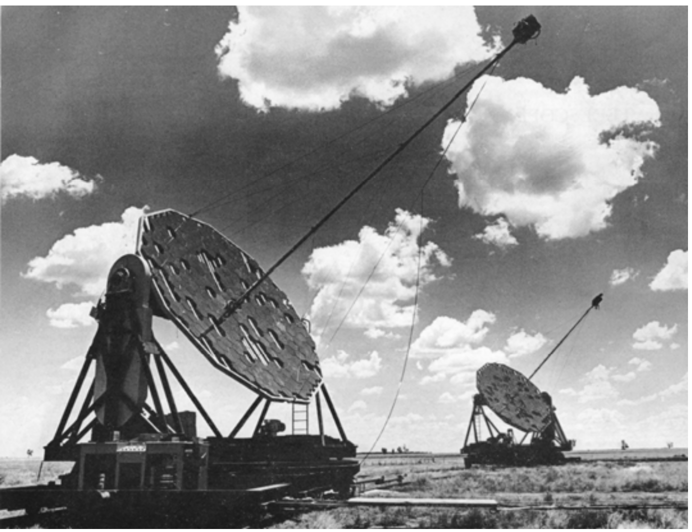
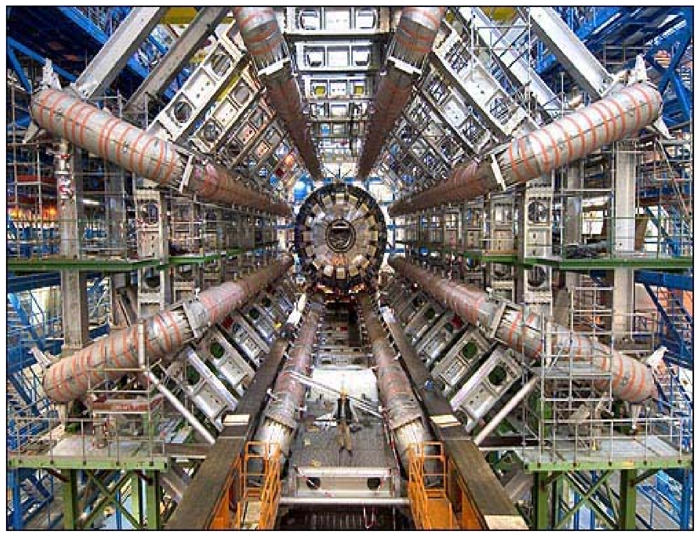
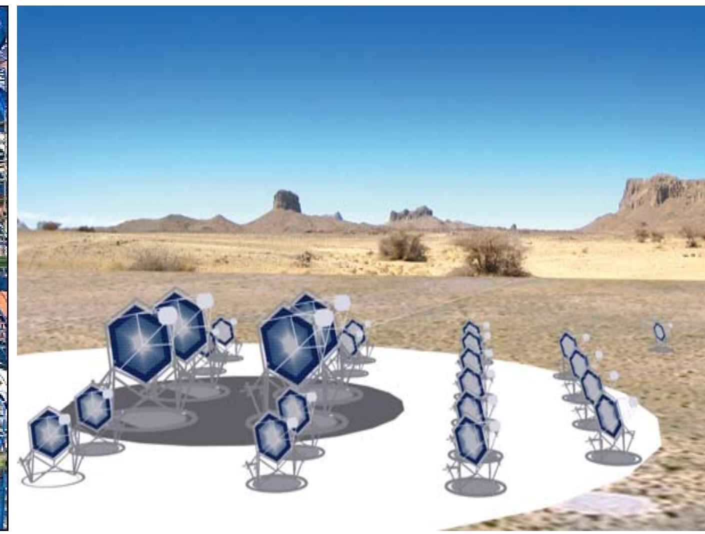
BOSON INTERFEROMETRY

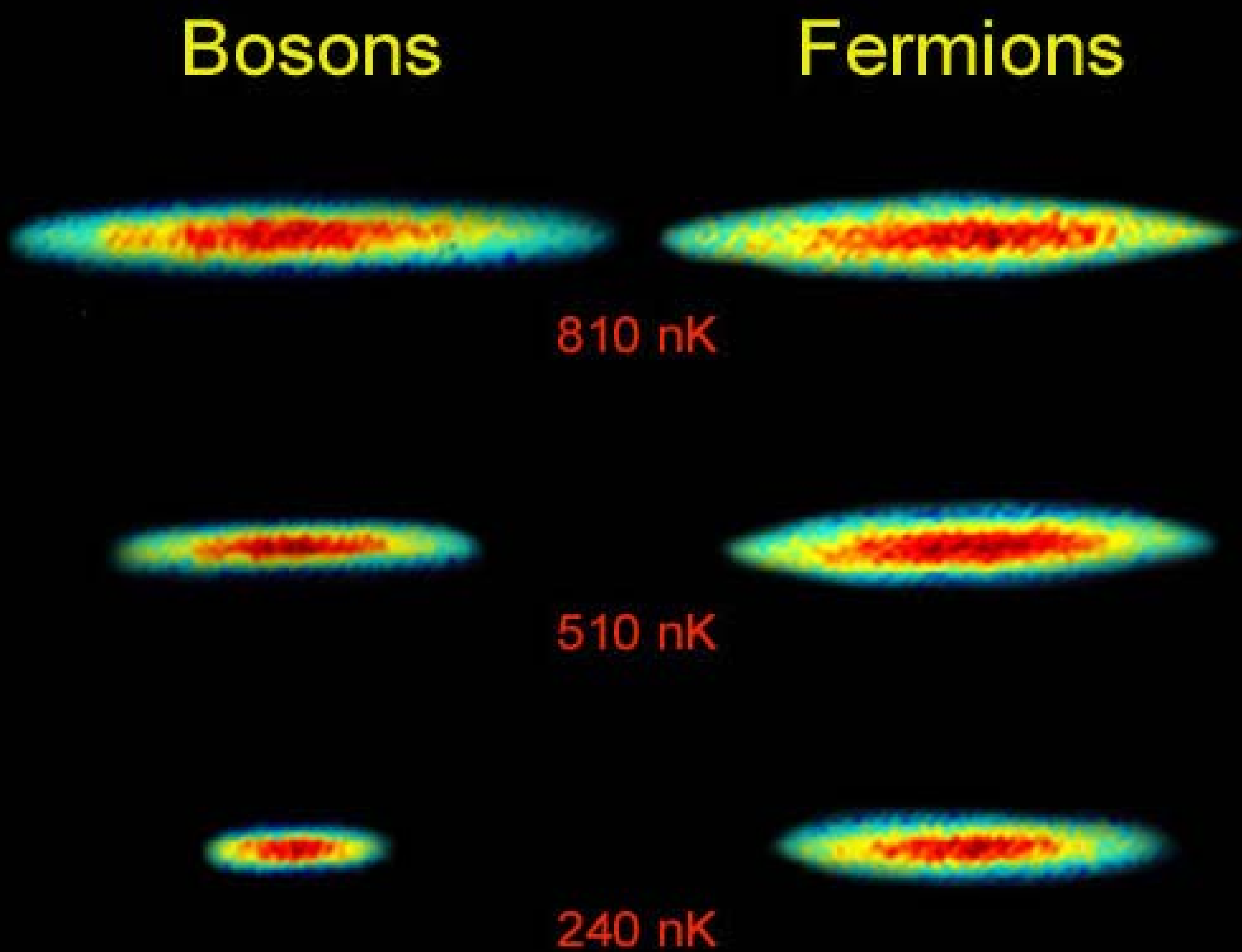
From astronomy to particle physics, and back

Dainis Dravins

www.astro.lu.se/~dainis

LUND UNIVERSITY



BOSONS BUNCH TOGETHER, FERMIONS DON'T

Pauli exclusion principle:
Fermions cannot share the same quantum state

(but bosons can! ☺)

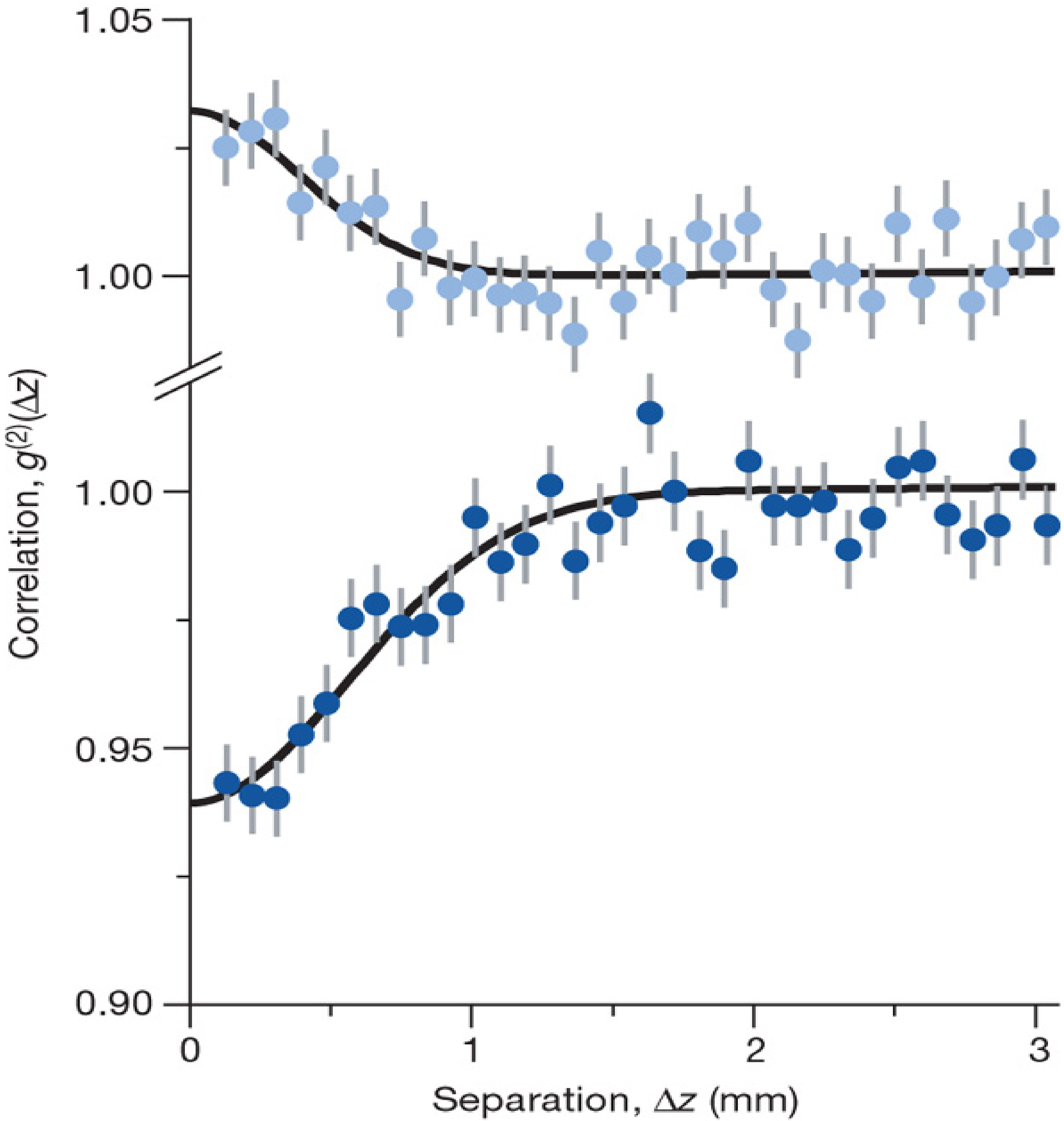
Bose-Einstein condensates of lithium isotopes;

Left: ^{7}Li bosons (integer spin)

Right: ^{6}Li fermions

As temperature drops, bosons bunch together, while fermions keep their distance

Truscott & Hulet (Rice Univ.)



Correlation functions at T=0.5 μK

Top: ^{4}He (bosons)

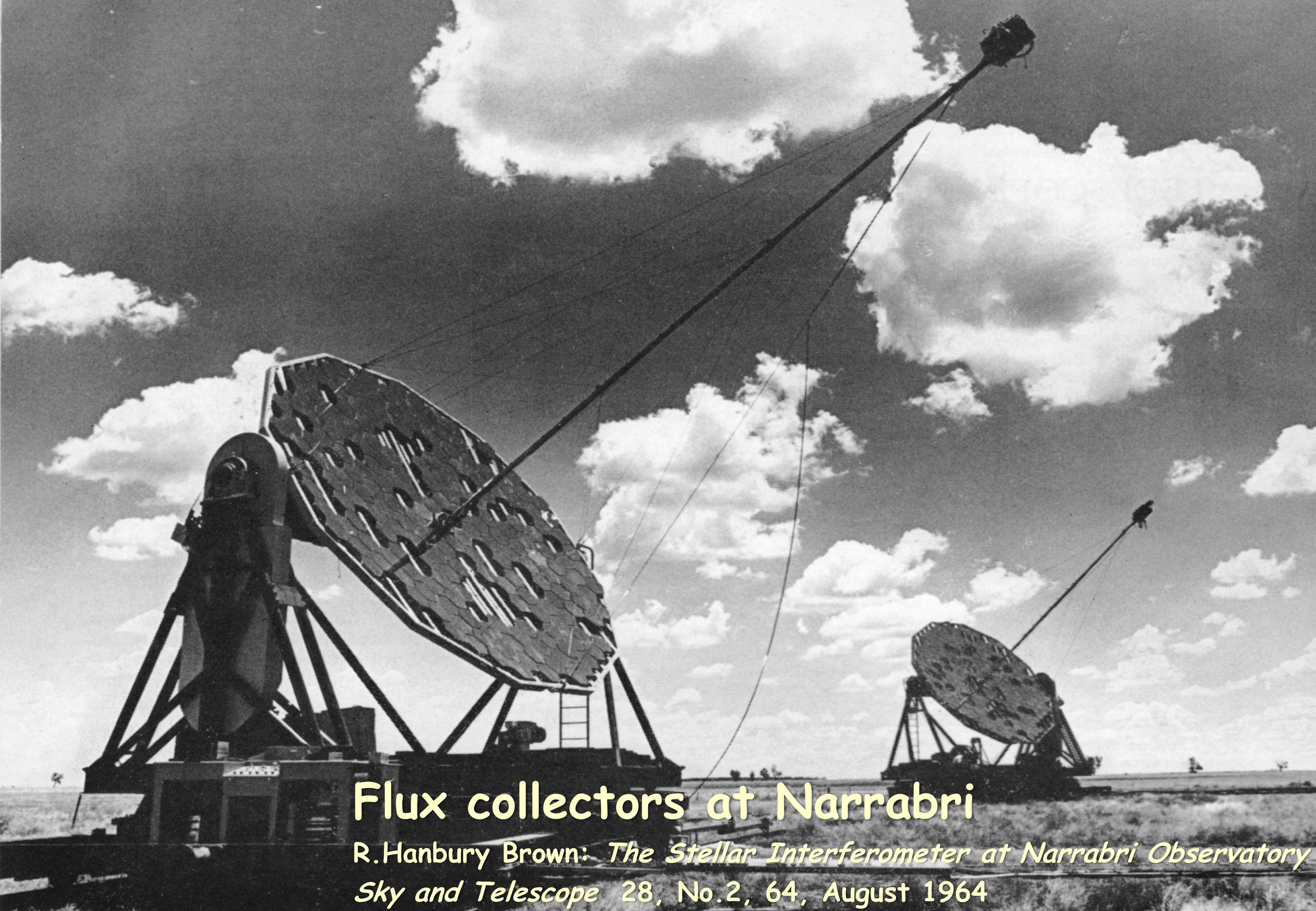
Bottom: ^{3}He (fermions)

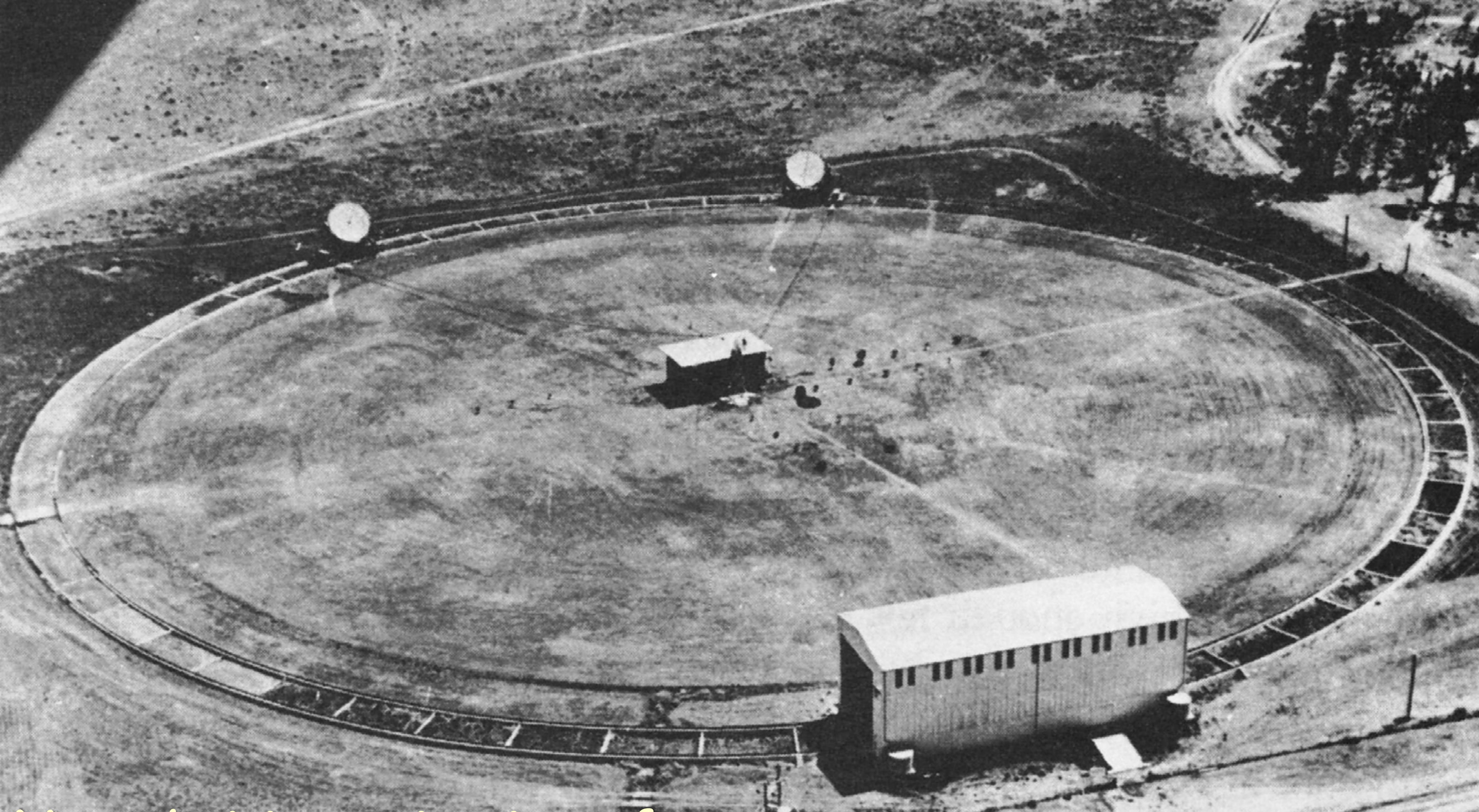
Bosons show bunching;
fermions show antibunching

Jeltes et al.: Comparison of the Hanbury Brown–Twiss effect for bosons and fermions
Nature **445**, 402 (2007)

It began a long, long time ago, in a place far, far away*…

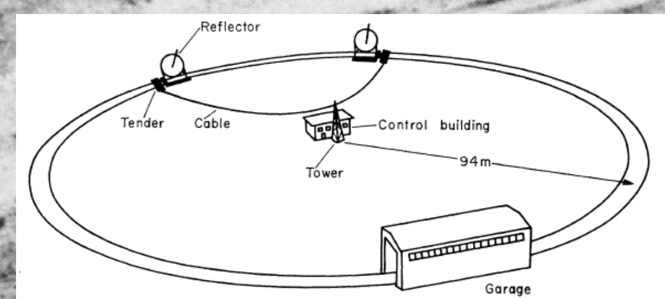
*Narrabri, New South Wales


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

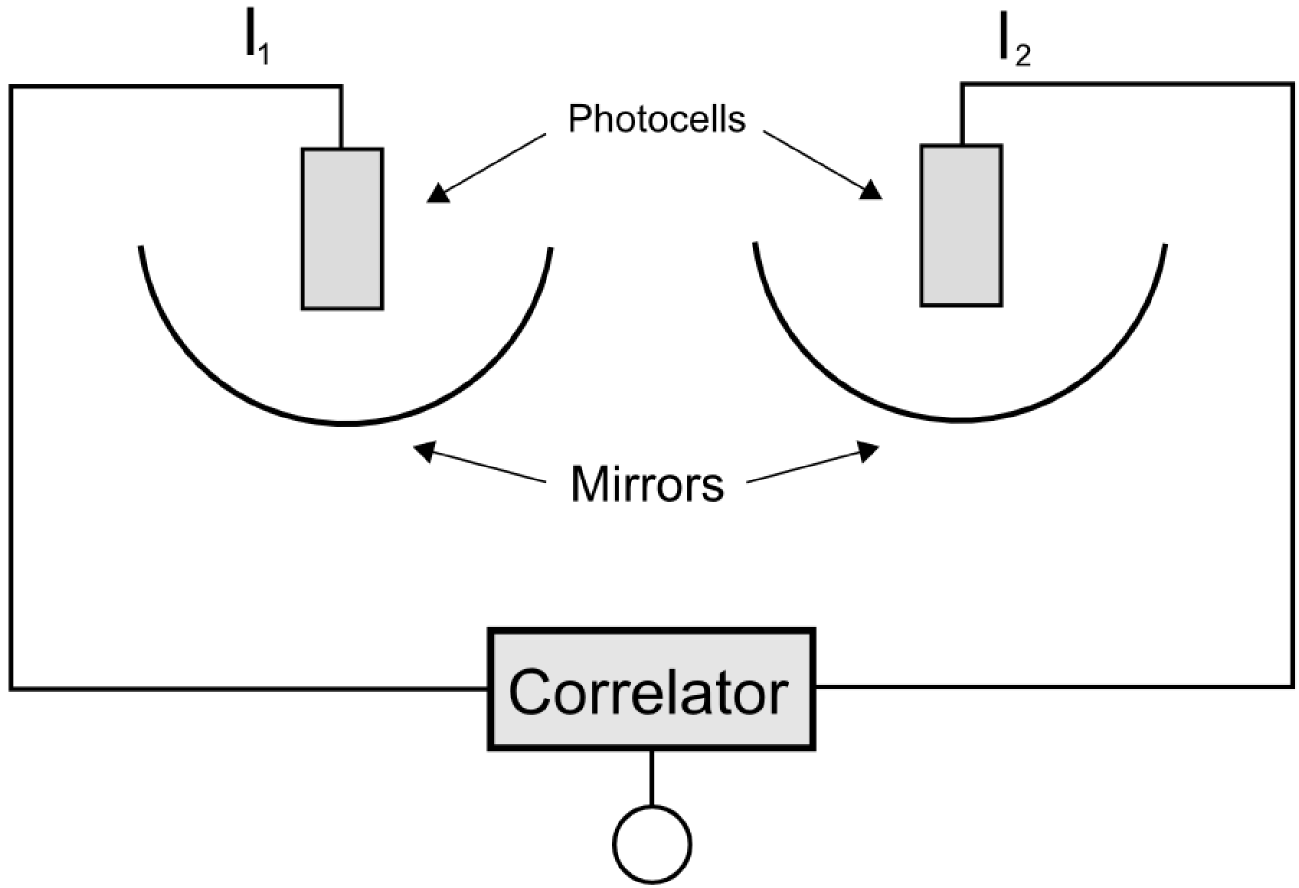


Narrabri intensity interferometer
with its circular railway track

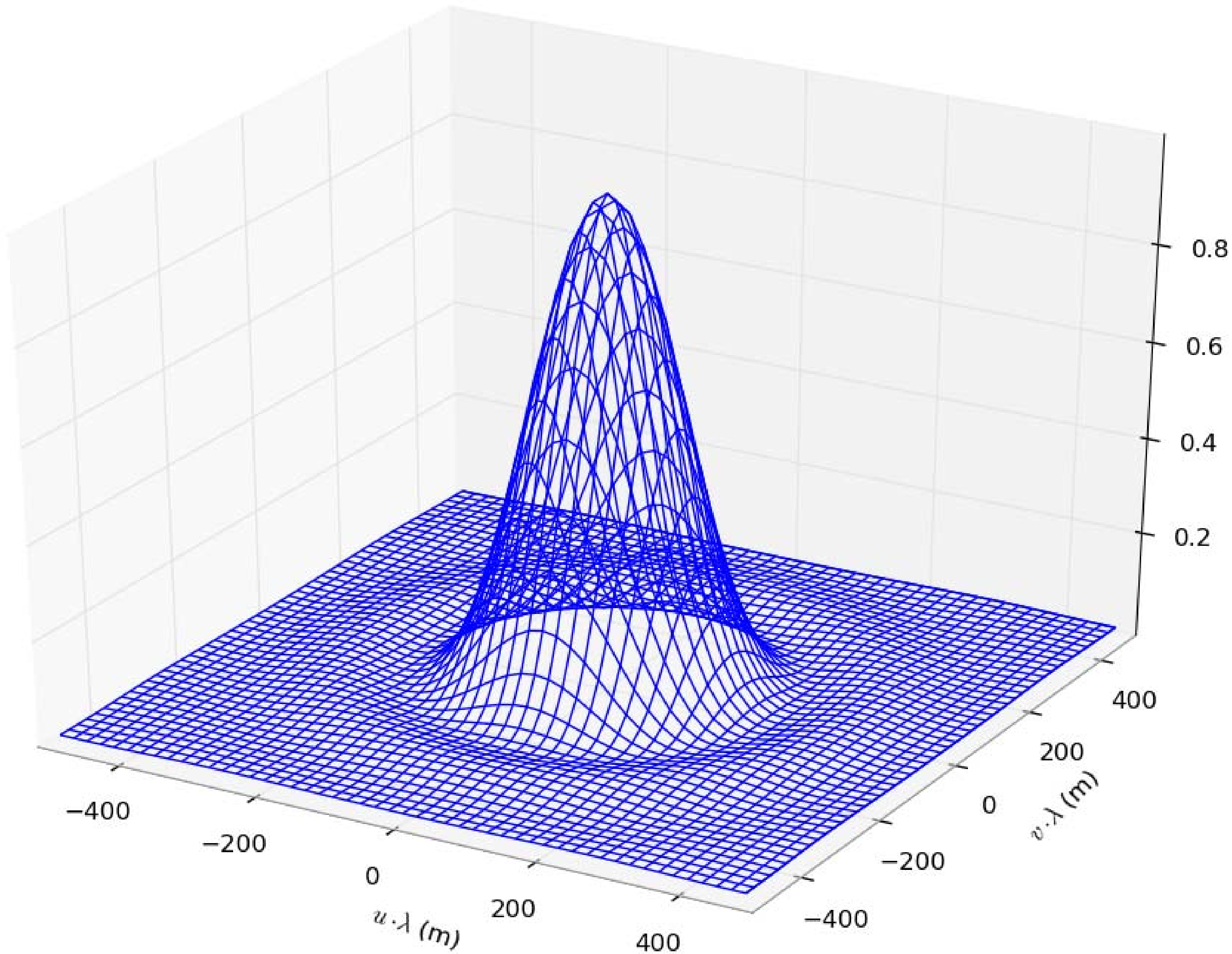
R.Hanbury Brown: *BOFFIN. A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics* (1991)



Intensity interferometry



OBSERVATIONS IN INTENSITY INTERFEROMETRY



Squared visibility ("diffraction pattern"), of a stellar disk of angular diameter 0.5 mas.

Z = normalized second-order coherence

(Hannes Jensen, Lund Observatory, 2010)

Intensity interferometry

Pro: Time resolution of 10 ns implies 3 m light travel time; no need for any more accurate optics nor atmosphere.

Short wavelengths no problem; hot sources observable

Con: Signal comes from two-photon correlations, increases as signal squared; requires large flux collectors

PHOTON CORRELATIONS*

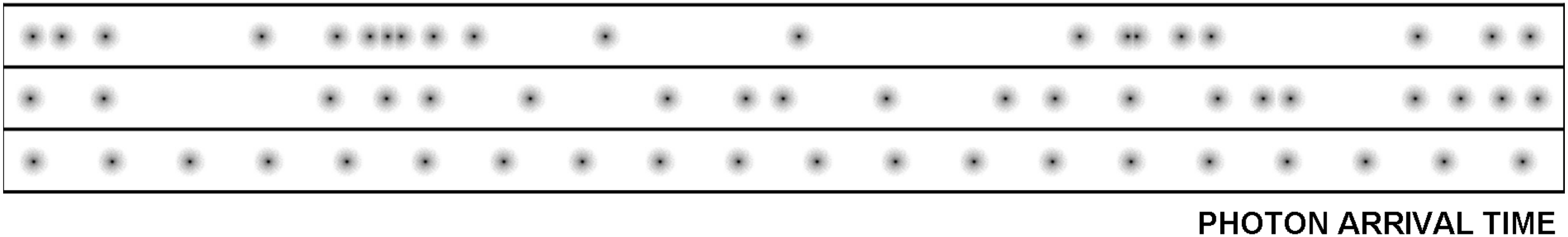
Roy J. Glauber
Lyman Laboratory, Harvard University, Cambridge, Massachusetts
(Received 27 December 1962)

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

PHOTON STATISTICS



Top: Bunched photons (Bose-Einstein; 'quantum-random')

Center: Antibunched photons (like fermions)

Bottom: Coherent and uniformly spaced (like ideal laser)

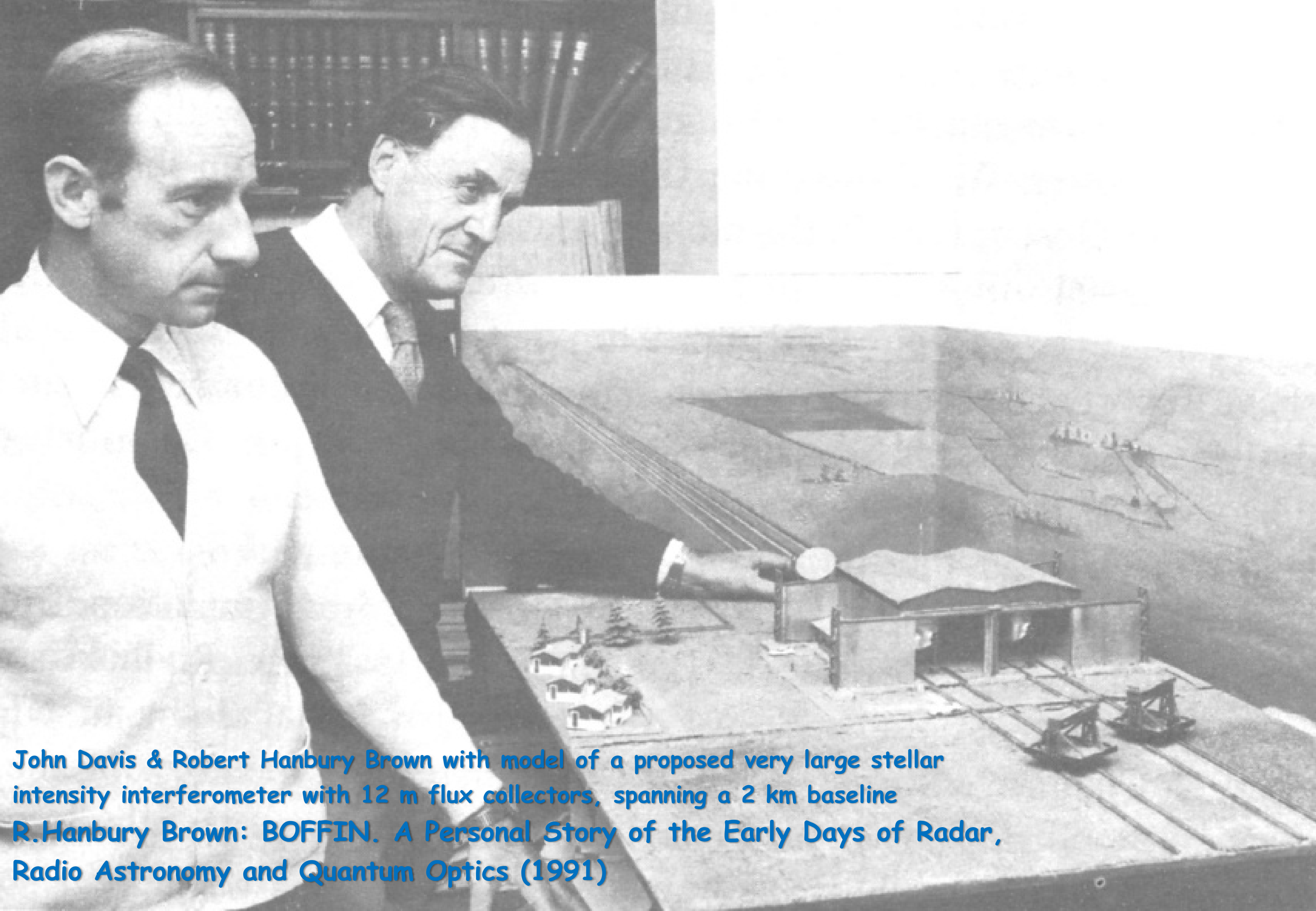
After R. Loudon: *The Quantum Theory of Light* (2000)

Roy Glauber

Nobel prize in physics

Stockholm, December 2005

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



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)



Sic transit gloria mundi…

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

Photos: D.Dravins

Astronomy out …
particle physics in

FIRST BOSON CORRELATIONS 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

(Received May 16, 1960)

Recent observations of angular distributions of π mesons in $\bar{p}$-p annihilation indicate a deviation from the predictions of the usual Fermi statistical model. In order to shed light on these phenomena, a modification of the statistical model is studied. We retain the assumption that the transition rate into a given final state is proportional to the probability of finding N free π mesons in the reaction volume, but express this probability in terms of wave functions symmetrized with respect to particles of like charge. The justification of this assumption is discussed. The model reproduces the experimental results qualitatively, provided the radius of the interaction volume is between one-half and three-fourths of the pion Compton wavelength; the dependence of angular correlation effects on the value of the radius is rather sensitive. Quantitatively, there seems to remain some discrepancy, but we cannot say whether this is due to experimental uncertainties or to some other dynamic effects. In the absence of information on π-π interactions and of a fully satisfactory explanation of the mean pion multiplicity for annihilation, we wish to emphasize the preliminary nature of our results. We consider them, however, as an indication that the symmetrization effects discussed here may well play a major role in the analysis of angular distributions. It is pointed out that in this respect the energy dependence of the angular correlations may provide valuable clues for the validity of our model.

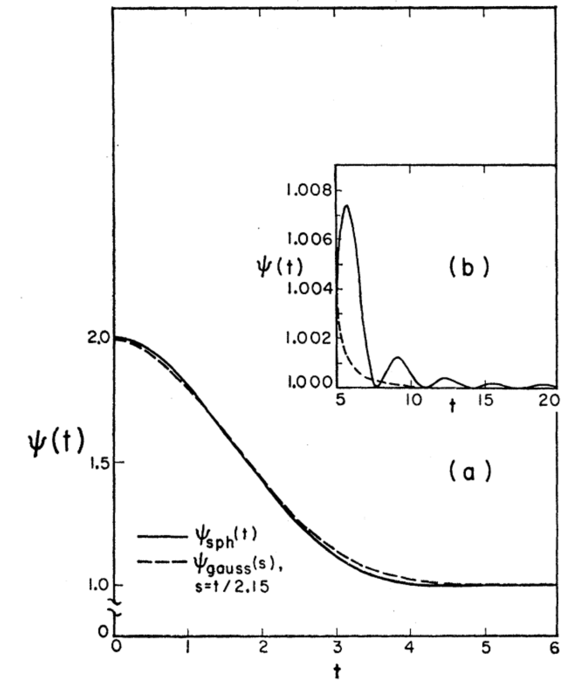


FIG. 1. Evaluation of the correlation functions as a function of the argument. Here $\psi_{\rm sph}{}^{(t)}$ and $\psi_{\rm gauss}{}^{(s)}$ correspond to the spherical and Gaussian models, respectively. As can be seen from the figure, the curves corresponding to the two models differ by about 2% at most. Note that the insert [Fig. 1(b)] is enlarged by a factor of 100 vertically and is reduced by a factor of 5 horizontally.

In a 1959 bubble-chamber study of charged pion production in proton/antiproton annihilation, the angular distribution of like-charge pion pairs was found to differ from the unlike-charge ones.

In a now classic paper, this was interpreted as due to Bose-Einstein correlations (GGLP 1960).

However, the connection with the Hanbury Brown-Twiss effect was realized only in the 1970's.

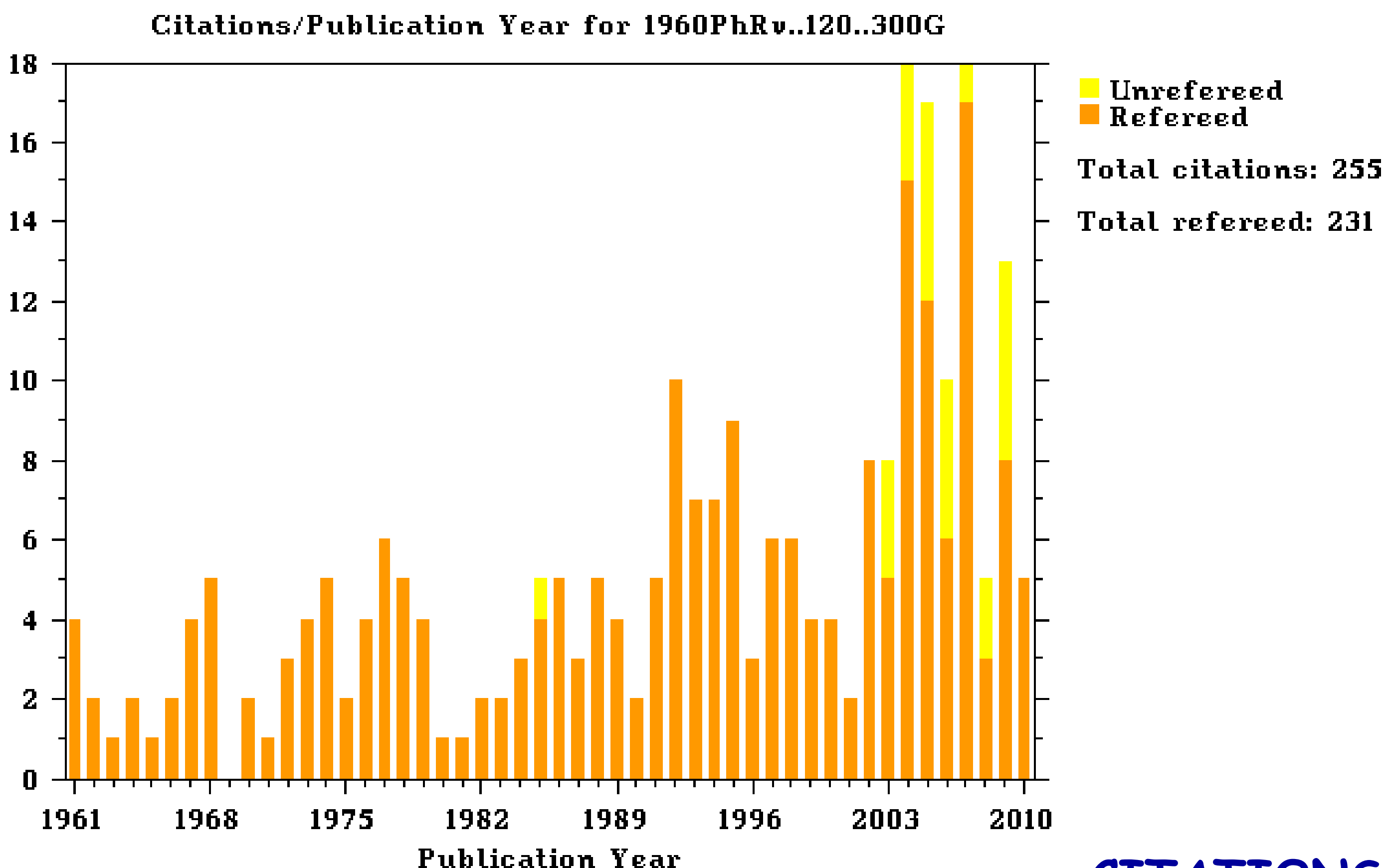
… and the rest is history

FIRST BOSON CORRELATIONS 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†



CITATIONS HISTORY [ADS]

PARTICLE PHYSICS

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
members of our Brazilian group.

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-Gaussian shape analysis as well as many other new directions. Existing models are compared to two-particle correlation measurements and the so-called RHIC HBT puzzle is resolved. Evidence for a (directional) Hubble flow is presented and the conclusion is confirmed by a successful description of the pseudorapidity dependence of the elliptic flow as measured in Au+Au collisions by the PHOBOS Collaboration.

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

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, Michigar
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

Annu. Rev. Nucl. Part. Sci. 1999. 49:529–79

TWO-PARTICLE CORRELATIONS IN RELATIVISTIC HEAVY-ION COLLISIONS

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Barbara V. Jacak
Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794; 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
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THE PHYSICS OF HANBURY BROWN–TWISS INTENSITY INTERFEROMETRY: FROM STARS 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 correlations of s
Their su
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quantum
has beco
providing
effect is
depends
the basic
in high e
matter a

Annu. Rev. Nucl. Part. Sci. 2005. 55:357–402
doi: 10.1146/annurev.nucl.55.090704.151533

FEMTOSCOPY IN RELATIVISTIC HEAVY ION COLLISIONS: Two Decades of Progress

Michael Annan Lisa
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Scott Pratt
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Ron Soltz
N-Division, Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550; email: soltz1@llnl.gov

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.

N·H
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 $e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2 q_3\bar{q}_4$ 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.

N·H
ELSEVIER
PHYSICS REPORTS
Physics Reports 319 (1999) 145–230
www.elsevier.com/locate/physrep

Particle interferometry for relativistic heavy-ion collisions

Urs Achim Wiedemann[a,*], Ulrich Heinz[b,c]

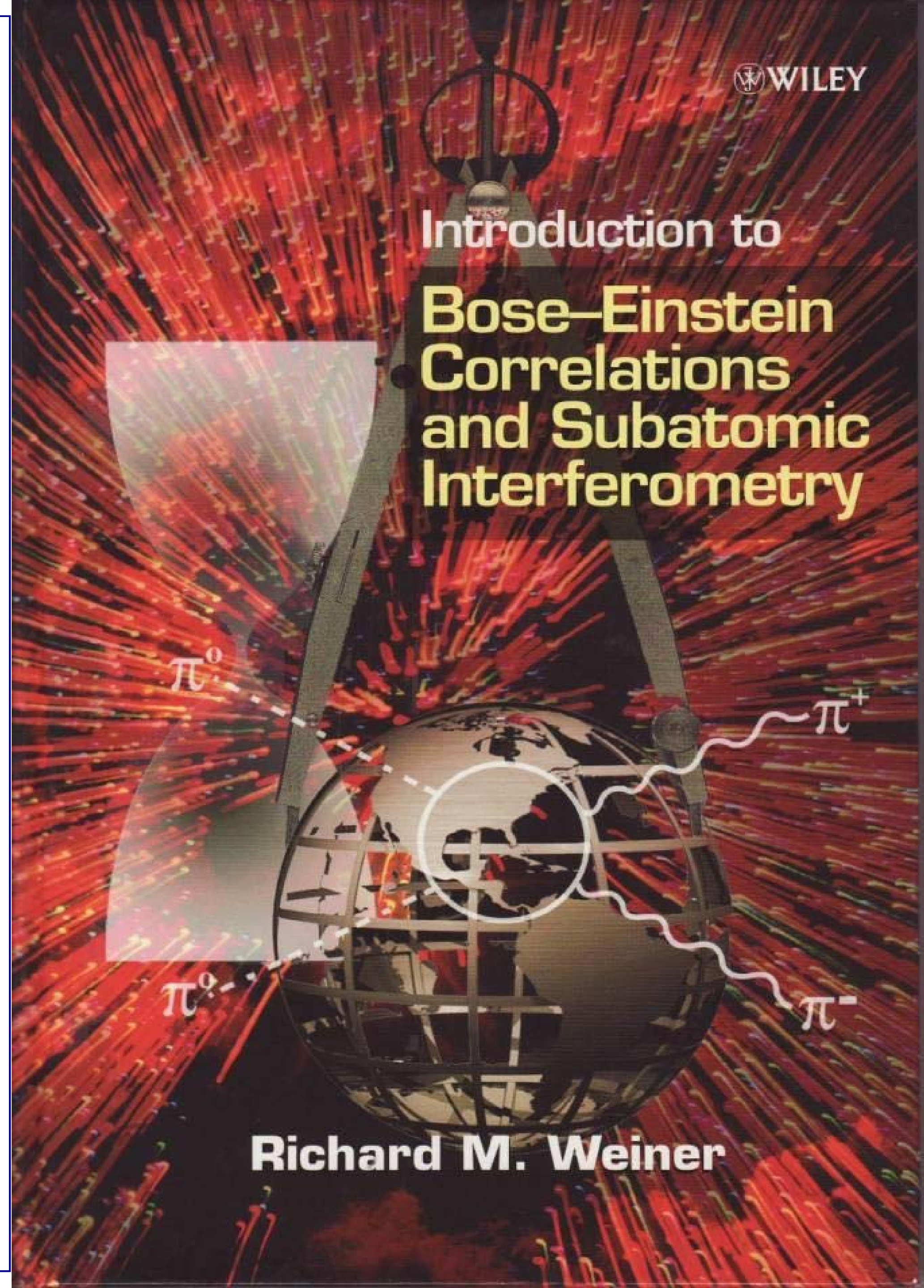
[a] *Physics Department, Columbia University, New York, NY 10027, USA*
[b] *Theory Division, CERN, CH-1211 Geneva 23, Switzerland*
[c] *Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany*

Received February 1999; editor: W. Weise

Contents

Abstract

In this report we give a detailed account on Hanbury Brown/Twiss (HBT) particle interferometric methods for relativistic heavy-ion collisions. These exploit identical two-particle correlations to gain access to the space-time geometry and dynamics of the final freeze-out stage. The connection between the measured correlations in momentum space and the phase-space structure of the particle emitter is established, both with and without final state interactions. Suitable Gaussian parametrizations for the two-particle correlation



PHYSICAL REVIEW A VOLUME 56, NUMBER 3 SEPTEMBER 1997

Hanbury-Brown-Twiss interferometry for sonoluminescence bubble

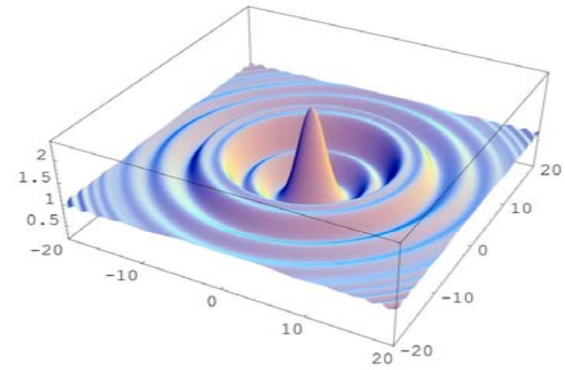
Y. Hama,[1] T. Kodama,[2] and Sandra S. Padula[3]
[1]*Instituto de Física, Universidade de São Paulo, Caixa Postal 66318, 05315-970 São Paulo, Brazil*
[2]*Instituto de Física, Universidade Federal do Rio de Janeiro, Caixa Postal 68.528, 21945-970 Rio de Janeiro, Brazil*
[3]*Instituto de Física Teórica, UNESP, Rua Pamplona 145, 01405-901 São Paulo-SP, Brazil*
(Received 30 December 1996; revised manuscript received 22 April 1997)

Two-photon correlation of the light pulse emitted from a sonoluminescence bubble is discussed. It is shown that several important features of the mechanism of light emission, such as the time scale and the shape of the emission region, could be obtained from Hanbury-Brown-Twiss interferometry. We also argue that such a measurement may serve to reject one of the two currently suggested emission mechanisms, i.e., the thermal process versus the dynamical Casimir effect.

ALSO OTHER FIELDS

The Origin of Sonoluminescence

(or measuring the size of the light-emitting region in a sonoluminescencing bubble)



Jeppe Seidelin Dam
Supervisor: Mogens T. Levinsen

June 2006
Niels Bohr Institute
University of Copenhagen

DET NATURVIDENSKABELIGE FAKULTET
KØBENHAVNS UNIVERSITET

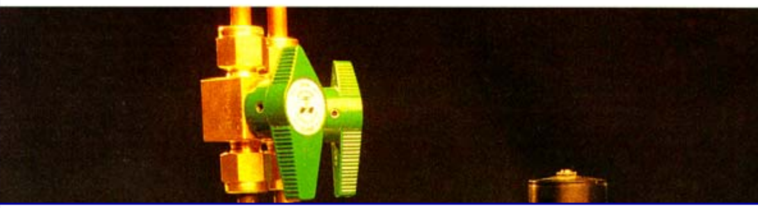
Sonoluminescence: Sound into Light

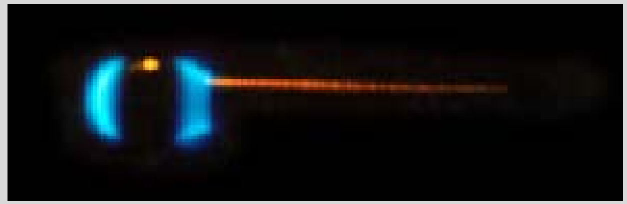
A bubble of air can focus acoustic energy a trillionfold to produce picosecond flashes of light. The mechanism eludes complete explanation

Sci.Am. Feb.1995

by Seth J. Putterman

Imagine you are riding a roller coaster. First, you chug up a long incline slowly. When you get to the top, your car free-falls, speeding up until it reaches the bottom of the drop, where the deceleration crams you into your seat. That sensation is what you would feel if you were riding a pulsating bubble of air trapped in water—except that the drop would reach supersonic speeds and at the bottom you would be crushed into your seat with a force equal to 1,000 billion times your weight. Obviously, more than your stomach would react to such a ride. As for the bubble, it responds to the extraordinary force by creating a flash of light only a tiny fraction of a second long. The light





(Excerpt from page 11-12)

Hanbury-Brown Twiss intensity interference

Astronomers measure the size of a star by a method developed by Hanbury-Brown and Twiss [32]. The same method can be applied on a much smaller scale, namely our star in a jar. Theoretical estimates for sonoluminescence have been made by Hama *et al* [33] and Slotta *et al* [34]. Estimates similar to the latter has been done by Putterman [35] and in my master thesis [36]. However, all estimates predict small correlations, which make it quite difficult to measure, firstly because the dataset has to be large, and furthermore because even small systematic errors and disturbances can cause much larger effects.

Using 1 nm filters for 400 nm wavelengths, the theoretical HBT-correlation for a 100 ps flash (according to [34]) is about 0.0002. To measure this value with some std. dev. certainty requires correlating about 10^9 photon events. If the two channelsyou correlate measure a photon 10% of the time, then you have to measure for 10^{11} flashes 2 months non-stop. In other words it easily takes a week or a month to acquire enough data to realize something is wrong. This makes it a very cumbersome and time consuming measurement, if not bordering on impossible. I spent a lot of time during the work for my master thesis trying to measure this effect (without success as you can guess).

REVIEWS OF MODERN PHYSICS, VOLUME 74, APRIL 2002

Single-bubble sonoluminescence

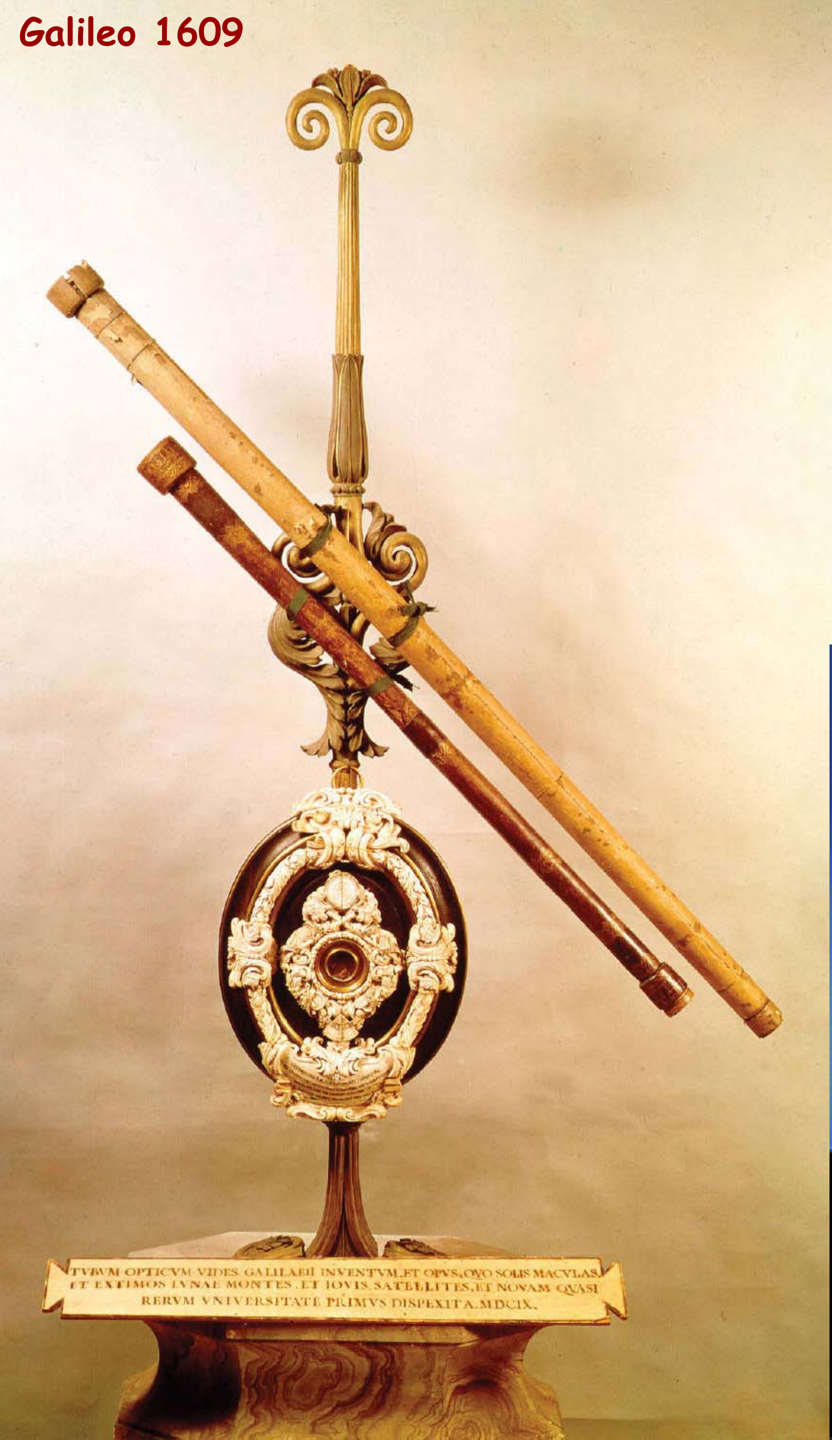
Michael P. Brenner
Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138

Sascha Hilgenfeldt and Detlef Lohse*
Department of Applied Physics and J. M. Burgers Centre for Fluid Dynamics, University of Twente, 7500 AE Enschede, The Netherlands

(Published 13 May 2002)

Single-bubble sonoluminescence occurs when an acoustically trapped and periodically driven gas bubble collapses so strongly that the energy focusing at collapse leads to light emission. Detailed experiments have demonstrated the unique properties of this system: the spectrum of the emitted light

Back to astronomy…

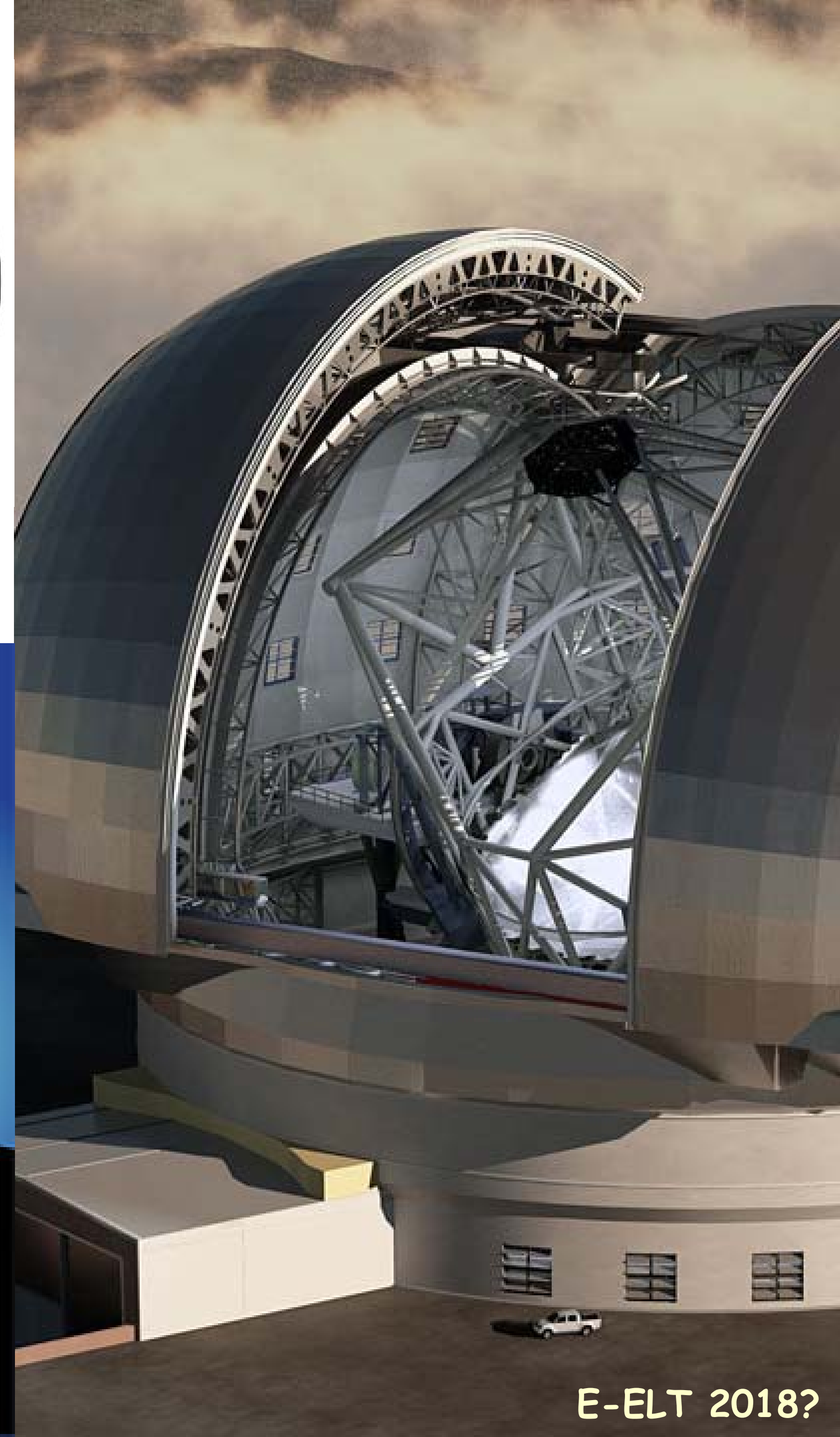


GALILEOSCOPE

IYA2009

UPPTÄCK
UNIVERSUM!

INTERNATIONELLA
ASTRONOMIÅRET
2009

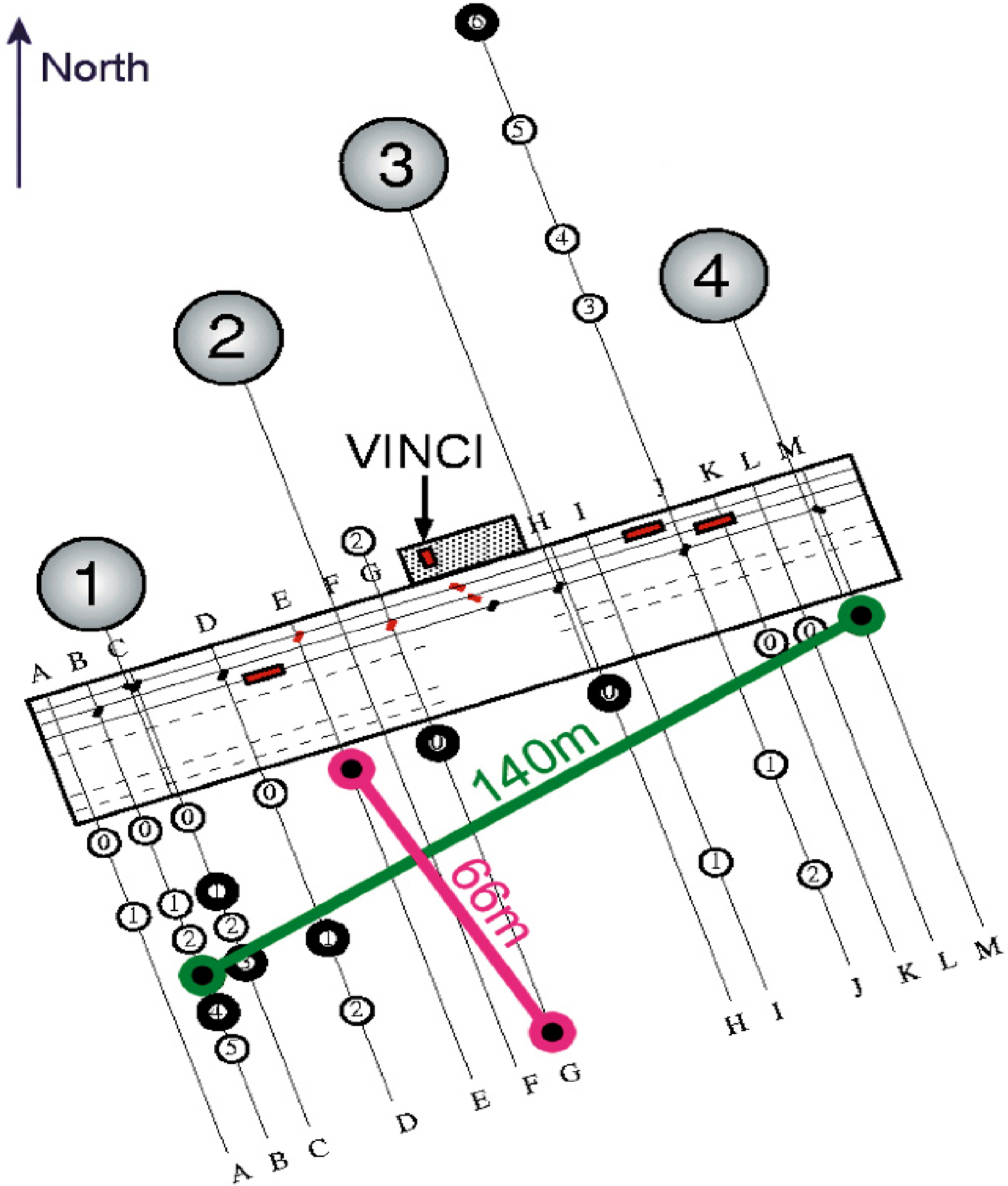


Spatial Resolution

1 arcsecond

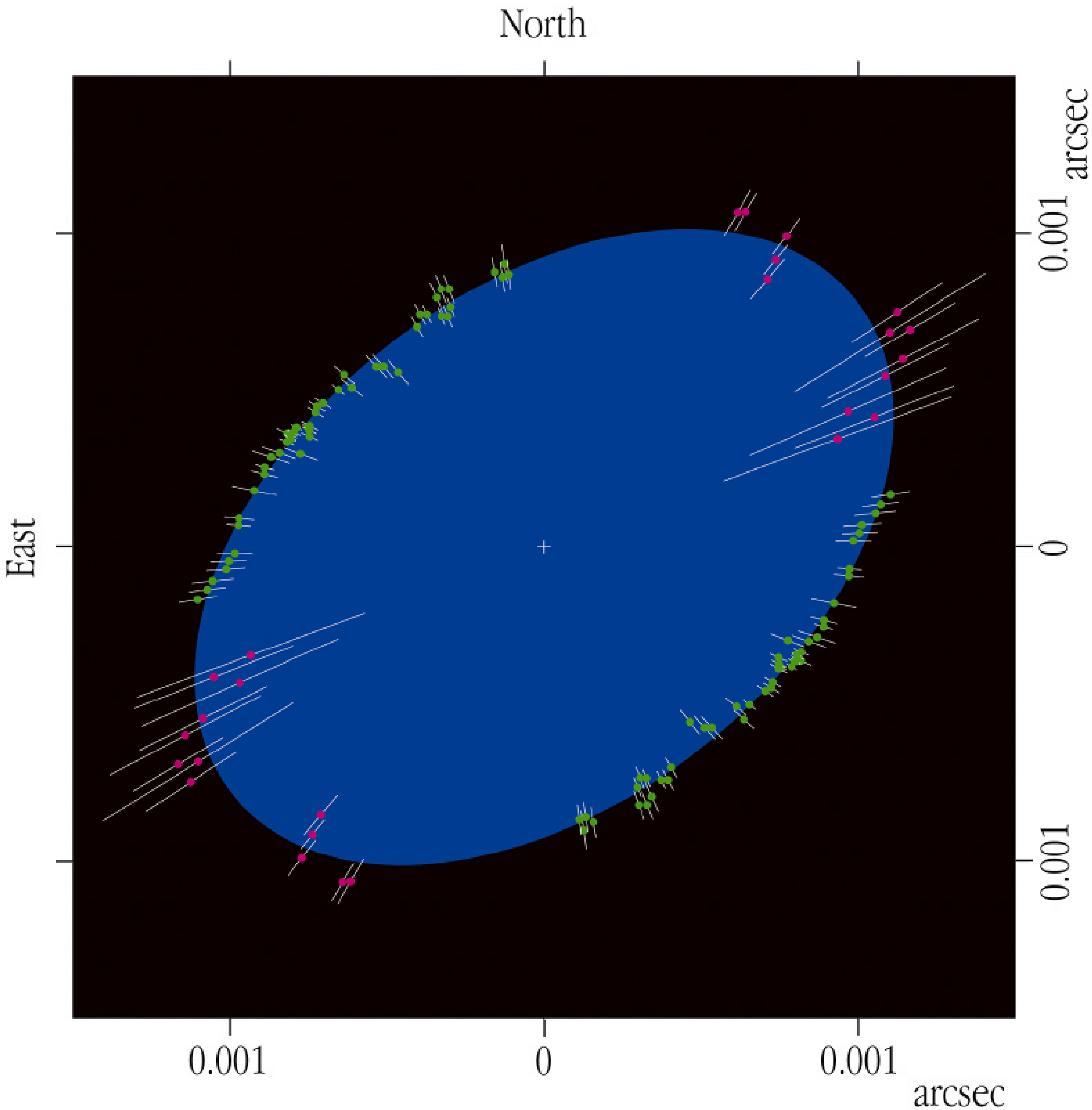
E-ELT
(diffraction limit a few milliarcsec in the near-IR)


ESO Paranal



VLTI Configuration for Measurements of Achernar

ESO PR Photo 15a/03 (11 June 2003)



SHAPE OF ACHERNAR

Image of the rapidly rotating (Vsin i ≈ 250 km/s) star *Achernar* (α Eri, B3 Vpe), from VLTI observations.

Axis ratio = 1.56, the most flattened star seen so far.

Because of the projection effect this ratio is a minimal value; the star could be even flatter.

Individual diameter measurements are shown by points with error bars.

Actual image of the Mira-type variable T Leporis from VLTI

Image obtained by combining hundreds of interferometric measurements

Central disc shows stellar surface, surrounded by a spherical shell of expelled molecular material

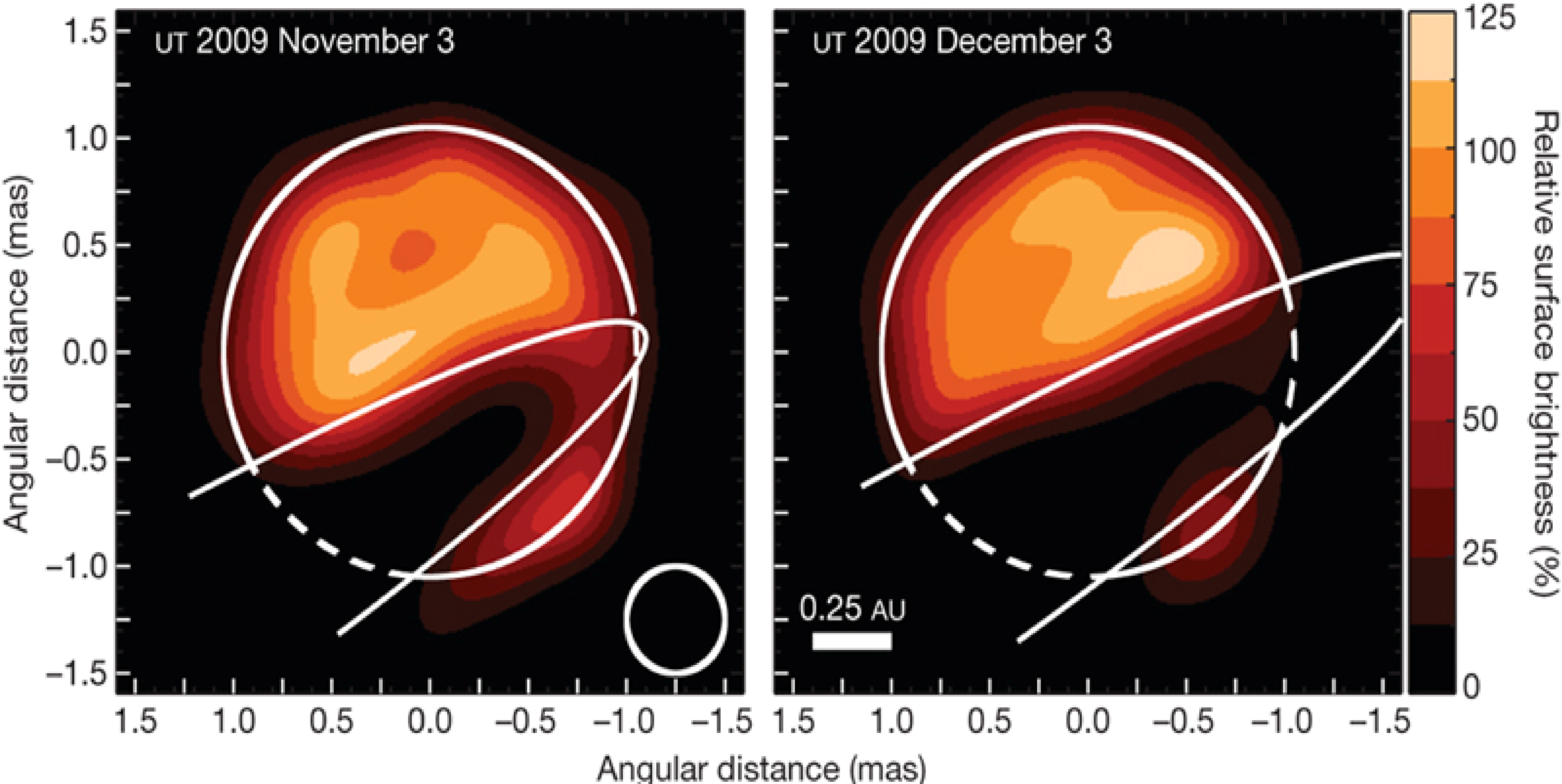
Infrared wavelengths color-coded:
Blue = 1.4 – 1.6 μm
Green = 1.6 – 1.75 μm
Red = 1.75 – 1.9 μm

In the green channel, the molecular envelope is thinner

The size of Earth's orbit is marked.

Resolution = 4 milli-arcseconds

(ESO press release 0906, Feb. 2009)



Interferometric images of the F-type giant ε Aurigae during its month-long eclipse by an opaque disk, occurring every 27 years

Infrared images of the transiting disk in the ϵ Aurigae system
Kloppenborg et al., Nature **464**, 870 (8 April 2010)

Many stars become resolved surface objects for baselines 100-1000 m

**The *Luciola* flotilla of many small collector mirrors operates like one giant diluted mirror.
Focal beam-combiners independently exploit the sky image formed at the focal surface.**

A.Labeyrie et al., *Luciola hypertelescope space observatory,* Exp.Astron. **23**, 463 (2009)
& ESA Cosmic Vision 2015-2025 proposal

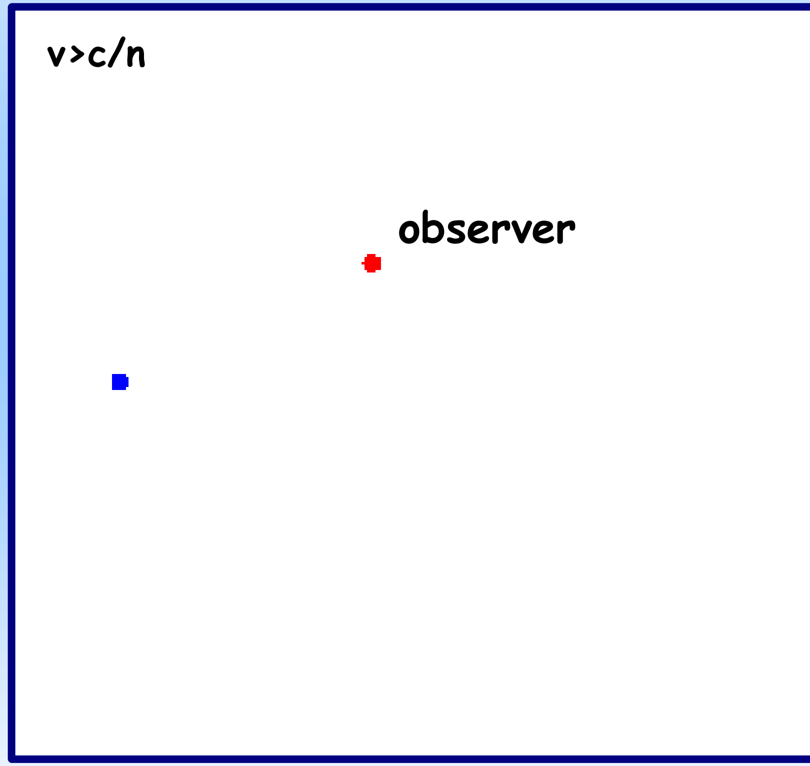
TOWARDS A DIFFRACTION-LIMITED SQUARE-KILOMETER OPTICAL TELESCOPE

DIGITAL REVIVAL OF INTENSITY INTERFEROMETRY

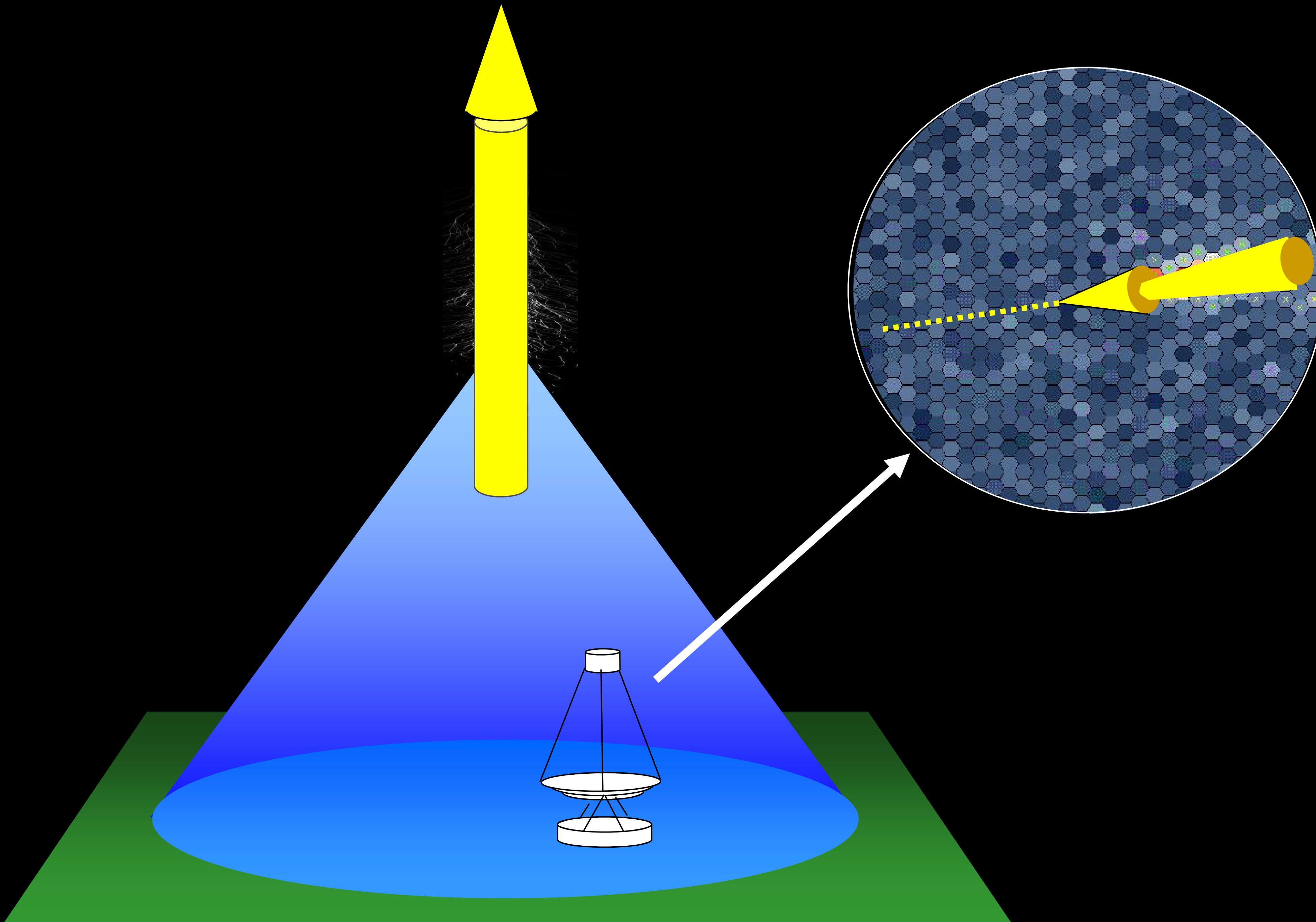
Air Cherenkov Telescopes

Cherenkov radiation

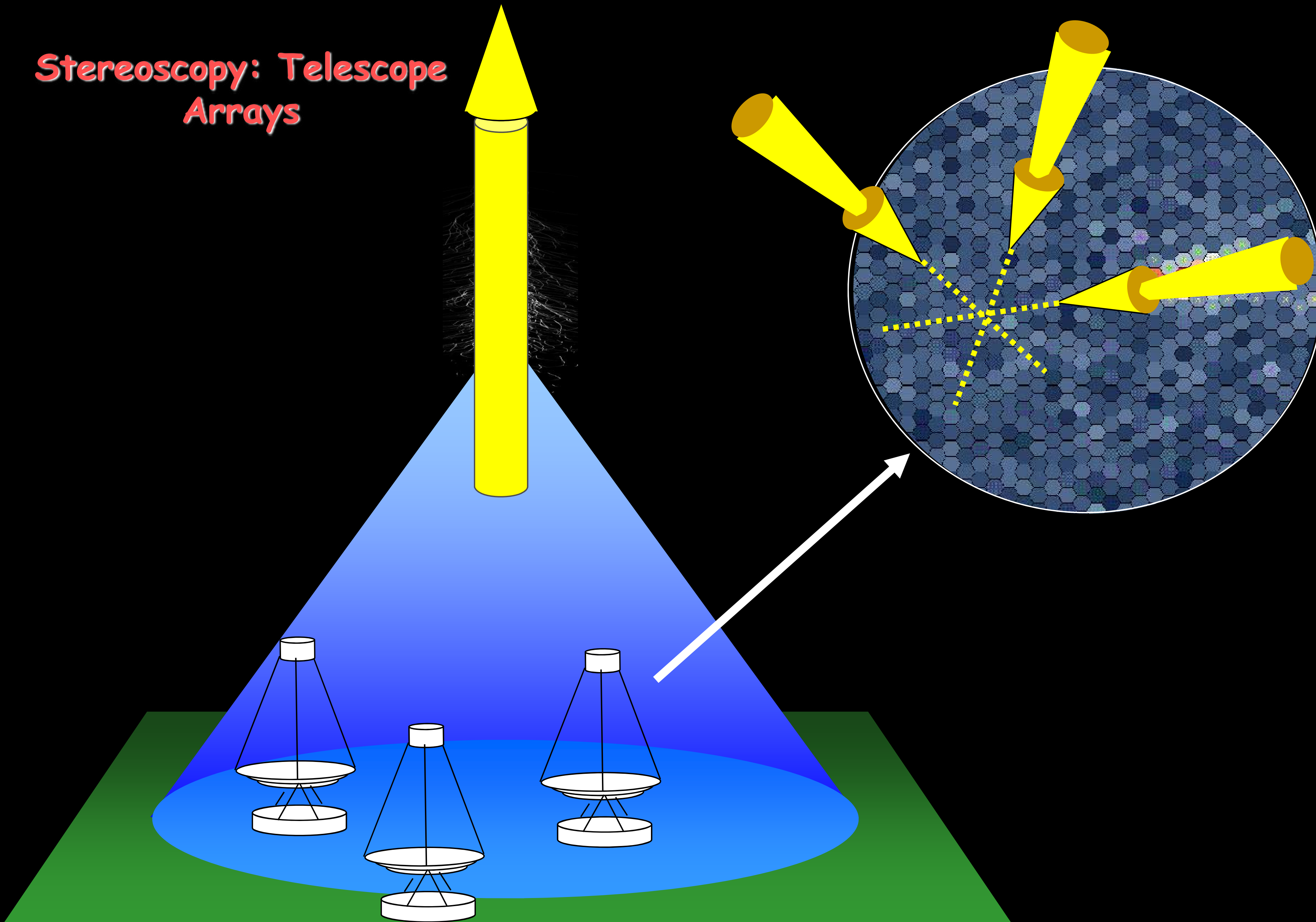
- The charged particles in the shower are moving faster than the speed of light in air (=c/n)
- A moving charge causes atoms in the atmosphere to become polarised and emit light

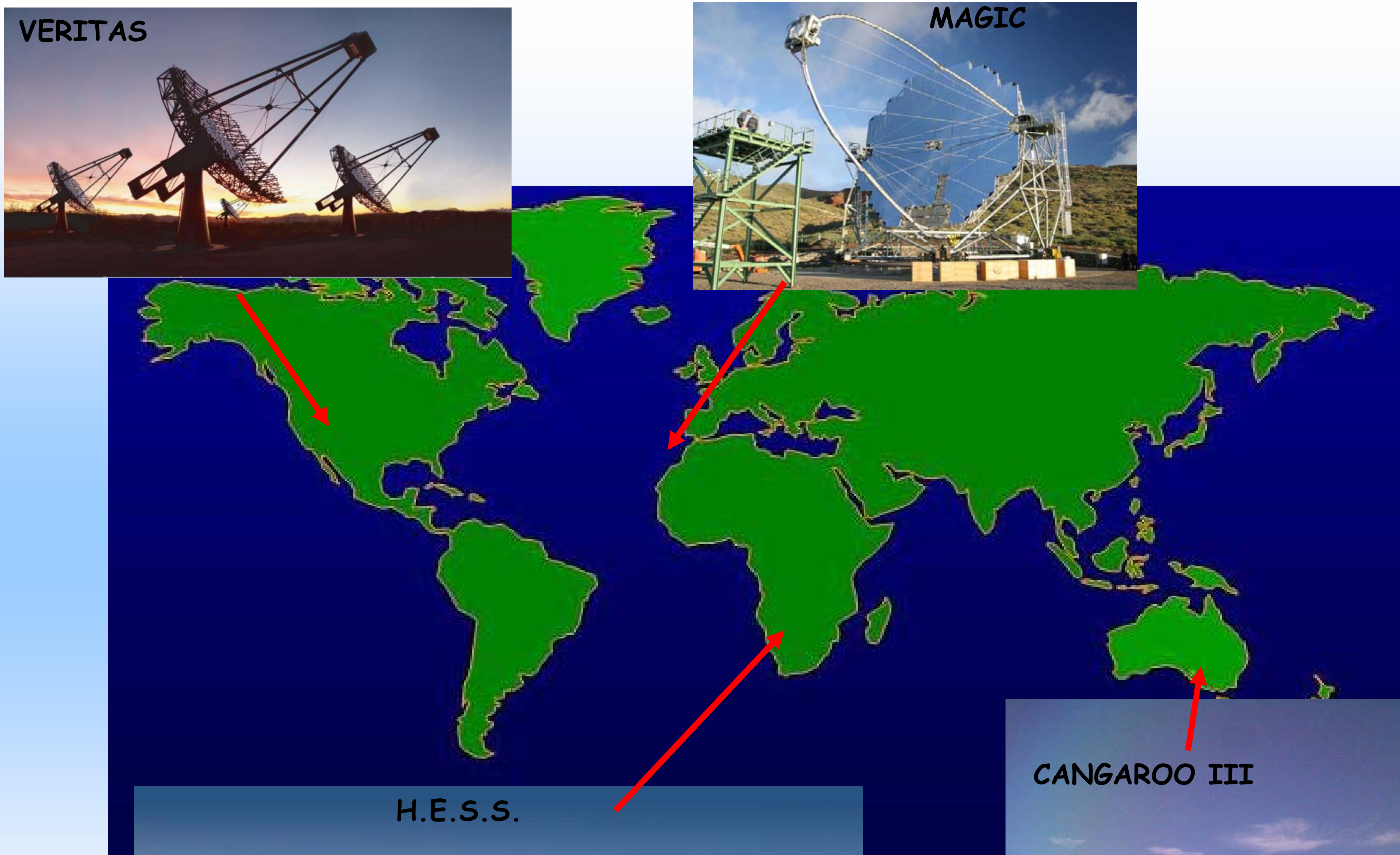


A fast particle causes a cone shaped "shock wave" -
The emission forms a coherent wavefront at the
Cherenkov angle $\cos\theta = 1/\beta n$ (~1.3° in air)



Stereoscopy: Telescope Arrays





AIR CHERENKOV TELESCOPES


MAGIC, Roque de los Muchachos, La Palma

MAGIC, Roque de los Muchachos, La Palma

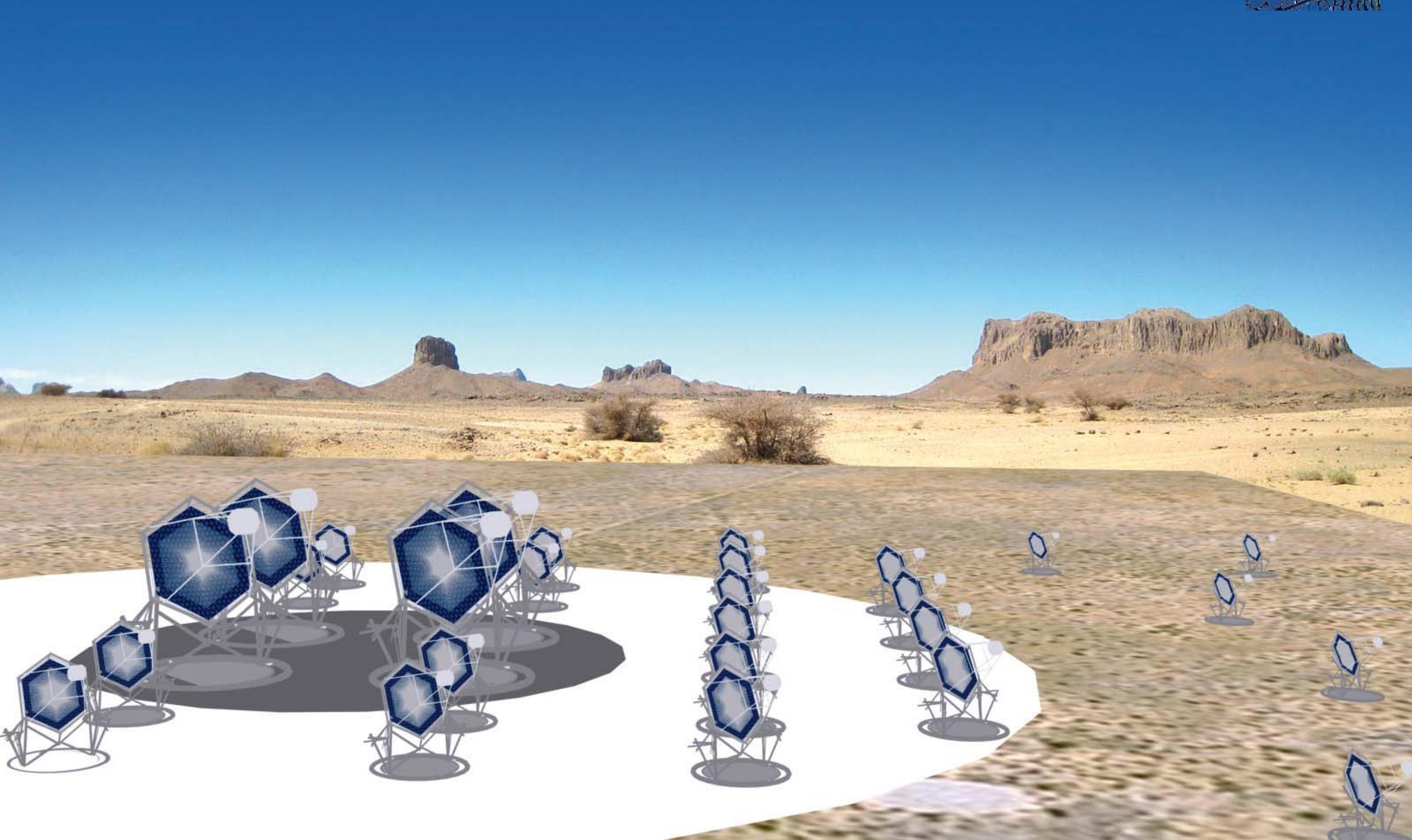
The four VERITAS telescopes at Basecamp, Arizona


VERITAS

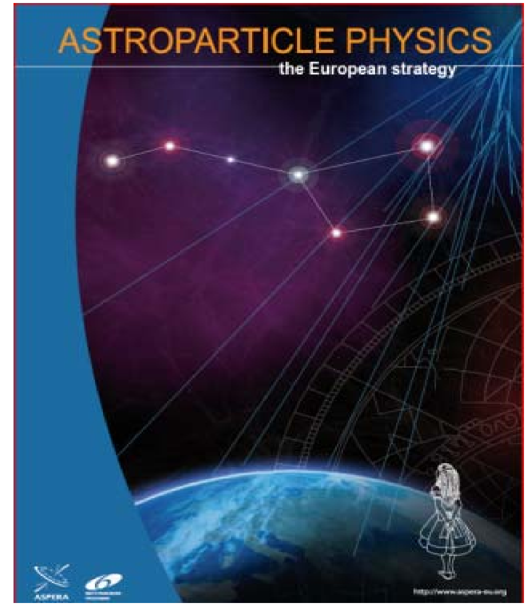
CTA, Cherenkov Telescope Array (2018?)

An advanced facility for ground-based gamma-ray astronomy

ASPERA, AStroParticle European Research Area / D.Rouable



PRIORITIES IN EUROPEAN ASTRONOMY 2010-2020

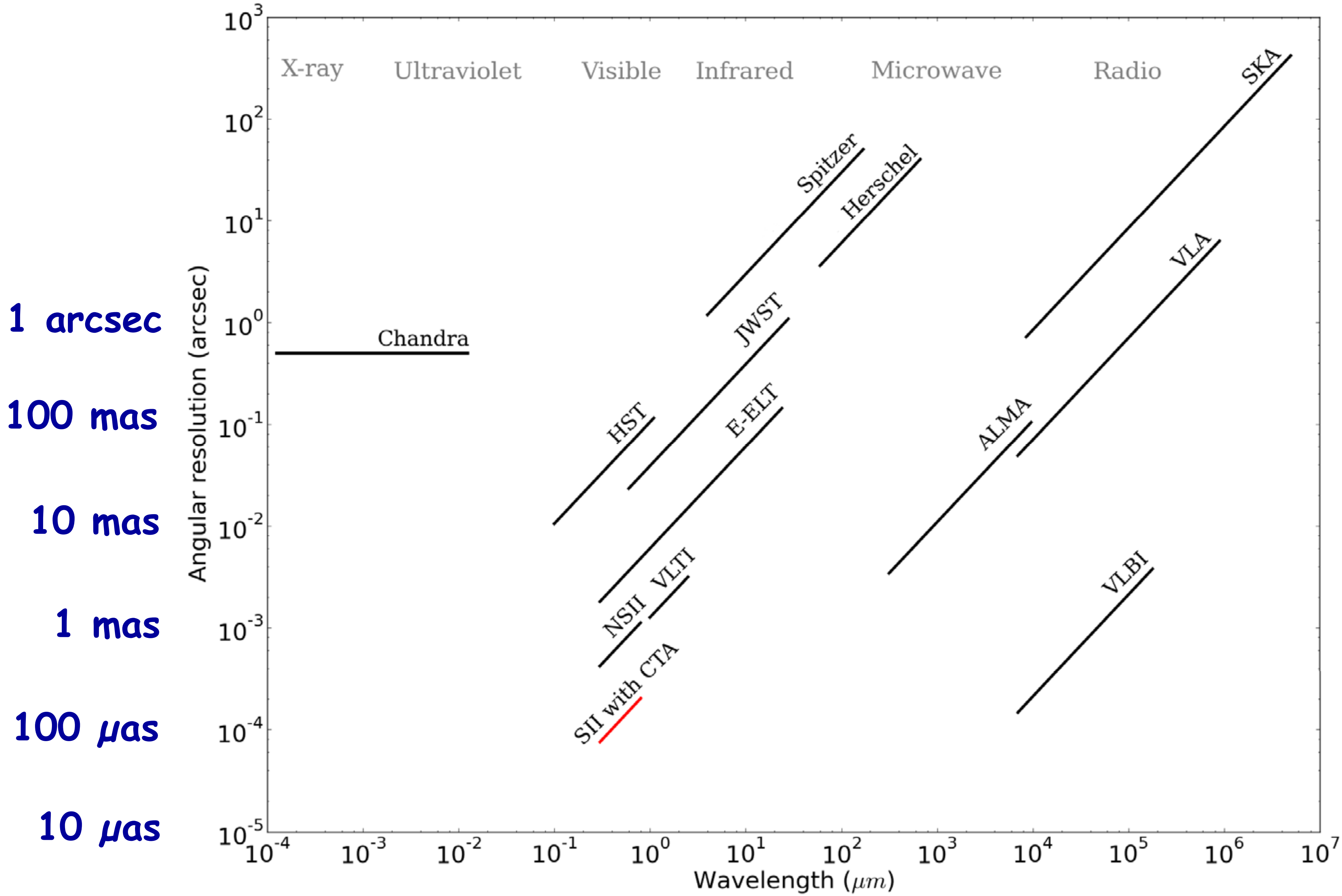


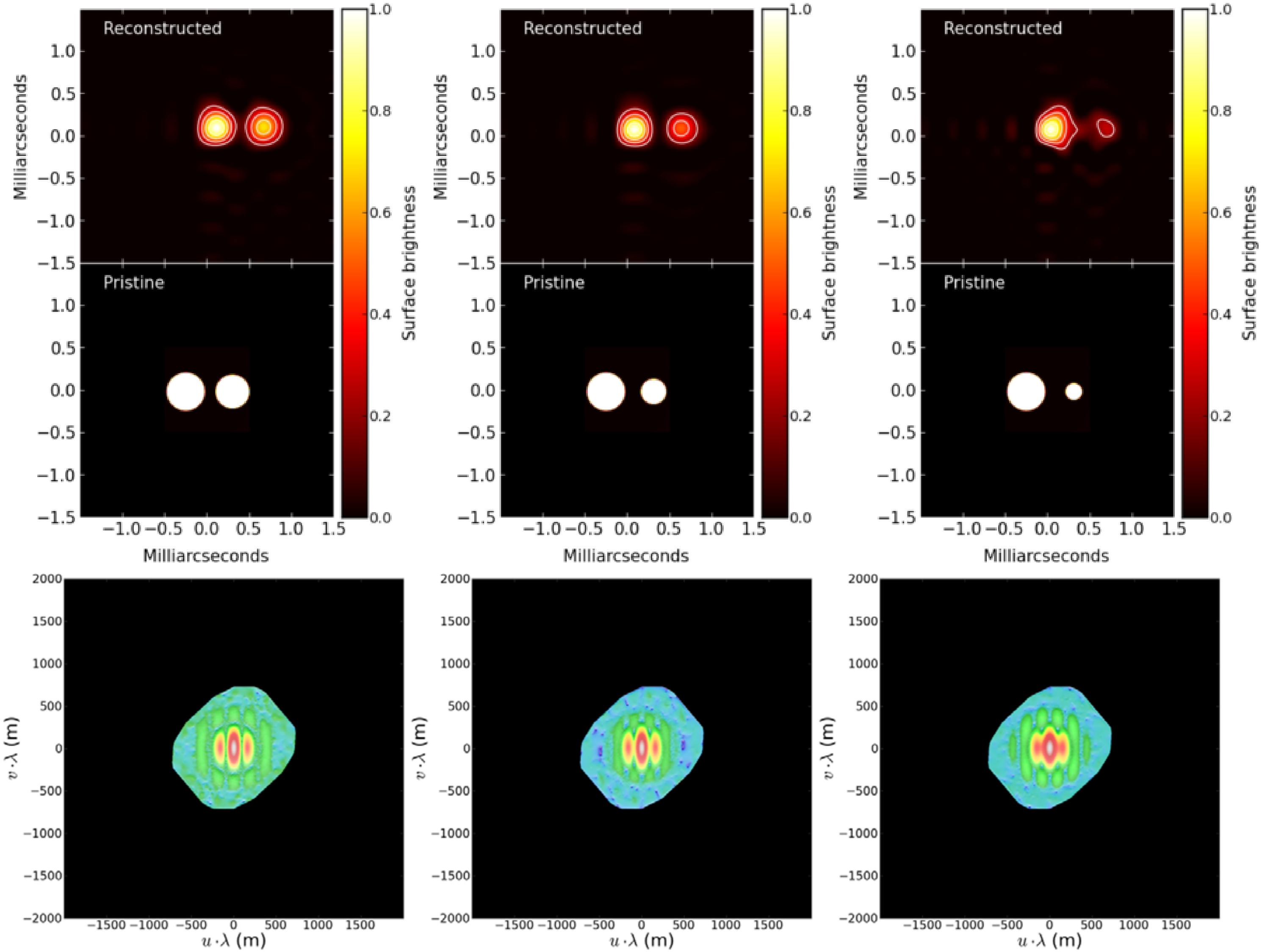
ASTRONET Infrastructure Roadmap
http://www.astronet-eu.org/
For the section on High-Energy Astrophysics, Astroparticle Physics and Gravitational Waves, highest-priority near-term (–2015) project is CTA; in overall list is 2nd highest priority among medium-scale ground-based projects (following the European Solar Telescope).

ESFPRI , European Strategy Forum on Research Infrastructures
ftp://ftp.cordis.europa.eu/pub/esfri/docs/esfri_roadmap_update_2008.pdf
Eight prioritized projects within Physical Sciences and Engineering, include CTA

ASPERA network on astroparticle physics
http://www.aspera-eu.org/
The priority project for VHE gamma astrophysics is the Cherenkov Telescope Array, CTA.

ANGULAR RESOLUTION IN ASTRONOMY





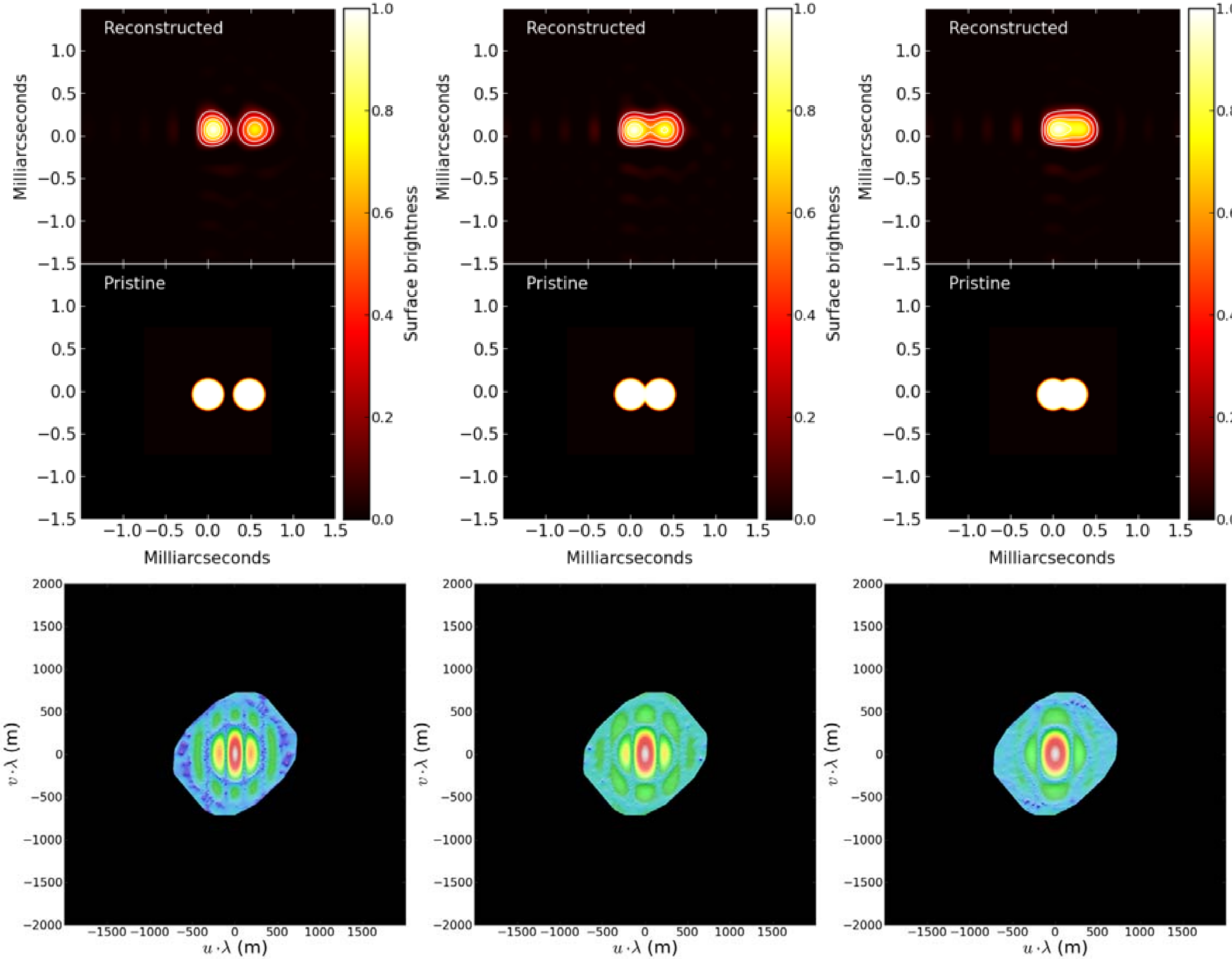
Simulated observations of binary stars with different sizes.

(m_V = 3; T_{eff} = 7000 K; T = 10 h; Δt = 1 ns; λ = 500 nm; $\Delta\lambda$ = 1 nm; QE = 0.7, array = CTA B)

Top: Reconstructed and pristine images; Bottom: Fourier magnitudes.

Already changes in stellar radii by only a few micro-arcseconds are well resolved.

(Hannes Jensen, Lund Observatory, 2010)



Simulated observations of binary stars with different separations.

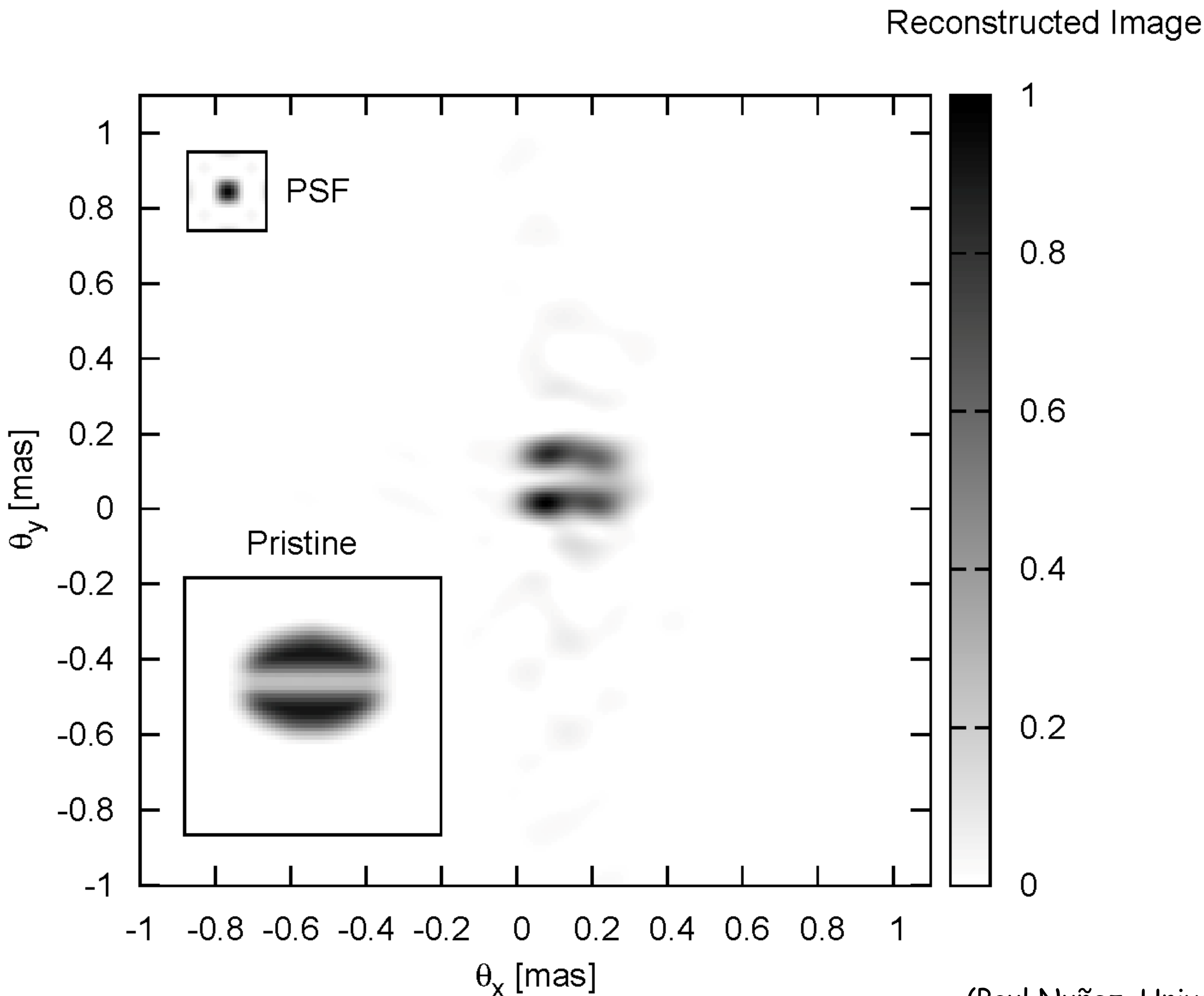
(m_V = 3; T_{eff} = 7000 K; T = 10 h; Δt = 1 ns; λ = 500 nm; $\Delta\lambda$ = 1 nm; QE = 0.7, array = CTA B)

Top: Reconstructed and pristine images; Bottom: Fourier magnitudes.

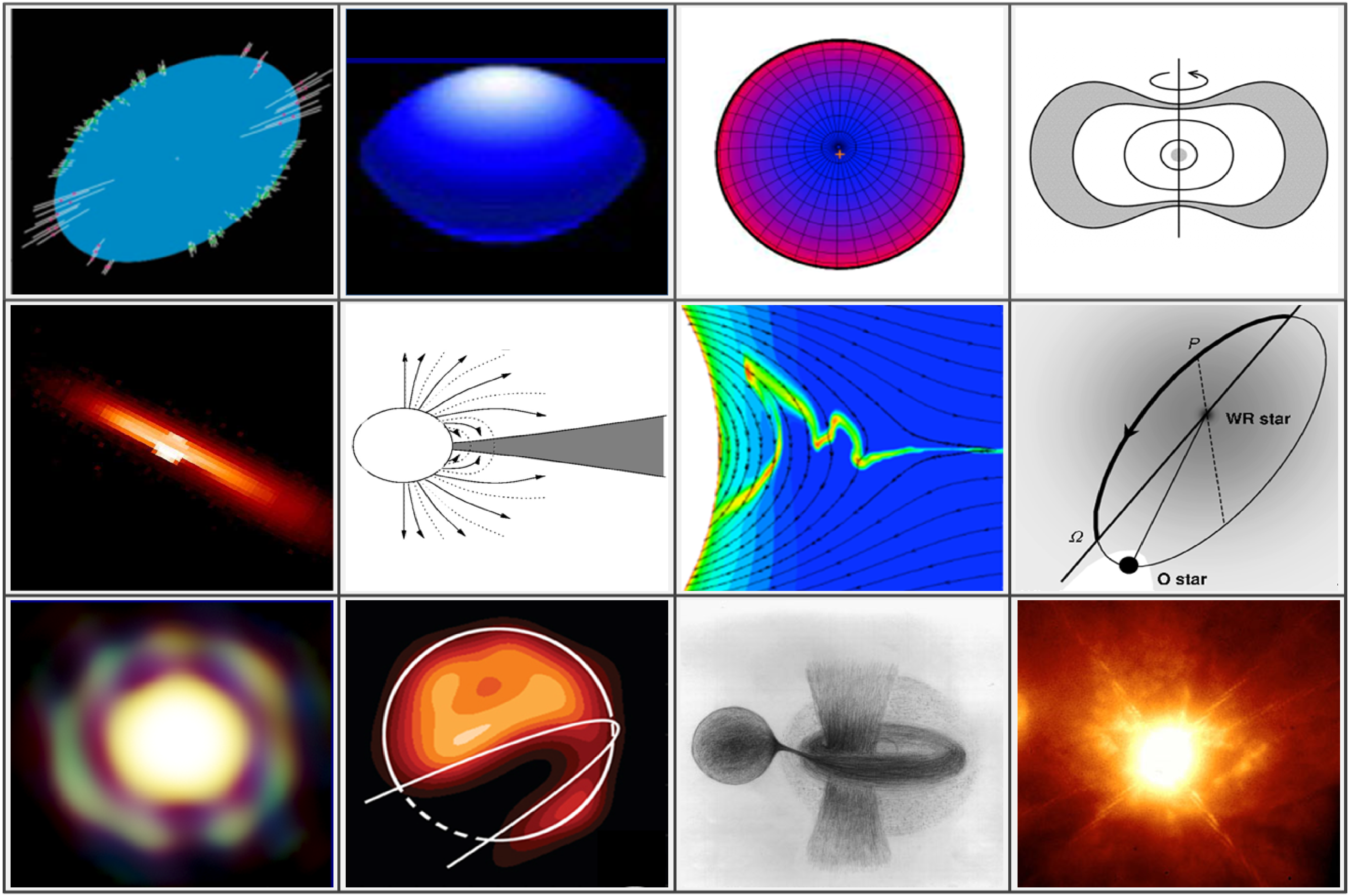
Stellar diameters and binary separations are well resolved.

(Hannes Jensen, Lund Observatory, 2010)

SIMULATED OBSERVATIONS IN INTENSITY INTERFEROMETRY



(Paul Nuñez, University of Utah, 2010)



ASTROPHYSICAL TARGETS FOR KILOMETRIC-SCALE INTENSITY INTERFEROMETRY (Dravins et al., SPIE Proc. **7734**, 2010)

In 2009, we celebrated 400 years of telescopic astronomy

"Our local Universe is teeming with stars, but despite 400 years of telescopic observations, astronomy is still basically incapable of observing stars as such!

Although we can observe the light radiated by them, we do not (with few exceptions) have the capability to observe the stars themselves, i.e., resolving their disks or viewing structures across and outside their surfaces (except for the Sun, of course!).

One can just speculate what new worlds will be revealed once stars no longer will be seen as mere point sources but as extended and irregular objects with magnetic or thermal spots, flattened or distorted by rapid rotation, and with mass ejections monitored in different spectral features as they flow towards their binary companions.

It is not long ago that the satellites of the outer planets passed from being mere point sources to a plethora of different worlds, and one might speculate what meager state extragalactic astronomy would be in, were galaxies observed as point sources only."

(Dravins & LeBohec, SPIE Proc. **6986**, 2008)

Unsolved theoretical issues:

How to exploit higher-order correlations?

Non-random photon statistics?

Radiative transfer of photon correlations?

Signatures of photon orbital angular momentum?

THE

END