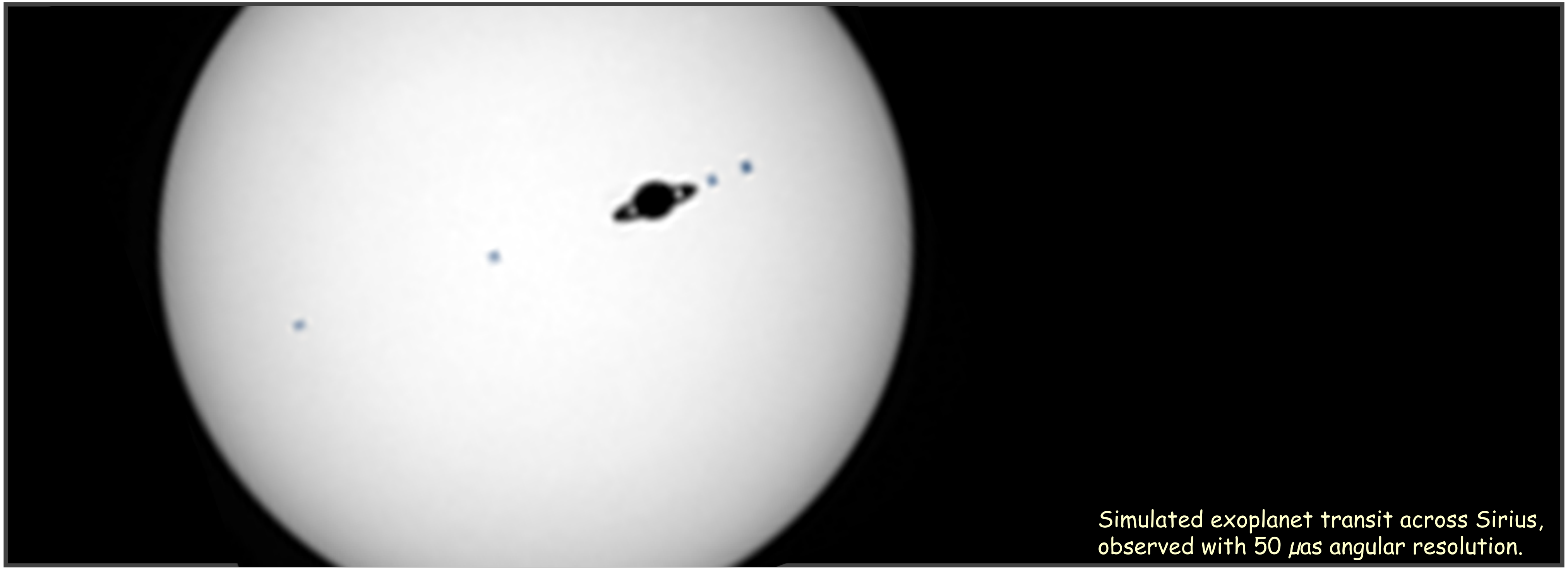


Simulated exoplanet transit across Sirius,
observed with 50 μas angular resolution.

Thousand Times Sharper than Hubble

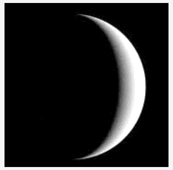
Optical Interferometry with the Cherenkov Telescope Array

Dainis Dravins — Lund Observatory

www.astro.lu.se/~dainis

ANGULAR SCALES IN ASTRONOMY


Sun, Moon ~30 arcmin



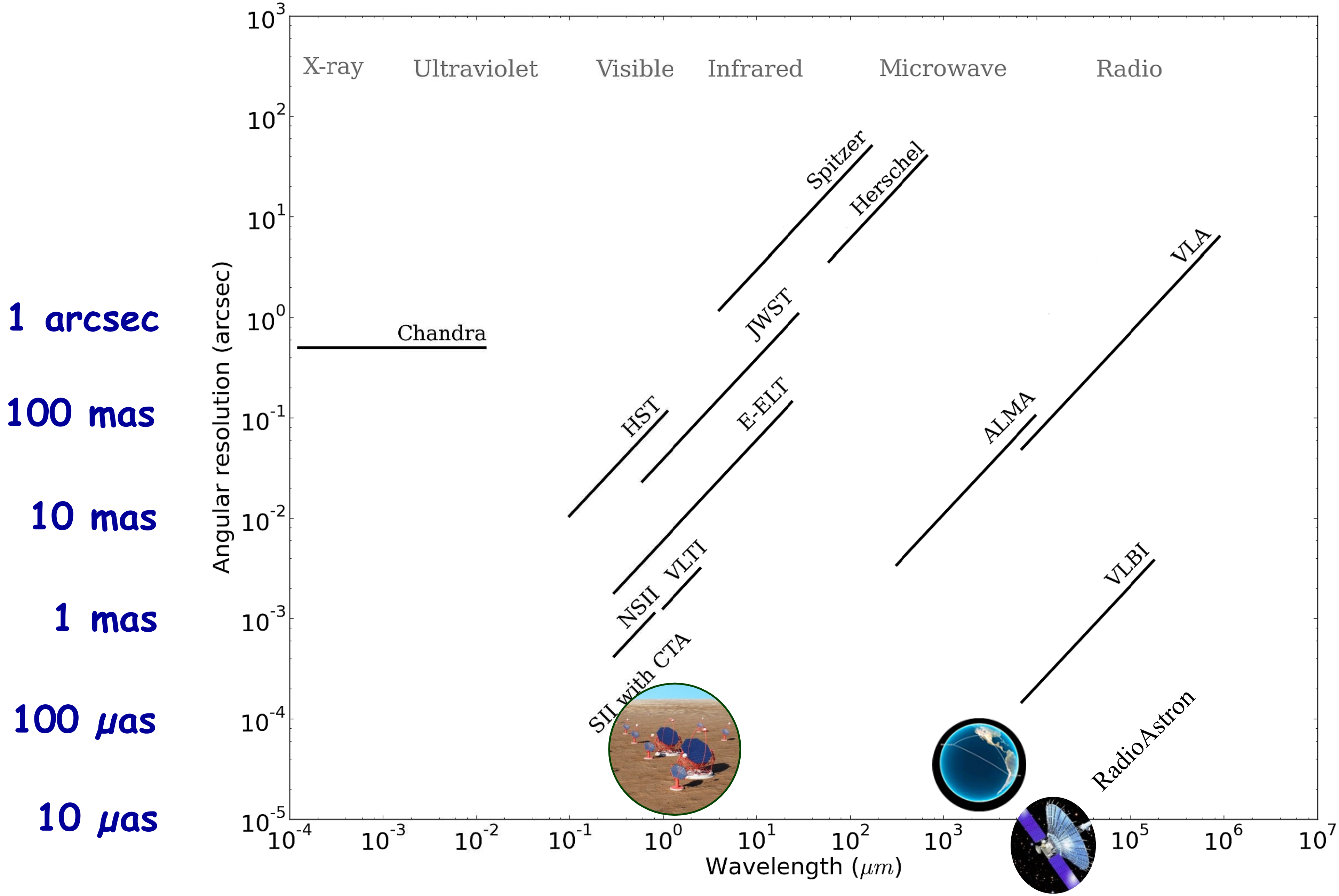

Planets ~30 arcsec



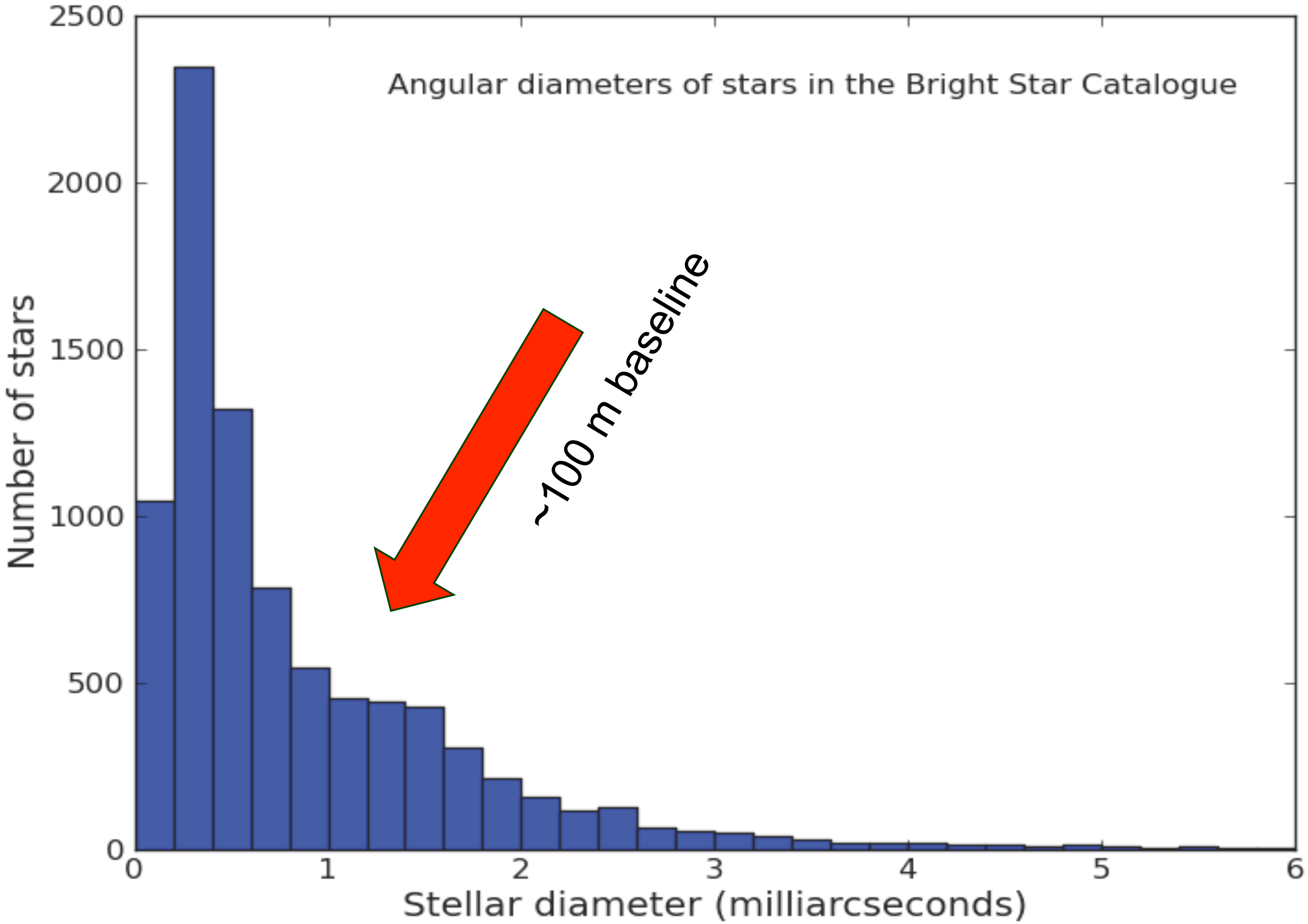
Largest stars ~30 mas

Typical bright stars ~1 mas

ANGULAR RESOLUTION IN ASTRONOMY



How large (i.e., *small*) are sources of interest?

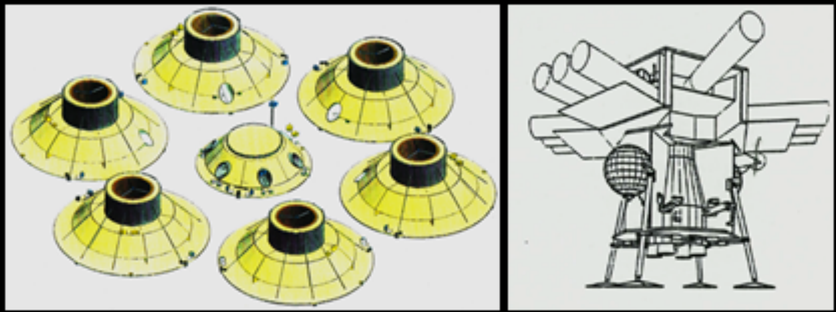


D.Dravins, S.LeBohec, H.Jensen, P.D.Nuñez:
Stellar Intensity Interferometry: Prospects for sub-milliarcsecond optical imaging, New Astron. Rev. **56, 143** (2012)

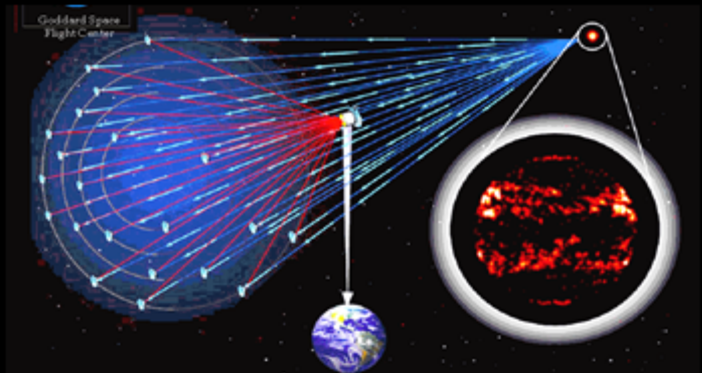
Many stars become resolved surface objects for baselines 100-1000 m

Kilometer-scale interferometry!?

Proposed kilometric diffraction-limited optical imagers



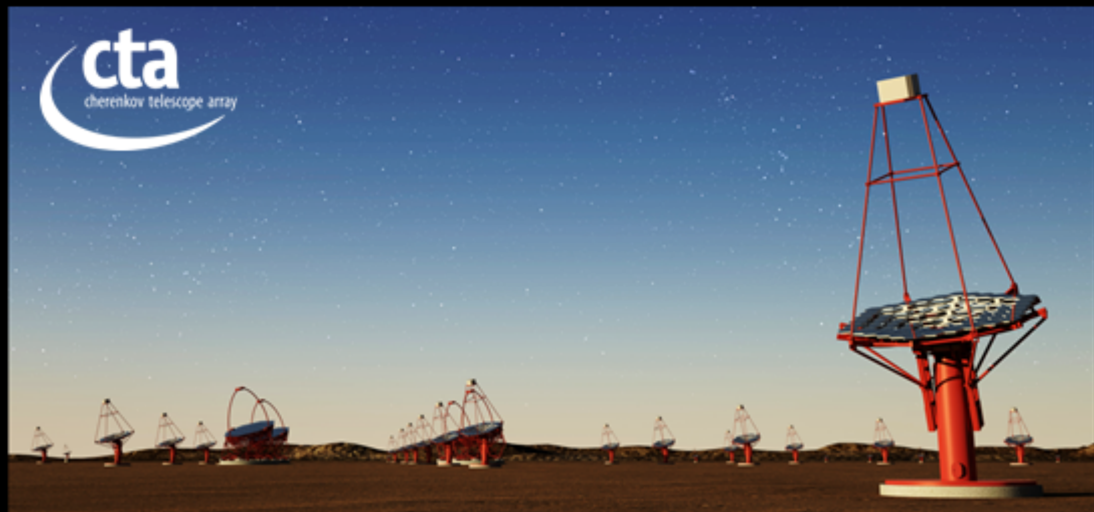
Kilometric Baseline Space Interferometry
Comparison of free-flyer and moon-based versions.
Report by the Space Interferometry Study Team, ESA (1996)



NASA *Stellar Imager* mission concept
K.G.Carpenter et al.: `http://hires.gsfc.nasa.gov/si/`

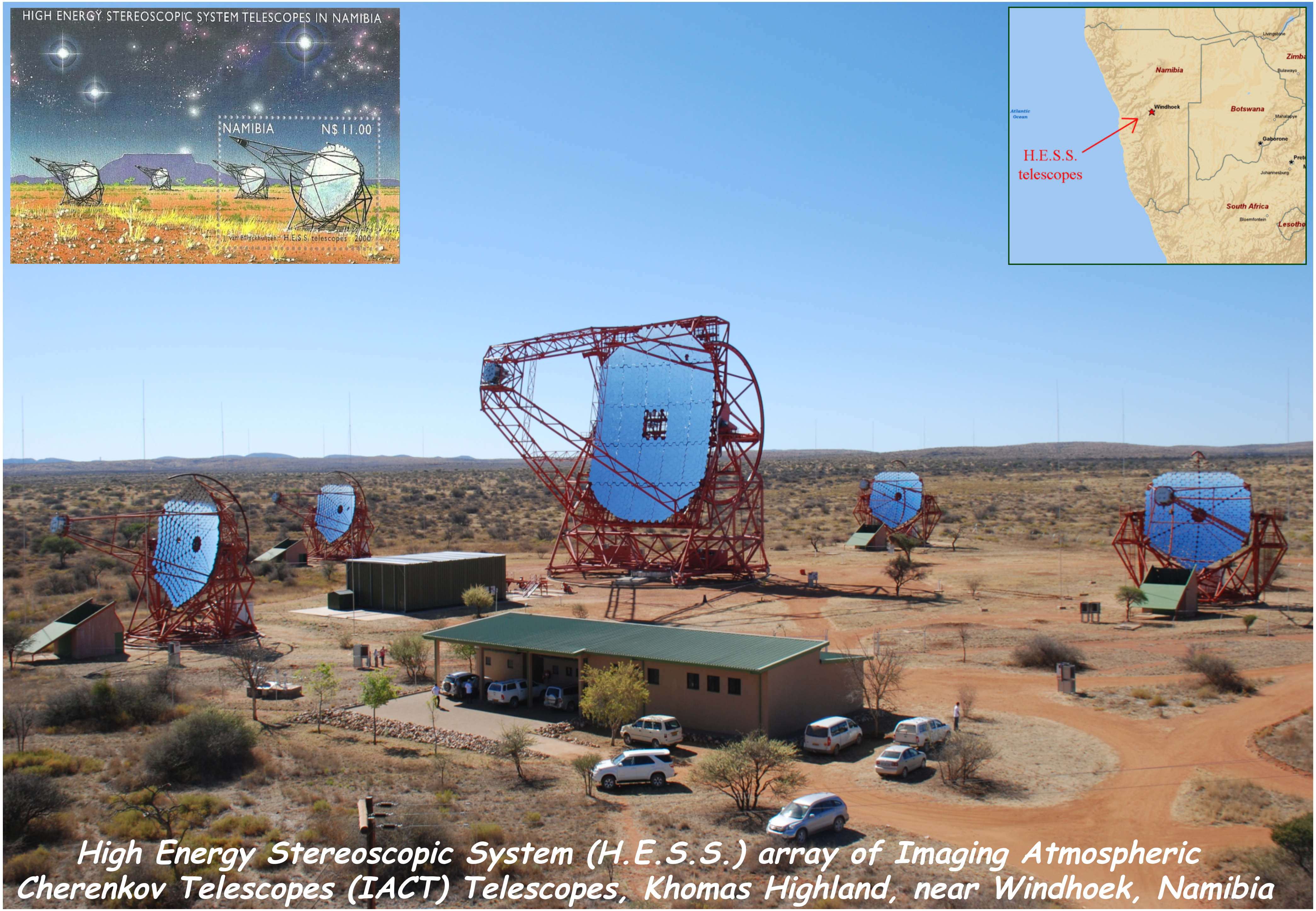
KEOPS optical array at Concordia Base in Antarctica
(Vakili et al.: EAS Publ. Ser. **14**, 211, 2005)

A many-mirror hypertelescope operates like a giant diluted telescope
(Labeyrie et al., Exp.Astron. 23, 463, 2009)



With telescopes distributed over a few km^2, the *Cherenkov Telescope Array* can operate as a kilometric optical intensity interferometer to achieve diffraction-limited imaging and optical aperture synthesis

Air Cherenkov Telescopes



High Energy Stereoscopic System (H.E.S.S.) array of Imaging Atmospheric Cherenkov Telescopes (IACT) Telescopes, Khomas Highland, near Windhoek, Namibia

The High Altitude Gamma Ray Telescope (HAGAR), Hanle, Ladakh, India

World's highest major optical observatory in the western Himalayas, 4,517 m above sea level.
Site of 21-m MACE (*Major Atmospheric Cherenkov Experiment*) telescope. Photo by Prabhu B. Doss

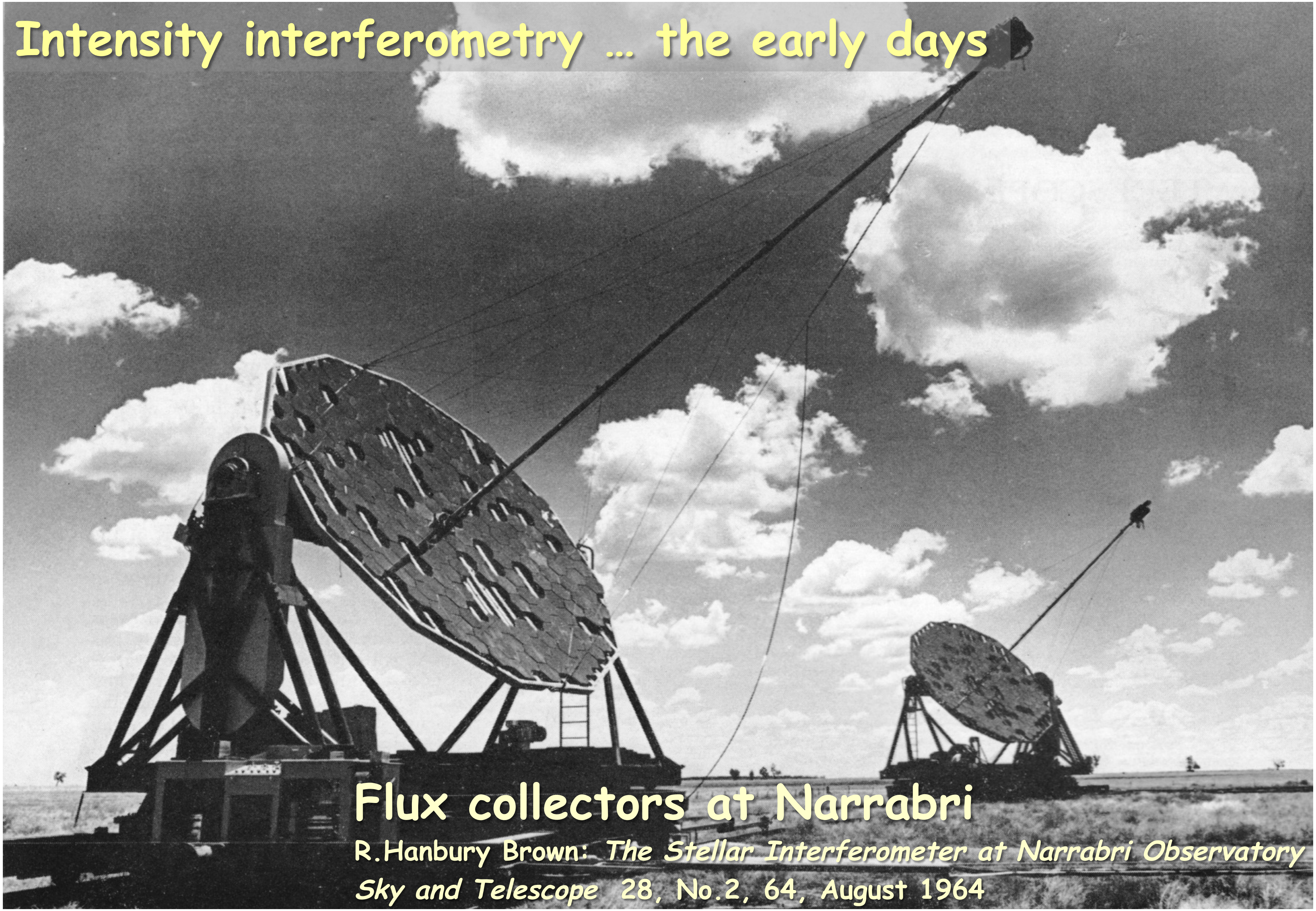

http://www.cta-observatory.org/
cta
cherenkov telescope array

CTA medium-size telescope prototype

A prototype for the 12-meter medium-size CTA telescopes, built at DESY in Berlin/Zeuthen

CTA Internal Newsletter Sept 2013; CERN Courier July 2013; `http://www.desy.de/cta`

Intensity interferometry … the early days

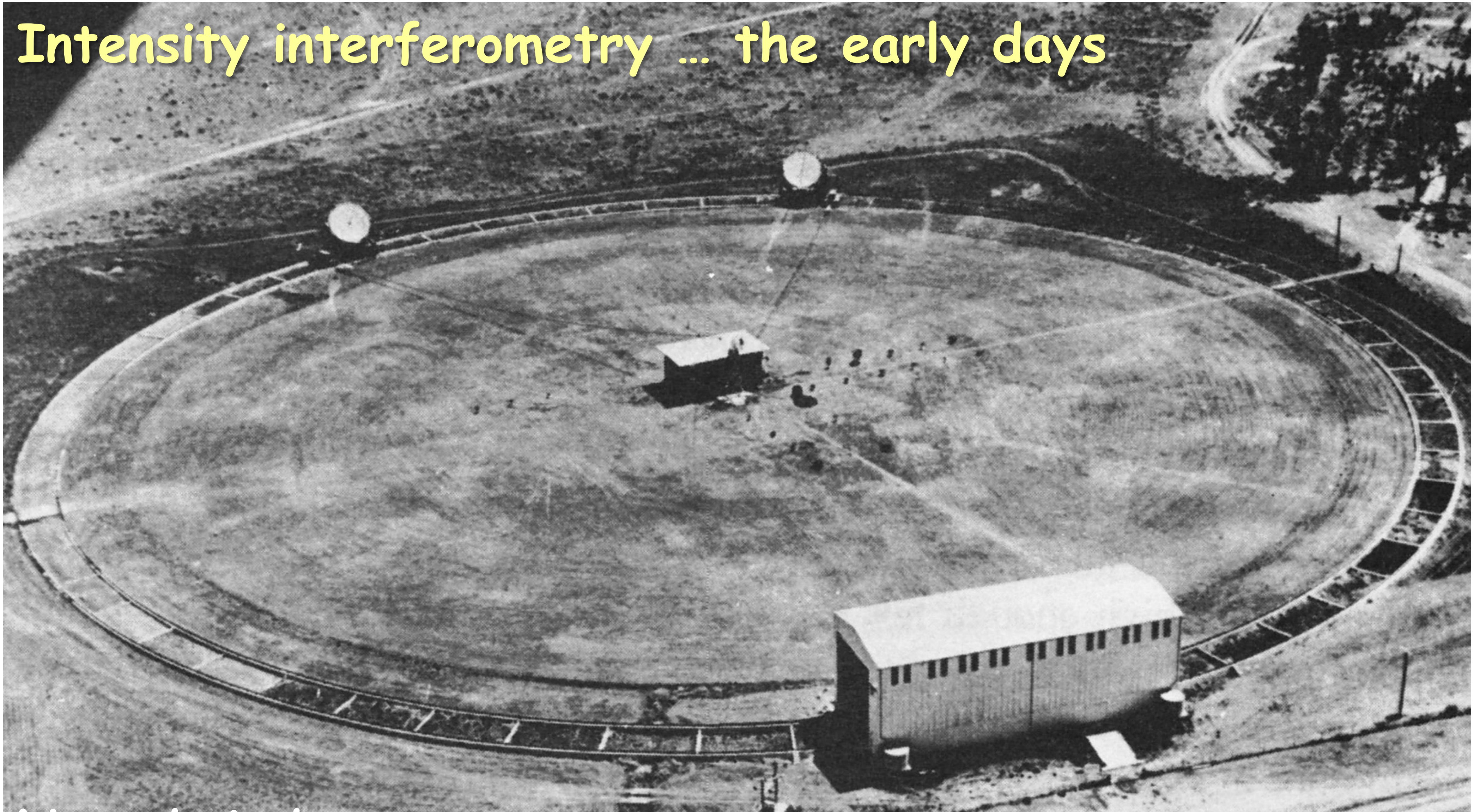


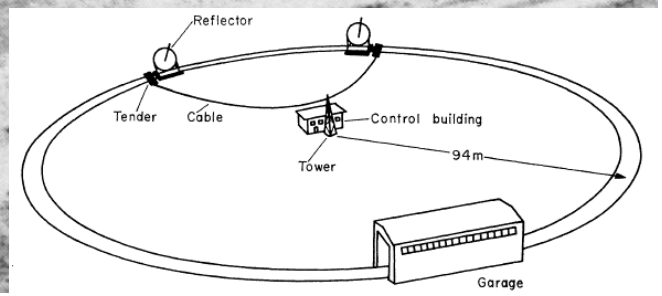
Flux collectors at Narrabri

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

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

Intensity interferometry … the early days





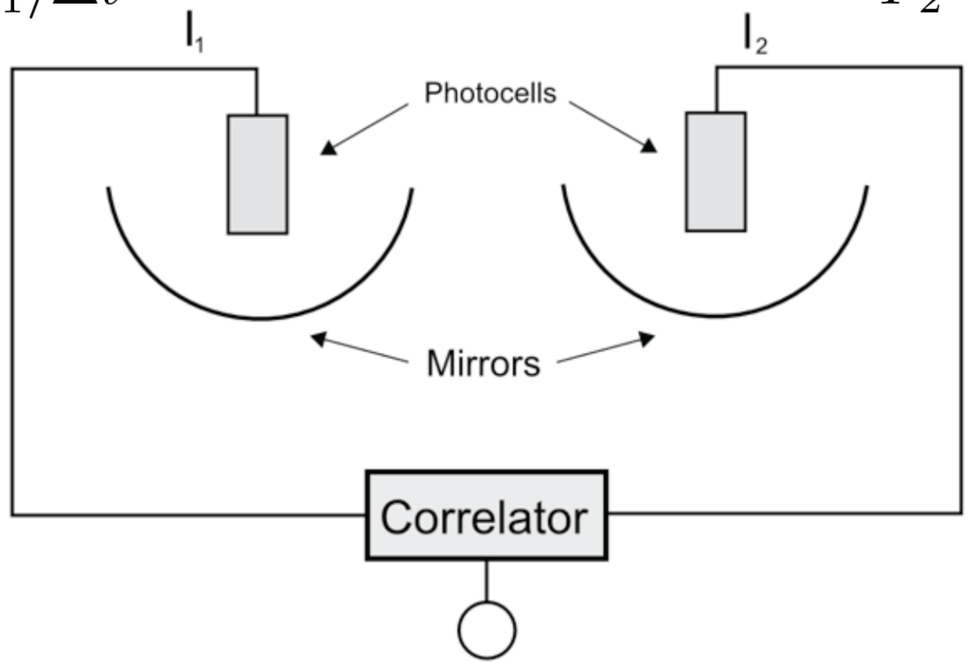
Narrabri observatory
with its circular railway track

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

INTENSITY INTERFEROMETRY

$$P_1 = \alpha_1 \langle I_1 \rangle \Delta t$$

$$P_2 = \alpha_2 \langle I_2 \rangle \Delta t$$

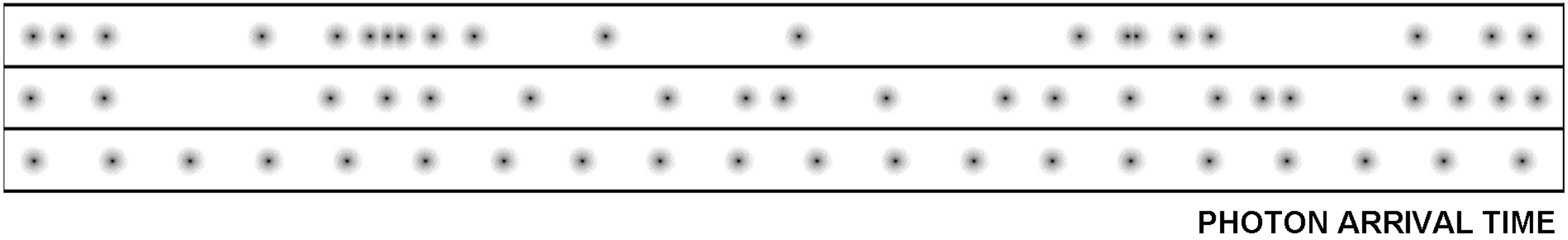


$$P_{12} = \alpha_1 \alpha_2 \langle I_1 \rangle \langle I_2 \rangle (1 + |\gamma_{12}|^2) \Delta t^2$$

↑ Photon clumping

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

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)

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

Roy Glauber

Nobel prize in physics

Stockholm, December 2005

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

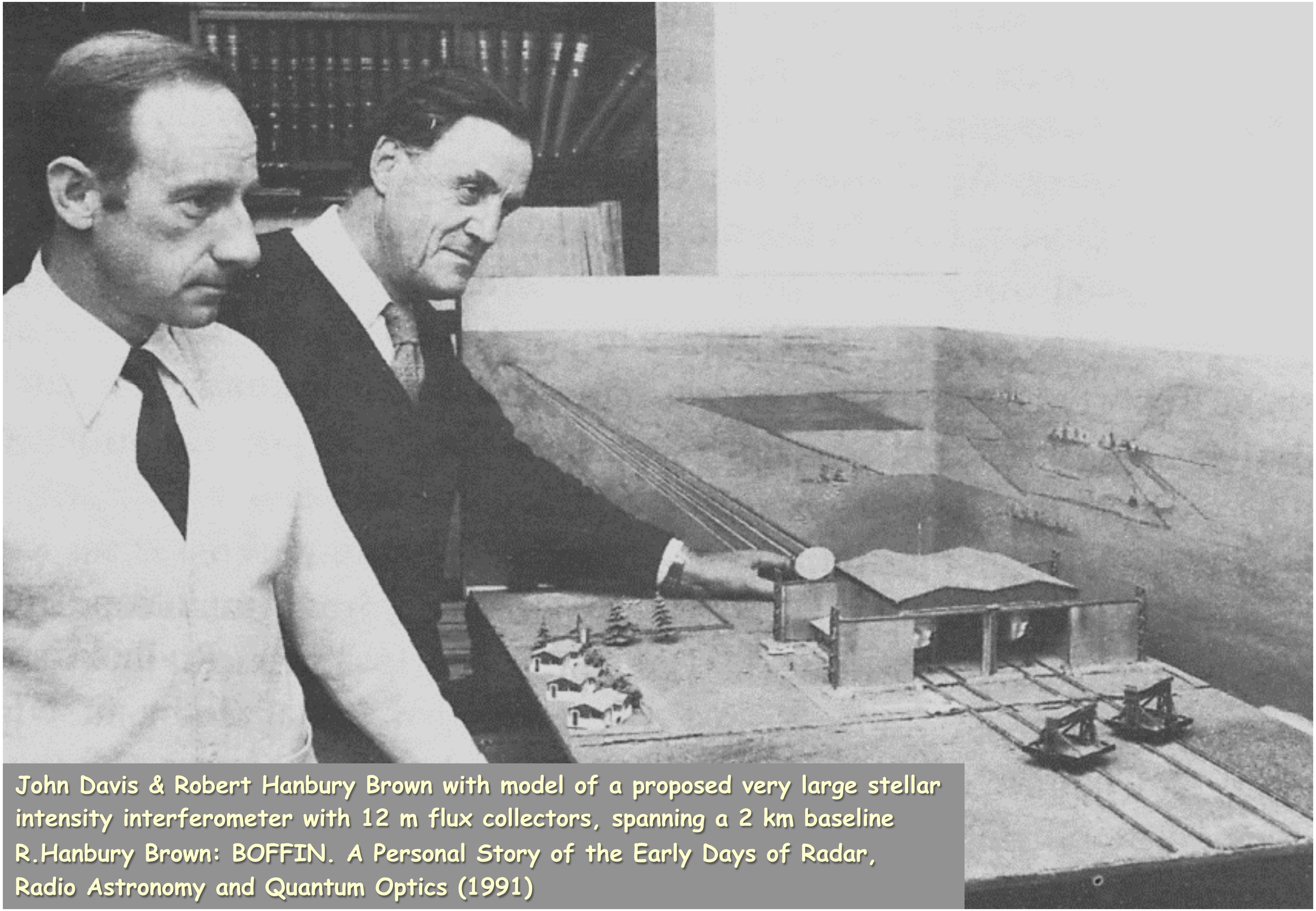
Intensity interferometry

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

Short wavelengths no problem; hot sources observable

Con: Signal comes from two-photon correlations, increases as signal squared.

Realistic time resolutions require high photometric precision, therefore large flux collectors.



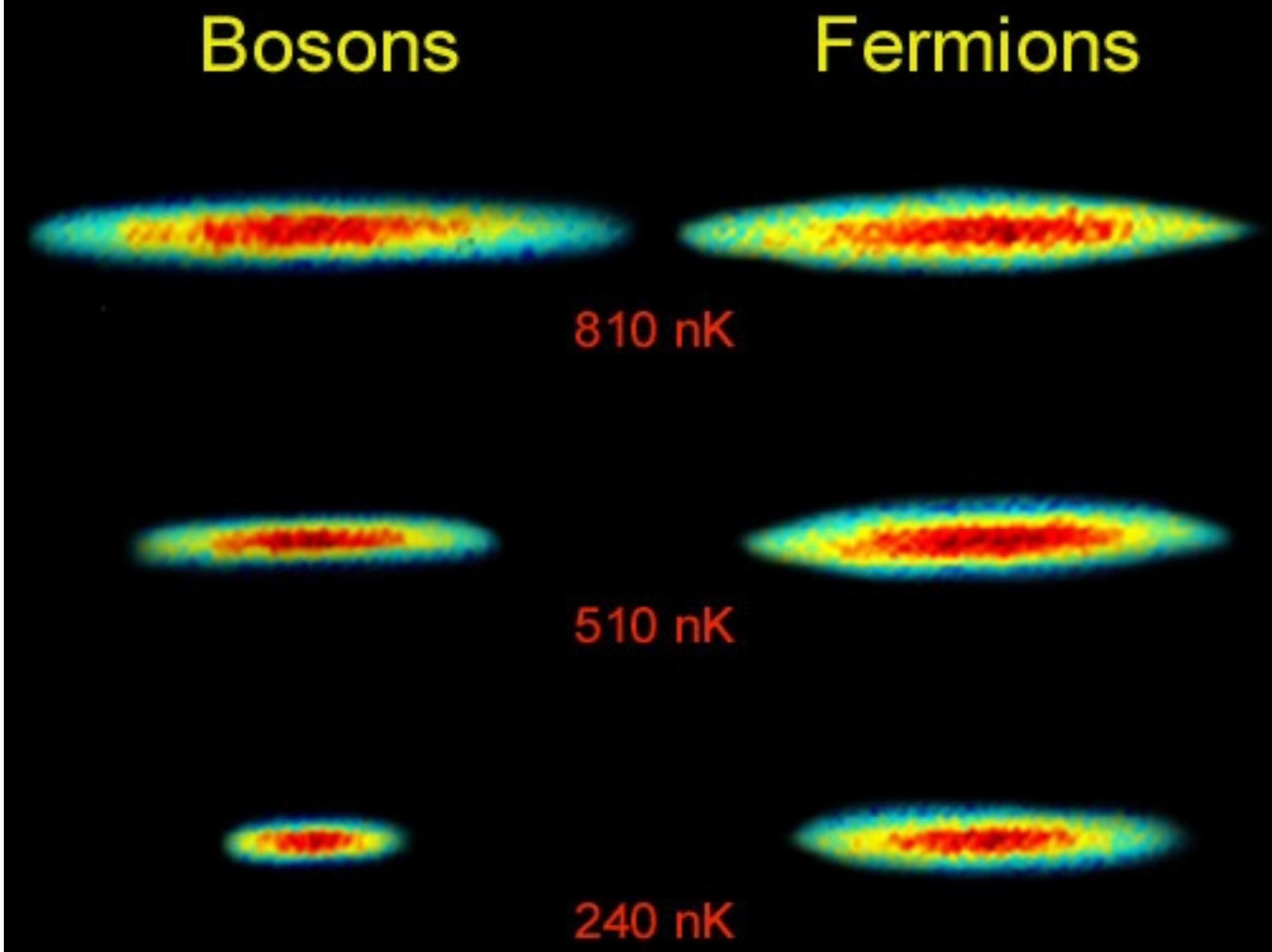
John Davis & Robert Hanbury Brown with model of a proposed very large stellar intensity interferometer with 12 m flux collectors, spanning a 2 km baseline
R.Hanbury Brown: BOFFIN. A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics (1991)

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



BOSONS BUNCH TOGETHER, FERMIONS DON'T

Pauli exclusion principle: Fermions cannot share the same quantum state

(but bosons can! ☺)

Bose-Einstein condensates of different lithium isotopes;

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

Truscott & Hulet (Rice Univ.)

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, 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

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

Two-Particle Correlations in Relativistic Heavy-Ion Collisions

Ulrich Heinz
Theory Division, CERN, CH-1211 Geneva 23, Switzerland; e-mail: ulrich.heinz@cern.ch, and Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany

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... of th... ased ... lision... for t...

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

Scott Pratt
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824; email: pratts@pa.msu.edu

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.

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.

Back to astronomy …

Software telescopes in radio and the optical

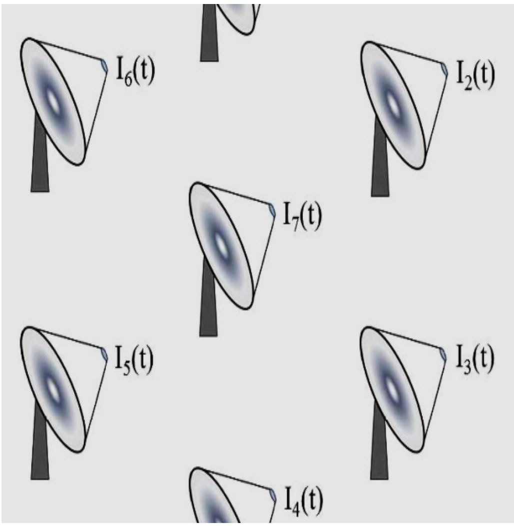
LOFAR

LOFAR low-band antennas at Onsala Space Observatory

Low-frequency radio waves, ~100 MHz

Many antennas, huge data flows.
Radio-wave amplitude sampled 12 bits deep.
Spectral resolution ~1 kHz, bandwidth 32 MHz.
Measures first-order coherence.
Large, central on-line data processing facility.

Optical Intensity Interferometer



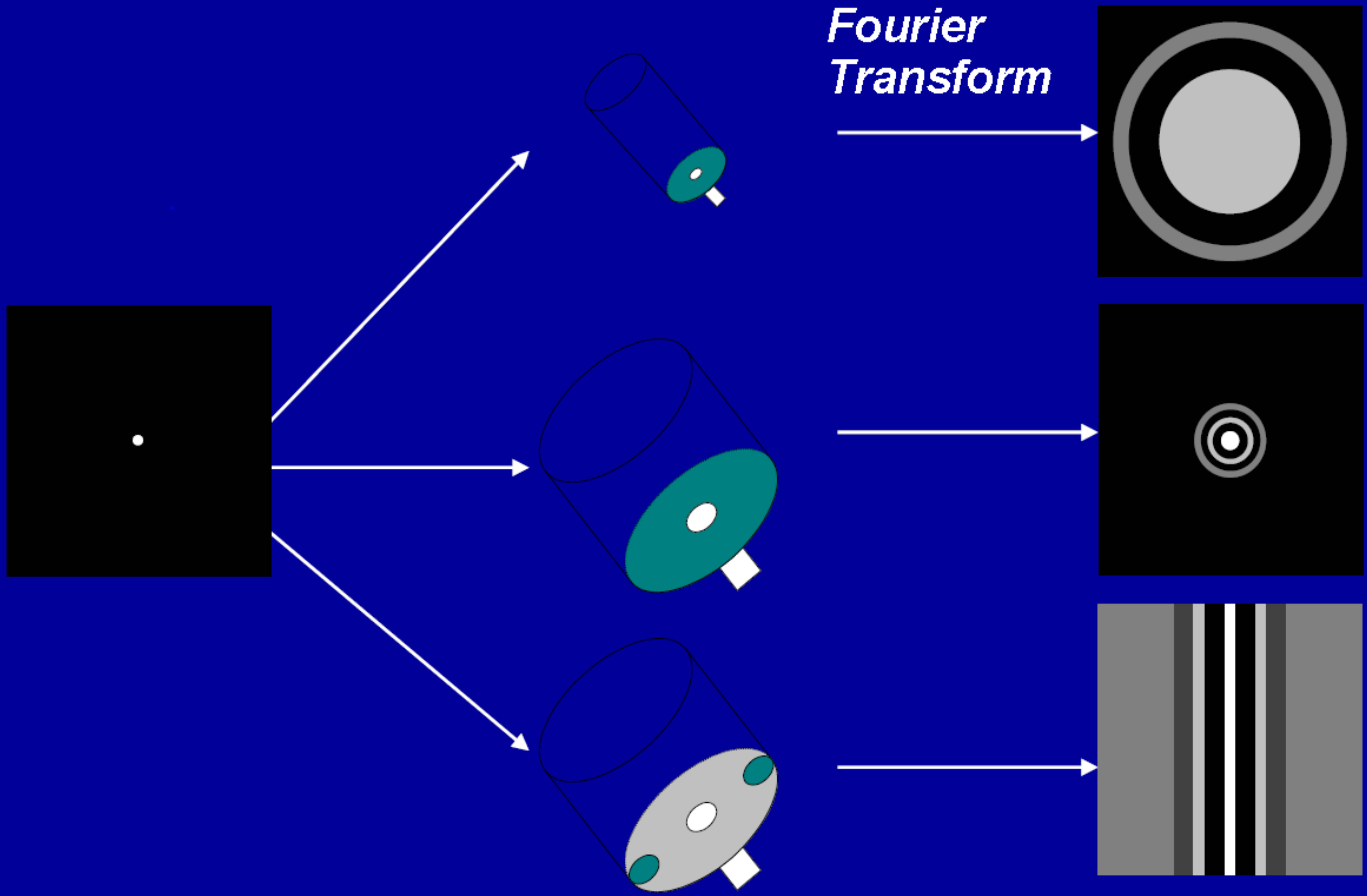
Low-frequency optical fluctuations, ~100 MHz

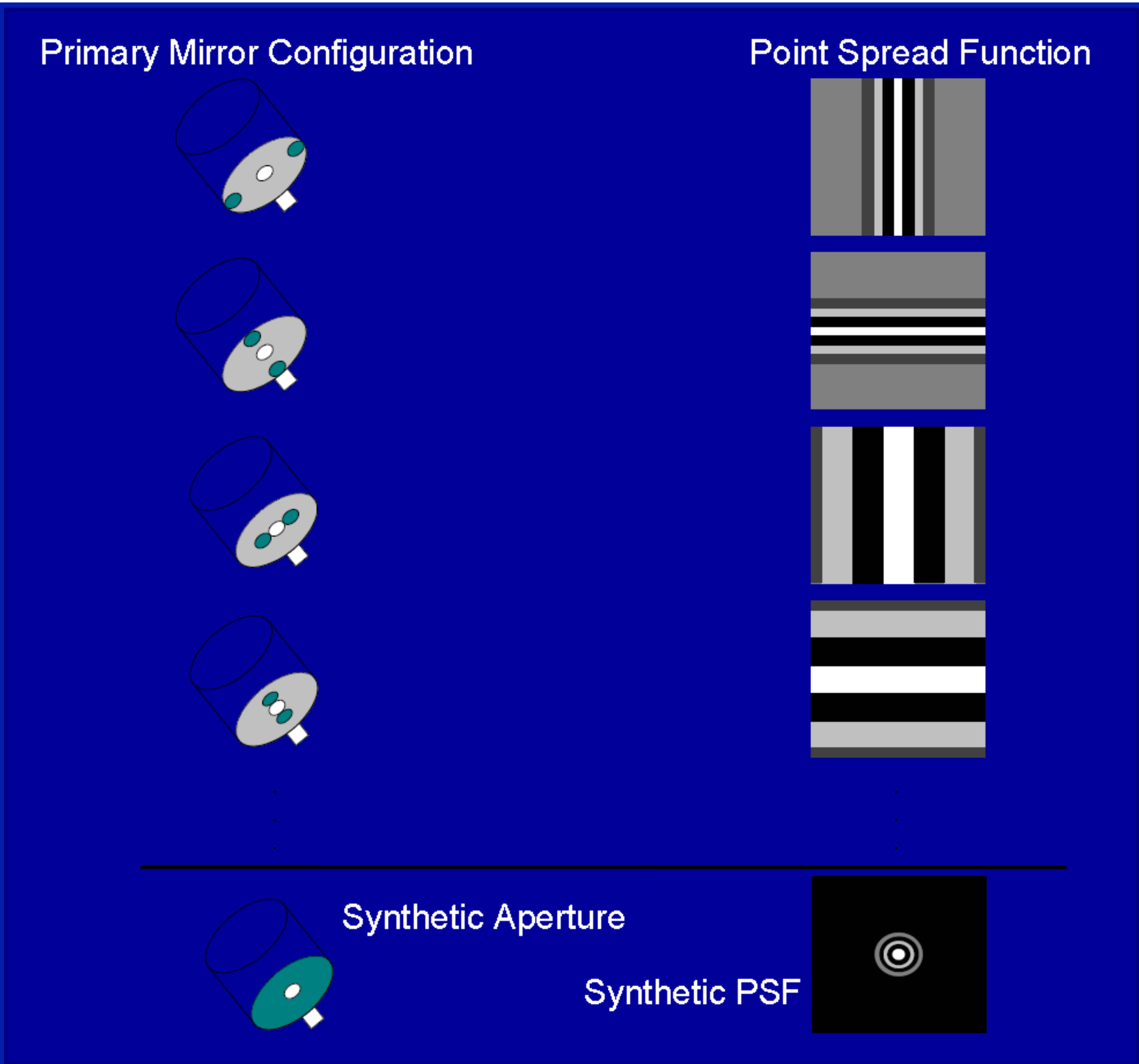
Many telescopes, moderate data flows.
Photon counts recorded (1 bit).
Spectral resolution by optical filters.
Measures second-order coherence.
On-line or off-line data processing.

D.Dravins, S.LeBohec, H.Jensen, P.D.Nuñez, CTA Consortium
Optical intensity interferometry with the Cherenkov Telescope Array, Astropart. Phys. **43**, 331 (2013)

Principle of aperture synthesis

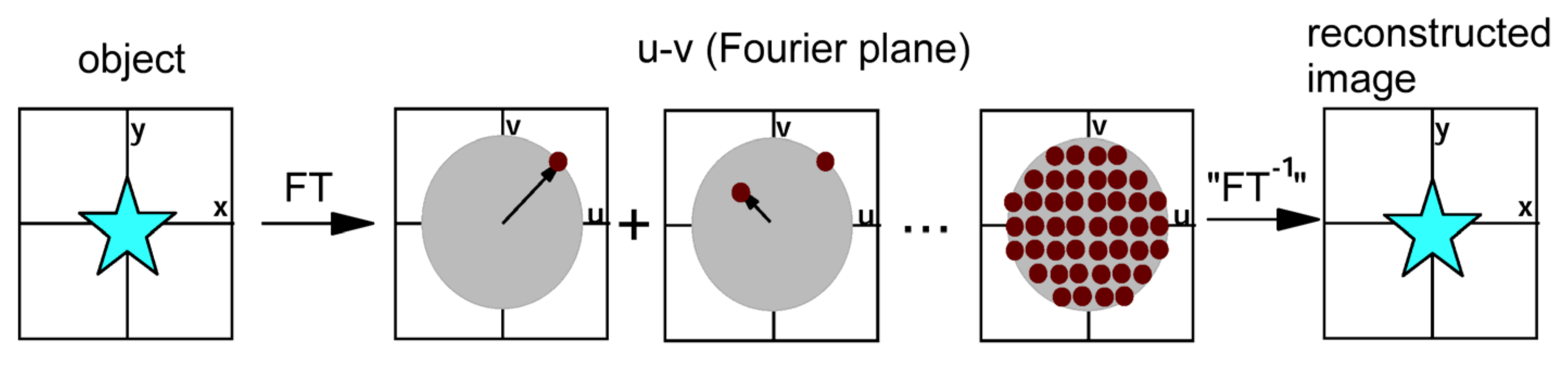
Point Spread Function of Telescopes / Interferometers





Synthetic Aperture Imaging with an Interferometer

Aperture synthesis imaging

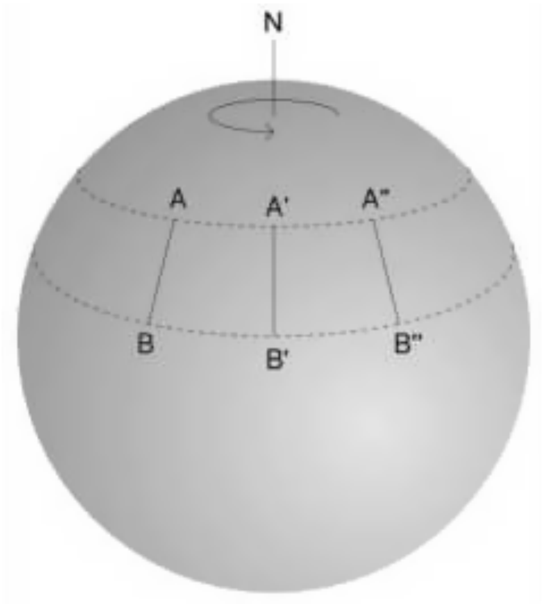


*** Each observation measures one Fourier component of the brightness distribution.**

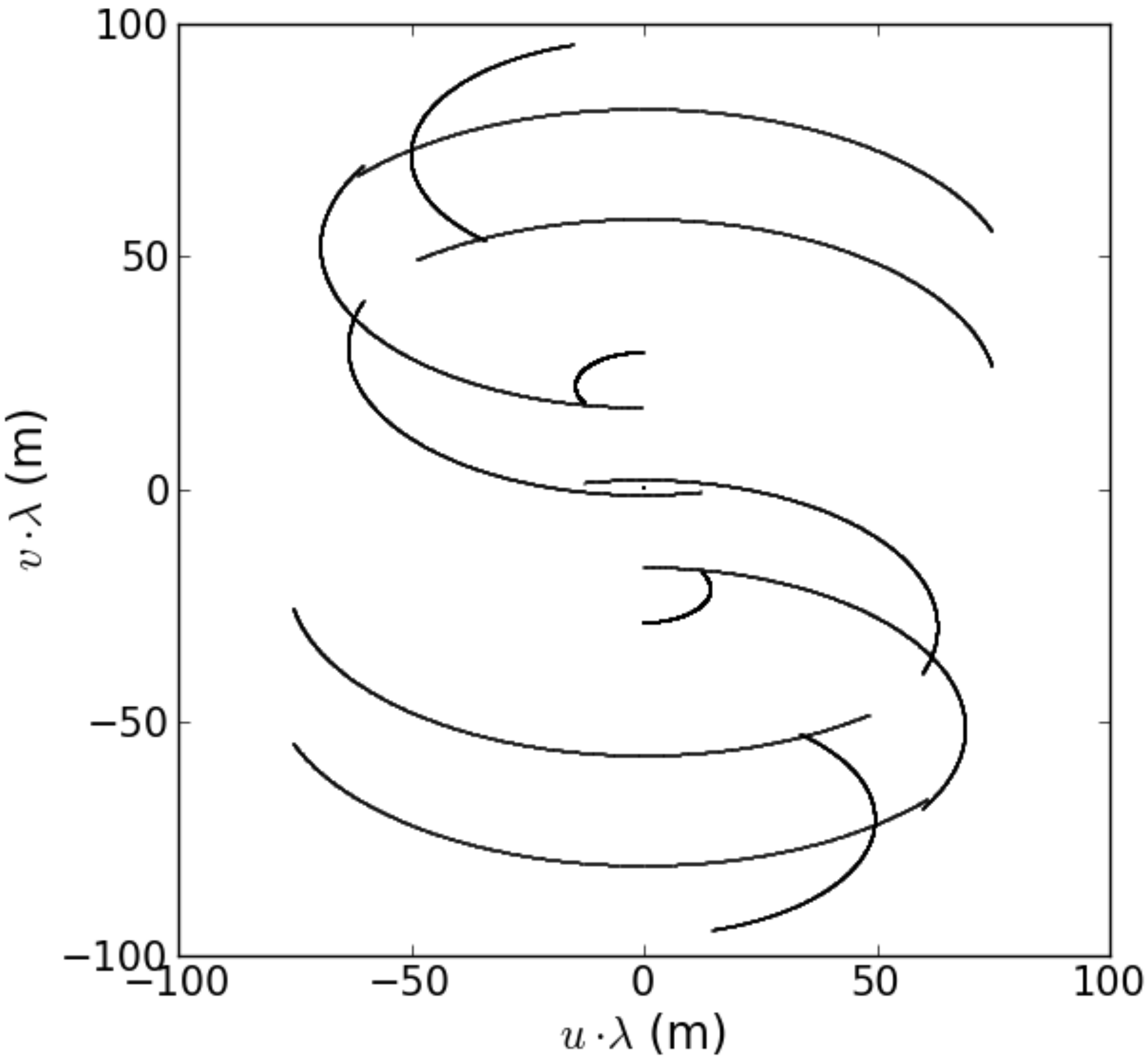
One observation thus contributes one data point in the (u,v)-plane, the coordinate plane of the two-dimensional Fourier transform of the brightness distribution of the source.

*** Complex visibilities (i.e., fringe amplitude and phase) required for Fourier inversion.**

FOURIER-PLANE COVERAGE BY FOUR VERITAS TELESCOPES



Projected baselines change
with Earth rotation



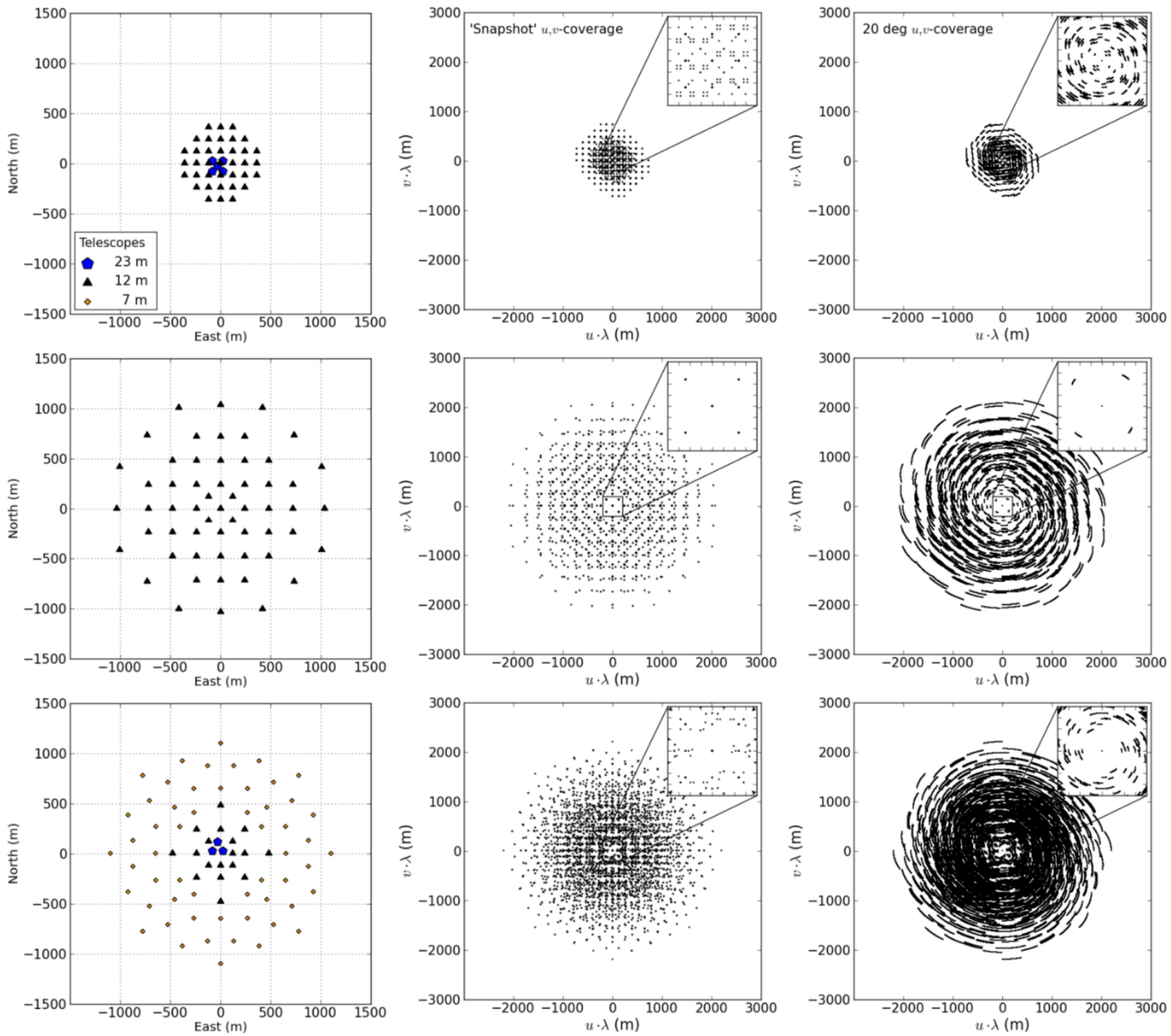
***VERITAS* Fourier plane coverage during 8 hours, as a star moves through the zenith**

FOURIER-PLANE COVERAGE BY VERY MANY CTA TELESCOPES

CTA B

CTA D

CTA I



Left: Telescopes for CTA configurations B, D, and I.

Center column: *(u,v)*-plane coverage for a star in zenith.

Right: *(u,v)*-plane coverage for a star moving from zenith through 20 degrees west.

Many telescopes combined in software 'fully' cover the interferometric (u,v)-plane

Digital intensity interferometry

- ★ Cherenkov telescopes: Large flux collectors
- ★ Fast digital detectors & high-speed signal handling
- ★ Combine optical telescopes in software
- ★ Huge number of baselines, no loss of digital signal
- ★ Example: 65 telescopes: $N \times (N-1)/2 = 2080$ baselines
- ★ Filled (u,v)-plane enables sub-milliarcsecond imaging

What can be observed?

S/N in intensity interferometry

PROPORTIONAL TO:

★ Telescope areas (geometric mean)

★ Detector quantum efficiency

★ Square root of integration time

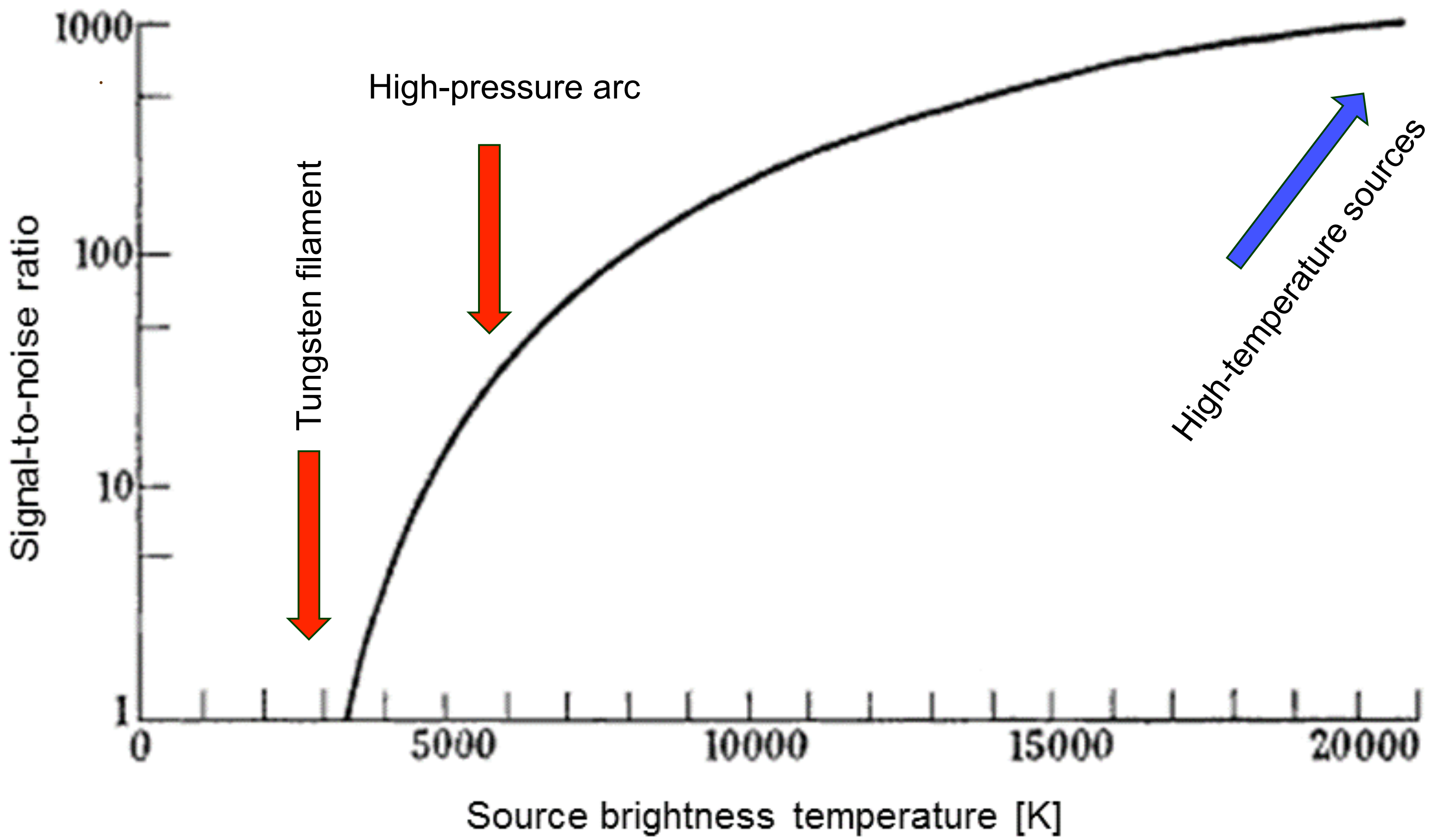
★ Square root of electronic bandwidth

★ Photon flux per optical frequency bandwidth

INDEPENDENT OF:

★ Width of optical passband

S/N dependence on source temperature



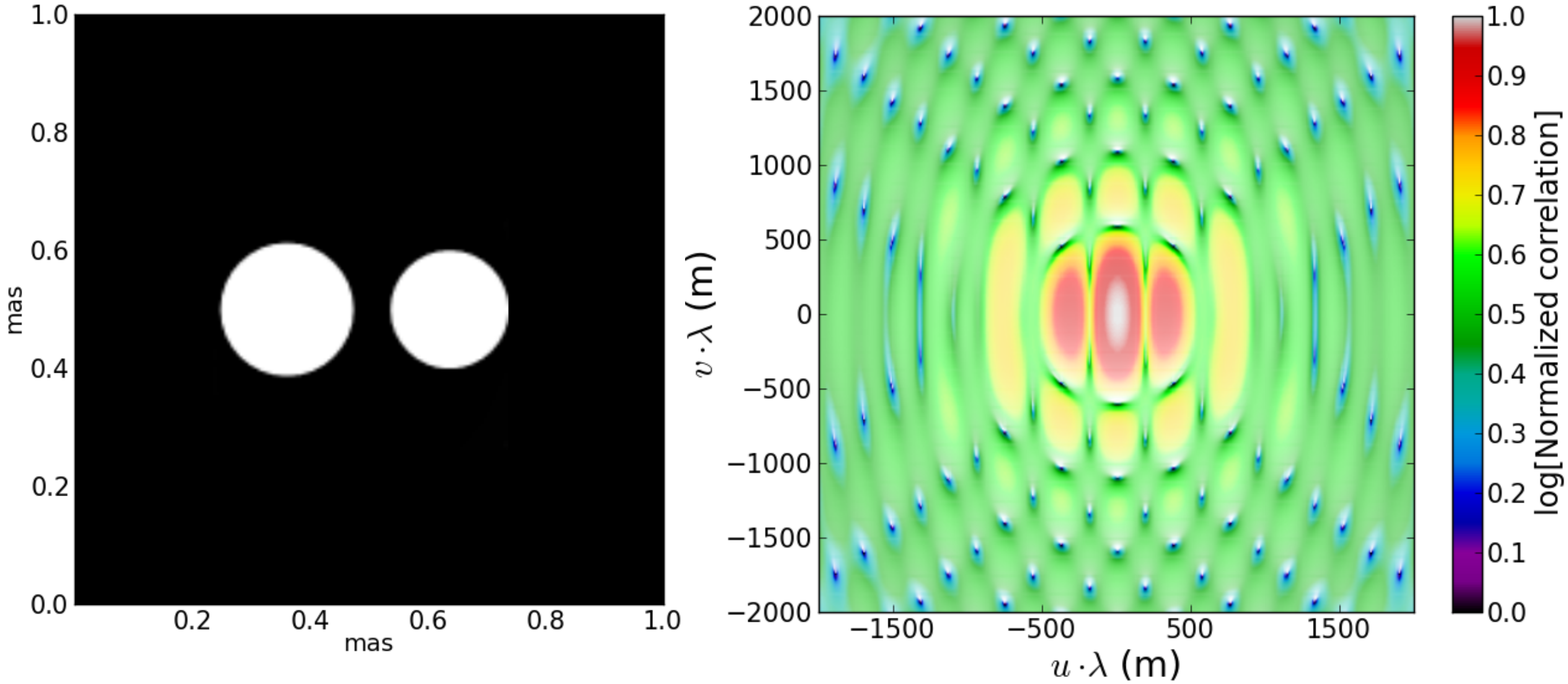
For stars with same angular diameter but decreasing temperatures (thus decreasing fluxes), telescope diameter must successively increase to maintain the same S/N.

When the mirrors become so large that the star is resolved by a single mirror, S/N drops.

For stars cooler than a given temperature, no gain results from larger mirrors.

R.Hanbury Brown, R.Q.Twiss: *Interferometry of the intensity fluctuations in light III. Applications to astronomy*, Proc.Roy.Soc.London Ser.A, **248**, 199 (1958)

Simulated observations in intensity interferometry



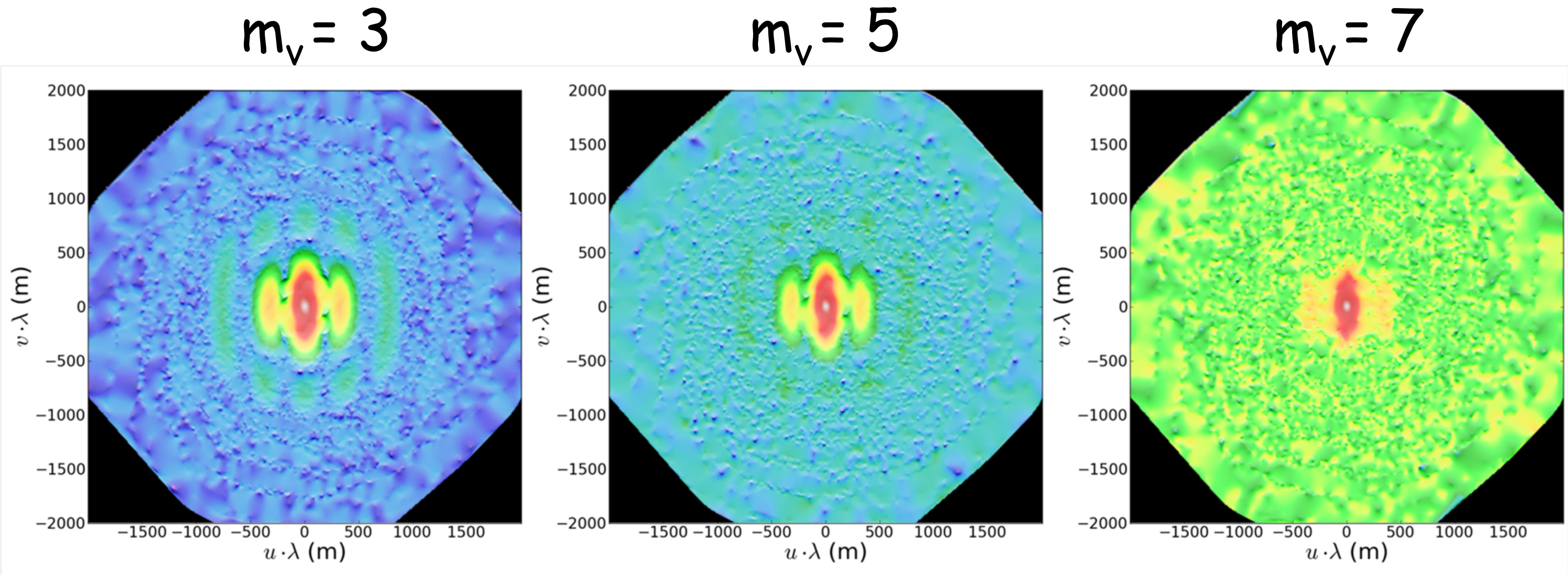
Squared visibility from a close binary star.

Left: Pristine image; Right: Logarithm of magnitude of Fourier transform

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

Simulated observations in intensity interferometry

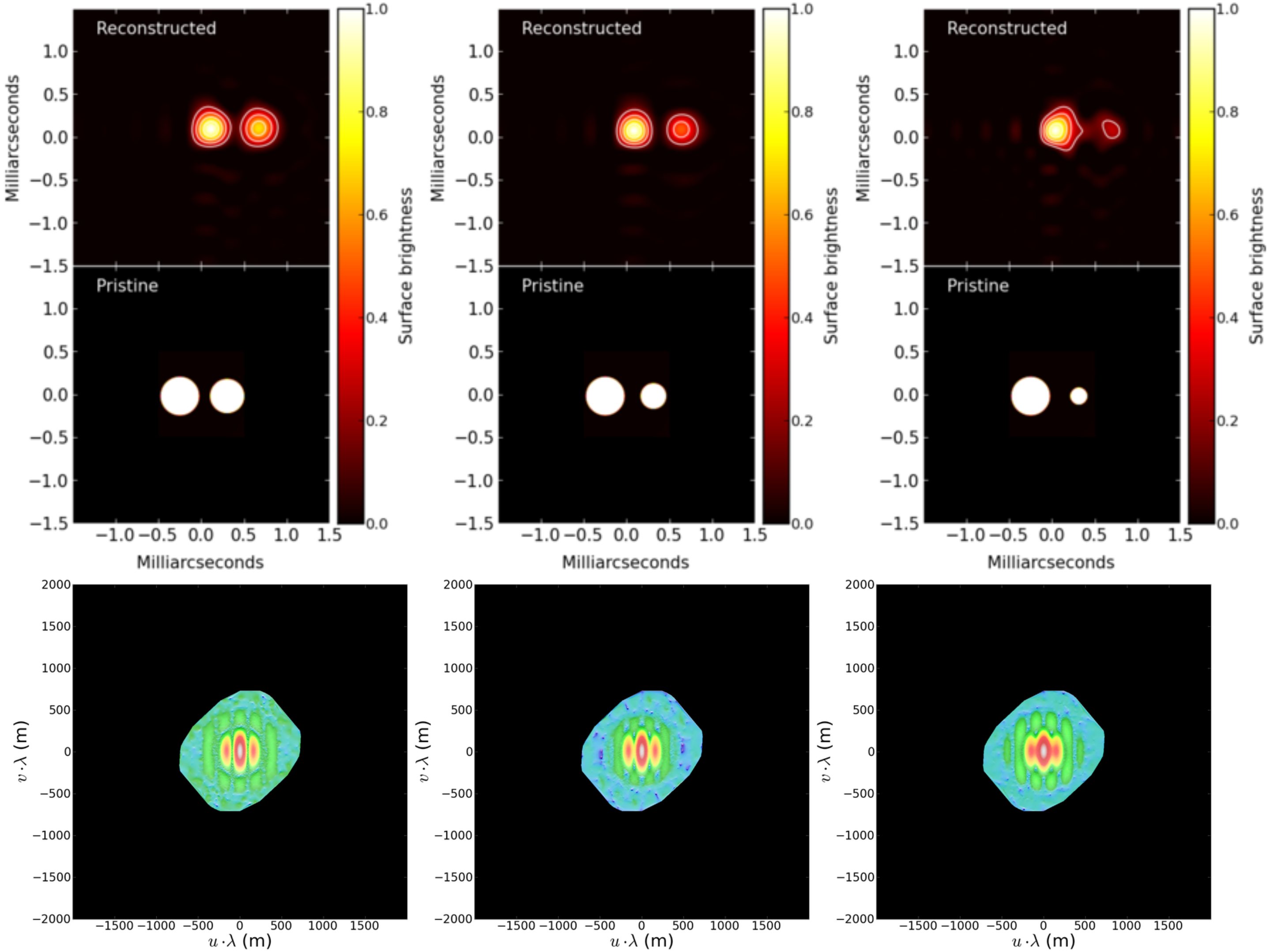
Limiting magnitude for CTA with foreseen instrumentation



Simulated observations of binary stars of visual magnitudes 3, 5, and 7.
Total integration time: 20 hours; λ 500 nm, time resolution 1 ns, quantum efficiency = 70%
Array: CTA D

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

CTA B



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 = 70%, array = CTA B)

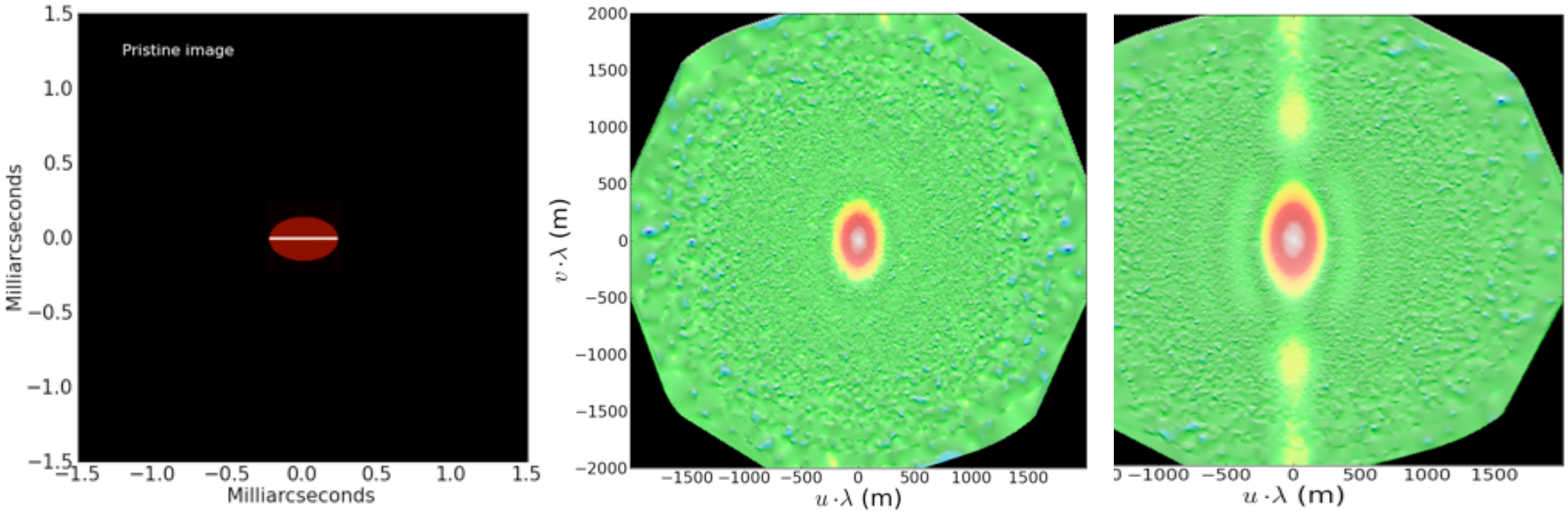
Top: Reconstructed and pristine images; Bottom: Fourier magnitudes.

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

D.Dravins, S.LeBohec, H.Jensen, P.D.Nuñez:, CTA Consortium
Optical intensity interferometry with the Cherenkov Telescope Array, Astropart. Phys. **43**, 331 (2013)

Simulated observations in intensity interferometry

S/N independent of spectral passband



SIMULATED OBSERVATIONS OF ROTATIONALLY FLATTENED STAR WITH EMISSION-LINE DISK

Left: Pristine image, 0.4 mas across with 10 μas equatorial emission-line disk, 6 times continuum intensity

Center: Observed magnitude of the Fourier transform in continuum light

Right: Same for a narrow-bandpass filter at He I λ 587 nm emission

Stellar magnitude: $m_v = 6$, $T_{eff} = 7000$ K; T = 50 h, QE=70%; Array = CTA I

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

Image reconstruction

Second-order coherence $g^{(2)}$

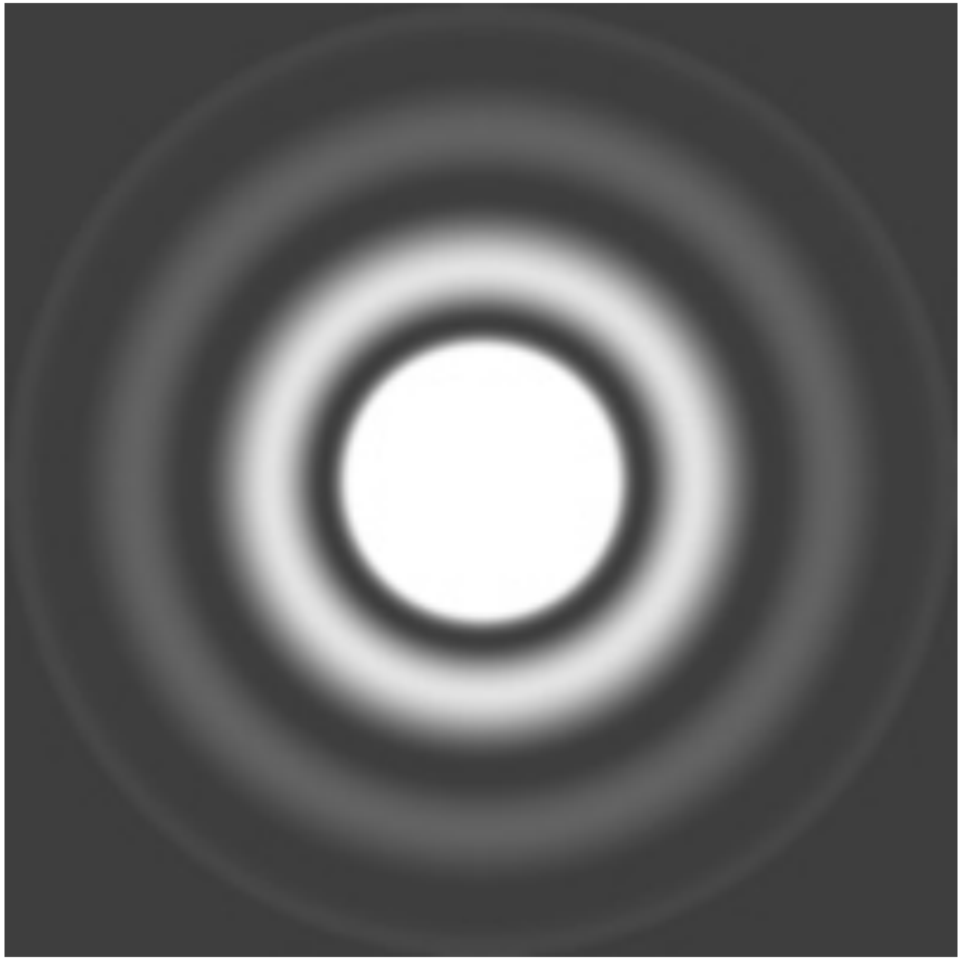
$$g^{(2)}(\tau) = 1 + |g^{(1)}(\tau)|^2$$

Does not retain phase information,
direct image reconstruction not possible.

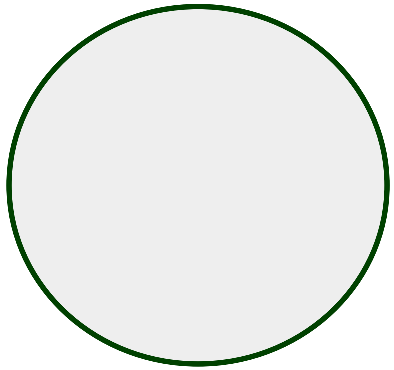
Imaging requires retrieval of
Fourier phases from amplitudes.

Feasible if dense coverage of (u,v)-plane

Image reconstruction from intensity interferometry

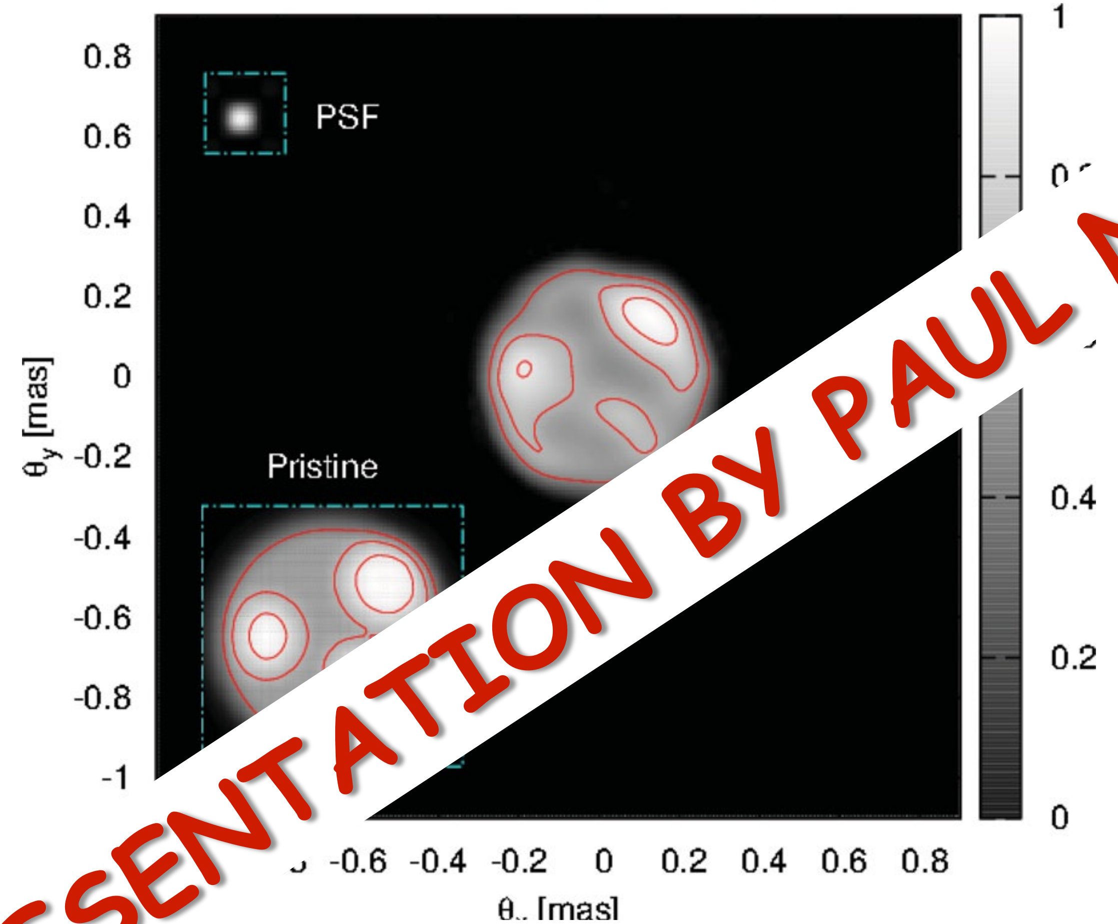


This Airy-disk diffraction pattern is immediately recognized as originating in a circular aperture, although only intensities are recorded.



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

Image reconstruction from intensity interferomet



SEE PRESENTATION BY PAUL NUÑEZ

Numerical ... of intensity-interferometry observations with a CTA-like ...th image reconstruction of a star with three hotspots

Pr... has T = 6000 K; spots have 6500K (top-right and left) and 6800K.

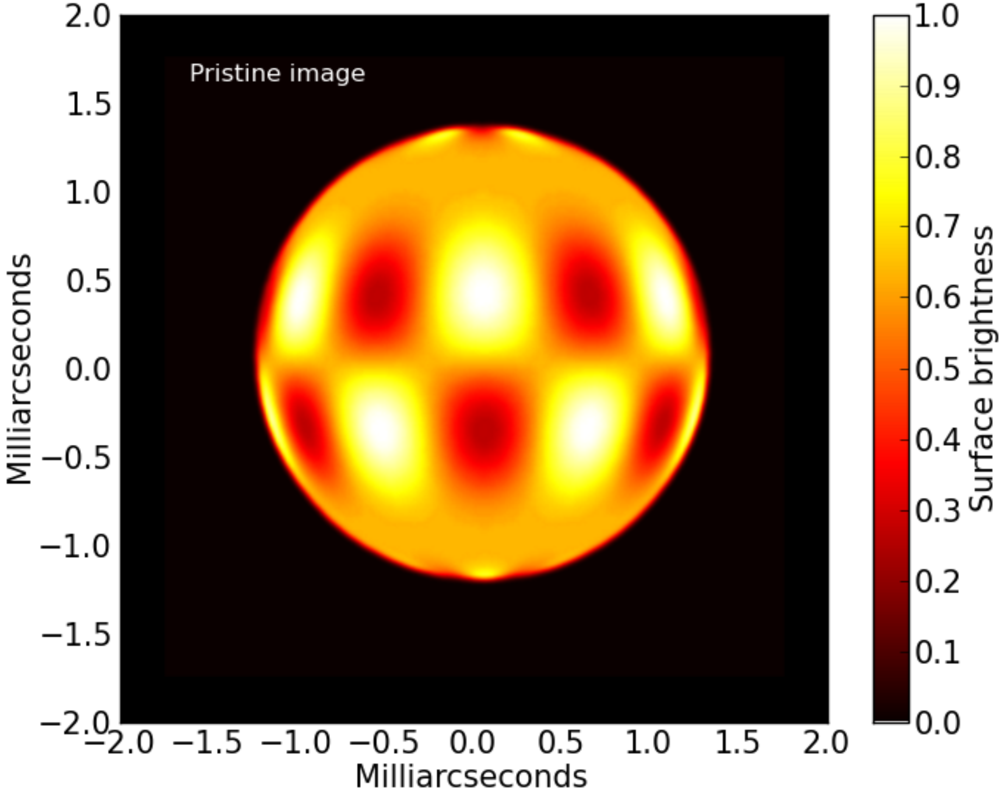
...d data correspond to visual magnitude m_V = 3, and 10 hours of observation.

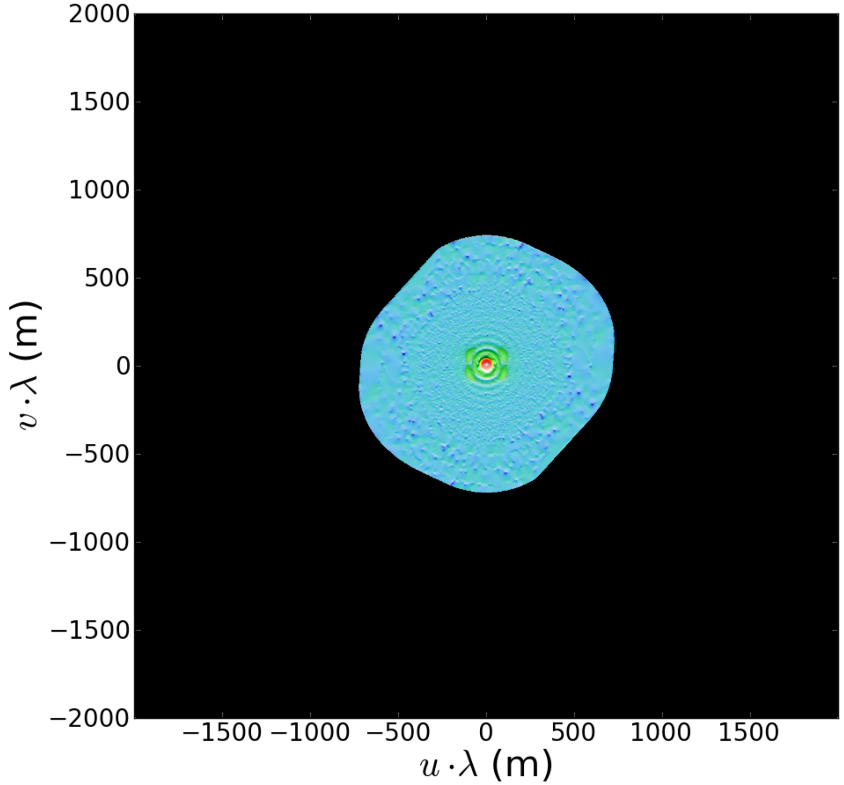
...uñez, R.Holmes, D.Kieda, J.Rou, S.LeBohec, *Imaging submilliarcsecond stellar features with intensity ...erferometry using air Cherenkov telescope arrays,* MNRAS **424**, 1006 (2012)

NON-RADIAL PULSATIONS & VELOCITIES ACROSS STELLAR SURFACES

Observations through very narrow bandpass filters, spanning one spectral line

(might require ordinary telescopes rather than Cherenkov ones)





Simulated observations of a Cepheid-like star undergoing non-radial pulsations
m_V = 3.4; T_{eff} = 7000 K; Δt = 1 ns; λ = 500 nm; Array = CTA B

Left: Pristine image; Right: Observed Fourier magnitude

Cherenkov Telescope Array as an Intensity Interferometer

Expected resolution for assumed exoplanet transit across the disk of Sirius

cta
cherenkov telescope array

Stellar diameter = 1.7 solar
Distance = 2.6 pc
Angular diameter = 6 mas

Assumed Jupiter-size planet with rings;
four Earth-size moons;
equatorial diameter = 350 μas.

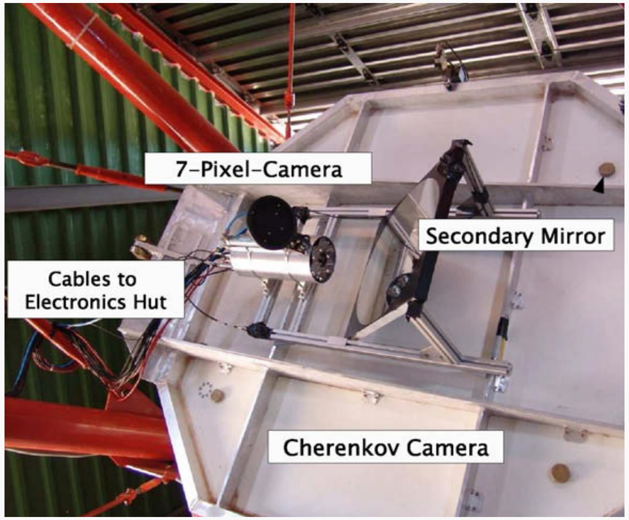
CTA array spanning 2 km;
Resolution 50 μas at λ 400 nm provides more than 100 pixels across the stellar diameter

Intensity interferometry

COULD BE: First km-scale optical imager with hundreds of baselines, imaging hot stars at short optical wavelengths.

IS NOT: An alternative to phase/amplitude interferometers. These are superior in imaging cool and extended sources.

Other optical astronomy with CTA?



HIGH SPEED TRANSIENTS

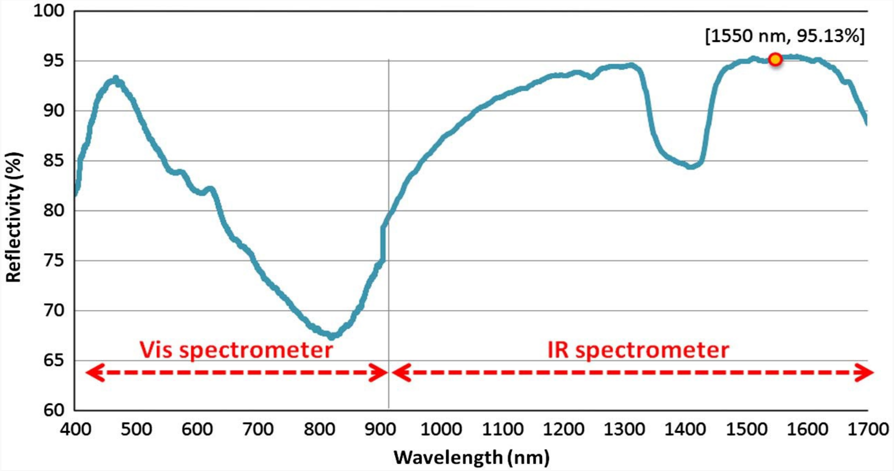
Detectors on outside lid of the H.E.S.S. Cherenkov camera

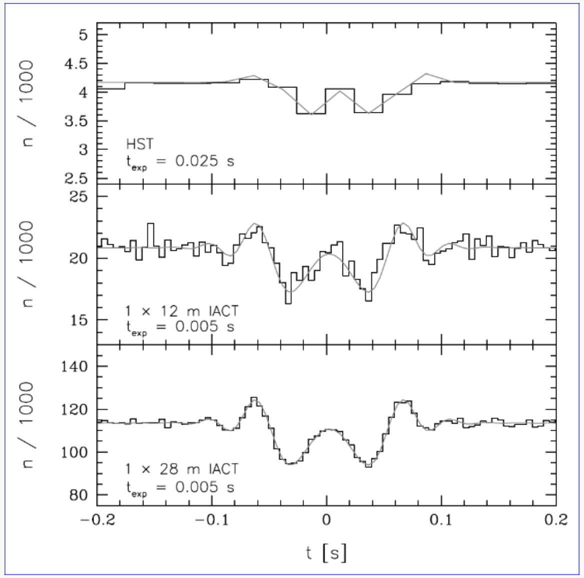
C.Deil, W.Domainko, G.Hermann, A.C.Clapson, A.Förster, C.van Eldik, W.Hofmann:
Capability of Cherenkov telescopes to observe ultra-fast optical flares
Astropart.Phys. **31**, 156 (2009)

OPTICAL SPACE COMMUNICATION

Reflectivity measurements of a MAGIC mirror

A.Carrasco-Casado, M.Vilera, R.Vergaz, J.Francisco Cabrero:
Feasibility of utilizing Cherenkov Telescope Array gamma-ray telescopes as free-space optical communication ground stations
Appl.Opt. **52**, 2353 (2013)





KUIPER-BELT OCCULTATIONS

Simulated occultation light curves

Brian C. Lacki:
On the Use of Cherenkov Telescopes for Outer Solar System Body Occultations
MNRAS (2014); arXiv1402.1179L

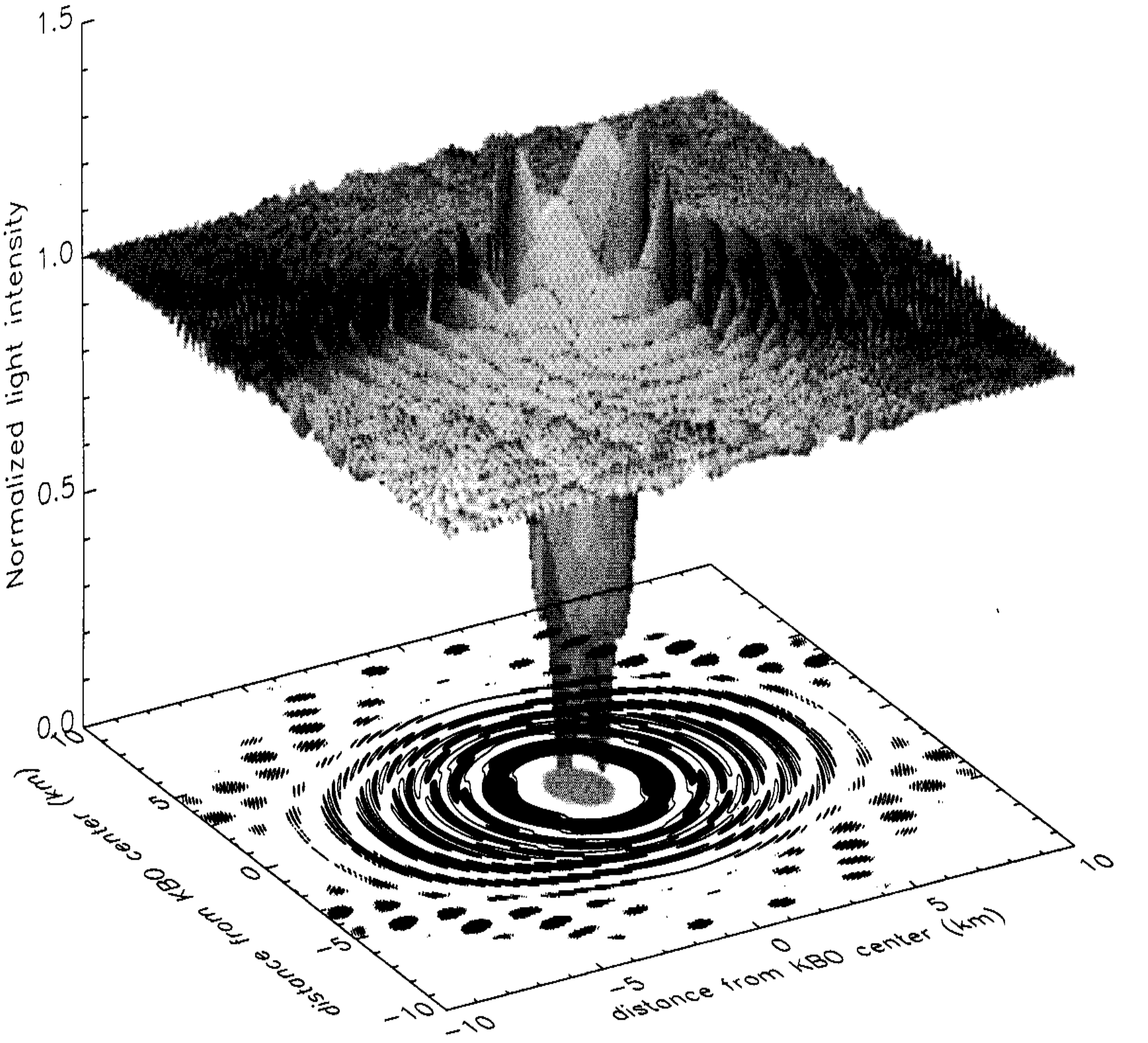
KUIPER-BELT OCCULTATIONS

Diffraction & shadow of irregular 1-km Kuiper-belt object in front of a point star.

Horizontal axes in km, vertical axis is stellar flux.

Grey central spot indicates the geometrical shadow.

(Roques & Moncuquet, 2000)



Intensity interferometry can be carried out in moonlight when Cherenkov observations are not efficient

Laboratory & field experiments

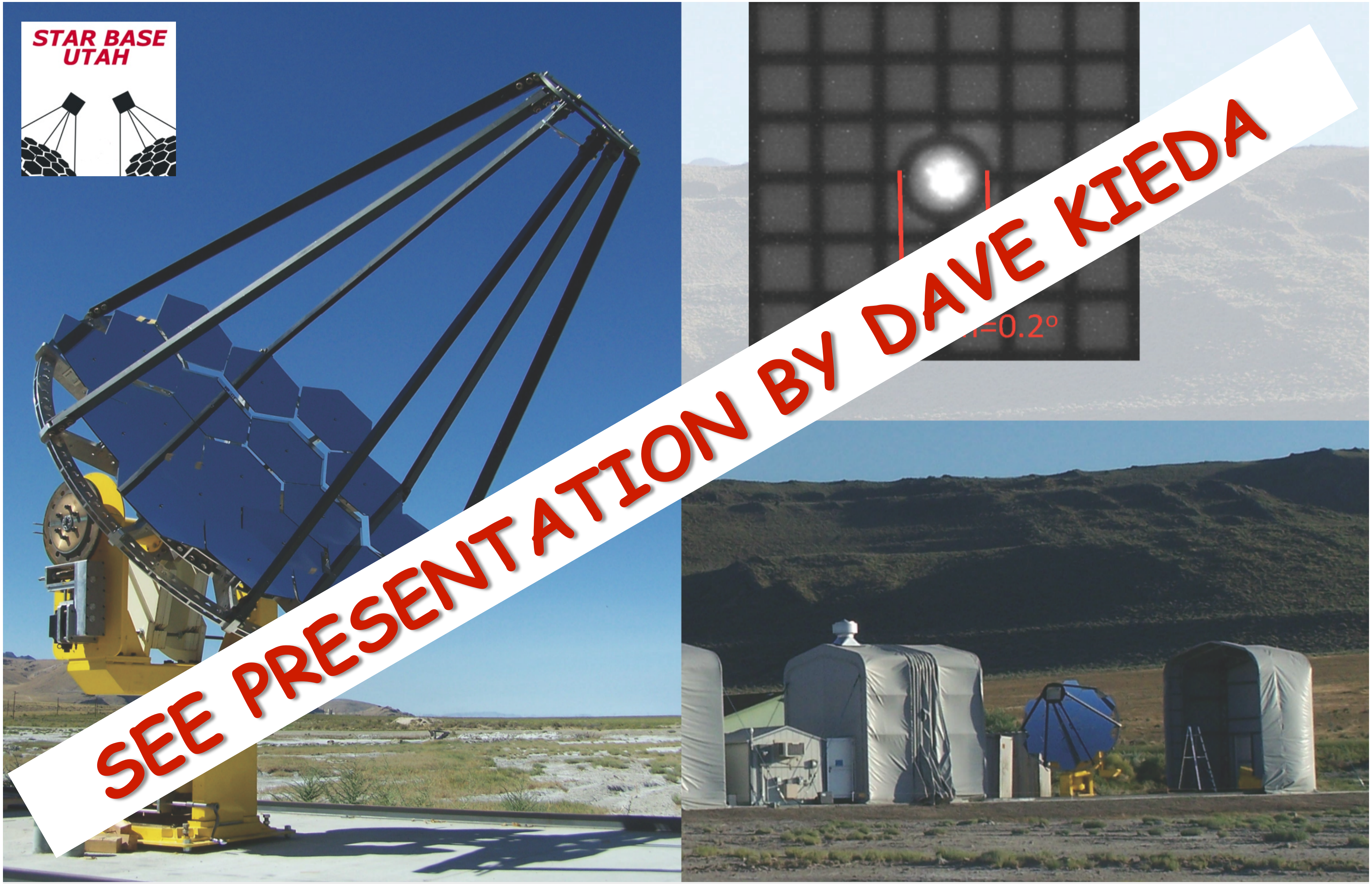
Verify operation of an intensity interferometer; understand detector properties, issues in data handling

VERITAS telescopes at Basecamp, Arizona

Site of first full-scale tests of digital intensity interferometry

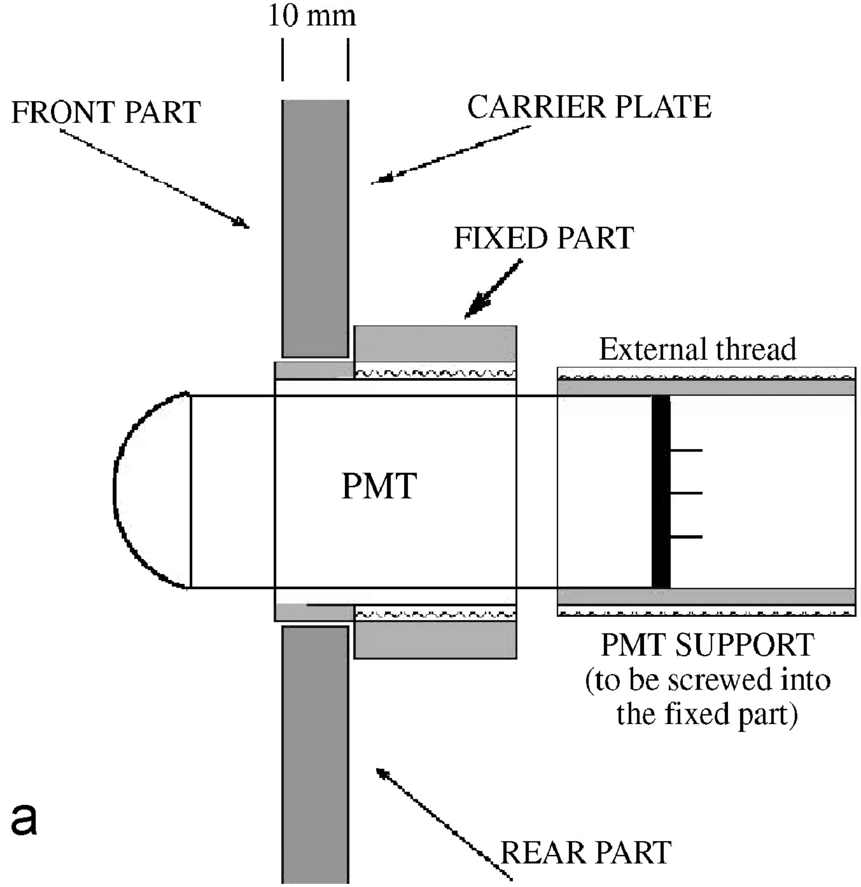
* Digitally correlated pairs of 12-m telescopes
* Photon rates >30 MHz per telescope
* Real-time cross correlation, Δt = 1.6 ns

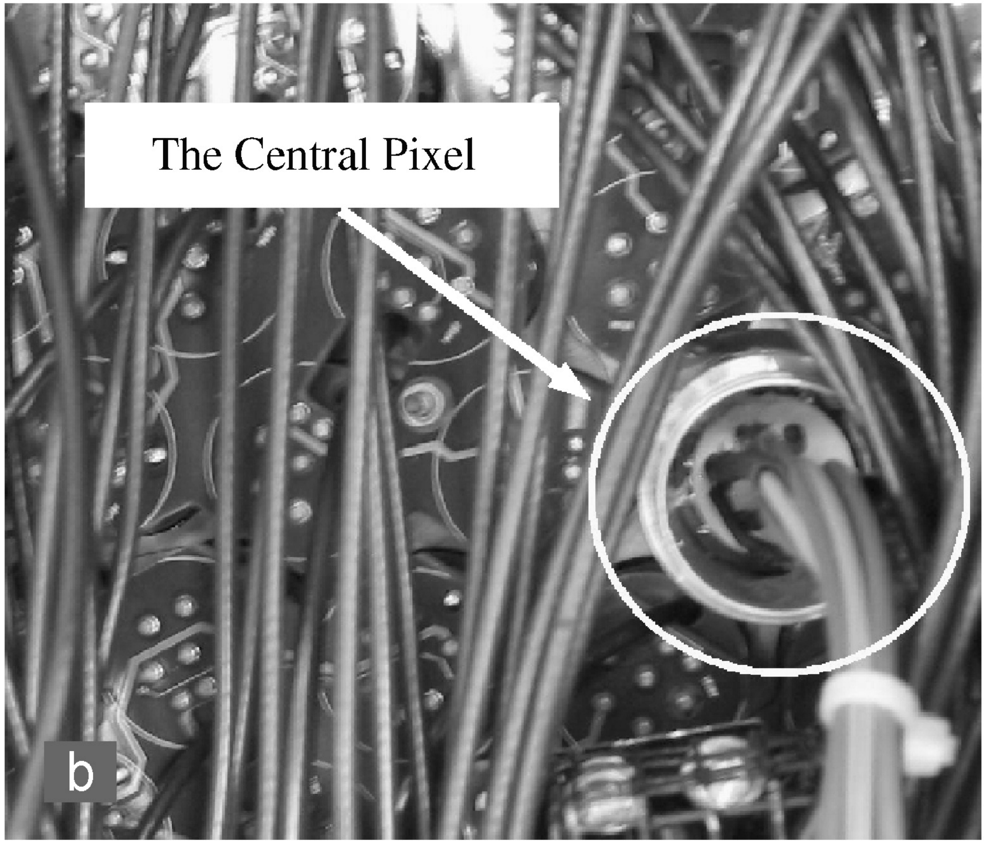
(D.Dravins & S.LeBohec, Proc. SPIE **6986**)



STAR BASE UTAH, A testbed for air Cherenkov telescope instrumentation and intensity interferometry.
(S.LeBohec et al., The University of Utah)

CENTRAL PIXEL IN THE *MAGIC I* TELESCOPE



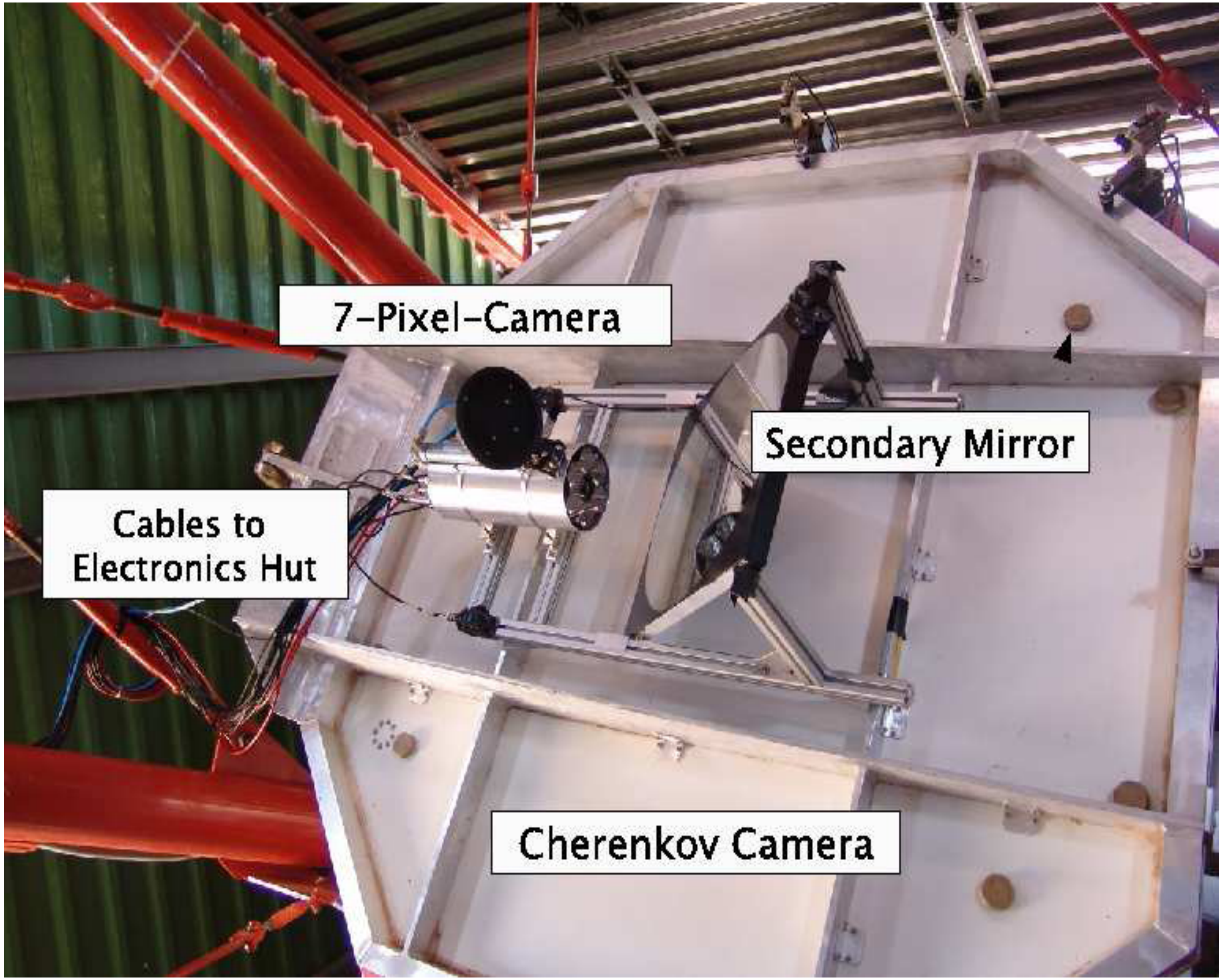


Support of the central pixel, and a camera rear-side photograph with the PMT installed

The mechanical support holding the PMT at the central aperture position, consists of two parts:

* One part is fixed to the metal support plate (dubbed "Swiss cheese" because of its many holes)
* The second part, containing the PMT, is screwed into the central aperture of the "Swiss cheese" plate

The Central Pixel of the MAGIC Telescope for Optical Observations
F.Lucarelli, J.A.Barrio, P.Antoranz, M.Asensio, M.Camara, J.L.Contreras, M.V.Fonseca, M.Lopez, J.M.Miranda, I.Oya, R.De los Reyes, R.Firpo, N.Sidro, F.Goebel, E.Lorenz, N.Otte
Nucl.Instr.Meth.Phys.Res.A, 589, 415 (2008)



7-pixel camera on the lid of the H.E.S.S. Cherenkov camera

A 7-pixel camera was custom-built and mounted on the lid of the Cherenkov camera of a H.E.S.S. telescope using a plane secondary mirror to put it into focus.

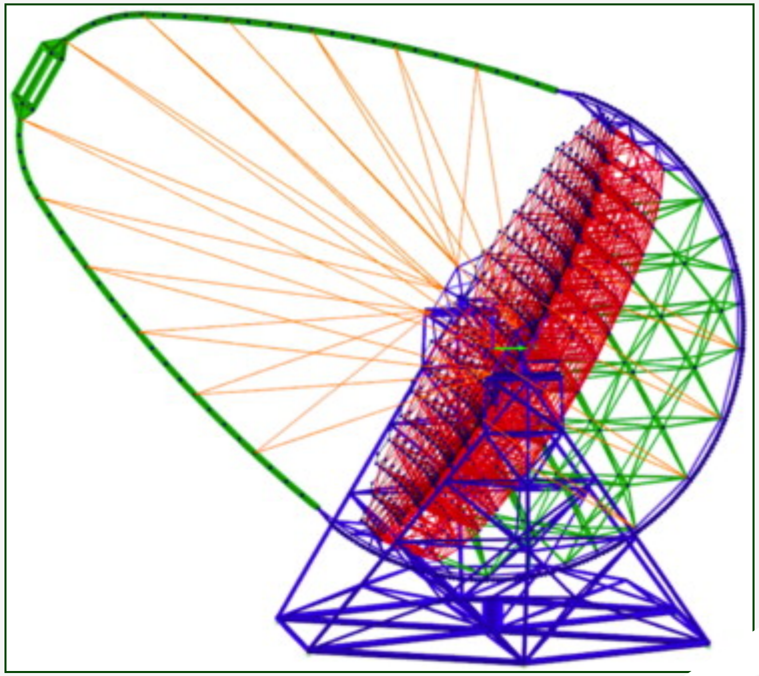
Its central pixel was used to continuously record the light curve of the target, while a ring of six 'outer' pixels was used both to monitor the sky background level and as a veto system to reject background events occurring in the atmosphere

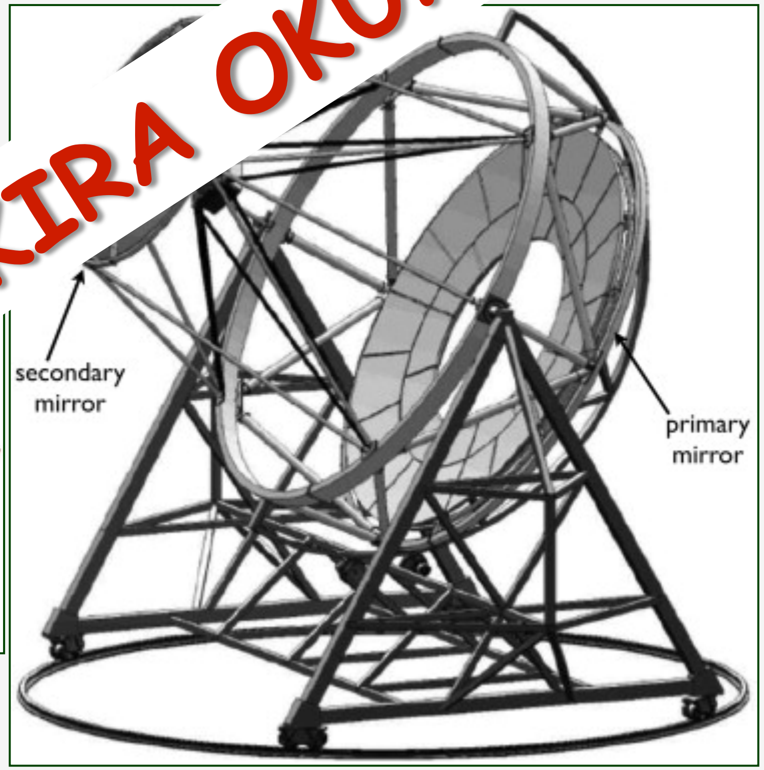
C.Deil, W.Domainko, G.Hermann, A.-C.Clapson, A.Förster, C.van Eldik, W.Hofmann: Capability of Cherenkov Telescopes to Observe Ultra-fast Optical Flares
Astropart.Phys. **31**, 156 (2009)

Limits to time resolution?
Isochronous telescopes?

Parabolic or Schmidt better than Davies-Cotton for Δt < few ns

CTA telescope concepts





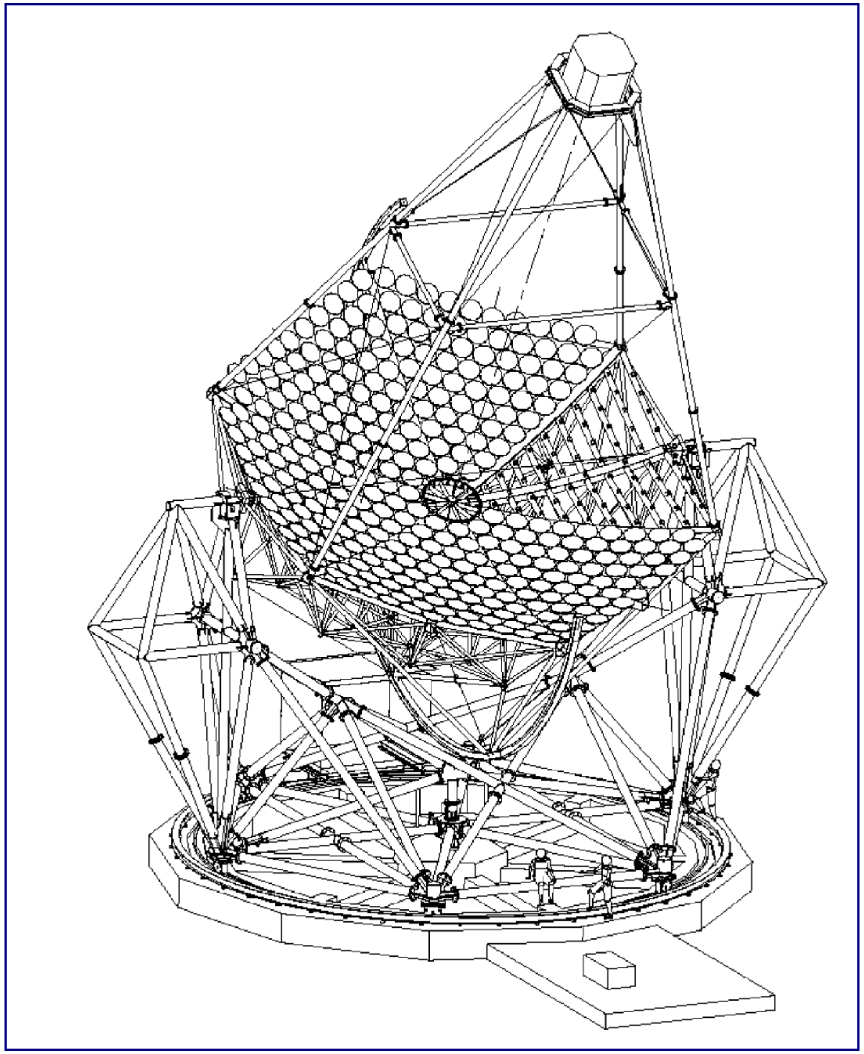
SEE PRESENTATION BY AKIRA OKUMURA

Left: Baseli… large telescope of 23 m diameter, with 4.5° field of view and 2500 pixels of 0.1° diameter.

Cente… …ign for the 12 m diameter medium-sized telescope of Davies–Cotton optical design (spherical pri… …oV and 1500 pixels of 0.18°.

…gn for a Schwarzschild–Couder dual-mirror telescope, with a compact camera close to the secondary mirror. …ave a FoV of 8° diameter, consisting of 11000 square pixels of 0.067° side length.

…S. Acharya et al.: *Introducing the CTA concept*, Astropart. Phys. **43**, 3, 2013



Cherenkov telescopes are usually Davies–Cotton or parabolic

In a Davies–Cotton layout, all reflector facets have same focal length f, arranged on a sphere of radius f.

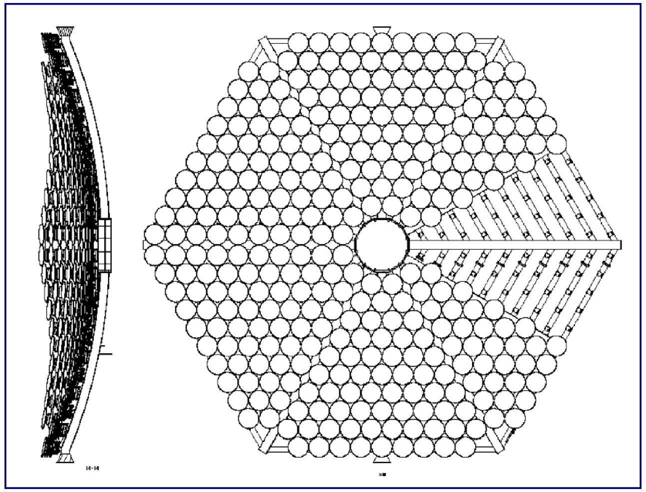
In a parabolic layout, mirrors are arranged on a paraboloid, and the focal length of the (usually spherical) mirror facets varies with the distance from the optical axis.

Both have significant aberrations off the optical axis, the parabolic slightly worse than Davies–Cotton.

Time dispersion introduced by the reflector should not exceed the intrinsic spread of the Cherenkov wavefront of a few ns.

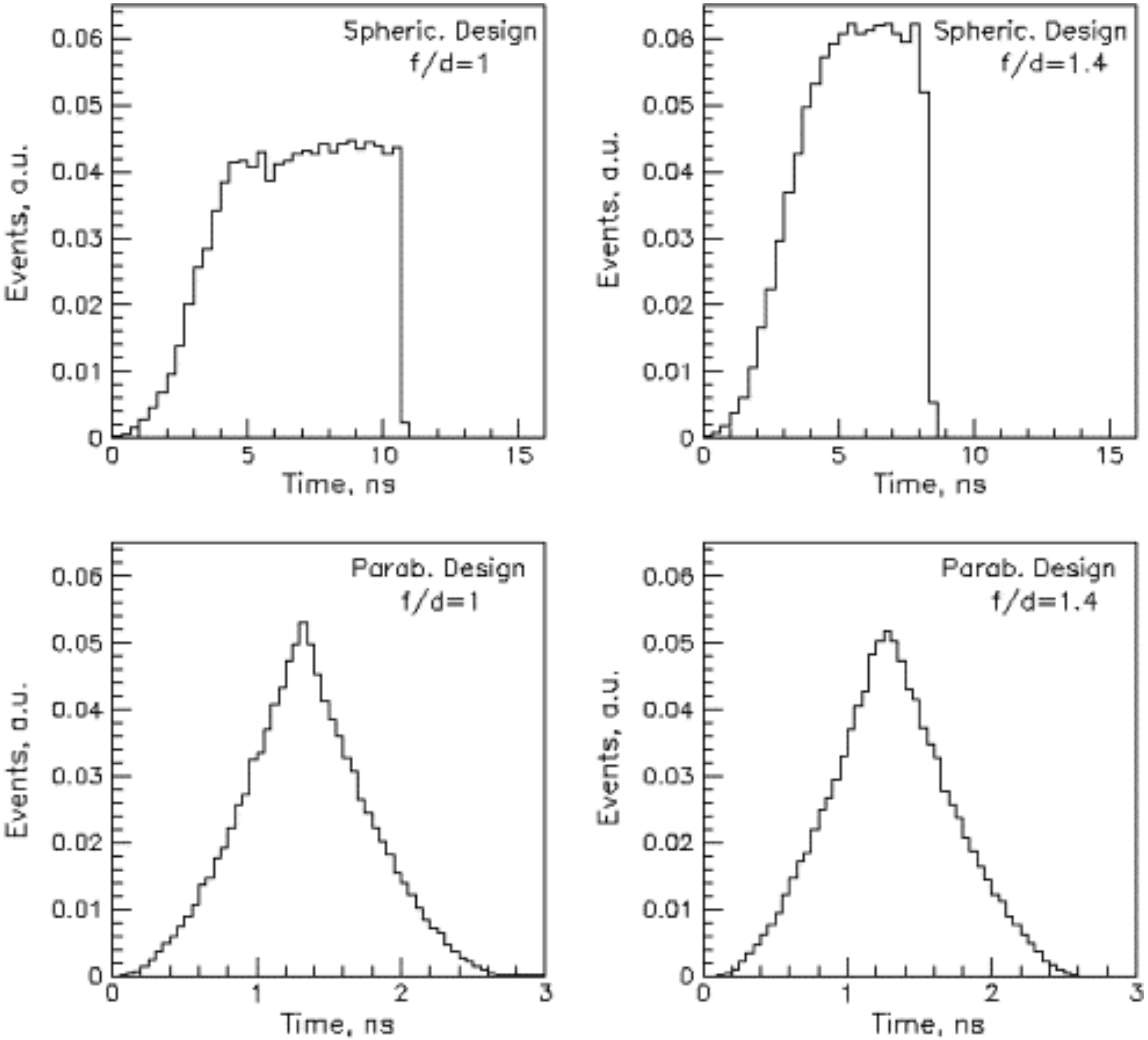
Parabolic reflectors are isochronal – apart from minute effects caused by individual mirror facets being spherical rather than parabolic.

Davies–Cotton layout causes a spread of photon arrival times at the camera; a plane incident wavefront results in photons spread over $\Delta t \approx 5$ ns, with an rms width ≈ 1.4 ns.



The optical system of the H.E.S.S. imaging atmospheric Cherenkov telescopes. Part I: Layout and components of the system
K.Bernlöhr, O.Carrol, R.Cornils, S.Elfahem P.Espigat, S.Gillessen, G.Heinzelmann, G.Hermann, W.Hofmann, D.Horns. I.Jung, R.Kankanyan, A.Katona, B.Khelifi, H.Krawczynski, M.Panter, M.Punch, S.Rayner, G.Rowell, M.Tluczykont, R.van Staa
Astropart.Phys. **20**, 111 (2003)

INTRINSIC TIME SPREAD IN 20 m ∅ CHERENKOV TELESCOPES



Top: Spherical (Davies–Cotton)

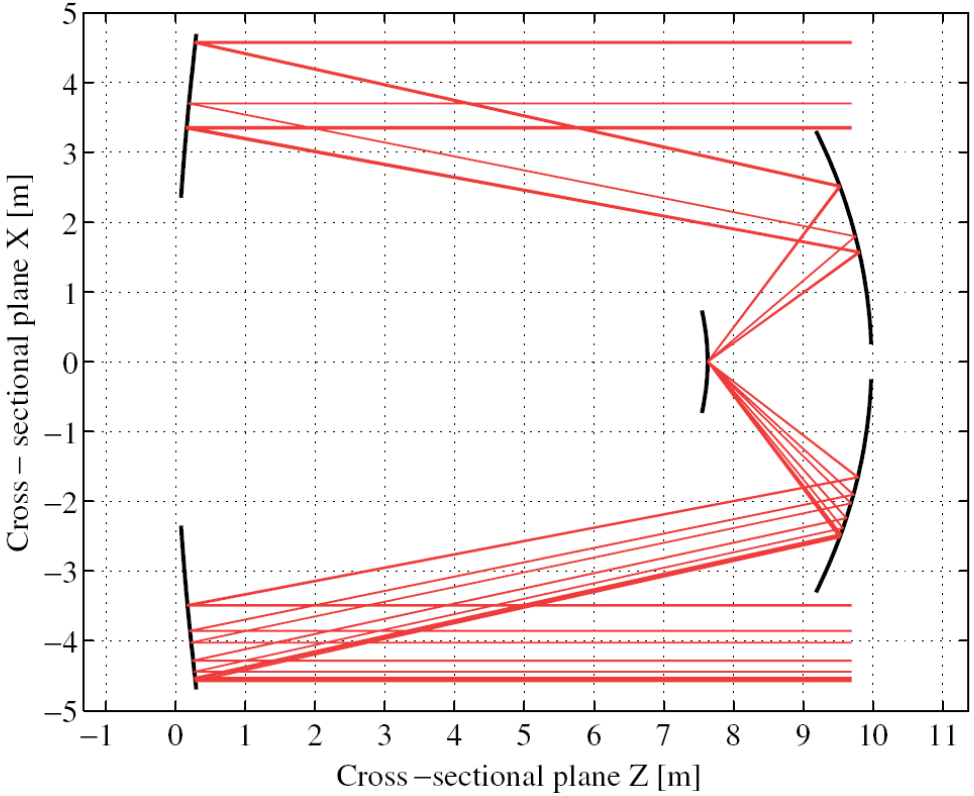
A spherical reflector substantially widens the photon pulse.

At detecting 10 GeV γ-showers, the pulse width on the spherical telescope's focal plane may reach 15–20 ns instead of the inherent 5–8 ns.

Angles of incidence = 2°

Bottom: Parabolic

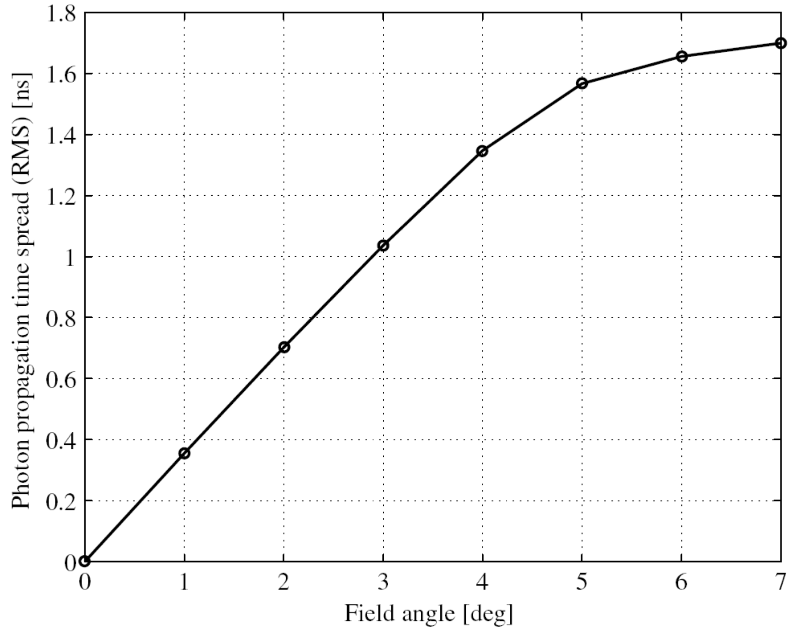
Performance of a 20 m diameter Cherenkov imaging telescope
A.Akhperjanian & V.Sahakian
Astropart.Phys. 21, 149 (2004)



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)

Photometric precision

First-order coherence: $g^{(1)} = 1$

Second-order coherence for chaotic light:

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

But... experimental $\Delta t \gg$ coherence time τ_c (10 fs?)

Realistic time resolution ~ 10 ns

$$g^{(2)}(\tau) = 1 + \varepsilon \sim 1.00001$$

Analyzing photon-counting detectors

Afterpulsing, afterglow and other signatures could mimic intensity correlations

Single-photon-counting avalanche photodiode detectors being evaluated @ Lund Observatory for digital intensity interferometry

(made by*: ID Quantique; Micro Photon Devices; PerkinElmer; SensL*)

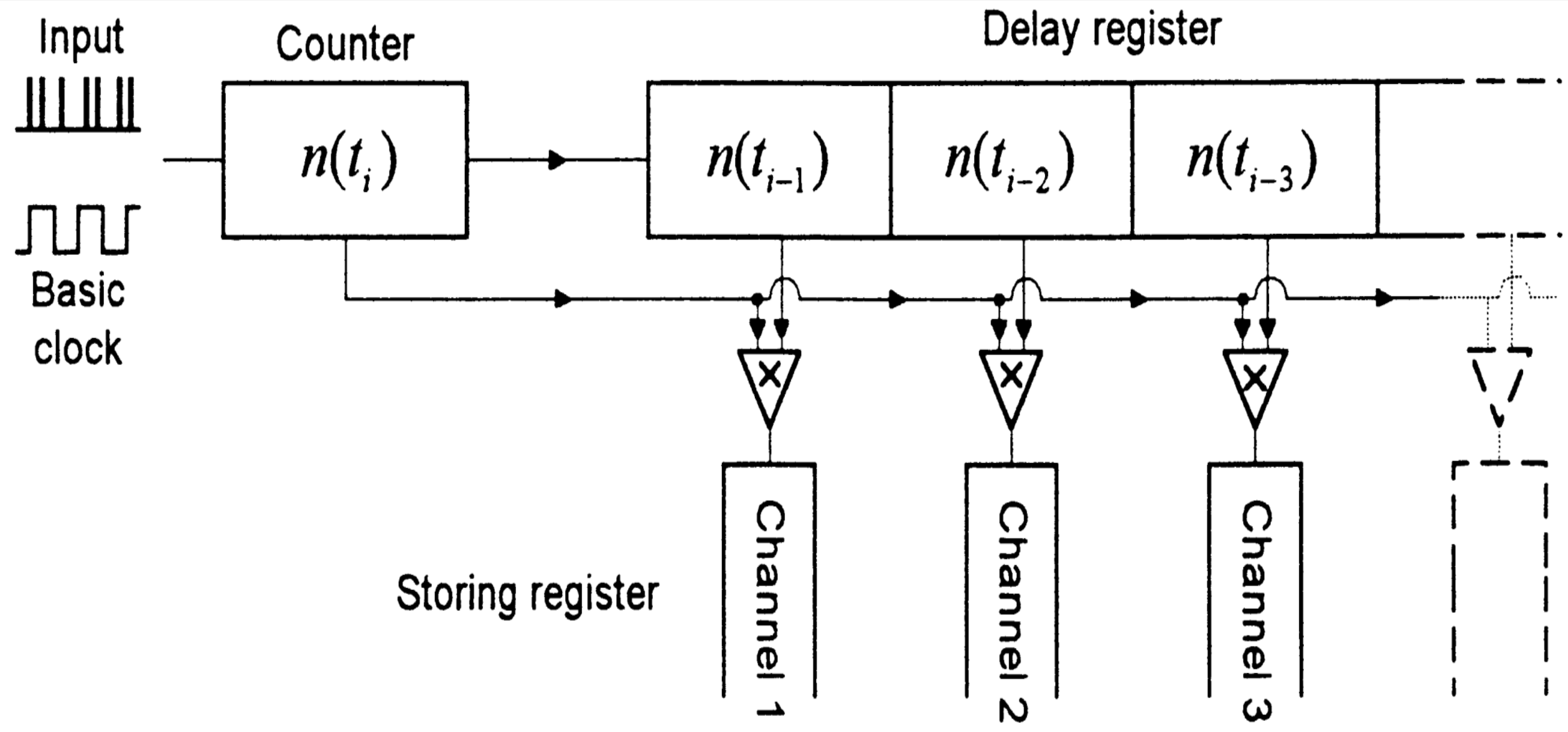
Real-time correlation

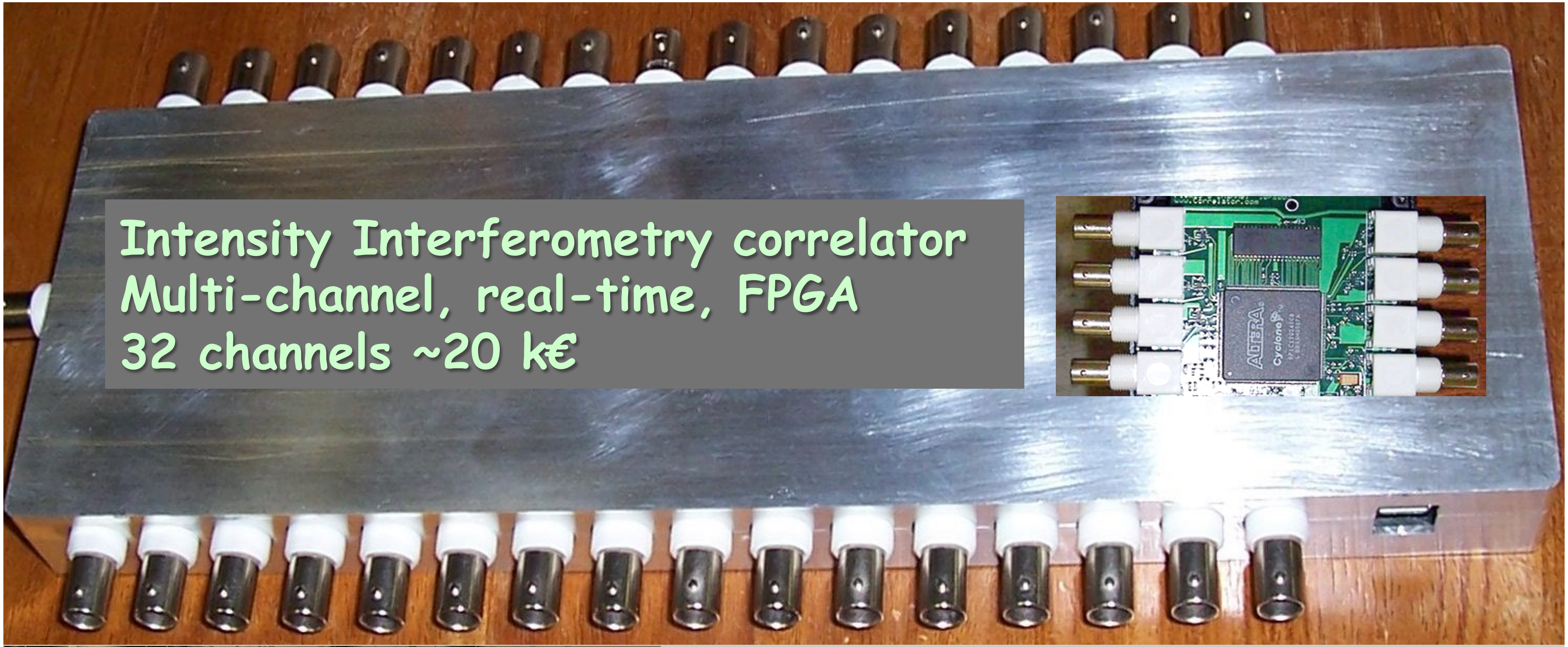
Pro: Search all timescales in real time, store only reduced data

Con: Lose information on transients, no alternative analyses

Real-time digital photon correlators

Permit to verify various observational modes,
both in the lab, and at telescopes





Intensity Interferometry correlator
Multi-channel, real-time, FPGA
32 channels ~20 k€

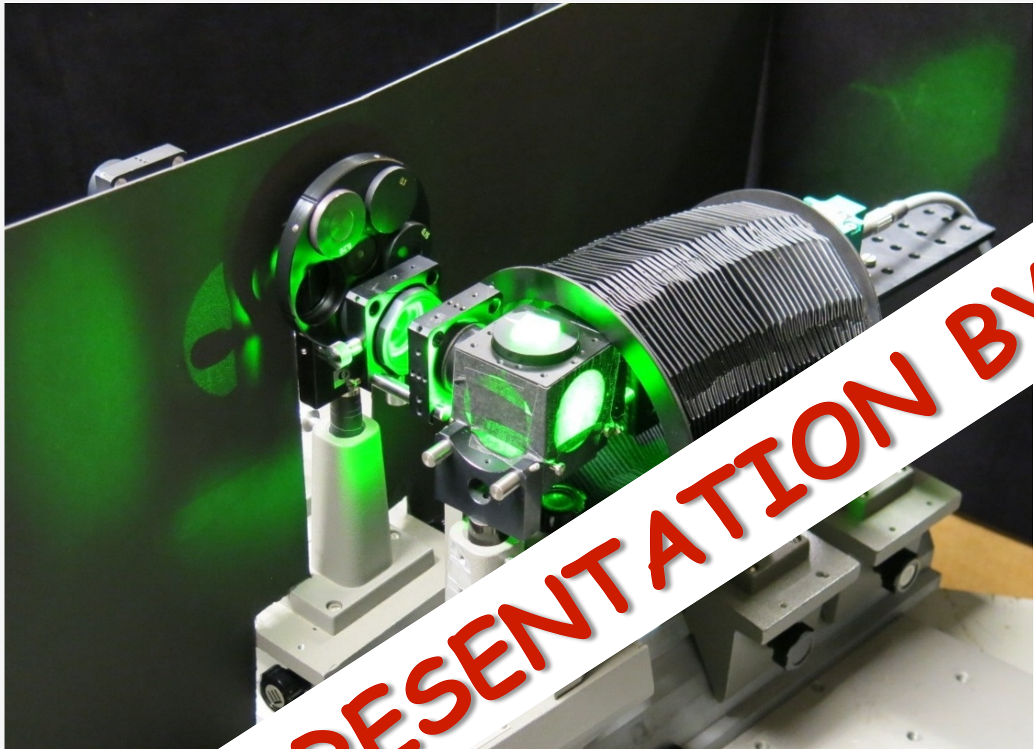
ALMA correlator
134 million processors

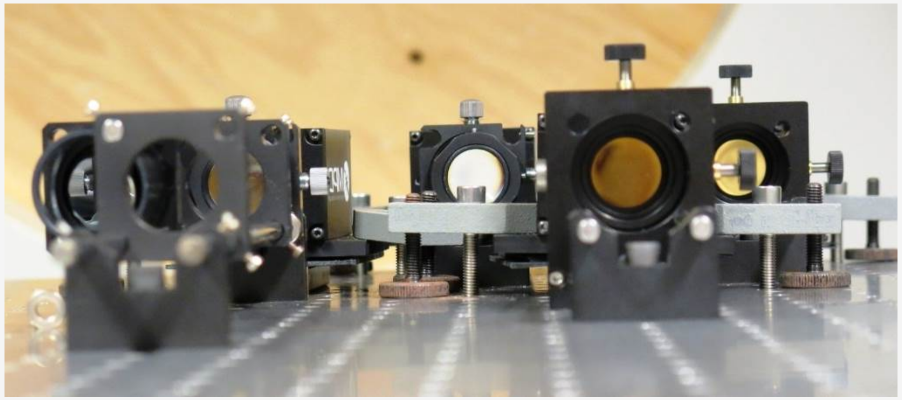
Very much more modest computations than in radio interferometry!

Laboratory simulations

End-to-end operation of intensity interferometry in the laboratory: artificial stars; telescope array; photon-counting detectors; reconstructed images.

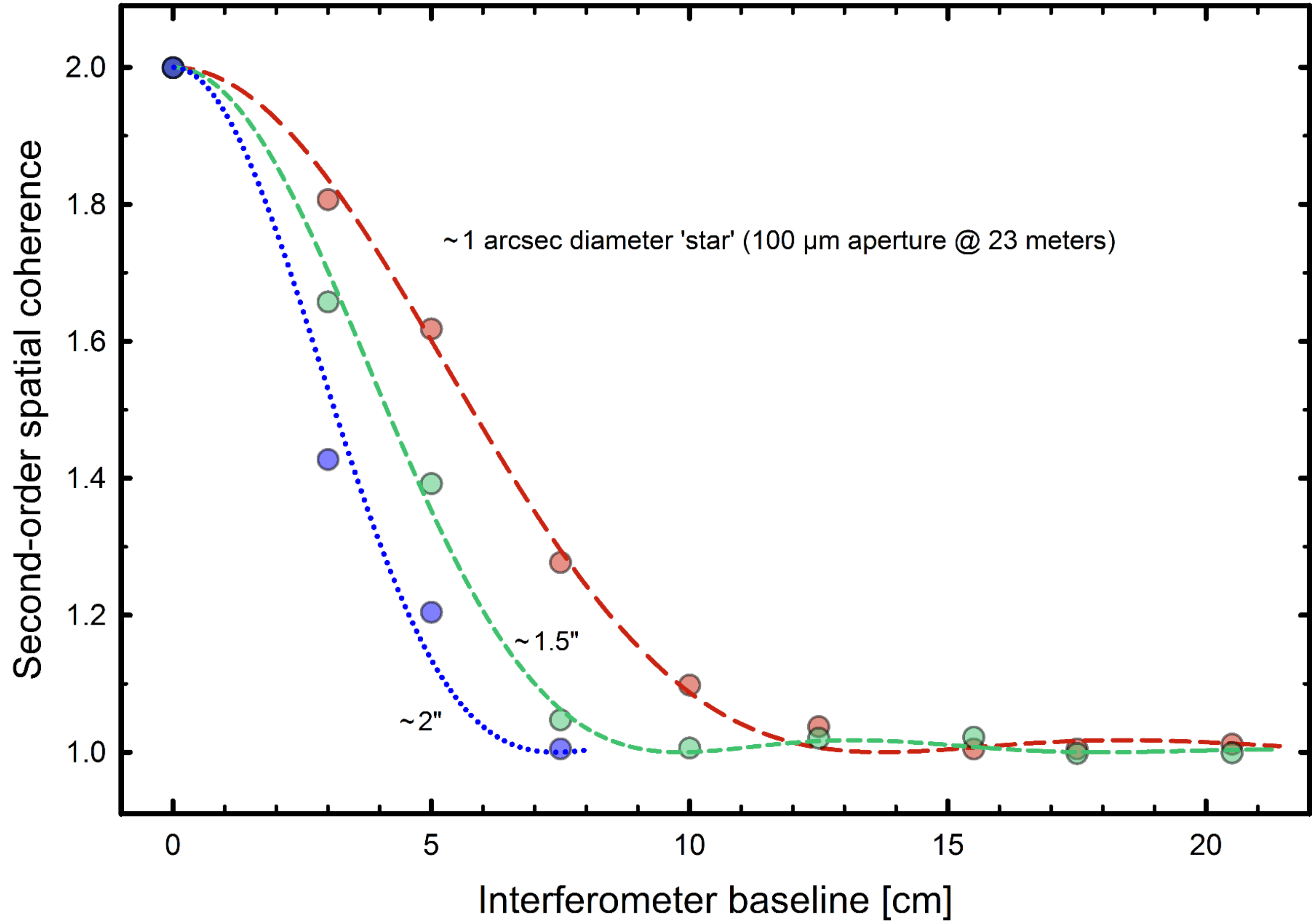
Laboratory intensity interferometer





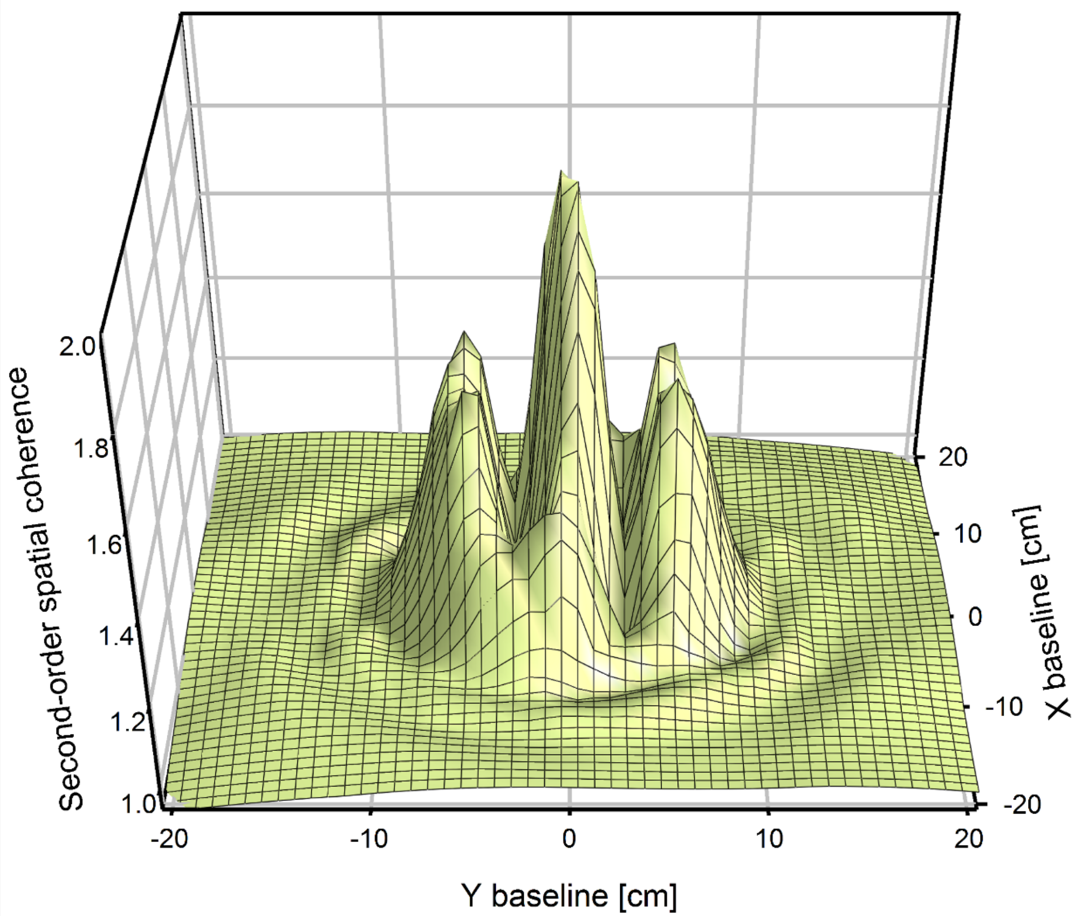
SEE PRESENTATION BY TIPHAINE LAGADEC

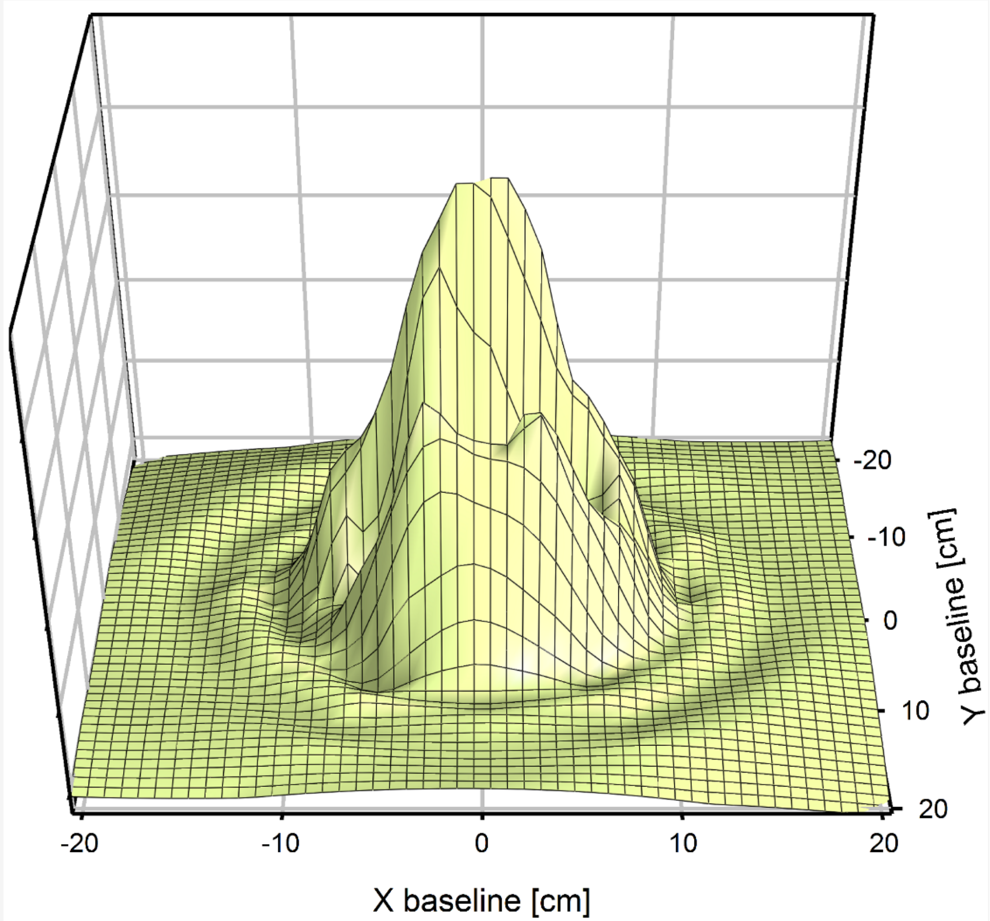
Laboratory intensity interferometry with few baselines



Second-order coherence g(2) measured for artificial single stars of different angular sizes.
Superposed are Airy functions for circular apertures (squared moduli of the Fourier transforms).
(D.Dravins & T.Lagadec, Proc. SPIE **9146**, 2014)

Laboratory intensity interferometry with many baselines

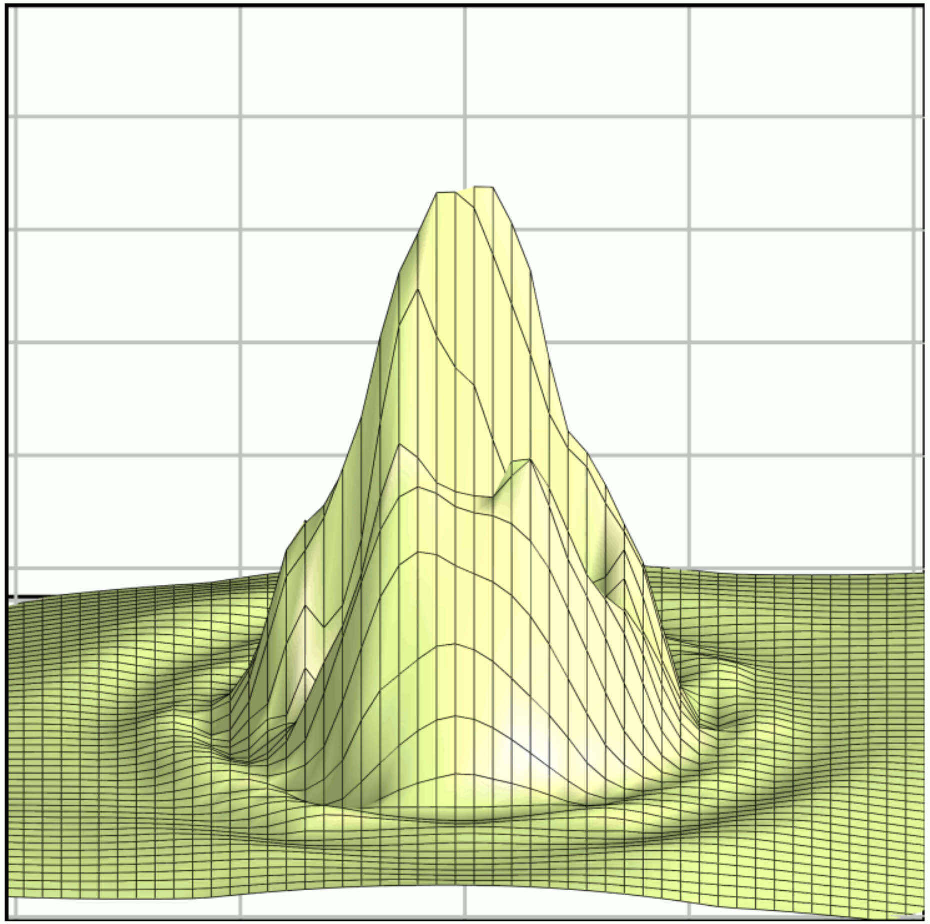




Second-order coherence g(2) for an artificial binary star with each component of diameter ~ 1 arcsec. This coherence surface was produced from intensity correlations measured across 60 different non-redundant baselines, illustrating how a telescope array fills in the interferometric plane. The central maxima (left) indicate the binary separation while the symmetric rings reveal the size of individual stars.

(D.Dravins & T.Lagadec, Proc. SPIE **9146**, 2014)

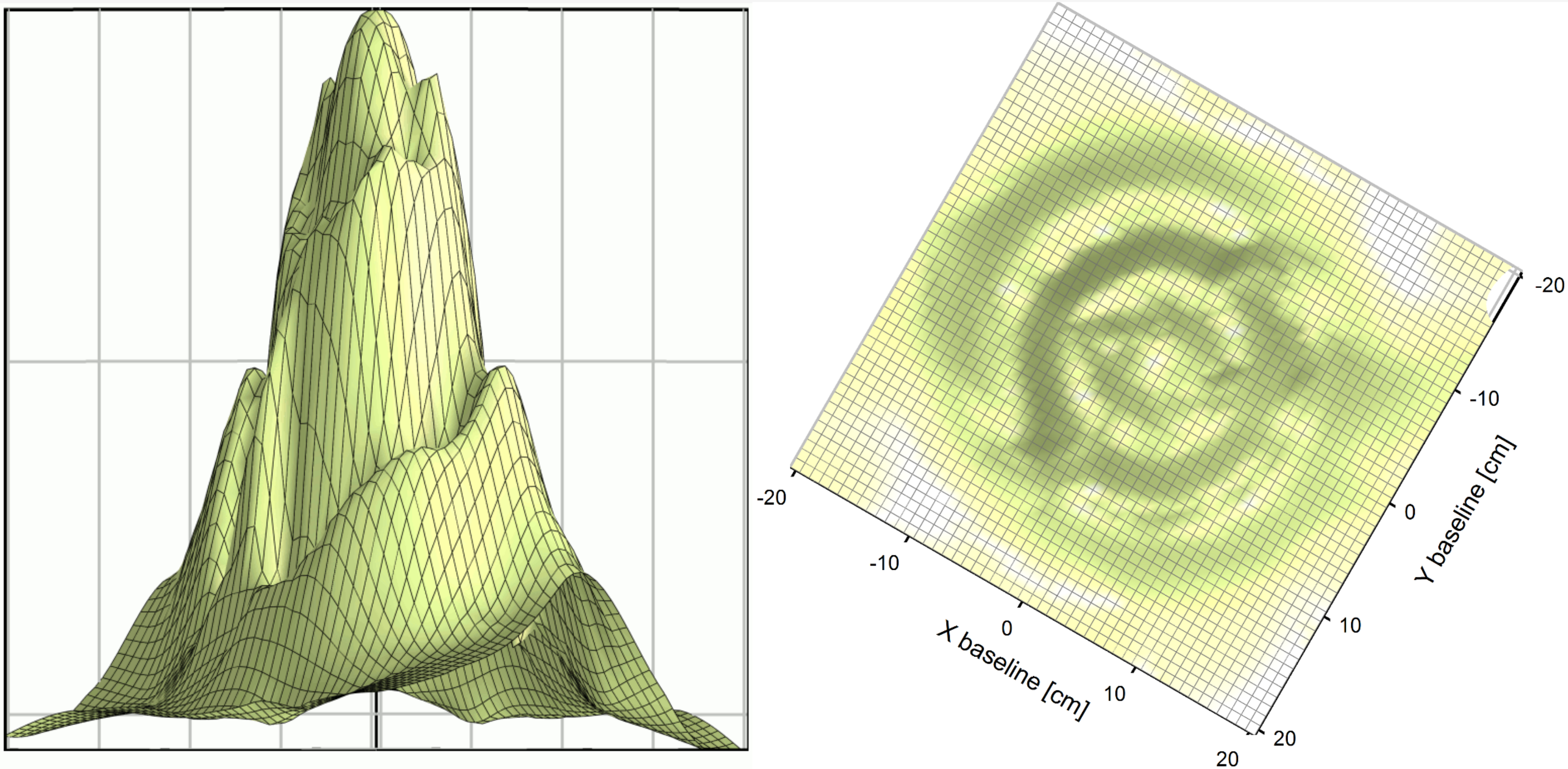
Laboratory intensity interferometry with 60 baselines



Second-order coherence g(2) for an artificial binary star with each component of diameter ~ 1 arcsec. This coherence surface was produced from intensity correlations measured across 60 different non-redundant baselines, illustrating how a telescope array fills in the interferometric plane. The central maxima indicate the binary separation while the symmetric rings reveal the size of individual stars.

(D.Dravins & T.Lagadec, Proc. SPIE **9146**, 2014)

Laboratory intensity interferometry with 100 baselines



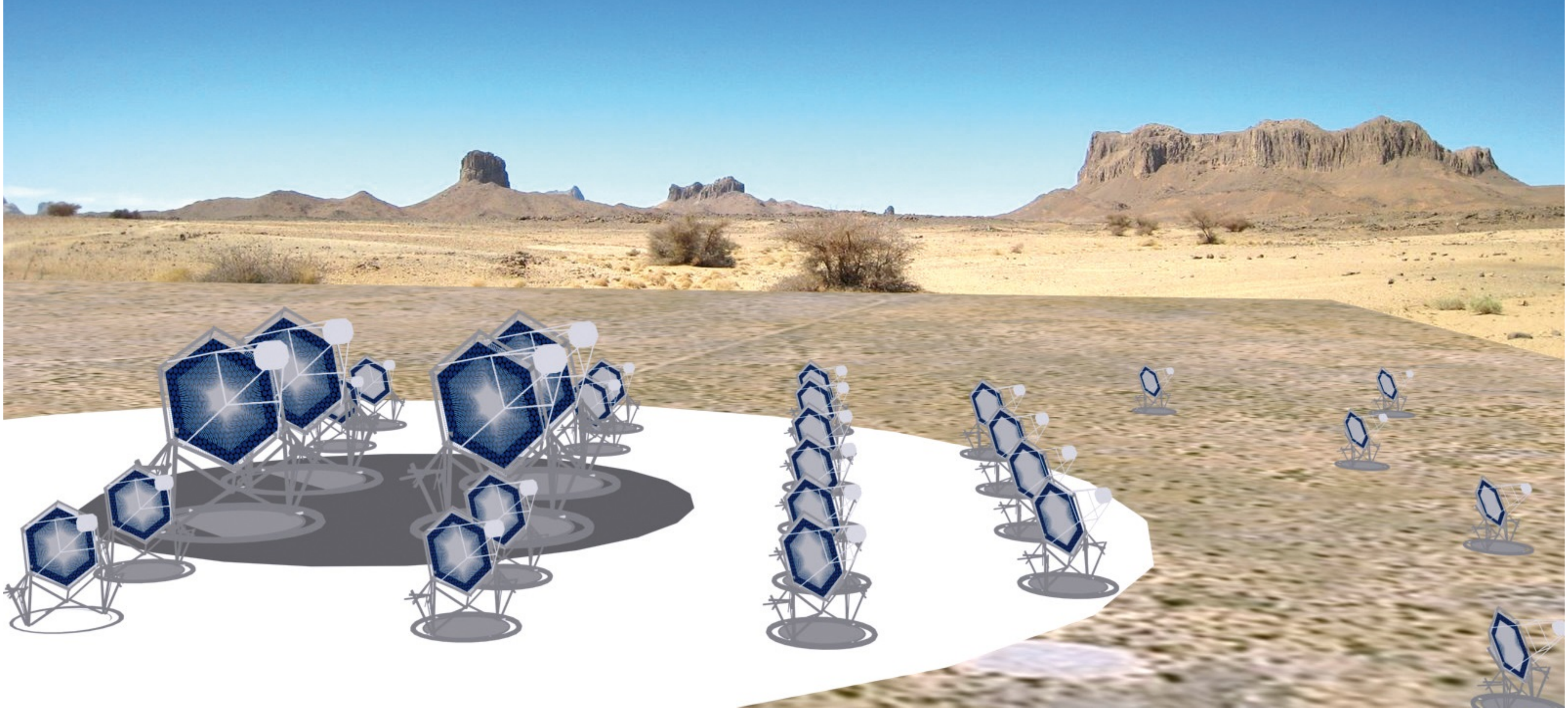
Intensity interferometry measurements with 100 different telescopic baselines. The data largely fill the interferometric (u,v)-plane of the second-order coherence g(2) for an artificial star, somewhat irregular and elliptic, with angular extent just below 1 arcsecond. At right, the projection of the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

(D.Dravins & T.Lagadec, Proc. SPIE **9146**, 2014)

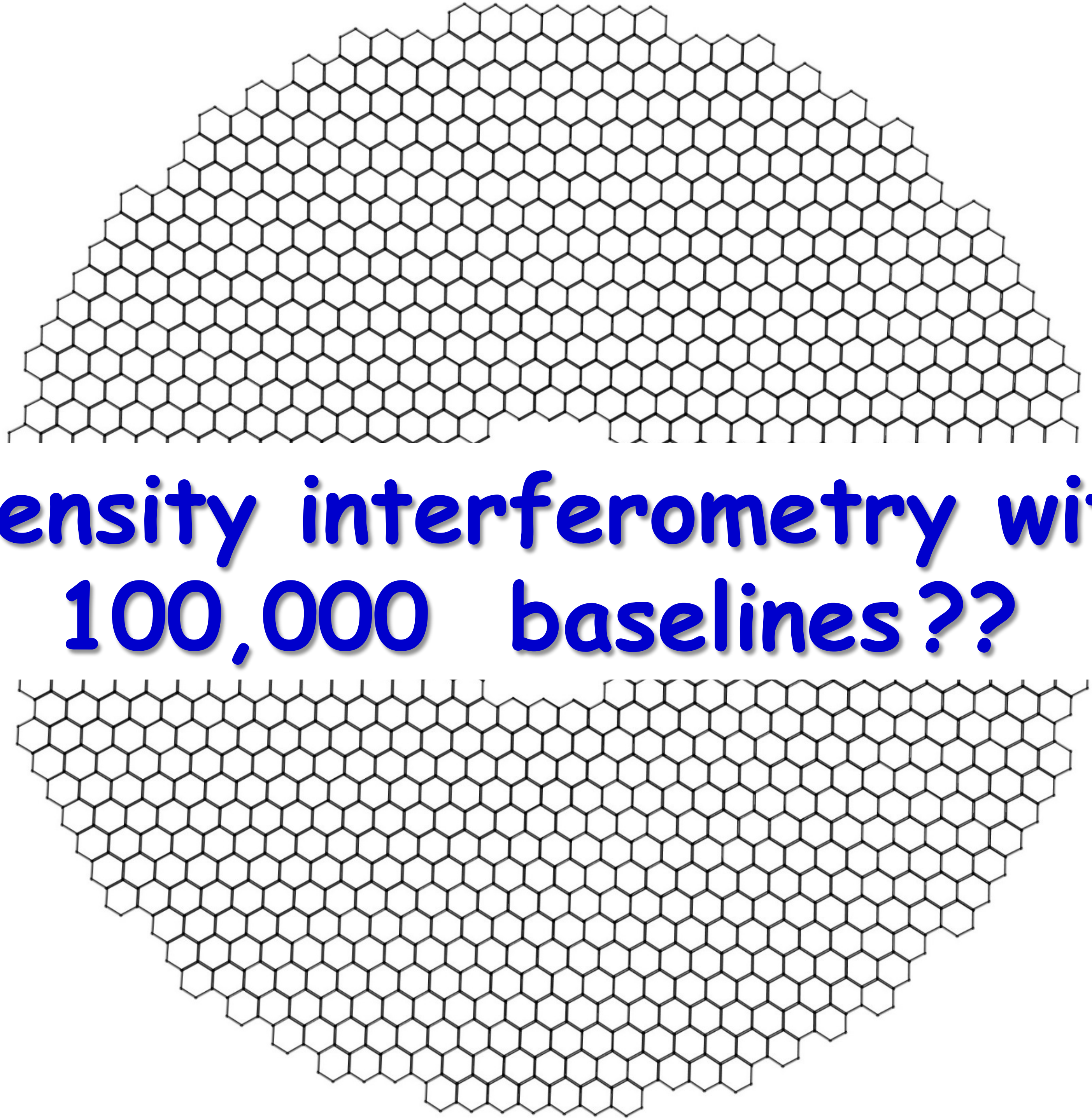
cta
cherenkov telescope array

http://www.cta-observatory.org/

Intensity interferometry with 1000+ baselines!



Intensity interferometry with 100,000 baselines??



E-ELT
European Extremely Large Telescope

…after CTA

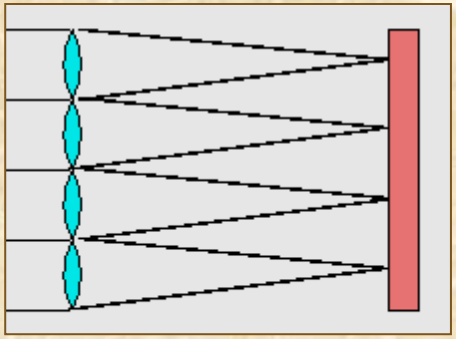
Mock-up of E-ELT 39.3 m main mirror with 798 hexagons, each 1.4 m wide
(ESO's Open House Day in Garching bei München)

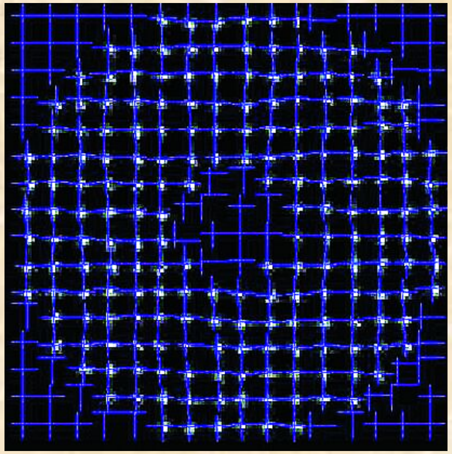
Cherenkov telescopes	E-ELT
★ Huge collecting area, ~ 10,000 m^2	★ 40 m ∅ ⇔ 64 telescopes of 5 m ∅
★ Davies-Cotton telescopes not isochronous, light spread ~ few ns	★ Isochronous optics permits very fast detectors down to ~ 10 ps
★ Large PSF, ~ few arcmin, PMT's	★ Small PSF reduces skylight, enables small solid-state detectors
★ Non-collimated light complicates use of color filters	★ Collimated light enables narrow-band filters, multiple spectral bands
★ Separated telescopes, long signal lines, electronic source tracking	★ Compact focus, no signal transmission, telescope tracks source
★ Limiting magnitude m_v ~ 8	★ Limiting magnitude might reach extragalactic sources

Small 'technical' instrument

(already during E-ELT construction phase?)

- ⋆ Lenslet array images E-ELT subapertures onto fast photon-counting detectors
- ⋆ Basically a Shack-Hartmann wavefront sensor
- ⋆ Electronic signal of photon streams is handled by on-line firmware or off-line software
- ⋆ Can use incompletely filled aperture, unadjusted mirror segments, poor seeing
- ⋆ Software access to signal enables intensity interferometry and high-speed photometry





Artist's vision image of SN 1987A from ESO press release eso1032

E-ELT
Adaptive optics @ 2 μm vs. Intensity interferometry @ 400 nm

Beyond intensity interferometry…

★ **Multi-photon correlations and higher-order spatial and temporal coherence** *(Ofir & Ribak, MNRAS* ***368****, 1646, 2006)*

★ **Ghost Imaging — a relative of intensity interferometry**
Natural light is a source of correlated photon pairs.
(Liu & Xiong, JOSA A ***30****, 956, 2013; Strekalov et al. J.Phys.Conf. 414, 012037, 2013)*

★ **Photon statistics from astrophysical sources**
Identify stimulated emission and light-emission processes?
(Dravins, ASSL ***351****, 95, 2008)*

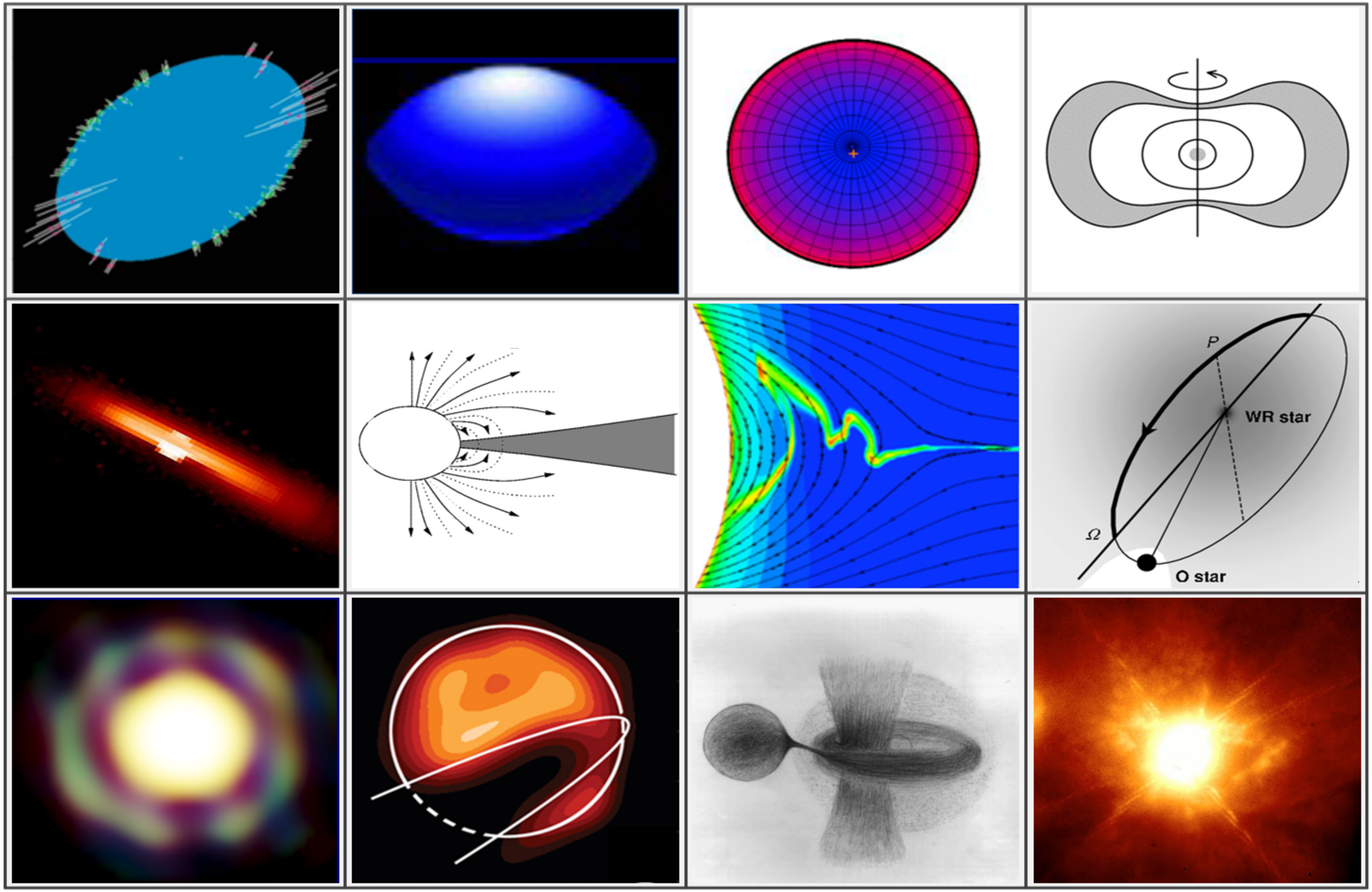
★ **Photon Orbital Angular Momentum from astrophysical sources**
Can be detected in signal from telecope wavefront sensors.
(Sanchez et al., A&A ***556****, A130, 2013)*

… the bottom line …

Observing stars…

(and not only starlight)

Astrophysical targets for km-scale interferometry



D.Dravins, S.LeBohec, H.Jensen, P.D.Nuñez:, CTA Consortium
Optical intensity interferometry with the Cherenkov Telescope Array, Astropart. Phys. **43**, 331-347 (2013)

THE
END