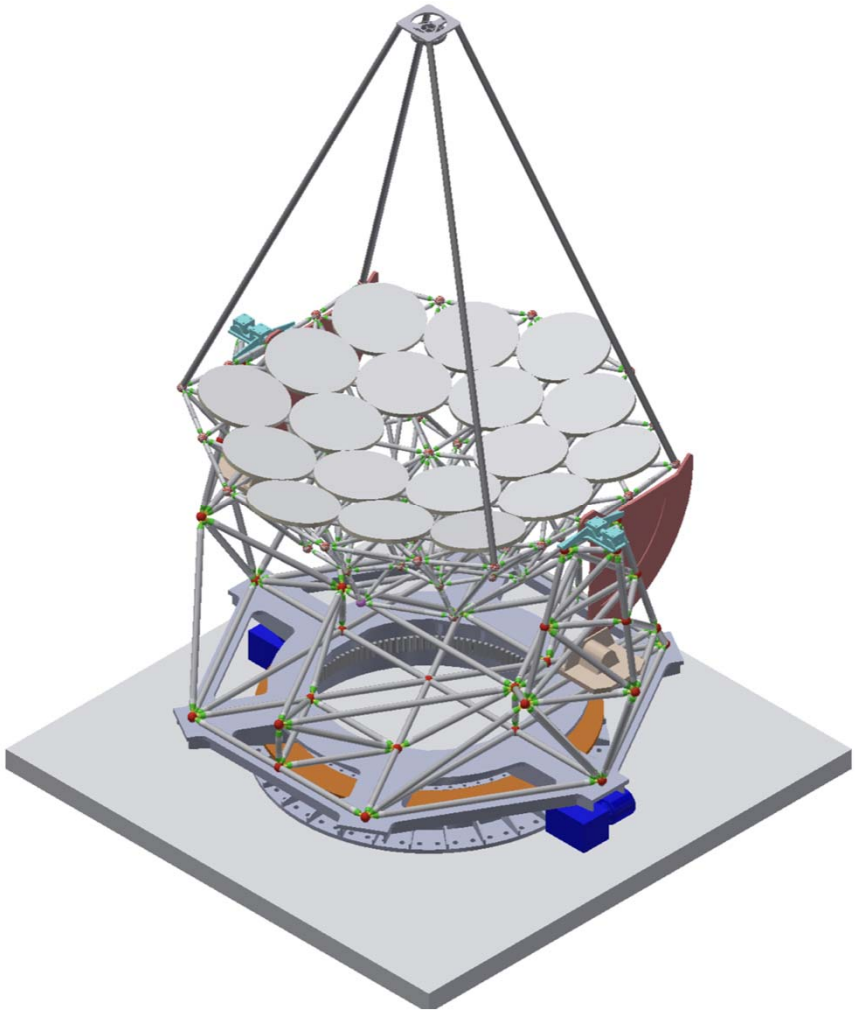
Left: Correlations between laboratory light of different wavelengths

Right: Hundreds of intensity-correlation peak appear in the spectrum

S.Kulkov et al.: *Hanbury Brown-Twiss interference with massively parallel spectral multiplexing for broadband light,* arXiv:2509.05649

“Simple” telescopes with “modest” but improved performance?

Telescopes for many spectral channels





4-meter telescope for multi-wavelength intensity interferometry

T.Schweizer, J.Eder, J.Besenrieder, R.Mirzoyan, C.Haider, O.Reimann, D.Strom, R.Walter:
EON-SII: Design of a transportable picosecond stellar intensity interferometer for compact-star astrophysics, arXiv:2608.17444 (2026)

Energy-resolving detectors

Superconducting nanowires / JPL proposal

"A trick of the light: A nanoarcsecond imaging Hanbury-Brown-Twiss interferometer in space"

NASA RESEARCH ANNOUNCEMENT
NNH14ZOA0001N

NASA INNOVATIVE ADVANCED CONCEPTS (NIAC)
A NANOARCSECOND IMAGING HBT INTERFEROMETER IN SPACE

1 Overview Chart

A trick of the light: a nanoarcsecond imaging Hanbury-Brown-Twiss interferometer in space
Matt Shaw, Jet Propulsion Laboratory

Concept

- A flotilla of ~50 space telescopes forming a Hanbury Brown-Twiss intensity interferometer with 1000 km baselines
- No light is directly interfered, photon counting at 1ps resolution is used to assemble synthetic aperture image in software from cross-correlations
- Fluctuations are correlated rather than interfering the light directly

Study Approach

- Explore parameter space to maximize advantage of HBT concept as applied to space observatory
- Perform mission concept study
- Identify most compelling science goals



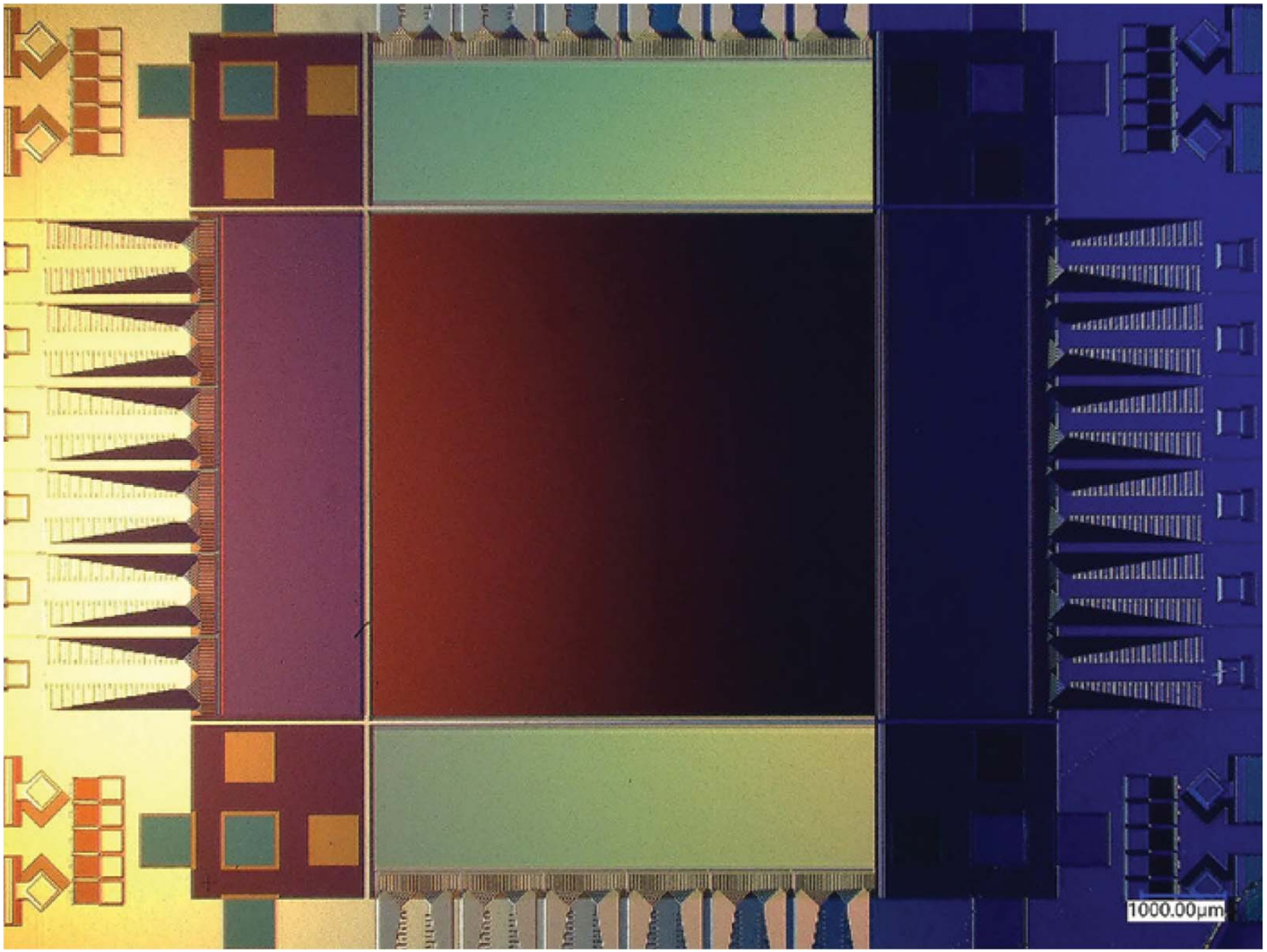
Benefits

- Imaging is performed with 30 nanoarcsecond resolution
- Three orders of magnitude higher resolution than SI (HBT technique enables 1000x longer baseline)
- Unprecedented new science opportunities for stellar physics and exoplanet searches
- Feasible technological pathway is present

Evaluation Notes

Matthew D. Shaw, P.I. (NASA Caltech-JPL), Kenneth G. Carpenter (NASA Goddard), Dainis Dravins (Lund)
NASA Innovative Advanced Concepts proposal 2014

Superconducting nanowire photon detectors

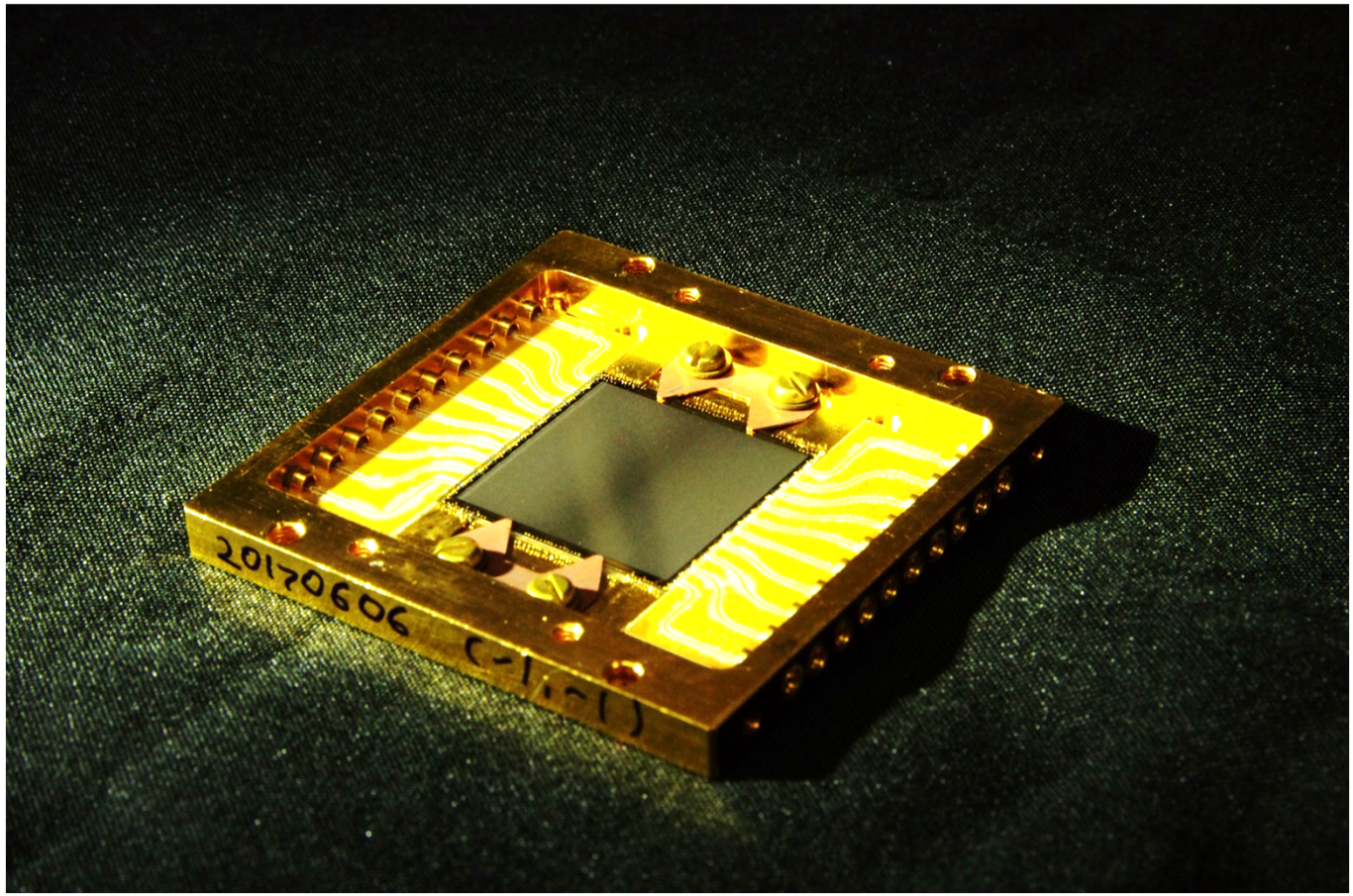


400,000 pixel camera with nanowire single-photon detectors

Time-domain multiplexing identifies each photon arrival at each pixel

B.G.Osipov, D.S.Rampini, J.Allmaras, M.D.Shaw, S.W.Nam, B.Korzh & A.N.McCaughan (JPL, NIST, Univ. Colorado Boulder):
A superconducting nanowire single-photon camera with 400,000 pixels, Nature **622**, 730, 2023

MKIDs
Microwave Kinetic Inductance Detectors



***MEC – 20,440-pixel MKID Exoplanet Camera on Subaru* 8-m telescope on Maunakea**

https://web.physics.ucsb.edu/~bmazin/mkids/

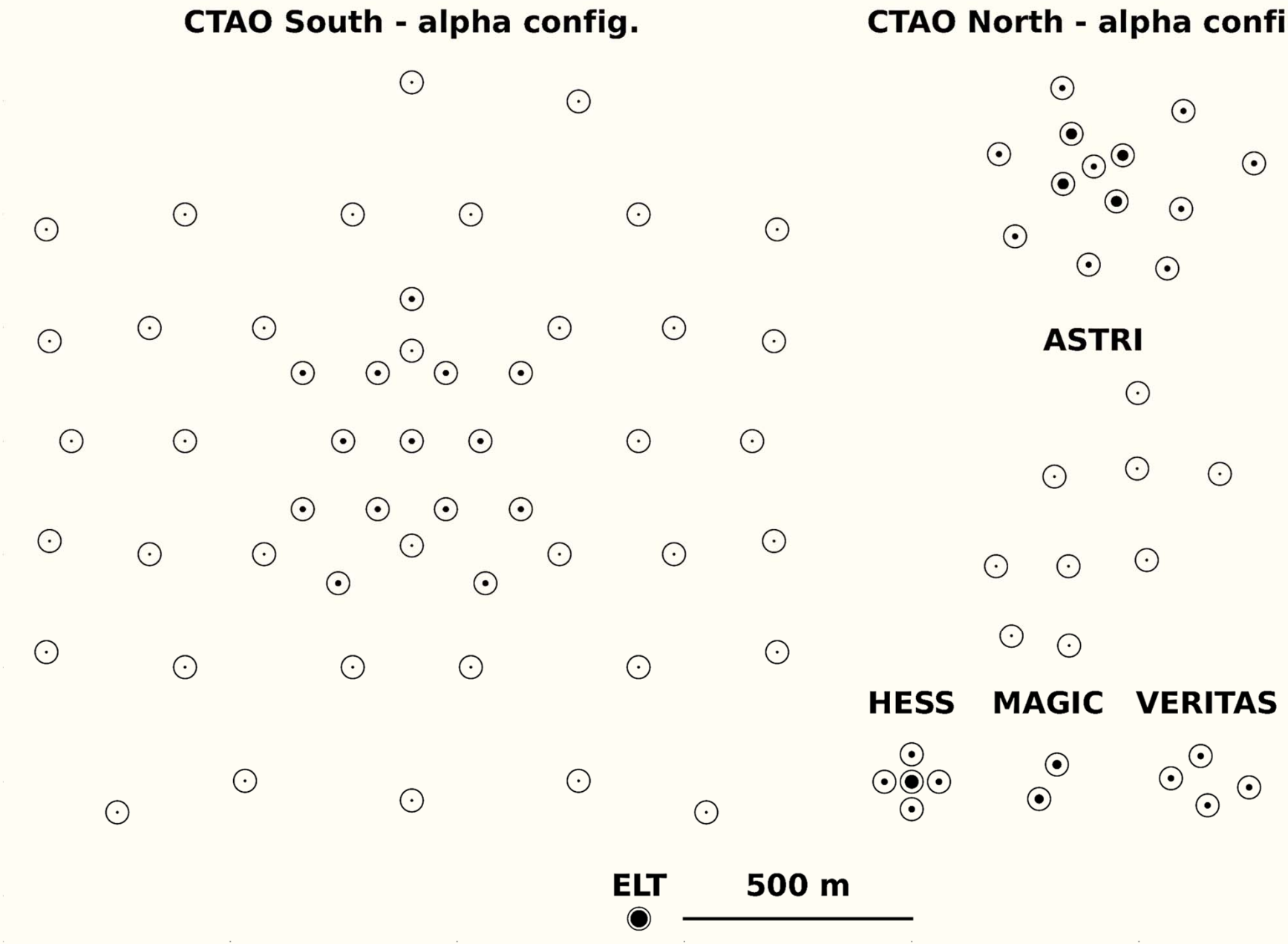
Future telescope arrays


Cerro Armazones
CTAO
Cerro Paranal
Photo: Dainis Dravins

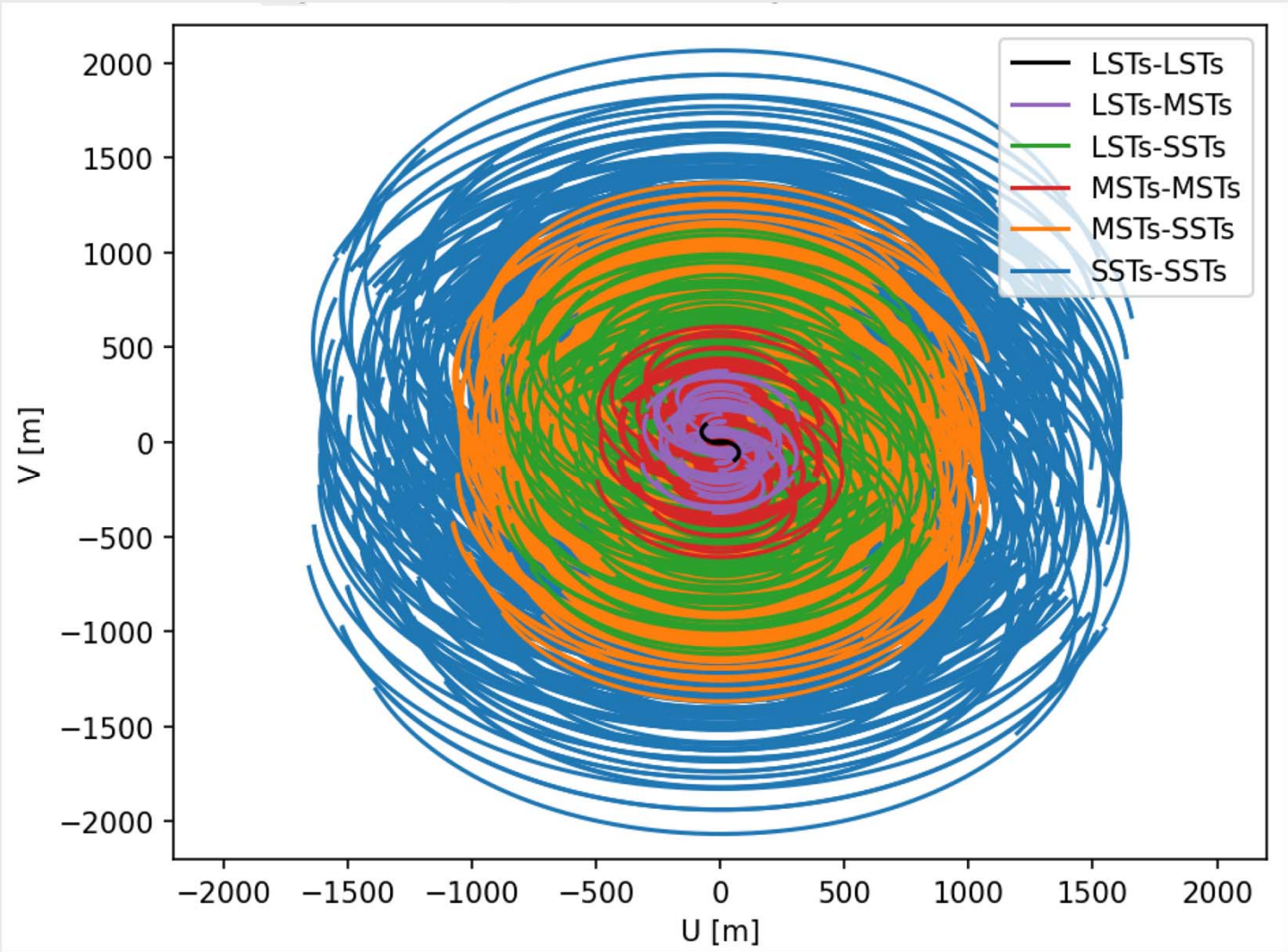
Chilean site construction



Cherenkov telescope observatories



CTAO-South (u,v)-plane coverage



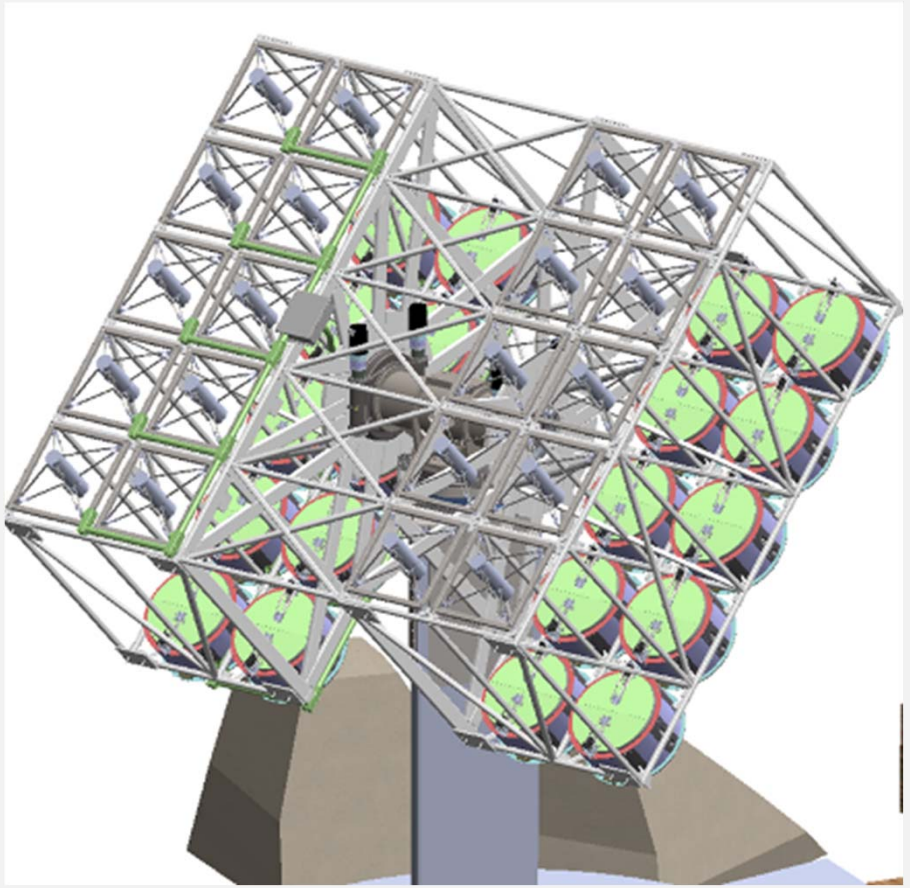
Example coverage of the interferometric (u,v)-plane in one night for all telescopes in CTAO-South

L.Zampieri et al.: *Stellar Intensity Interferometry with CTAO*, to be submitted (2026)

Synergies with optical telescope arrays?

Arrays of many telescopes





LFAST: The Large Fiber Array Spectroscopic Telescope Project

Scalable telescope array for photon-starved science in the visible and near-infrared;
76 cm diameter, f/3.3 unit telescopes, optical fibers to spectrometers

https://astro.arizona.edu/research-groups/lfast



Each unit telescope (2-meter class) is technologically modest but has adaptive optics.
Each telescope has a high-speed photometer.
Telescope groups are feeding spectrographs through fibers.
This is *not* a survey telescope.

https://www.tdtelescope.org

Synergies with solar optical flux collectors??

Solar flux collectors



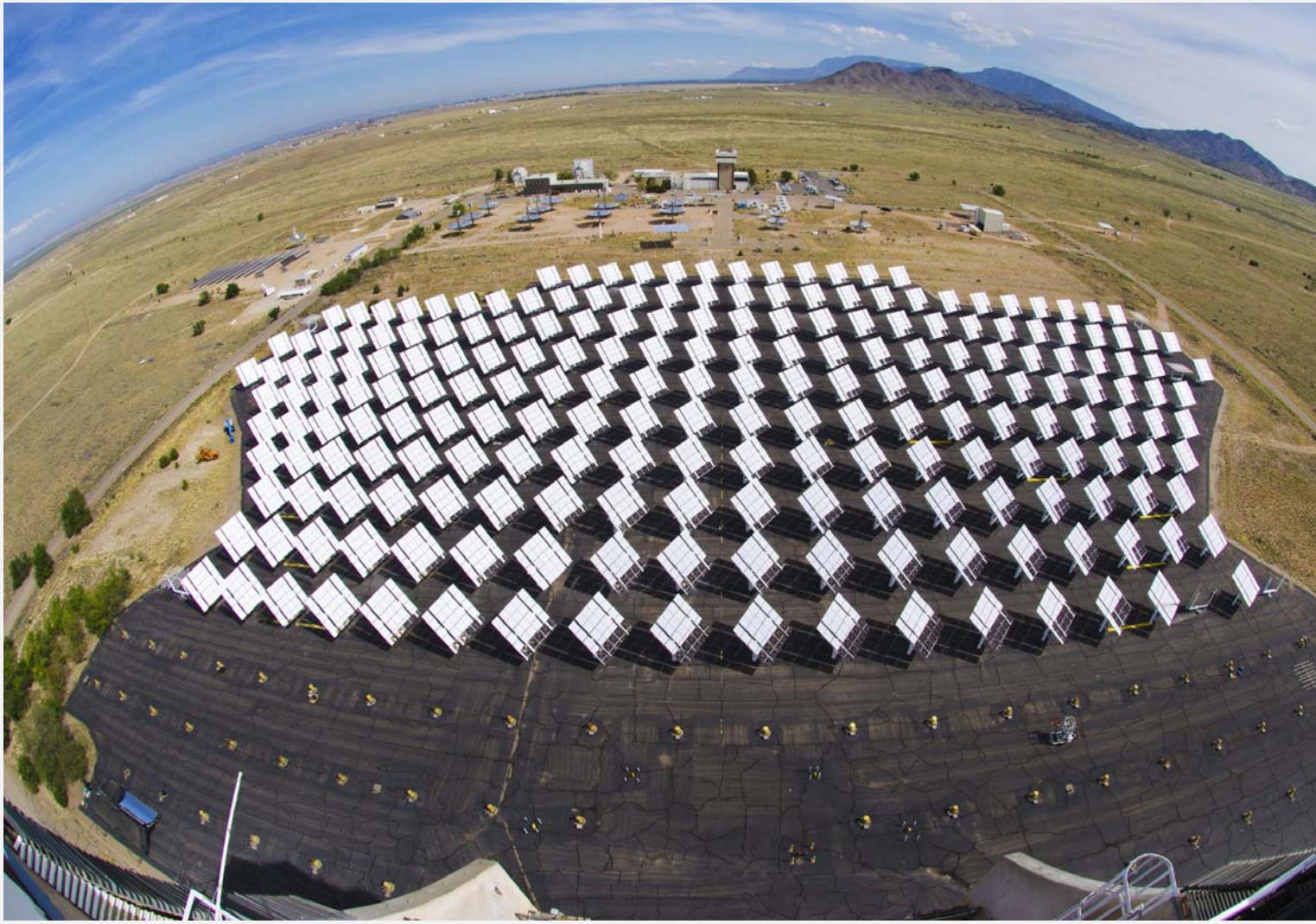
(Wikipedia)



***Planta Solar 20* and *Planta Solar 10* in *Sanlucar la Mayor* near Seville**

PS20 has 1,255 movable heliostats, each 120 m^2

Solar flux collectors

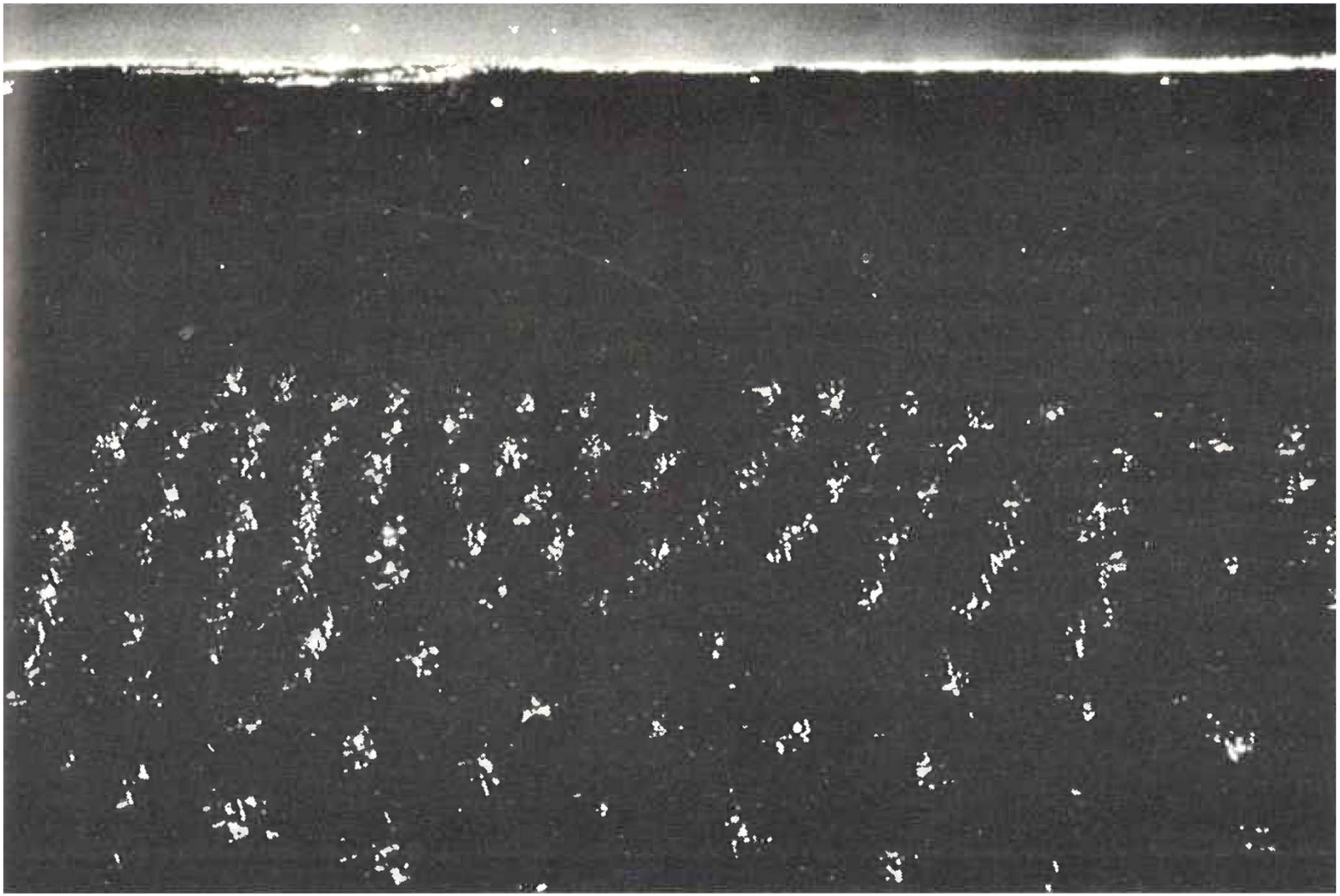




National Solar Thermal Test Facility, Sandia National Laboratories, Albuquerque, New Mexico

https://www.energy.gov/eere/solar/project-profile-national-solar-thermal-test-facility
https://newsreleases.sandia.gov/nsttf_upgrades/

Solar (& Stellar?) flux collectors

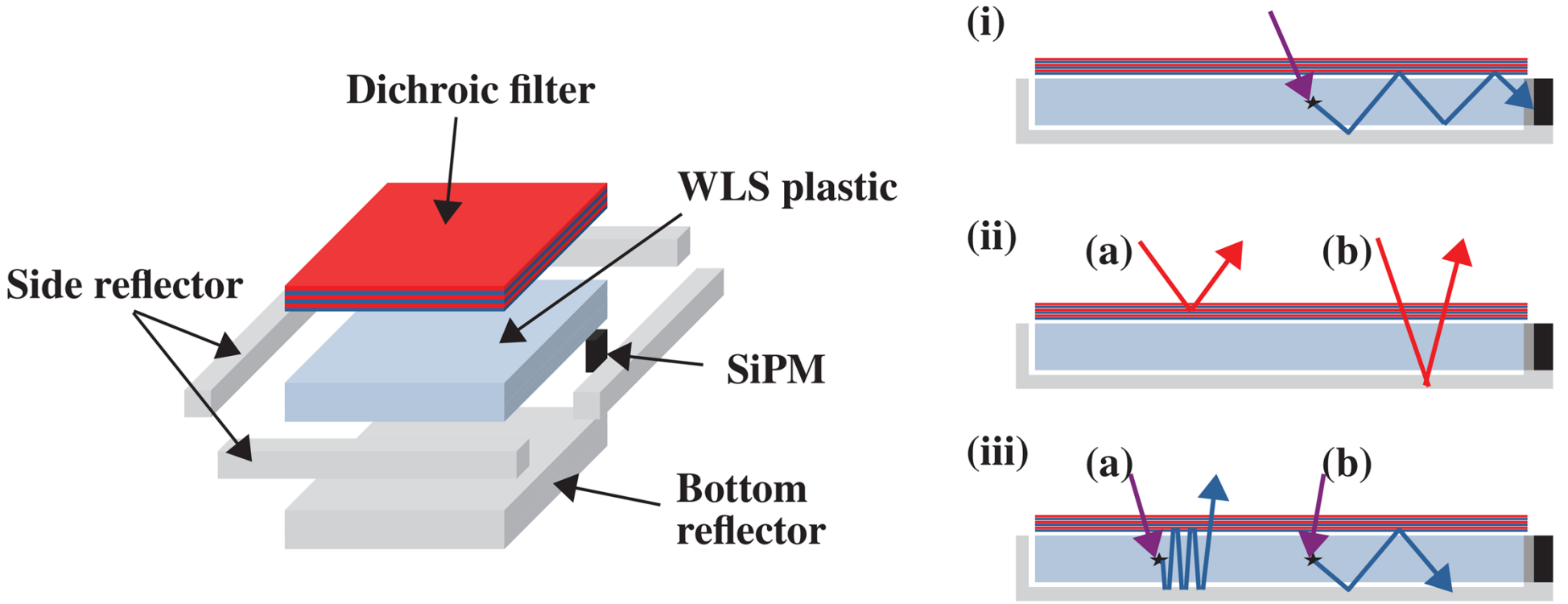


Each cluster of lights is the star *Vega*

View from the central tower of the Solar Thermal Test Facility in Albuquerque, NM

Jerry Myers: *An acre of Vegas*, Sky and Telescope **59**, 2, 119, February 1980

Solar (& Stellar?) flux collectors



Light-traps to collect light over large areas?

A plastic sheet, coupled to a SiPM, is doped with a wavelength-shifter absorbing short wavelengths, re-emitting at longer. On front, a dichroic filter has high transmittance at short wavelengths, high reflectivity at long. Absorbed photons are re-emitted isotropically and trapped inside until they eventually reach the SiPM.

D.Guberman, C.Wunderlich, G.Barillaro, J.Cortina, A.Paghi, R.Paoletti, A.Rugliancich:
Photo-Trap: A low-cost and low-noise large-area SiPM-based pixel
Nuclear Inst. and Methods in Physics Research, A **1057**, 168670 (2023)

The ultimate?
A dedicated SII array

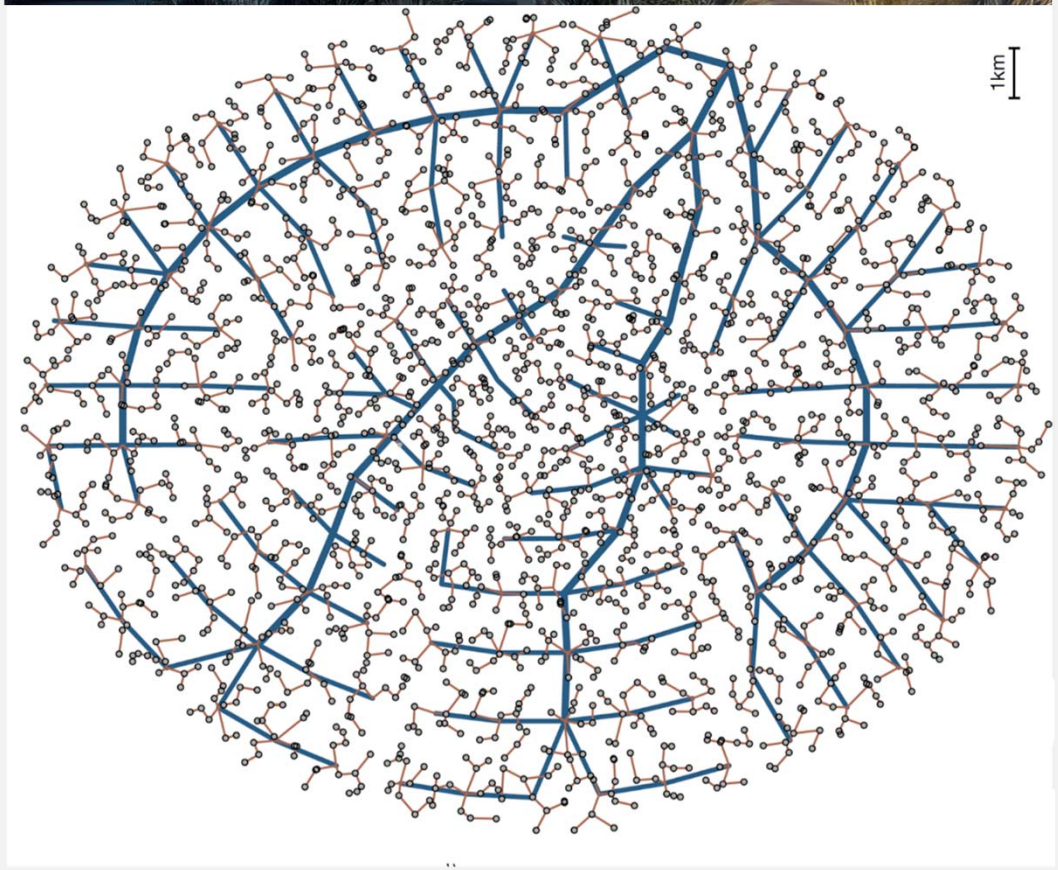
STELLAR INTENSITY INTERFEROMETER ARRAY

SIITAR

Colin Carlile*: Perspectives and opportunities for stellar intensity interferometers*
(SPIE Proc.14148, 141481P, 2026)







Deep Synoptic Array (DSA) project
1,650 radio dishes spanning 19×15 km^2 in Nevada

https://www.deepsynoptic.org/

Maybe a more immediate concept

(*ESO Expanding Horizons 2040's?*)



Each unit telescope (2-meter class) is technologically modest but has adaptive optics.
Each telescope has a high-speed photometer.
Telescope groups are feeding spectrographs through fibers.
This is *not* a survey telescope.

https://www.tdtelescope.org



TIME DOMAIN TELESCOPE

What is the Time Domain Telescope?

- Robotic *spectroscopic* telescope array for time-domain, time-constrained observations
  → *Global coverage in 2040s*

- 100 unit telescopes of ~2 m, AO enabled → Diffraction limited : 0.12*”* @ *2m* @ 400nm
  → *Essential in background-limited regime (m > 21)*
  → *Essential in crowding-limited regions*

- Unit telescopes *individually* steerable/programmable
  → *Go big or go wide: N x 1 unit, or 1 x N units, or m x n units*

- Multiple units (‘25’) feed cluster of spectrographs
  (e.g. $\Re = 10^3$, 10^4 and 10^5 per cluster): VIS-NIR: 0.35 – 2.5 µm

- Facility: Proposal/PI-based observing where ‘Hard ToO’ is default:
  → *Scheduling challenge*

<u>Key technological characteristics:</u>

1) Robotic AO in the visual
2) Near read-noise-free detectors (≤ 0.2 e^-)
3) On-the-fly scheduling (<1 min response time)

Paul Groot: *The Time Domain Telescope* (ESO workshop “Expanding Horizons: What are the astronomical challenges of the 2040’s”, July 2026; https://zenodo.org/records/21841546

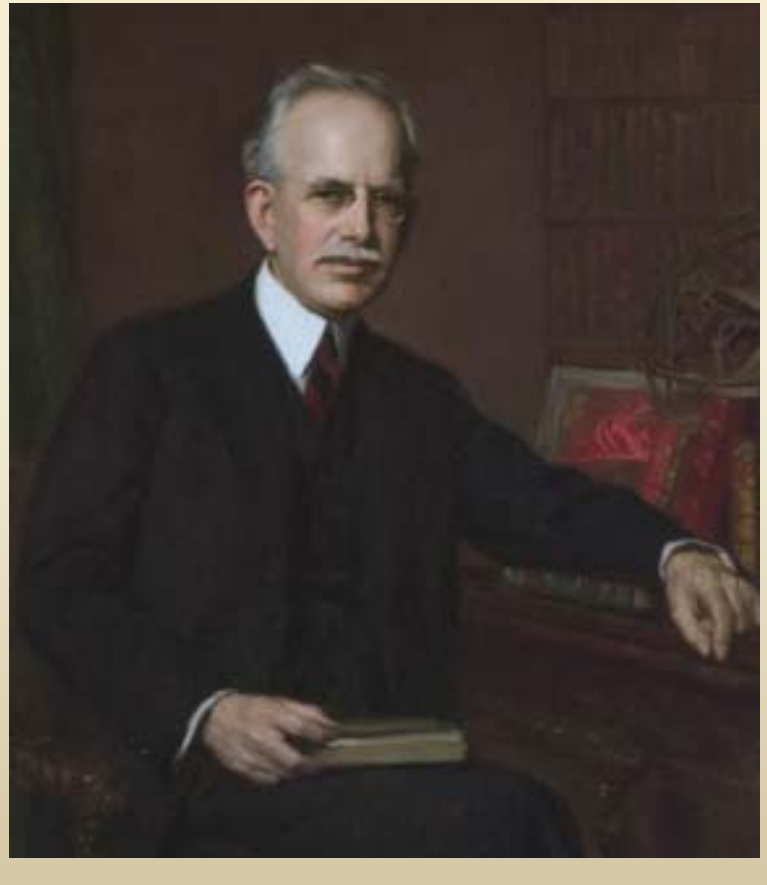
SPECTROSCOPY & IMAGING ARRAY

TIME DOMAIN TELESCOPE

SPECTRA WHEN YOU NEED THEM. ANYWHERE, ANYTIME!

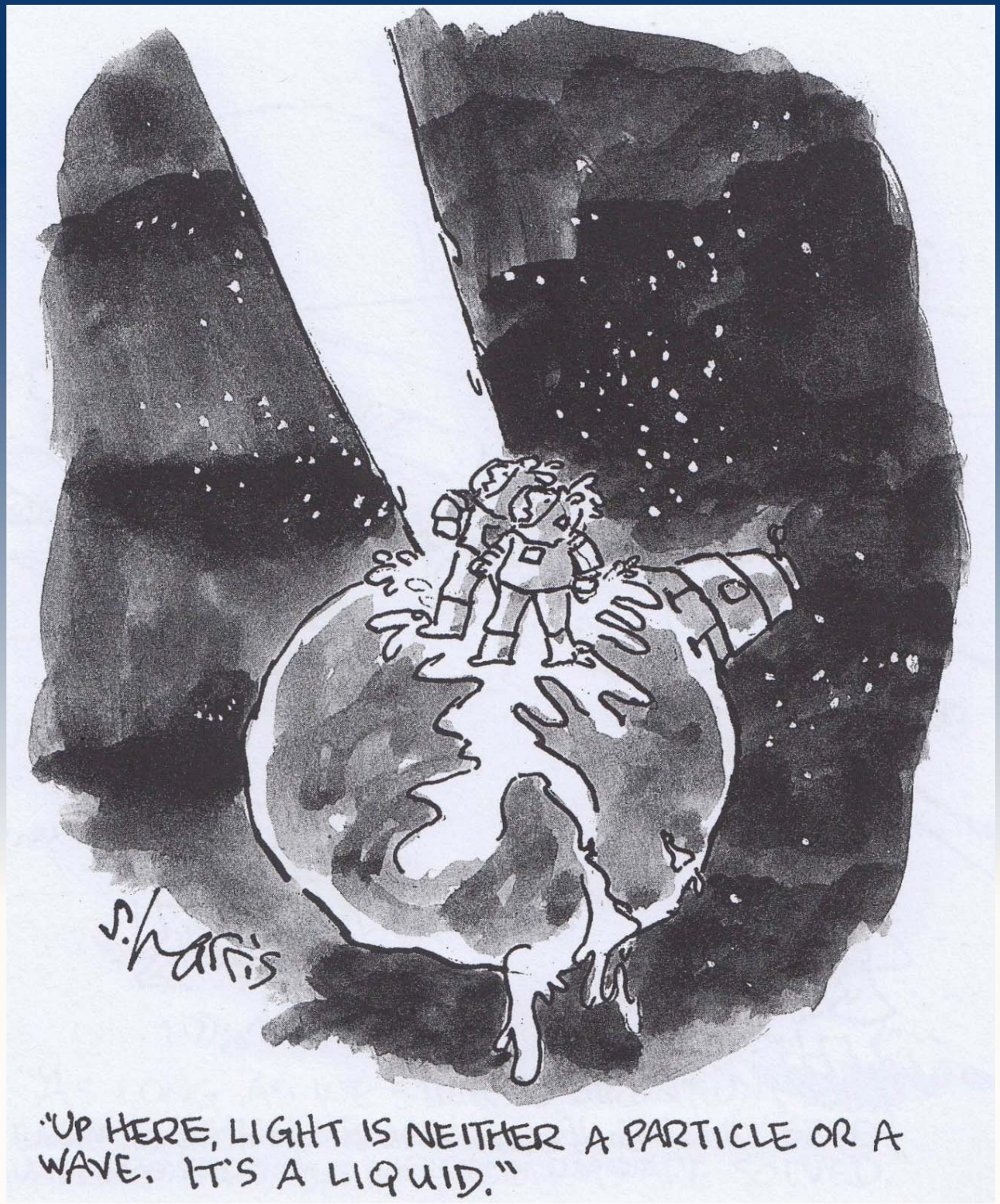


“Make no small plans Dream no small dreams”



George Ellery Hale

(1868-1938)



(Sidney Harris)


THE
END