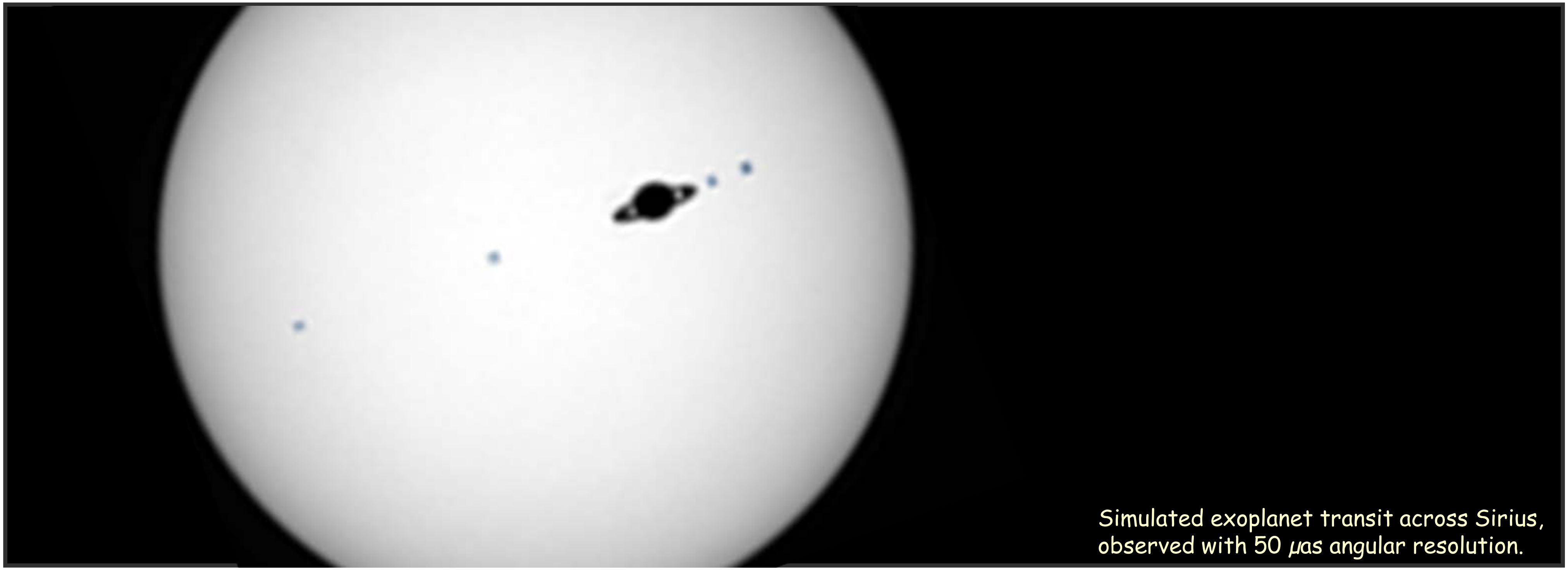


Simulated exoplanet transit across Sirius, observed with 50 μas angular resolution.

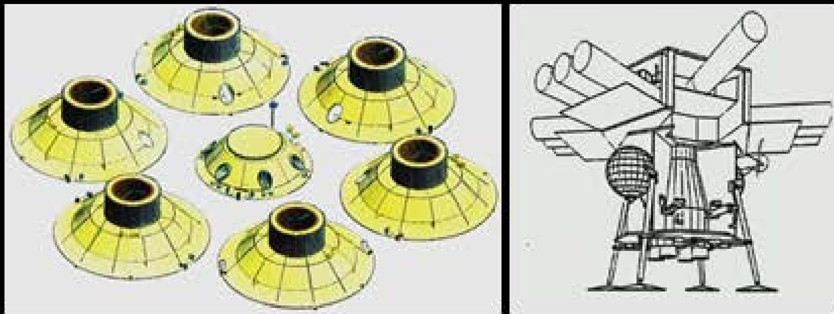
INTENSITY INTERFEROMETRY WITH CHERENKOV TELESCOPE ARRAYS

Prospects for submilliarcsecond optical imaging

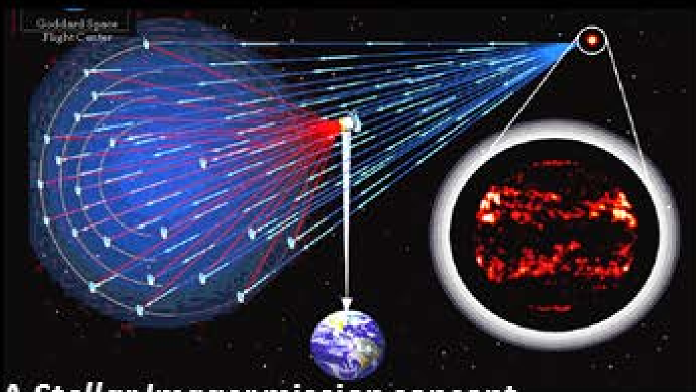
Dainis Dravins — Lund Observatory

www.astro.lu.se/~dainis

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)

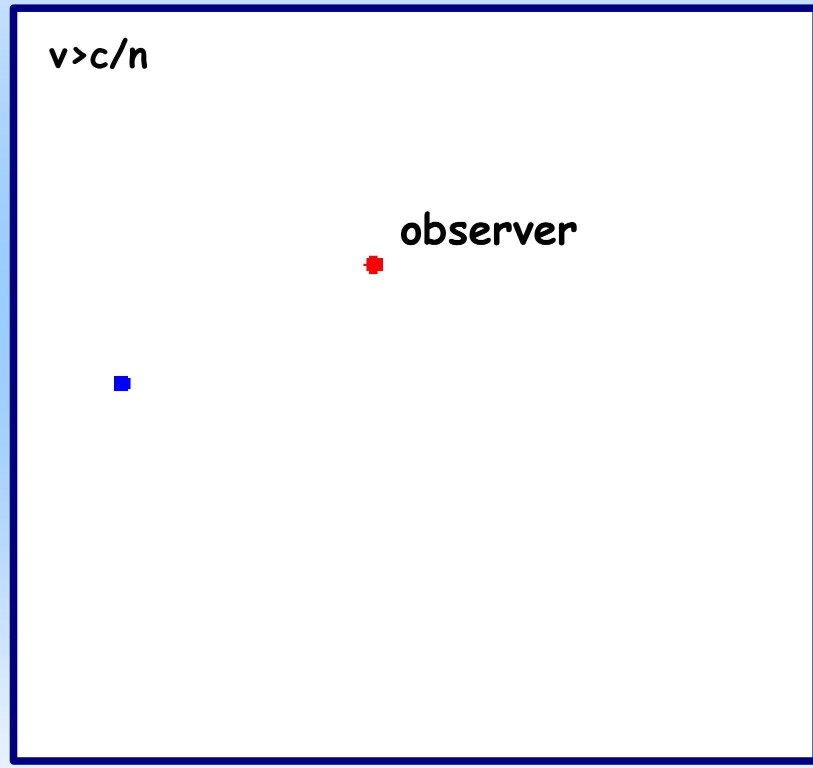
With telescopes distributed over a few km^2, the *Cherenkov Telescope Array* can operate as a kilometric optical intensity interferometer to achieve diffraction-limited imaging and optical aperture synthesis


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

Air Cherenkov Telescopes

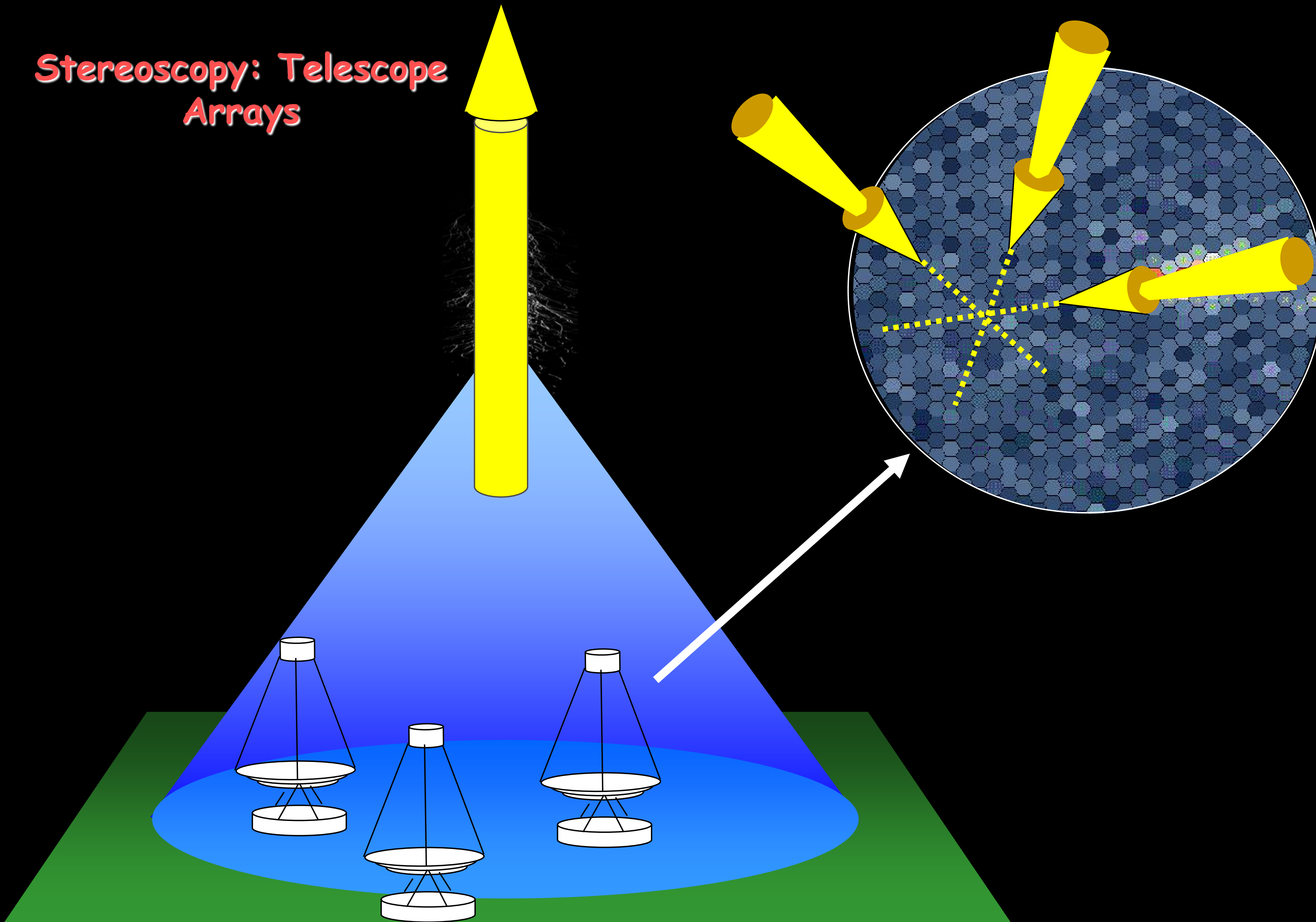
Cherenkov radiation

- 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

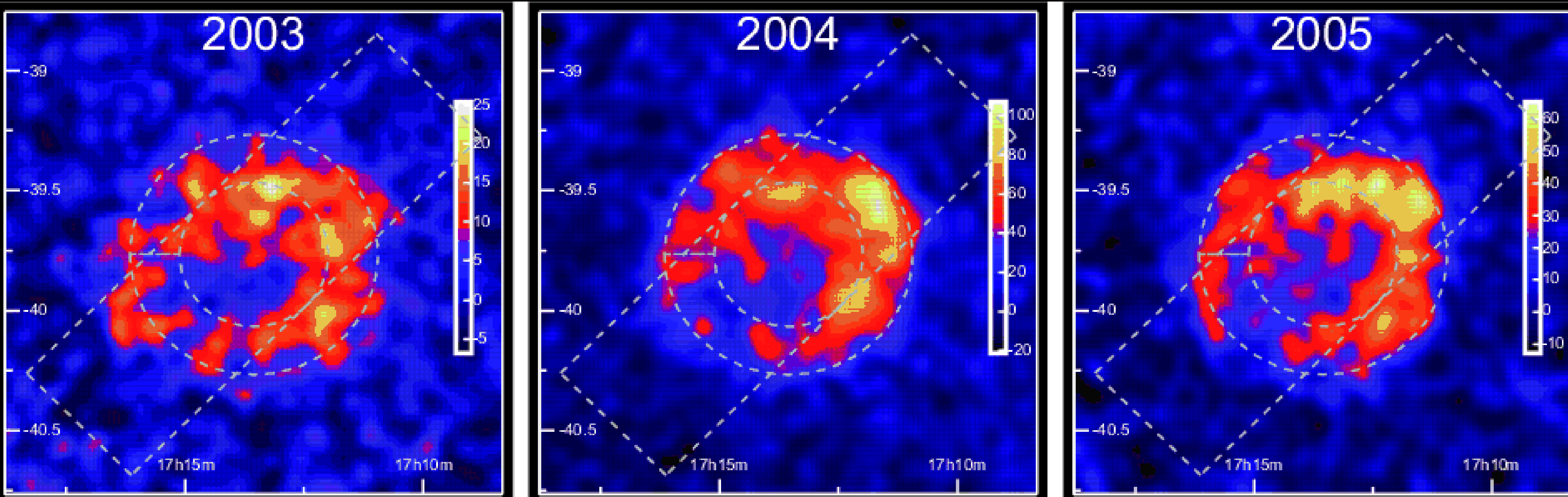


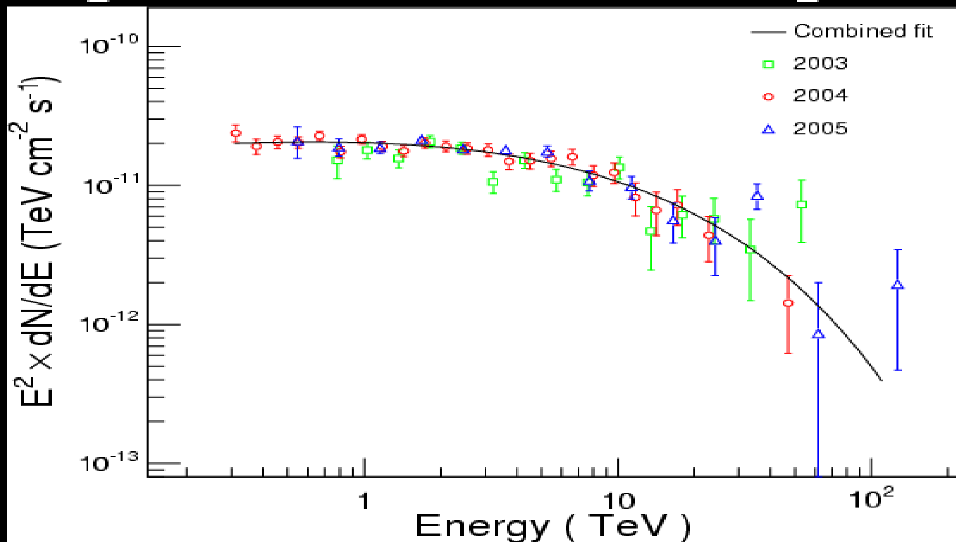
A fast particle causes a cone shaped "shock wave" -
The emission forms a coherent wavefront at the Cherenkov angle $\cos\theta = 1/\beta n$ (~1.3° in air)

Stereoscopy: Telescope Arrays



AIR CHERENKOV TELESCOPES

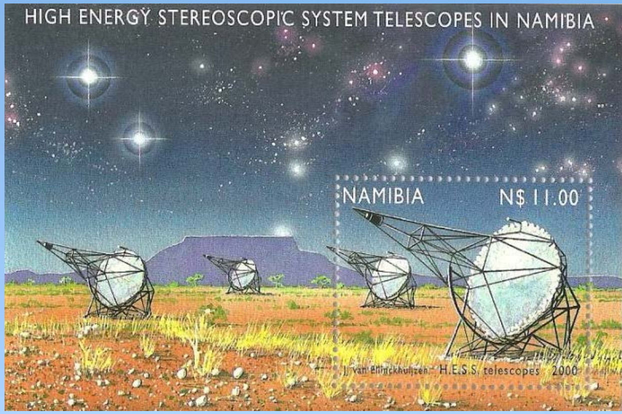




HIGH-ENERGY GAMMA RAYS FROM SUPERNOVA REMNANTS

Aharonian et al.,: *Primary particle acceleration above 100 TeV in the shell-type supernova remnant RX J1713.7-3946 with deep HESS observations*, A&A 464, 235


MAGIC, Roque de los Muchachos, La Palma



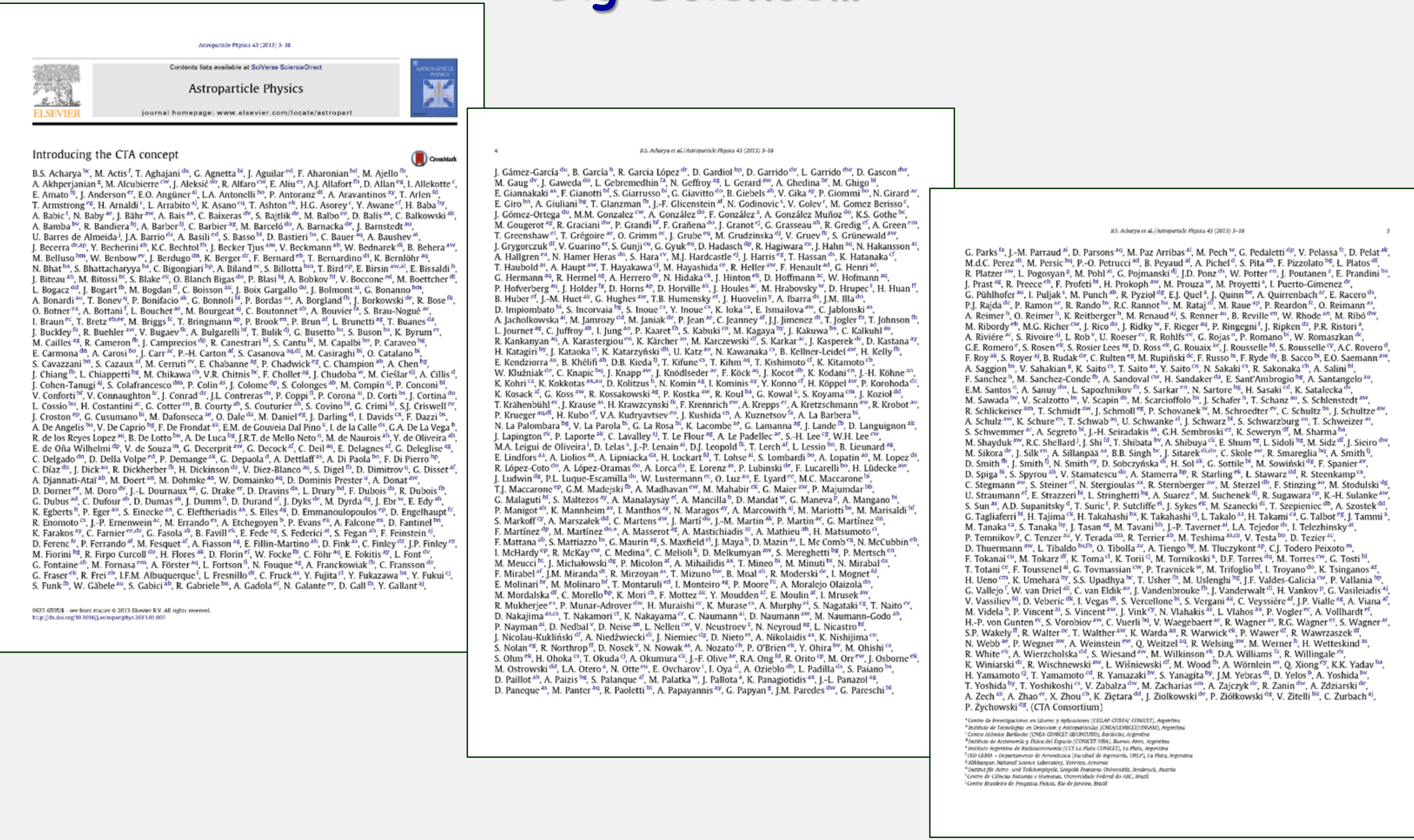
High Energy Stereoscopic System (H.E.S.S.) array of Imaging Atmospheric Cherenkov Telescopes (IACT) Telescopes, Khomas Highland, near Windhoek, Namibia

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

The Indian Astronomical Observatory, world's highest major optical observatory is in the western Himalayas, 4,517 m above sea level in the village of Hanle. Photo by Prabhu B. Doss

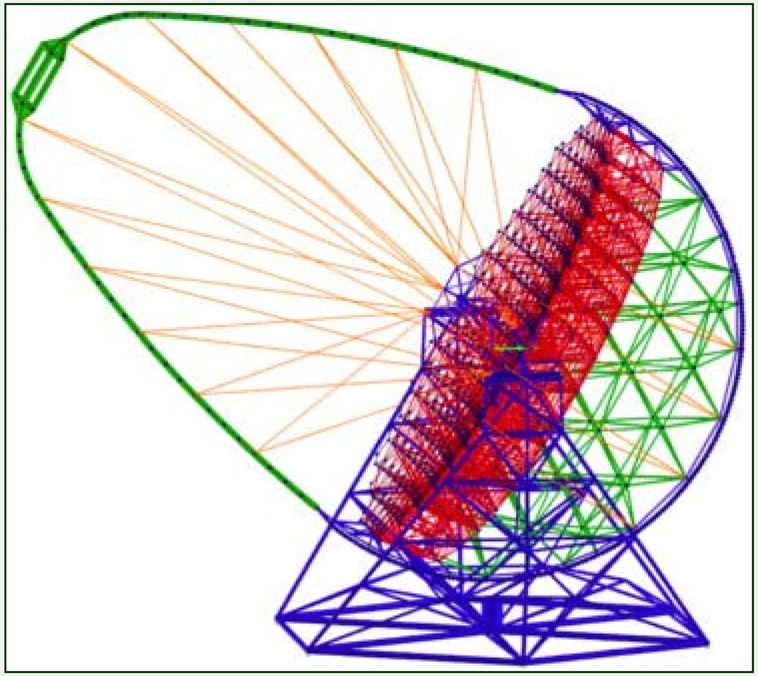

http://www.cta-observatory.org/
cta
cherenkov telescope array

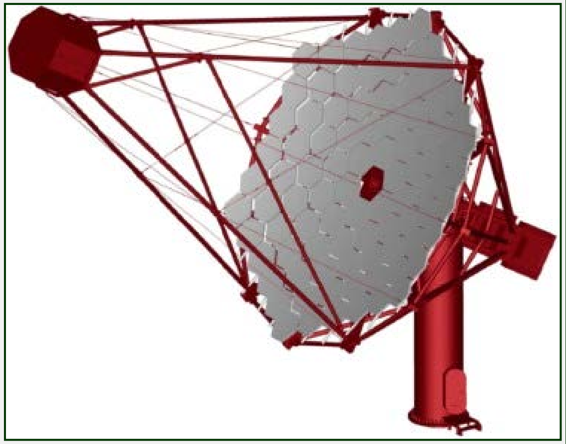
Big Science…

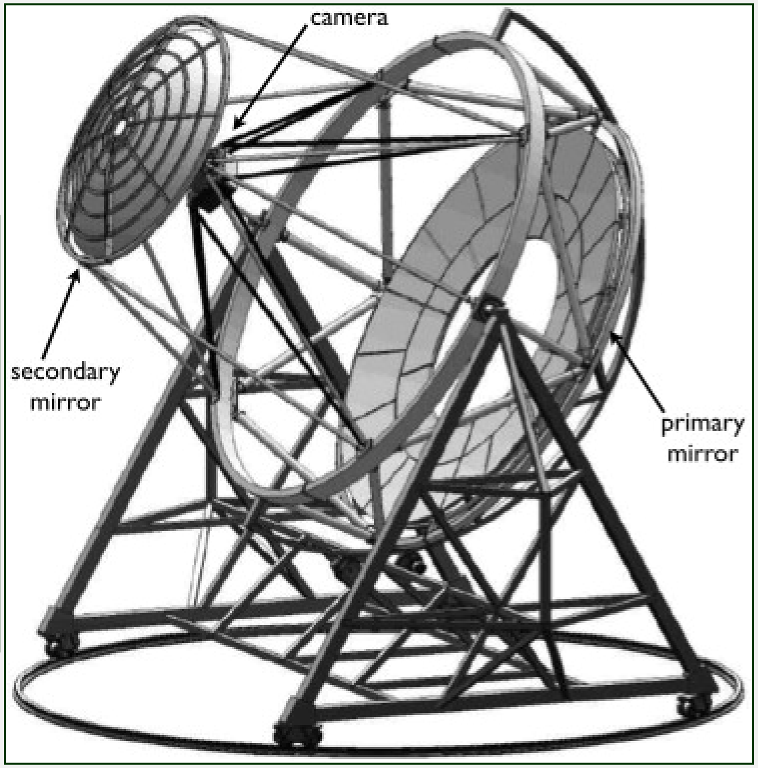


B.S. Acharya et al. (988 co-authors!): *Introducing the CTA concept*, Astropart. Phys. **43**, 3 (2013)

CTA telescope concepts







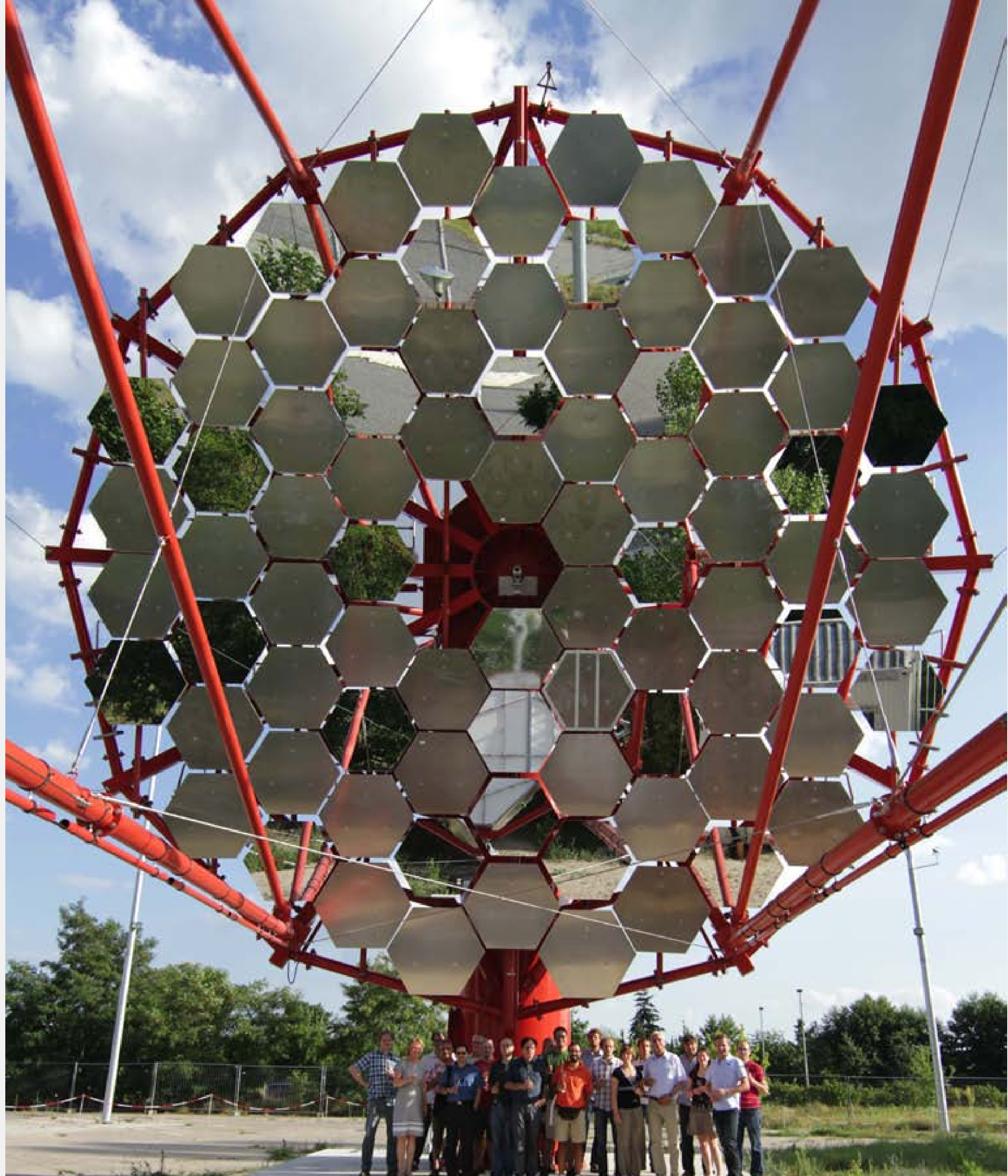
Left: Baseline design for a large telescope of 23 m diameter, with 4.5° field of view and 2500 pixels of 0.1° diameter.

Center: Baseline design for the 12 m diameter medium-sized telescope of Davies–Cotton optical design (spherical primary), with 8° FoV and 1500 pixels of 0.18°.

Right: Design for a Schwarzschild–Couder dual-mirror telescope, with a compact camera close to the secondary mirror. It will have a FoV of 8° diameter, consisting of 11000 square pixels of 0.067° side length.

B.S. Acharya et al.: *Introducing the CTA concept*, Astropart. Phys. 4**3**, 3 (2013)

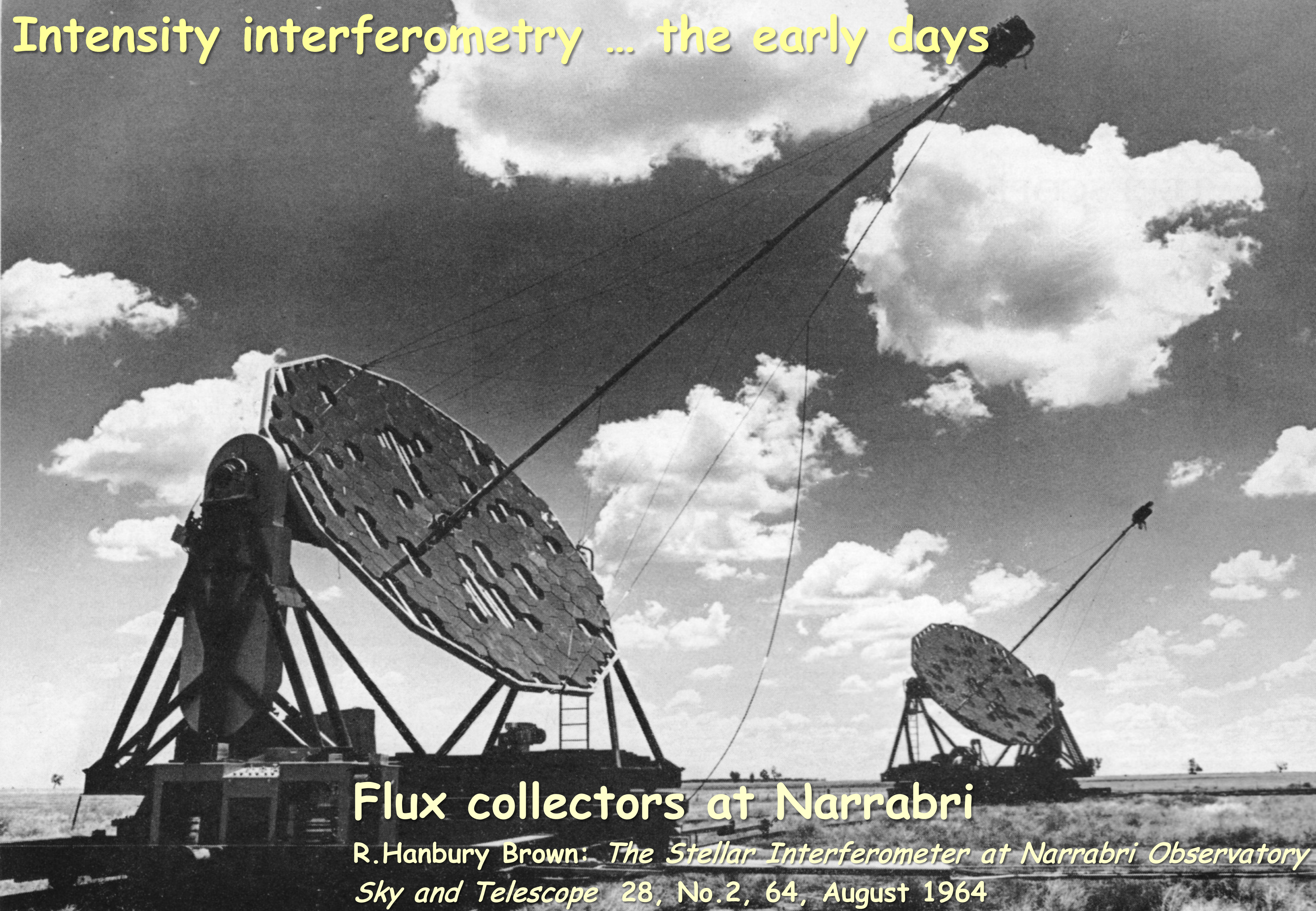
CTA medium-size telescope prototype



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

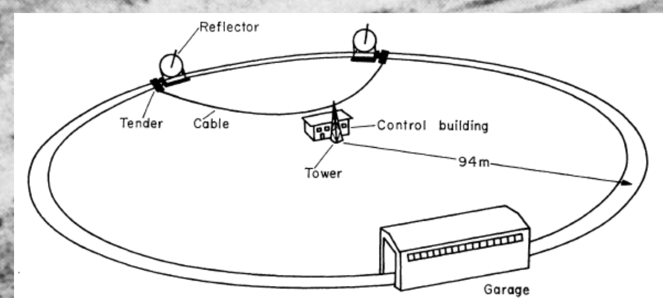
R.Hanbury Brown: *The Stellar Interferometer at Narrabri Observatory*
Sky and Telescope 28, No.2, 64, August 1964

Intensity interferometry … the early days

Narrabri observatory

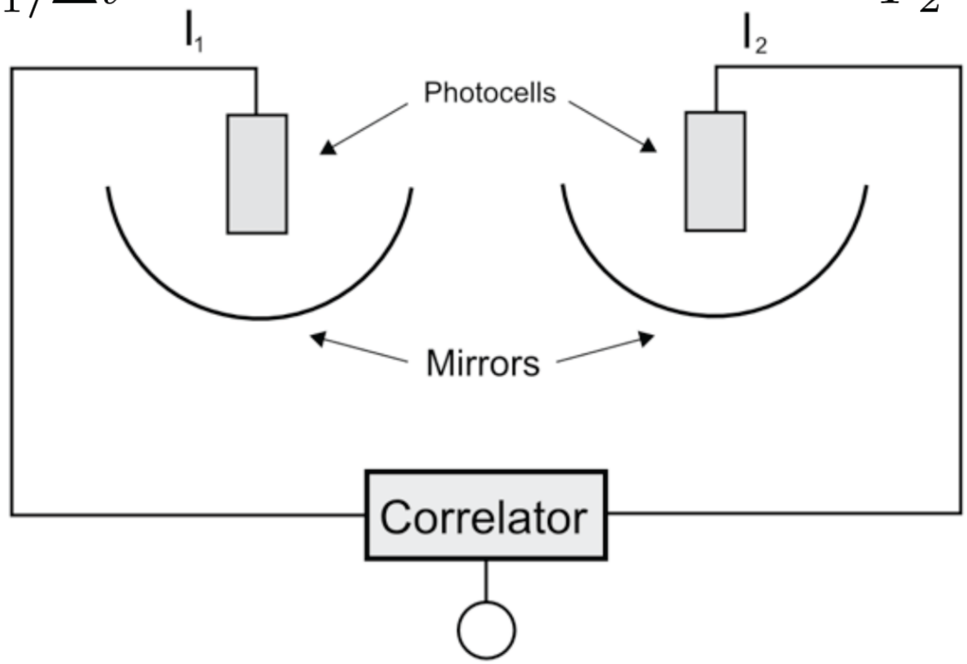
with its circular railway track

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



INTENSITY INTERFEROMETRY

$$P_1 = \alpha_1 \langle I_1 \rangle \Delta t \qquad\qquad P_2 = \alpha_2 \langle I_2 \rangle \Delta t$$



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

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)

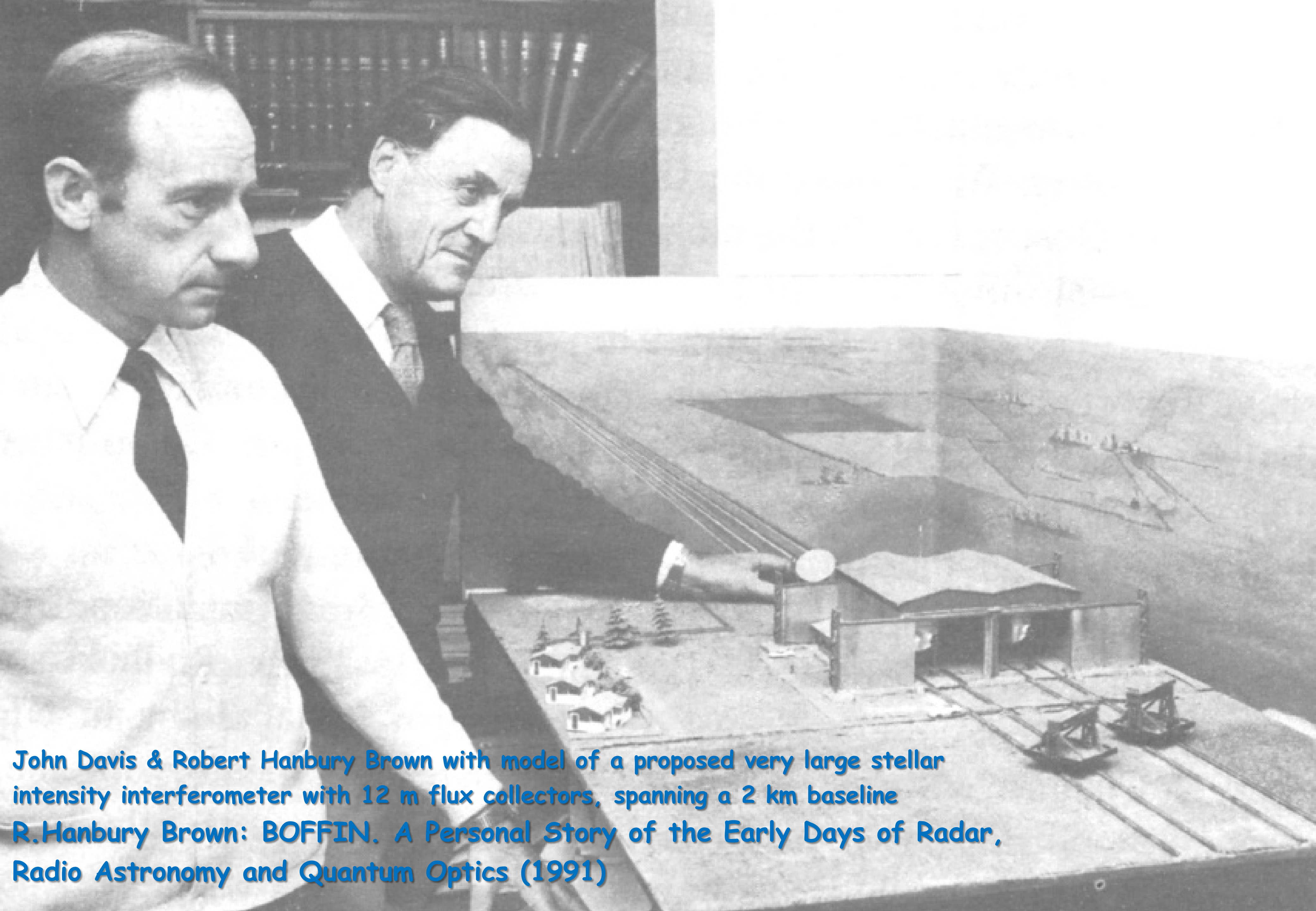
Intensity interferometry

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)

Software telescopes in radio and the optical

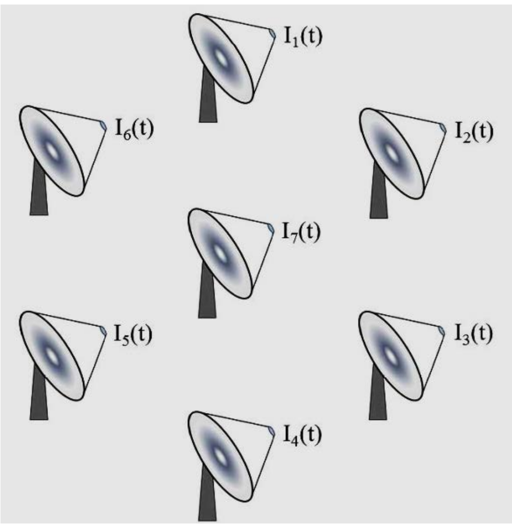
LOFAR

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

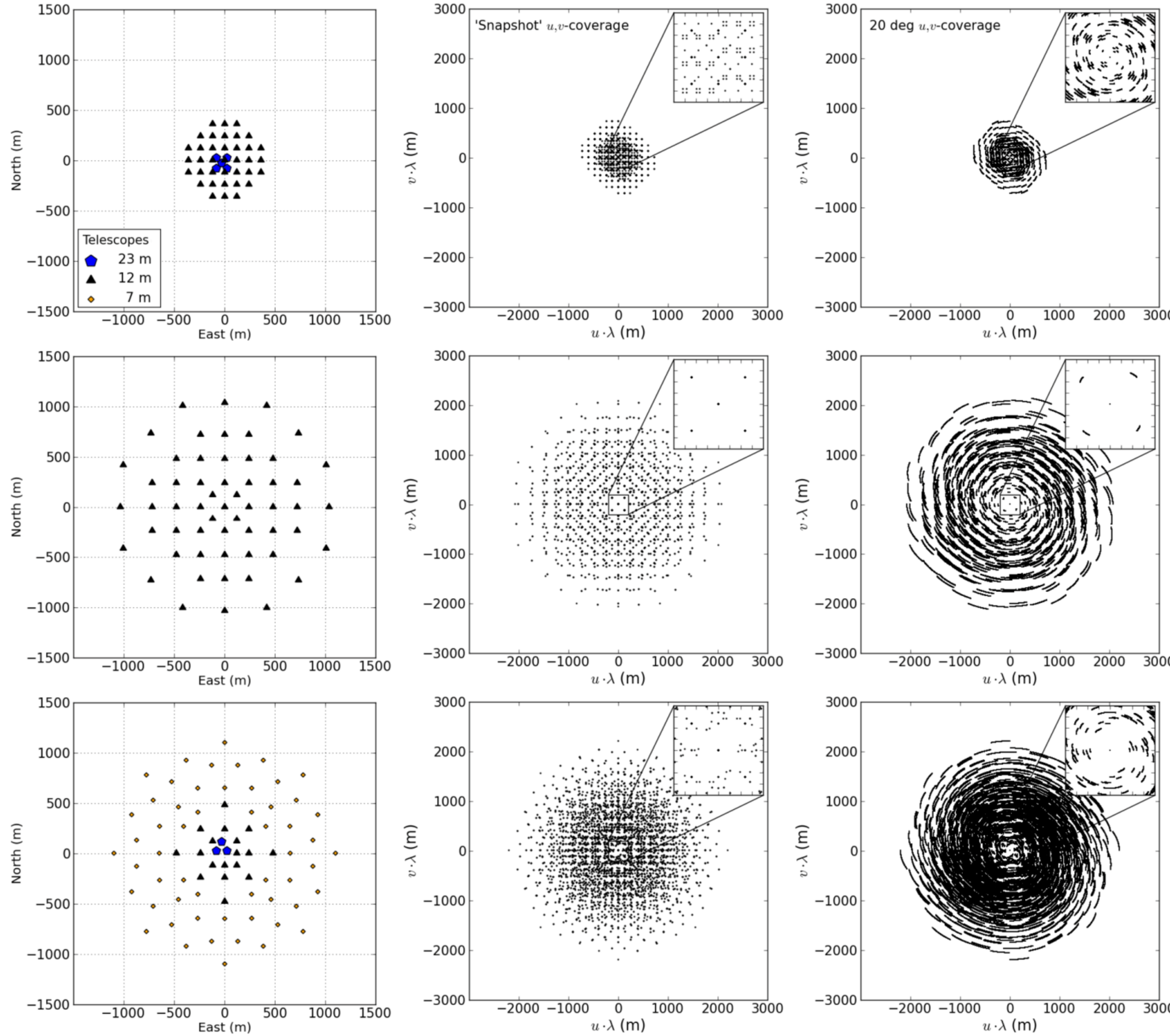
Many telescopes, moderate data flows.
Photon counts recorded (1 bit).
Spectral resolution by optical filters.
Measures second-order coherence.
On-line or off-line data processing.

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

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

S/N in intensity interferometry

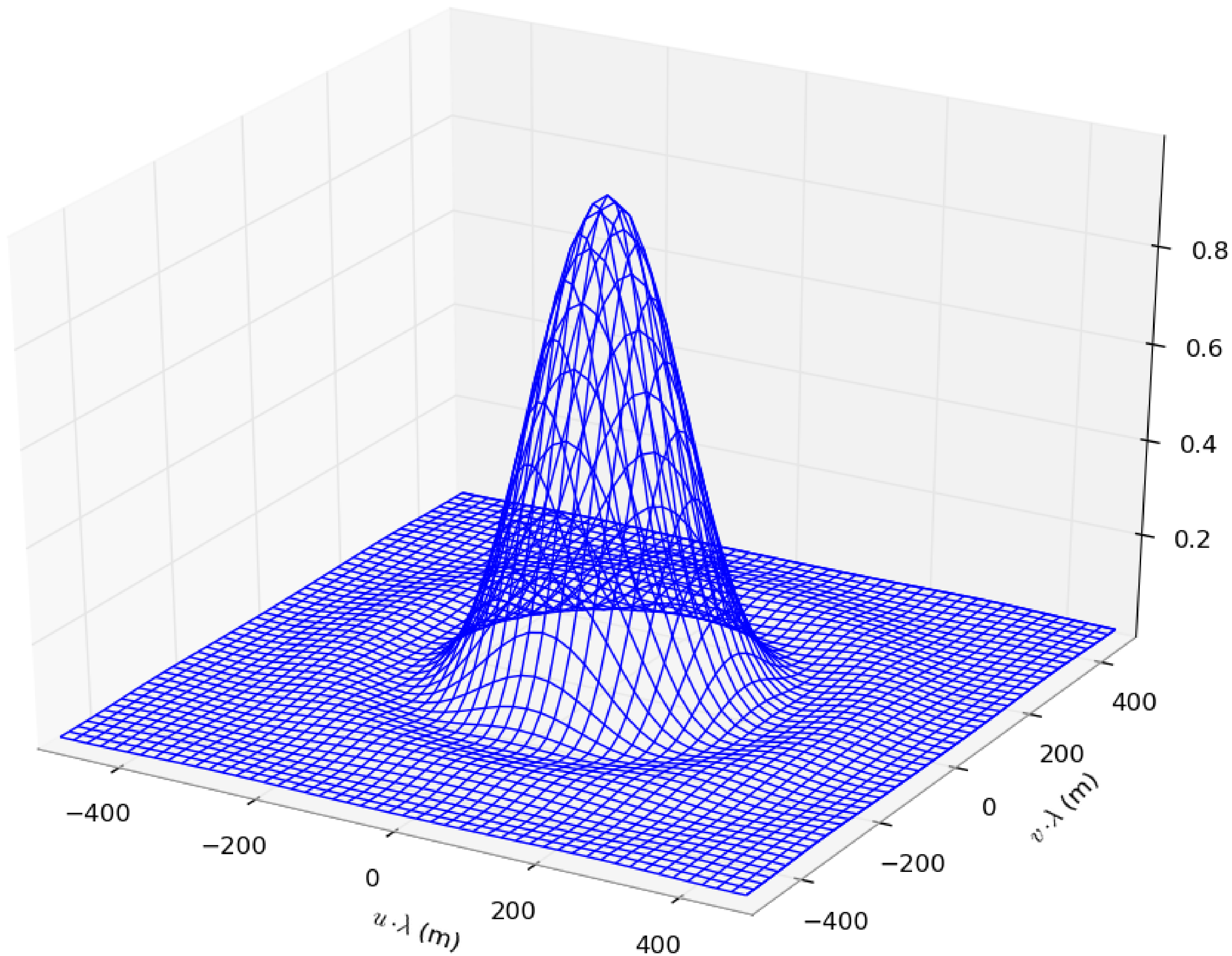
PROPORTIONAL TO:

- ★ 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:

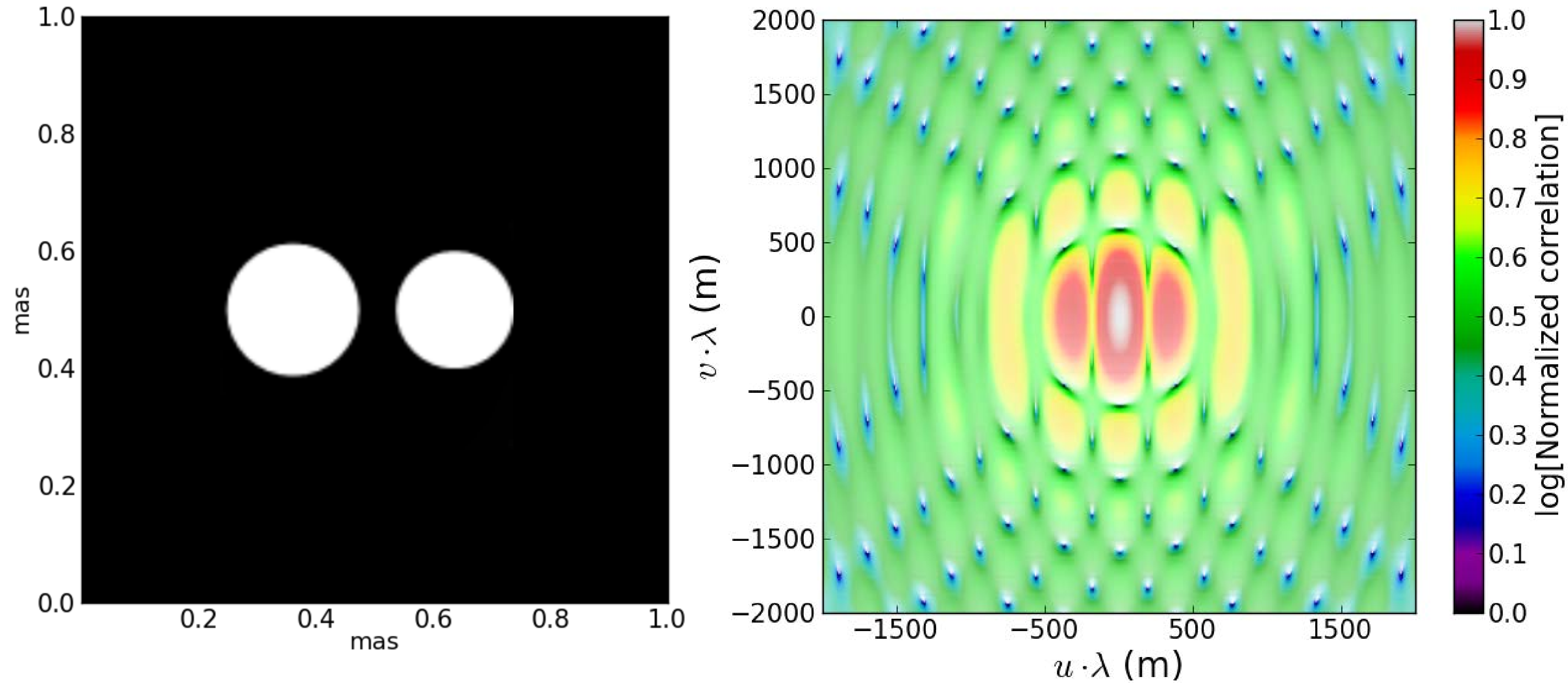
- ★ Width of optical passband

SIMULATED OBSERVATIONS IN INTENSITY INTERFEROMETRY



Squared visibility ("diffraction pattern"), of a stellar disk of angular diameter 0.5 mas.
Z = normalized second-order coherence

Simulated observations in intensity interferometry



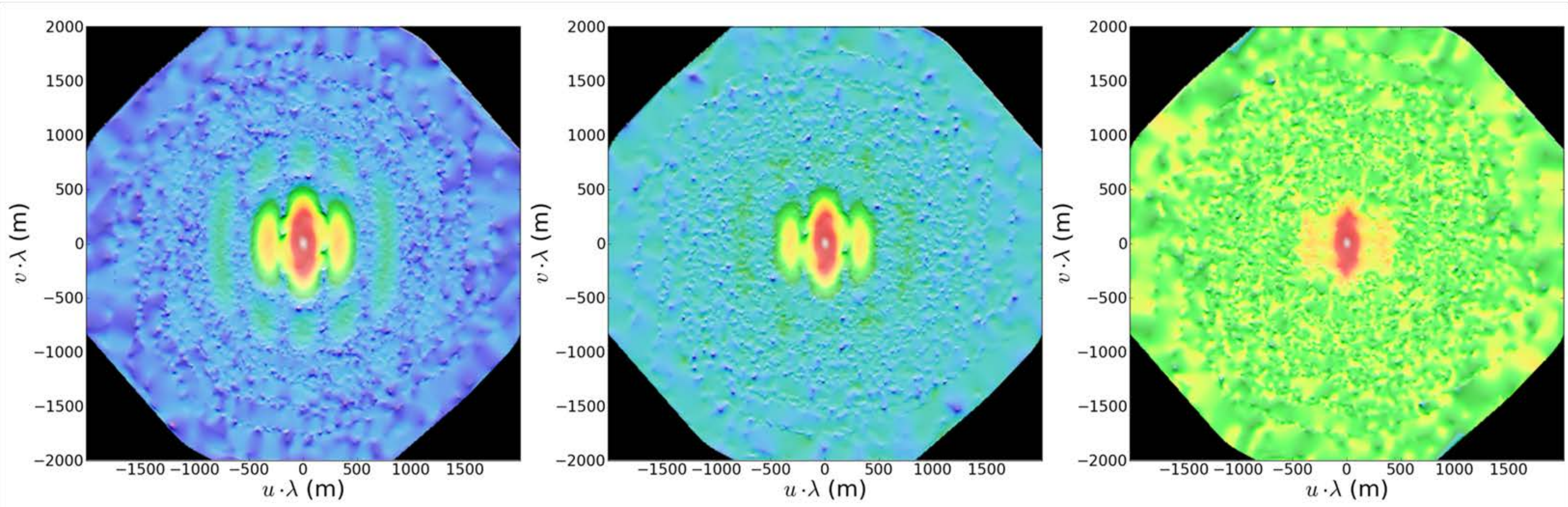
Squared visibility from a close binary star.
Left: Pristine image; Right: Logarithm of magnitude of Fourier transform

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

$m_V = 3$ $m_V = 5$ $m_V = 7$

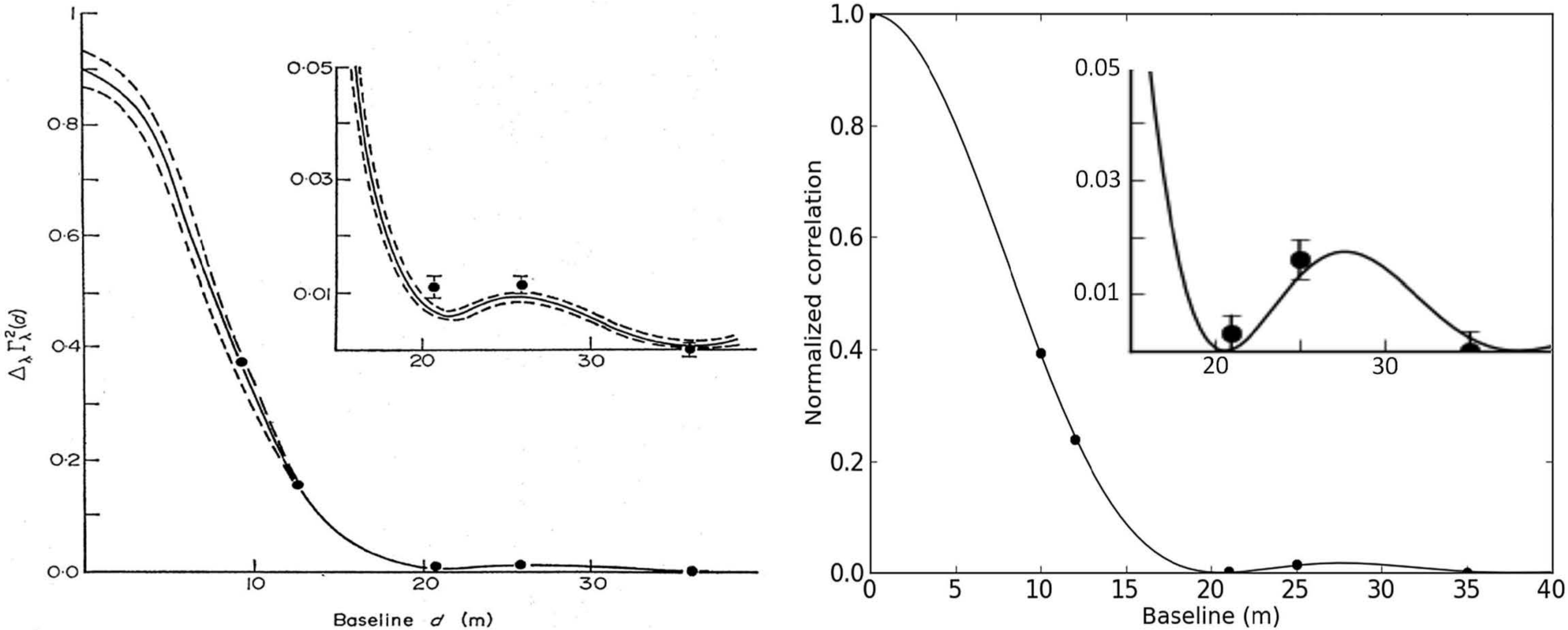


Simulated observations of binary stars of visual magnitudes 3, 5, and 7.
Total integration time: 20 hours; λ 500 nm, time resolution 1 ns, quantum efficiency = 70%
Array: CTA D

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

SIMULATED OBSERVATIONS IN INTENSITY INTERFEROMETRY

Verification of simulation software against
classical observations by Hanbury Brown et al.

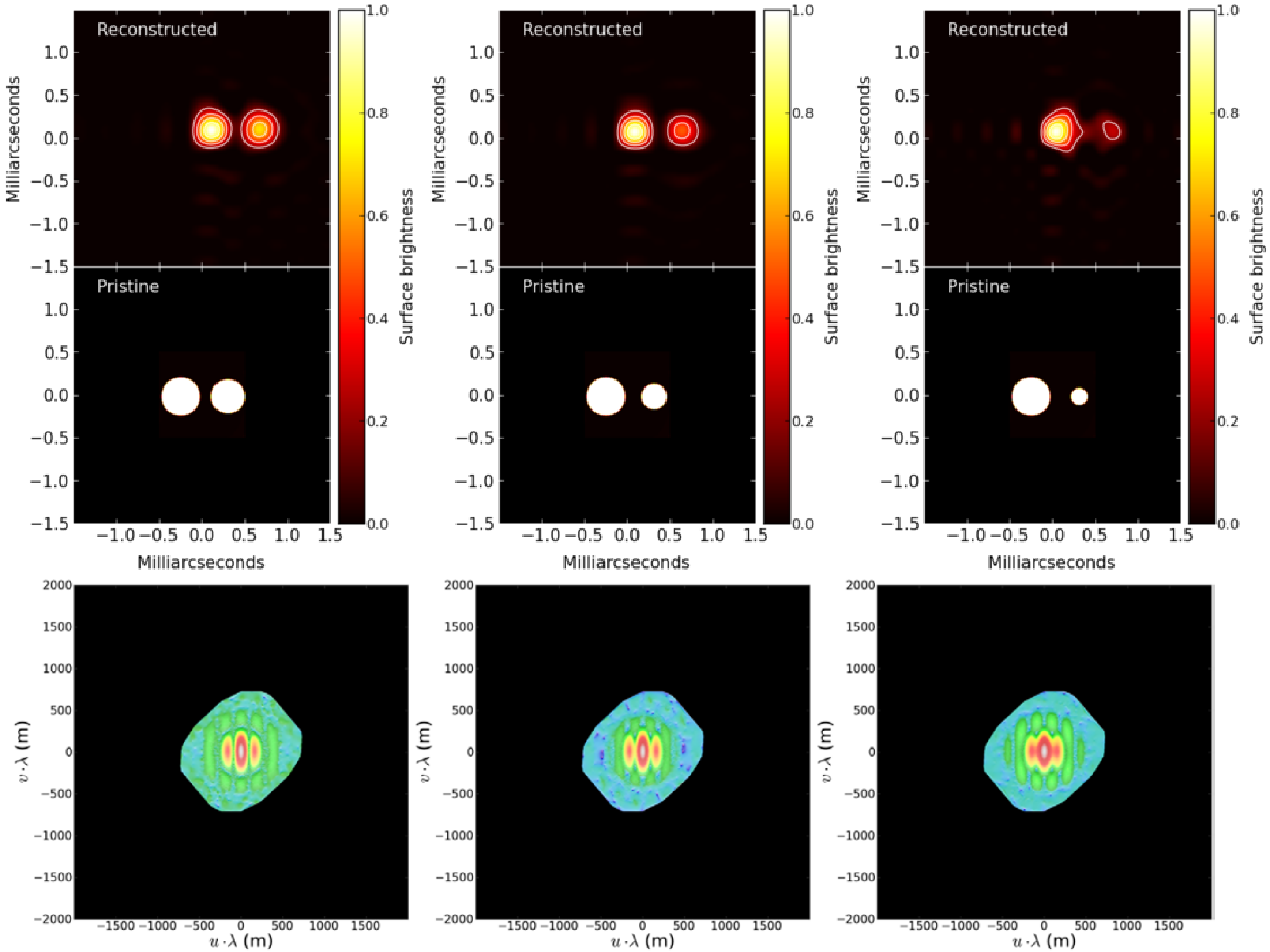


Left: Sirius observed with the Narrabri stellar interferometer
(R.Hanbury Brown, J.Davis, R.J.W.Lake & R.J.Thompson; MNRAS **167**, 475, 1974)

Right: Simulated observations with Narrabri instrumental parameters

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; Δλ = 1 nm; QE = 70%, array = CTA B)

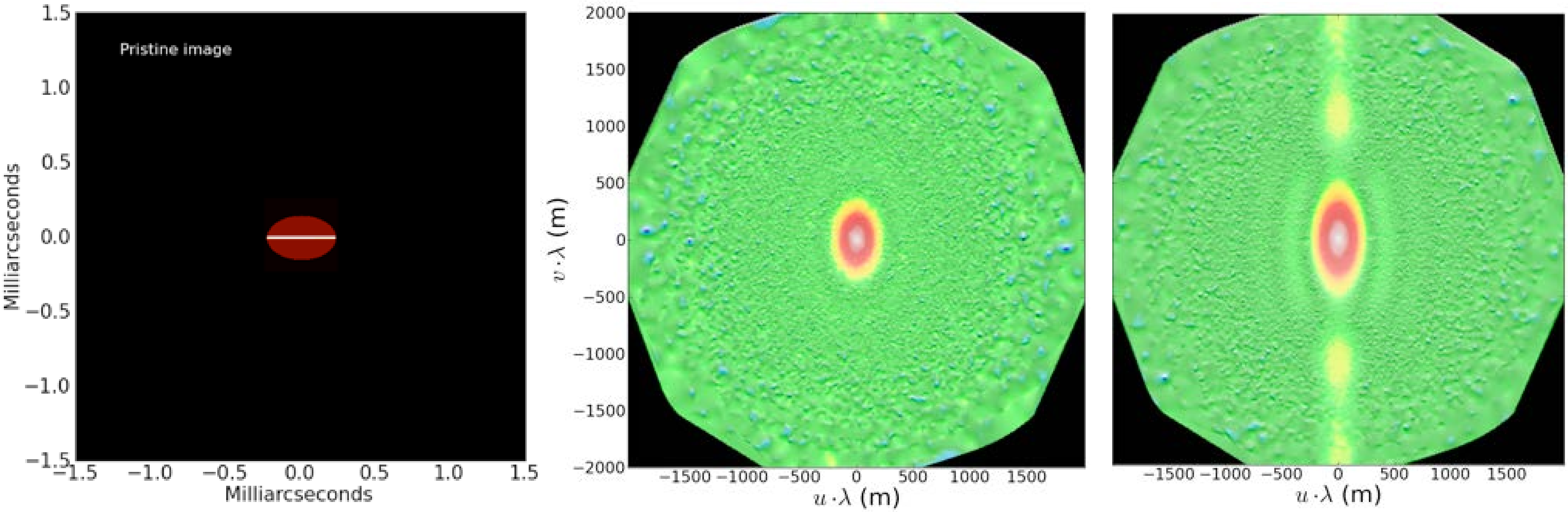
Top: Reconstructed and pristine images; Bottom: Fourier magnitudes.

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 $g^{(2)}$

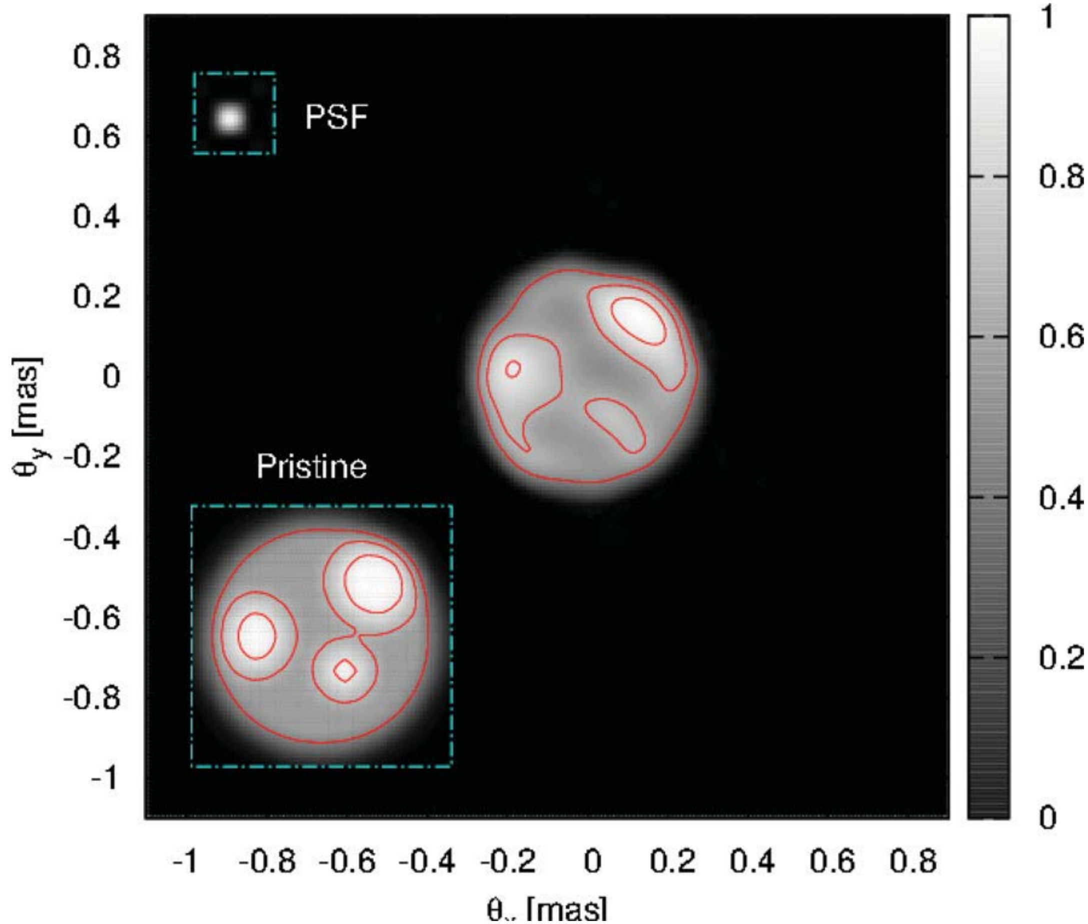
$$g^{(2)}(\tau) = 1 + \left| g^{(1)}(\tau) \right|^2$$

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



Numerical simulations of intensity-interferometry observations with a CTA-like array, with image reconstruction of a star with three hotspots

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

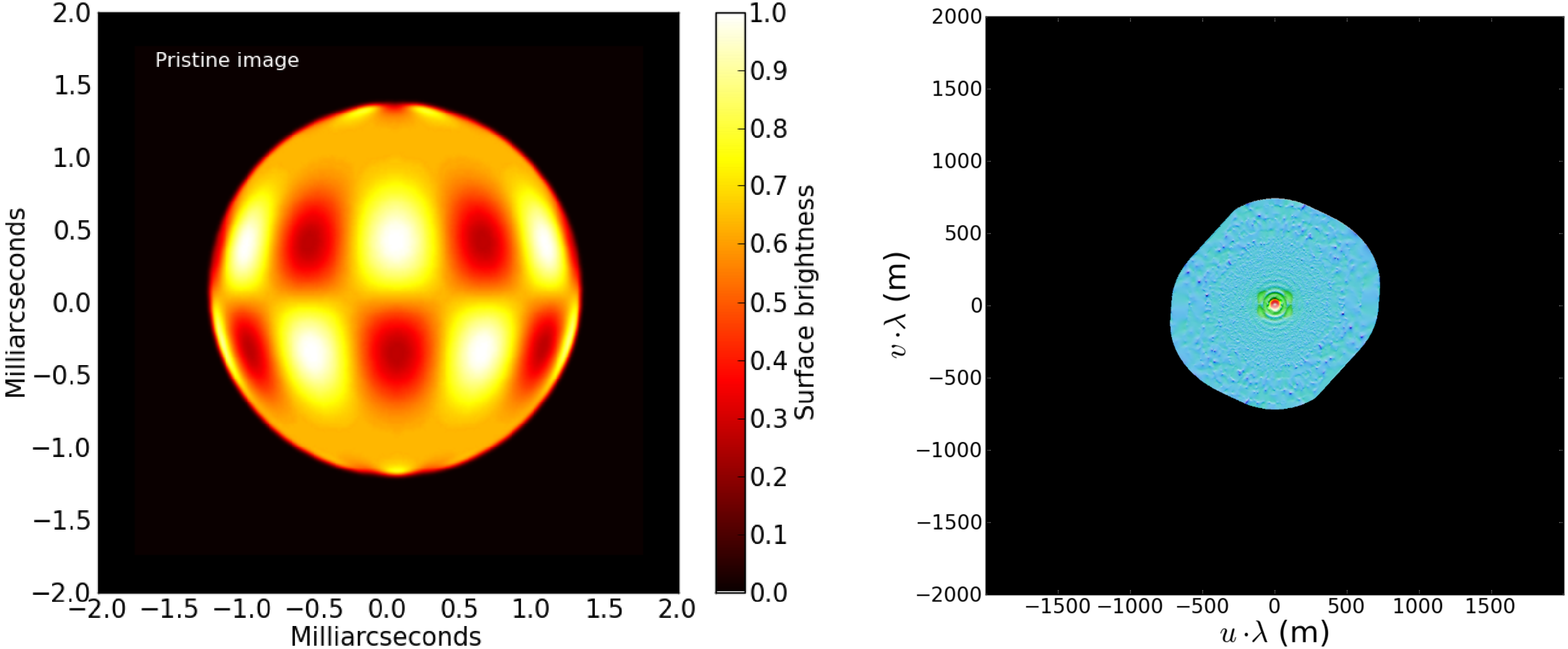
Simulated data correspond to visual magnitude m_V = 3, and 10 hours of observation.

P.D.Nuñez, R.Holmes, D.Kieda, J.Rou, S.LeBohec, *Imaging submilliarcsecond stellar features with intensity interferometry 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

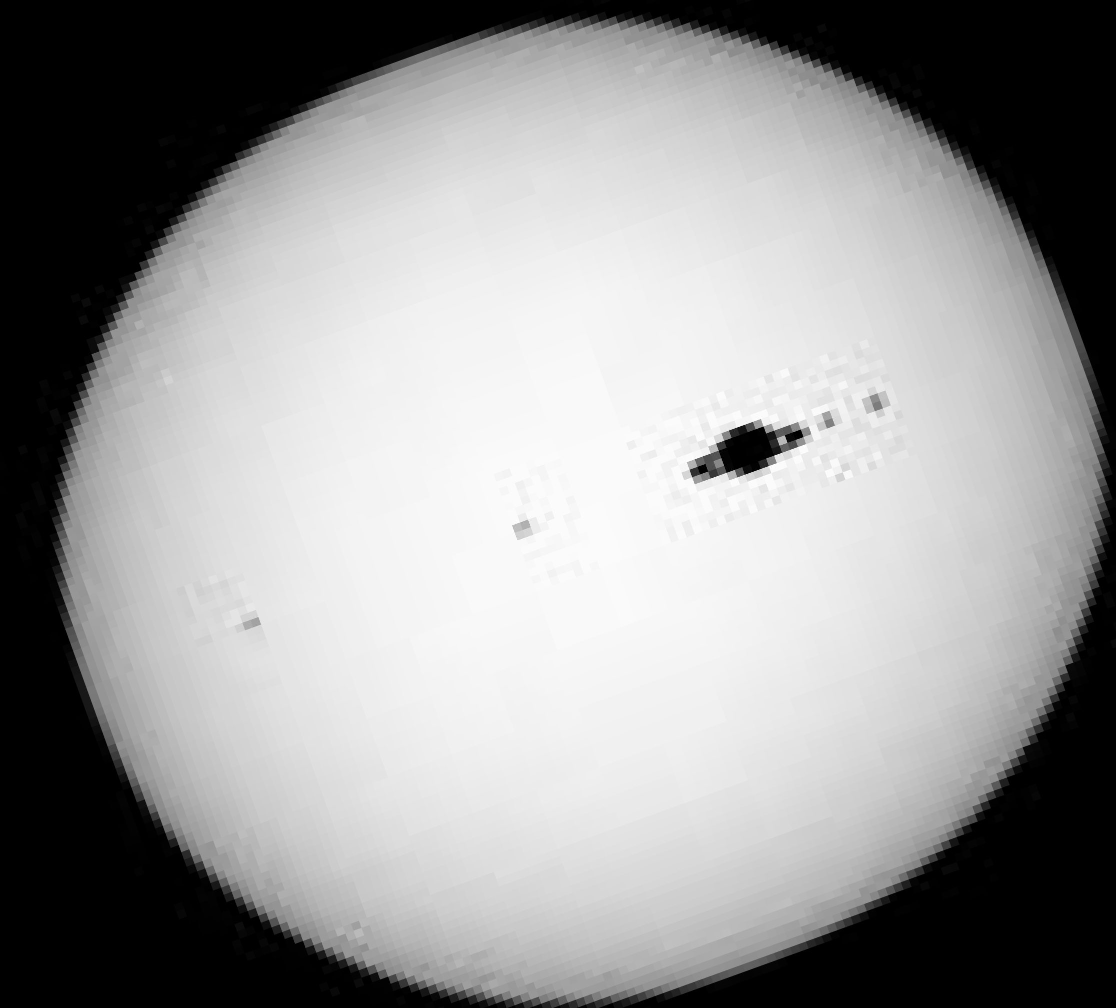
m_V = 3.4; T_{eff} = 7000 K; Δt = 1 ns; λ = 500 nm; Array = CTA B

Left: Pristine image; Right: Observed Fourier magnitude

Kilometer-scale diffraction-limited optical imager:

Cherenkov Telescope Array as an Intensity Interferometer

Expected resolution for assumed exoplanet transit across the disk of Sirius



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

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 Δt >> coherence time τ_c (10 fs?)

Realistic time resolution = 10 ns (?)

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

Understanding detectors

Afterpulsing, afterglow and other detector signatures can mimic intensity correlations

Analyzing photon-counting detectors

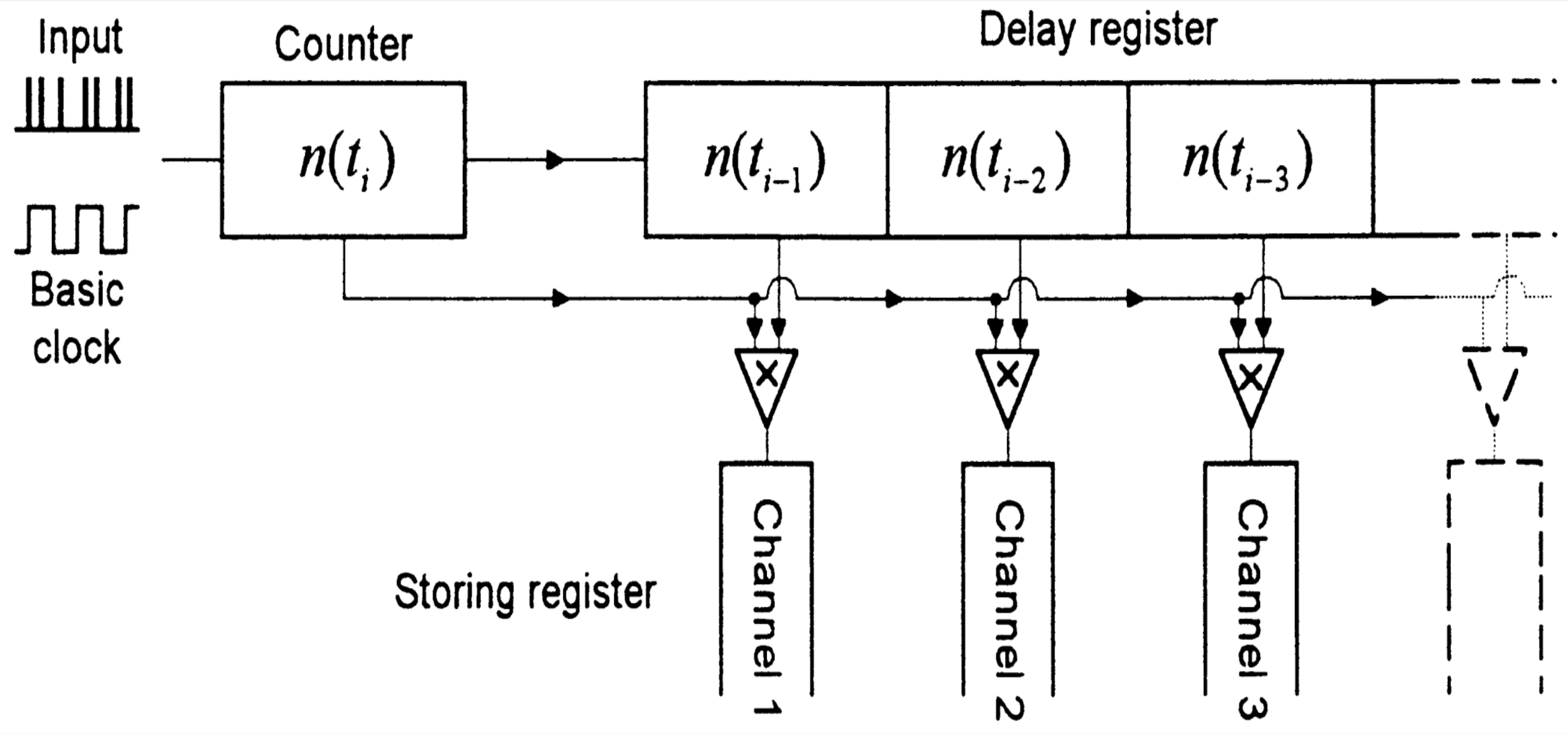
Afterpulsing, afterglow and other signatures could mimic intensity correlations

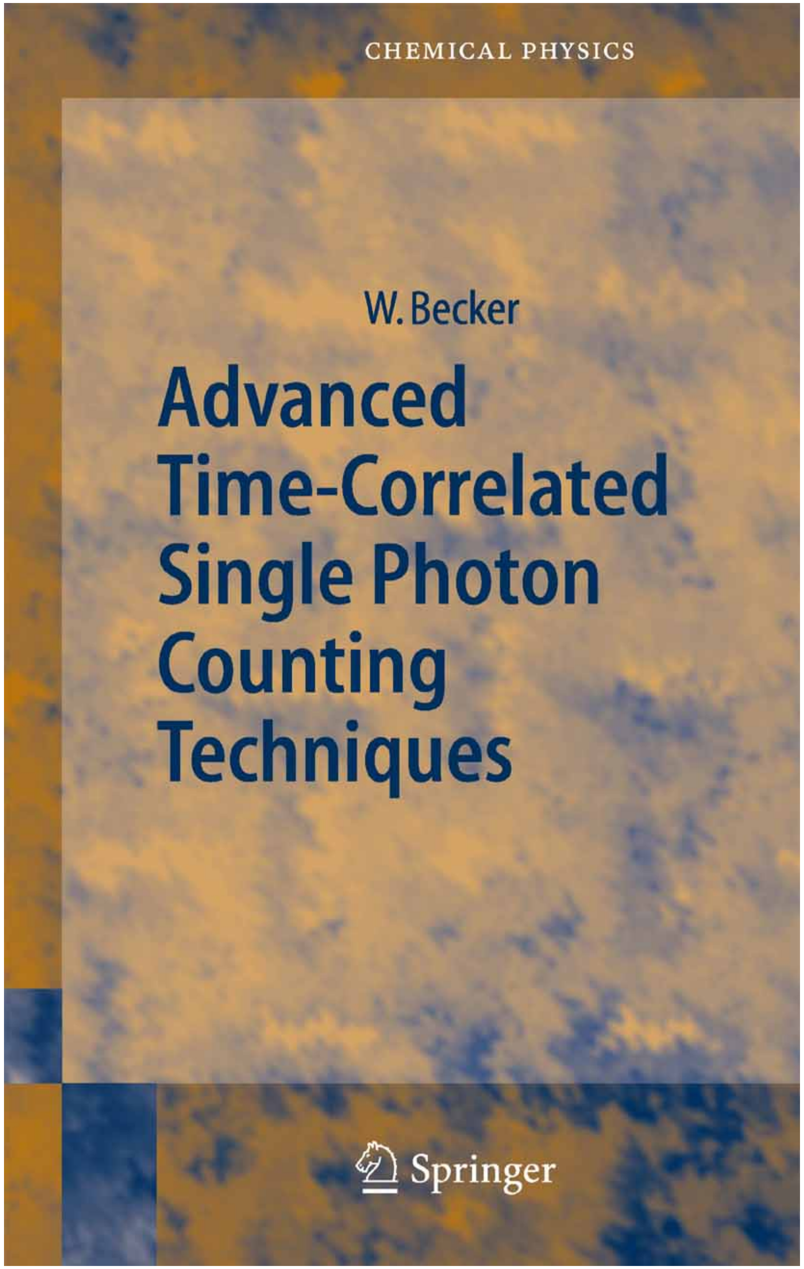
Single-photon-counting avalanche photodiode detectors being evaluated @ Lund Observatory for digital intensity interferometry

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

Real-time digital photon correlators

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





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

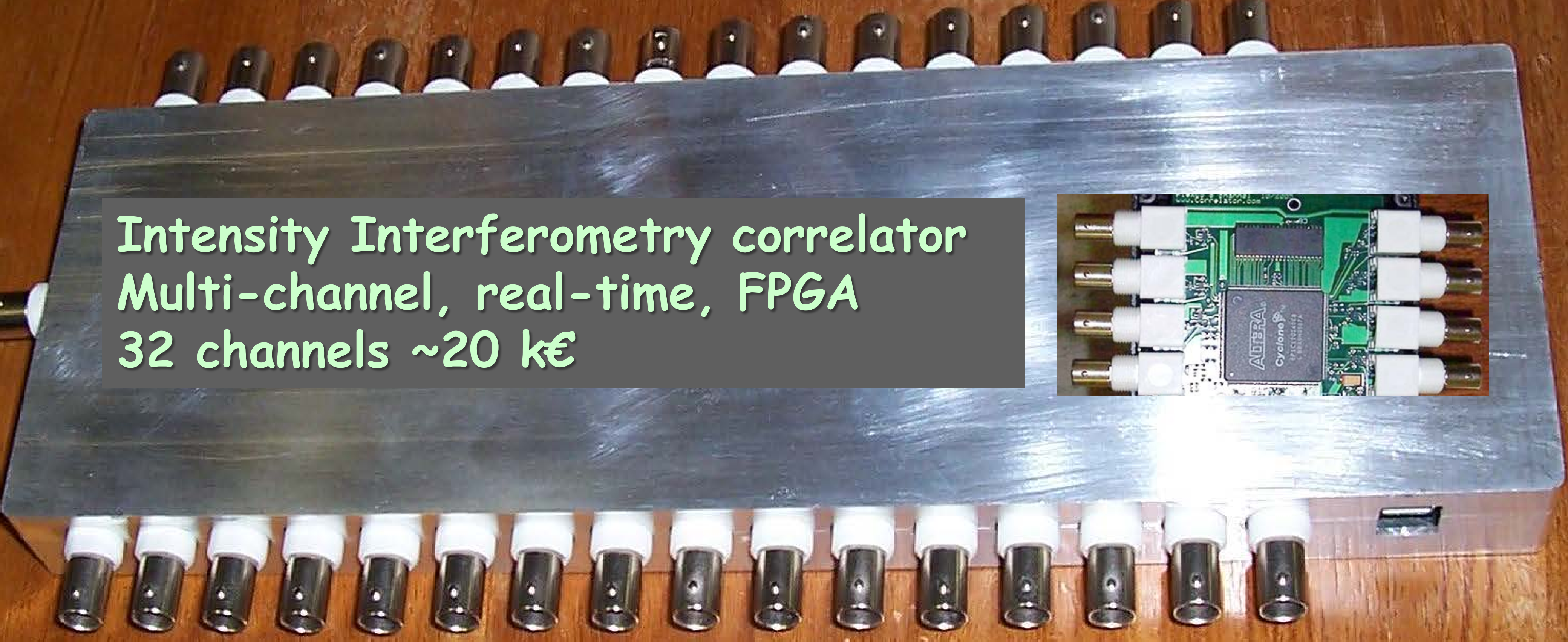
5.13 Time-Resolved Single Molecule Spectroscopy

5.14 Miscellaneous TCSPC Applications

(Springer 2005)

DIGITAL PHOTON CORRELATORS @ Lund Observatory
700 MHz clock rate (1.4 ns time resolution)
200 MHz maximum photon count rates per channel (pulse-pair resolution 5 ns)
8 input channels for photon pulses at TTL voltages

Custom-made by Correlator.com for
applications in intensity interferometry



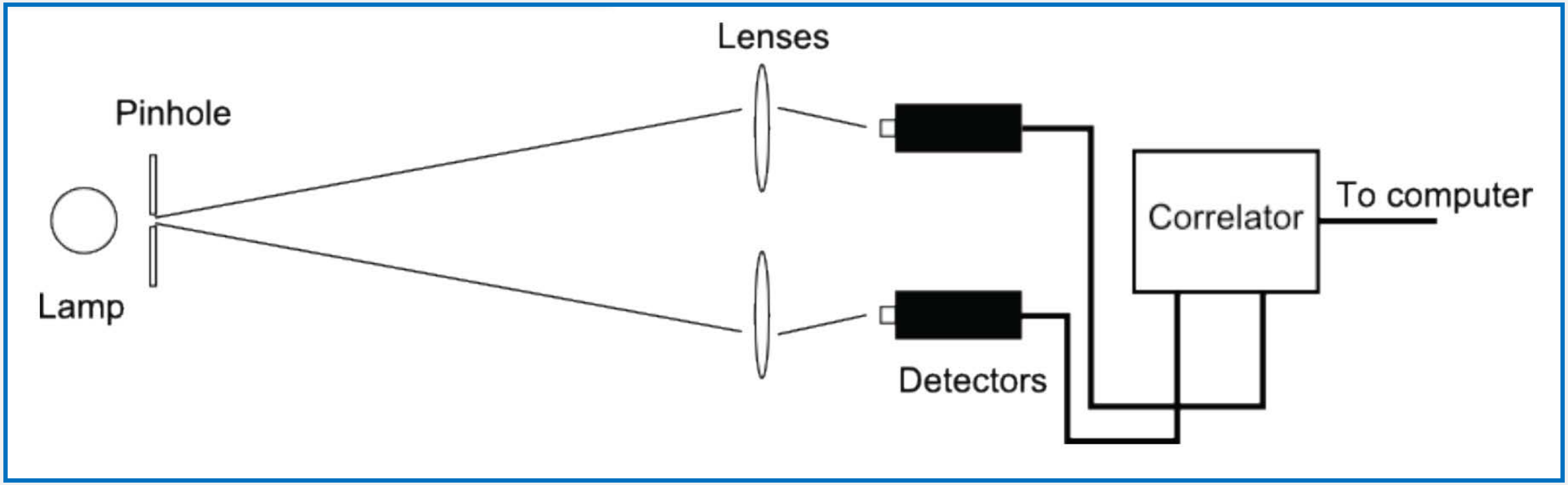
Very much more modest computations than in radio interferometry!

Real-time correlation

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

Con: Lose information on transients, no alternative analyses

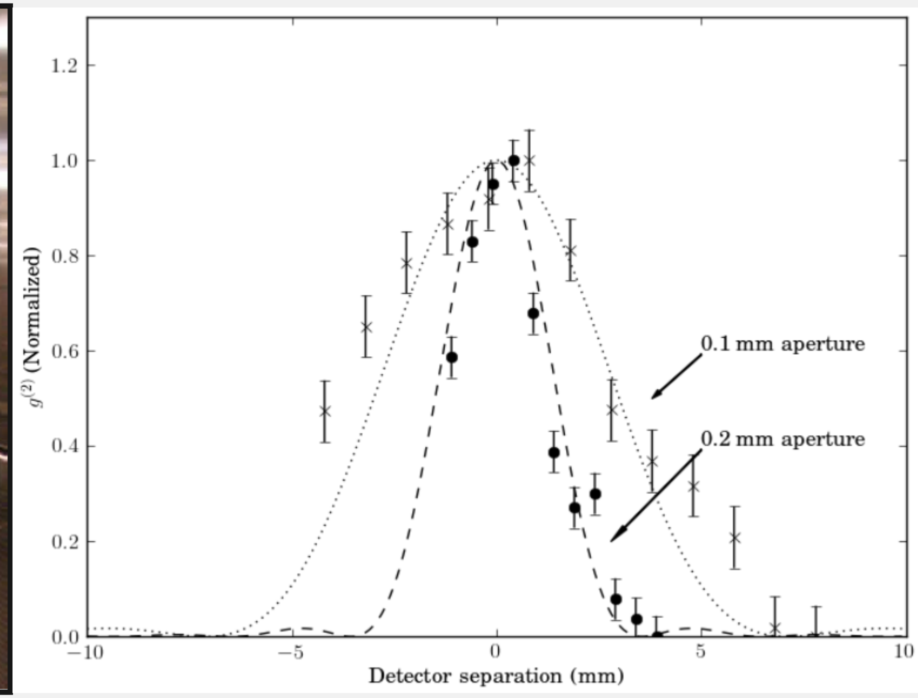
Stellar Intensity Interferometry
Laboratory experiments @ Lund Observatory



An artificial star is observed by a pair of movable telescopes.
Detected photon streams are cross correlated in real time.

Stellar Intensity Interferometry

Laboratory experiments @ Lund Observatory



Artificial stars are observed by movable telescopes across a long optics lab; photon-counting avalanche photodiodes and on-line digital correlators.

The plot shows the measured and expected second-order coherence for two “stars”.

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

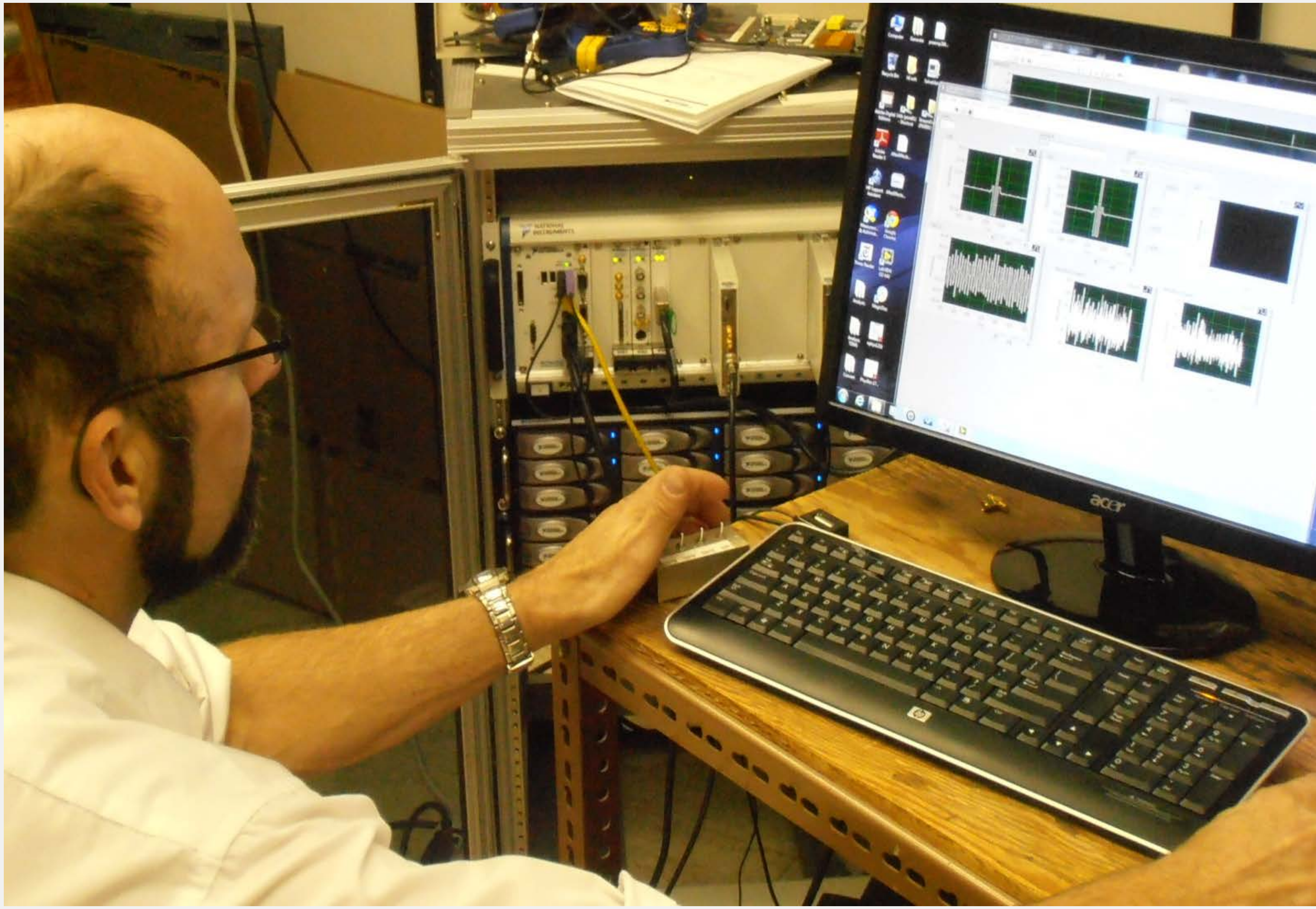
STAR BASE UTAH (near Salt Lake City)

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)

Stellar Intensity Interferometry
VERITAS upgrade & laboratory experiments @ The University of Utah



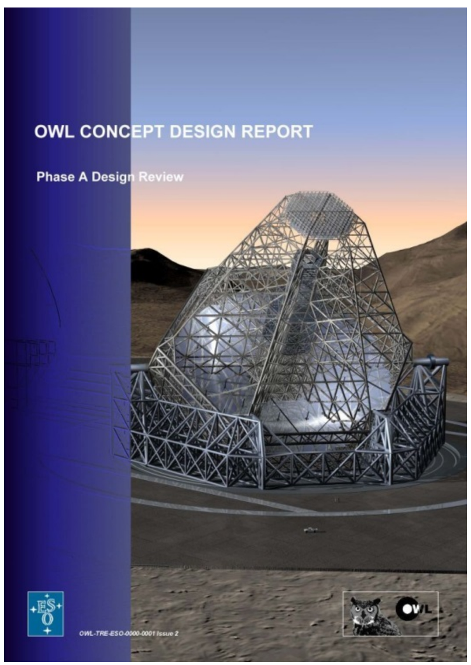
The ongoing VERITAS upgrade includes provisions also for intensity interferometry. Here, David Kieda examines correlation functions computed off-line in electronics for real-time digitization and storage of photomultiplier signals.

ESO Instrument Studies for OWL and Extremely Large Telescopes (2005)

QUANTEYE

HIGHEST TIME RESOLUTION, REACHING QUANTUM OPTICS

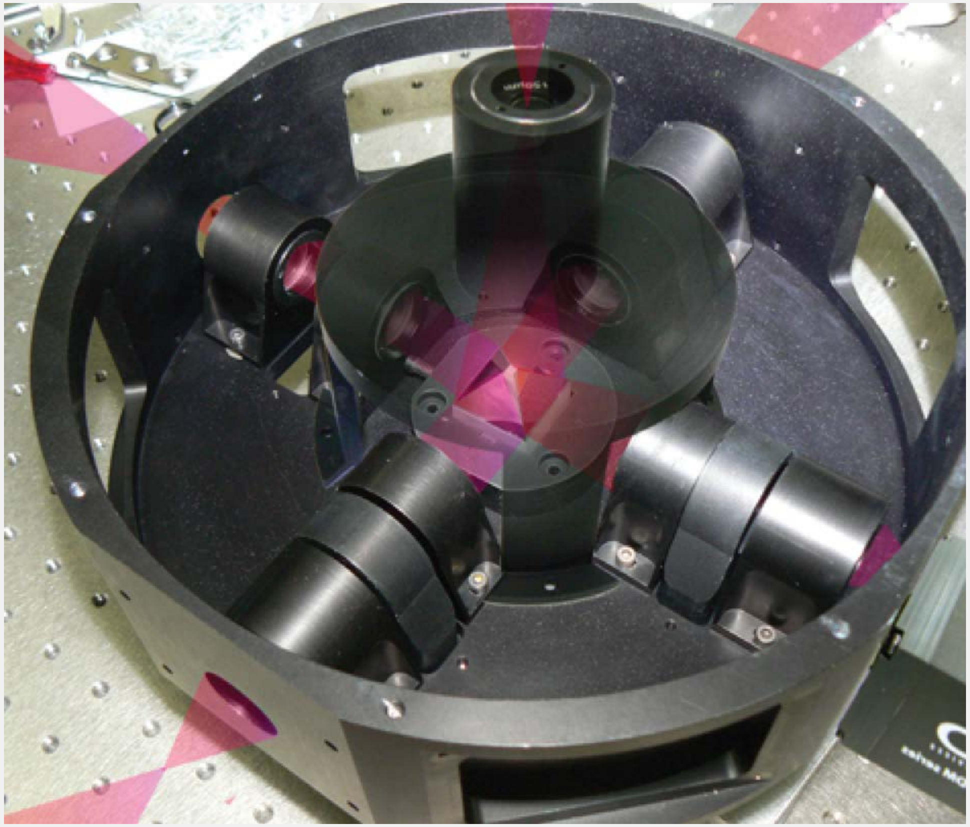
- Other instruments cover seconds and milliseconds
- *QuantEYE* will cover milli-, micro-, and nanoseconds, down to the quantum limit !

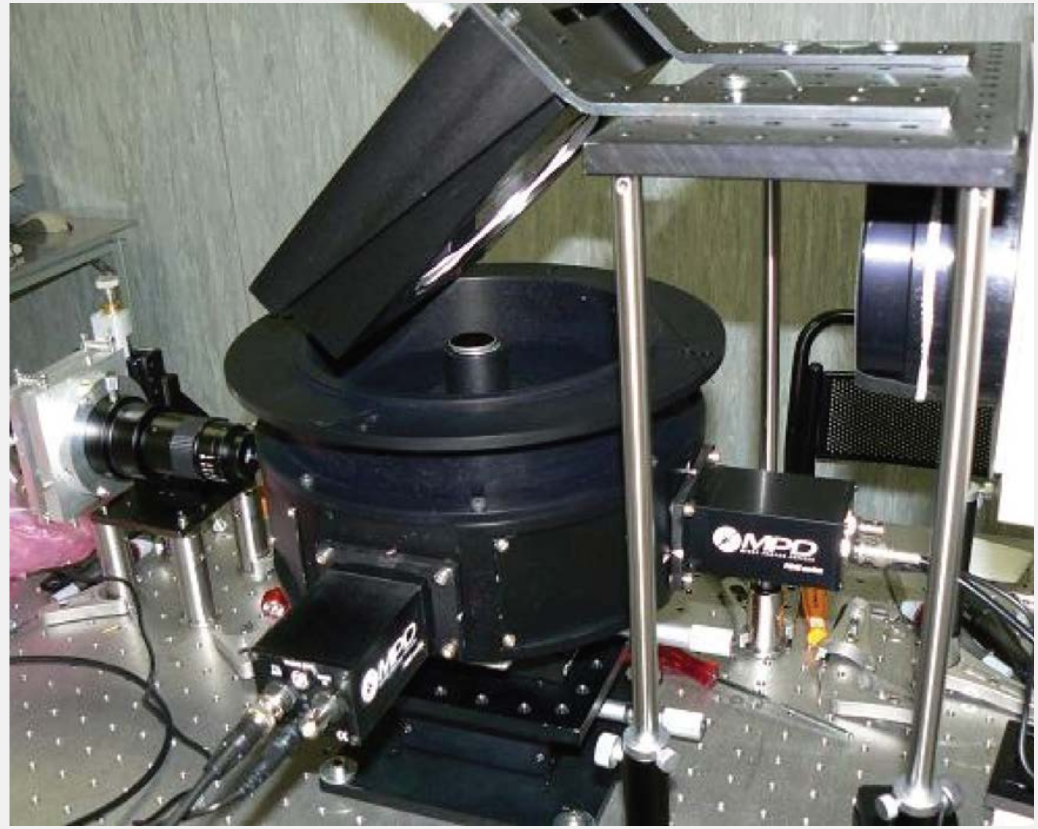


D. Dravins [1], C. Barbieri [2], V. Da Deppo [3], D. Faria [1], S. Fornasier [2], R. A. E. Fosbury [4], L. Lindegren [1], G. Naletto [3], R. Nilsson [1], T. Occhipinti [3], F. Tamburini [2], H. Uthas [1], L. Zampieri [5]

(1) Lund Observatory, (2) Dept. of Astronomy, Univ. of Padova
(3) Dept. of Information Engineering, Univ. of Padova
(4) ST-ECF, ESO Garching, (5) Astronomical Observatory of Padova

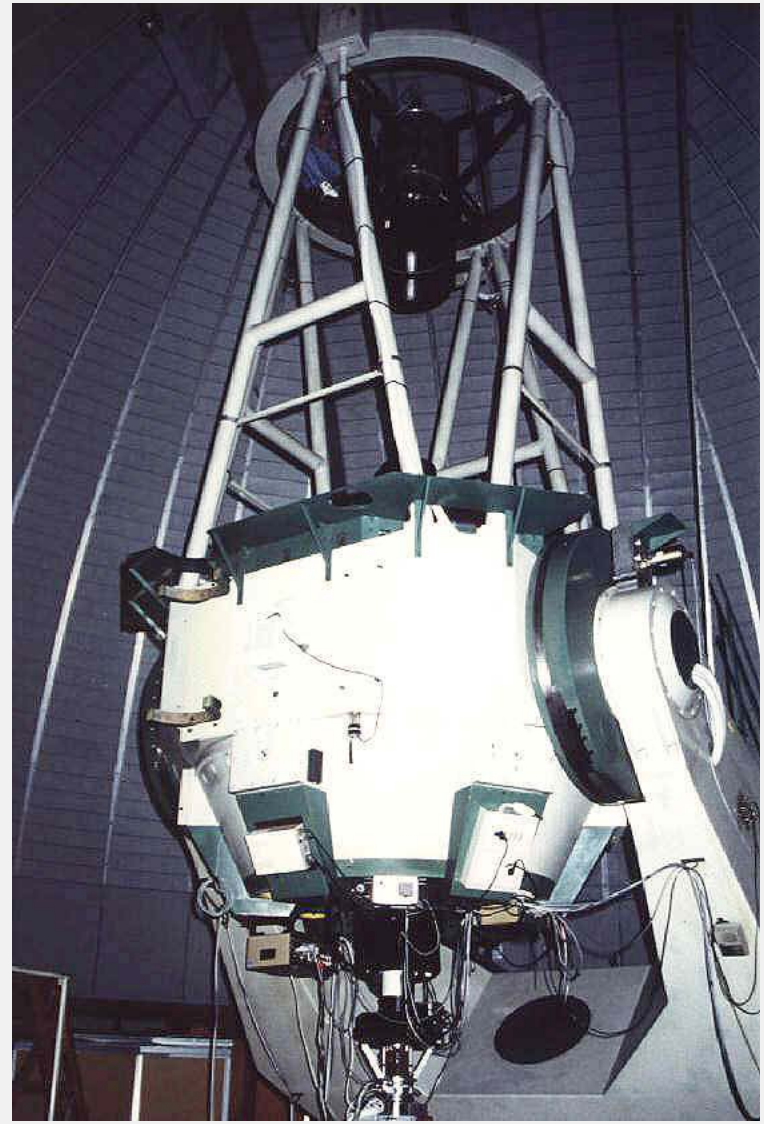
AQuEYE
Asiago





Left: AquEYE mechanics. Above the pyramid is the pinhole defining the aperture on the sky and used also for the mechanical alignment on the optical bench.
Right: AquEYE optomechanical assembly during alignment. Two of the four MPD SPADs are visible. The mirror above AquEYE feeds the reference beam from the interferometric unit used for alignment and laboratory tests.

AQuEYE
Asiago



AquEYE on the rear side of another instrument on the 182-cm telescope at Asiago.
The VME box is mounted on the telescope central section, and a fiber optics cable brings the signal to the main control room in the dome.

Steps towards a km^2 optical telescope

First full-scale observations with *VERITAS*

Dainis Dravins (Lund Observarory)
Stephan LeBohec (University of Utah)
Michael Daniel (University of Leeds)

Digitally correlated pairs of 12-meter telescopes

*** Photon rates > 30 MHz per telescope**

*** Real-time cross correlation, Δt = 1.6 ns**

The four VERITAS telescopes at Basecamp, Arizona

Site of first full-scale tests of digital intensity interferometry


VERITAS

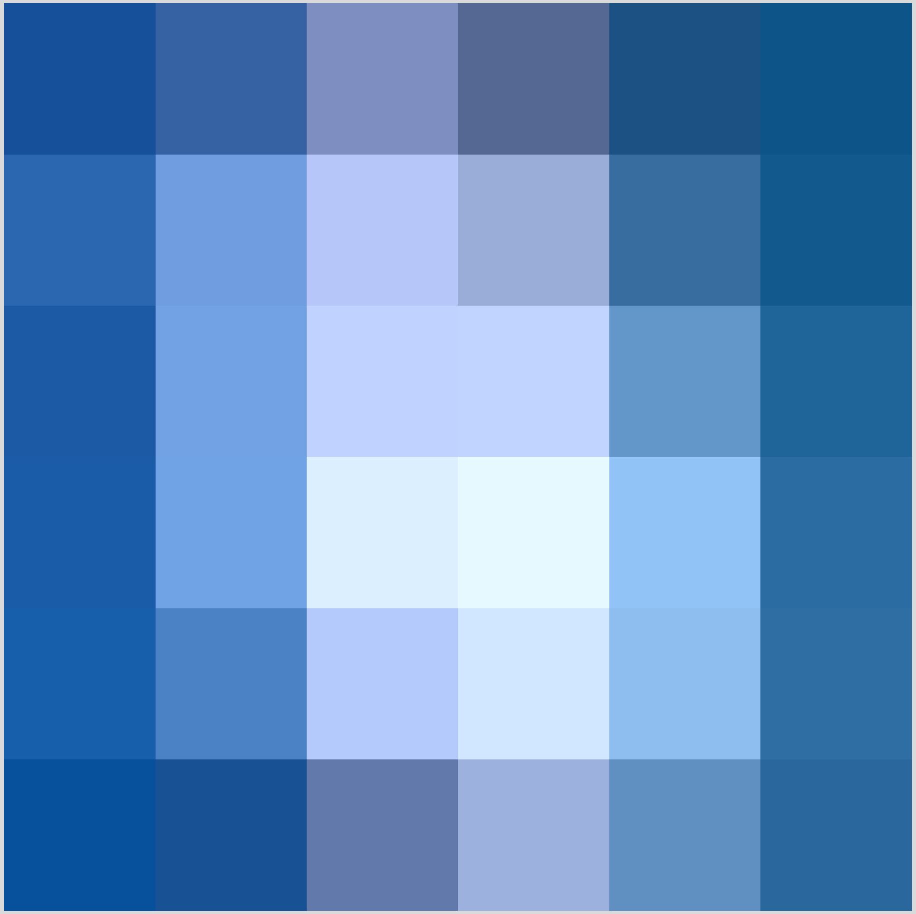
Intensity interferometry
can be carried out in moonlight
when Cherenkov observations
are not feasible

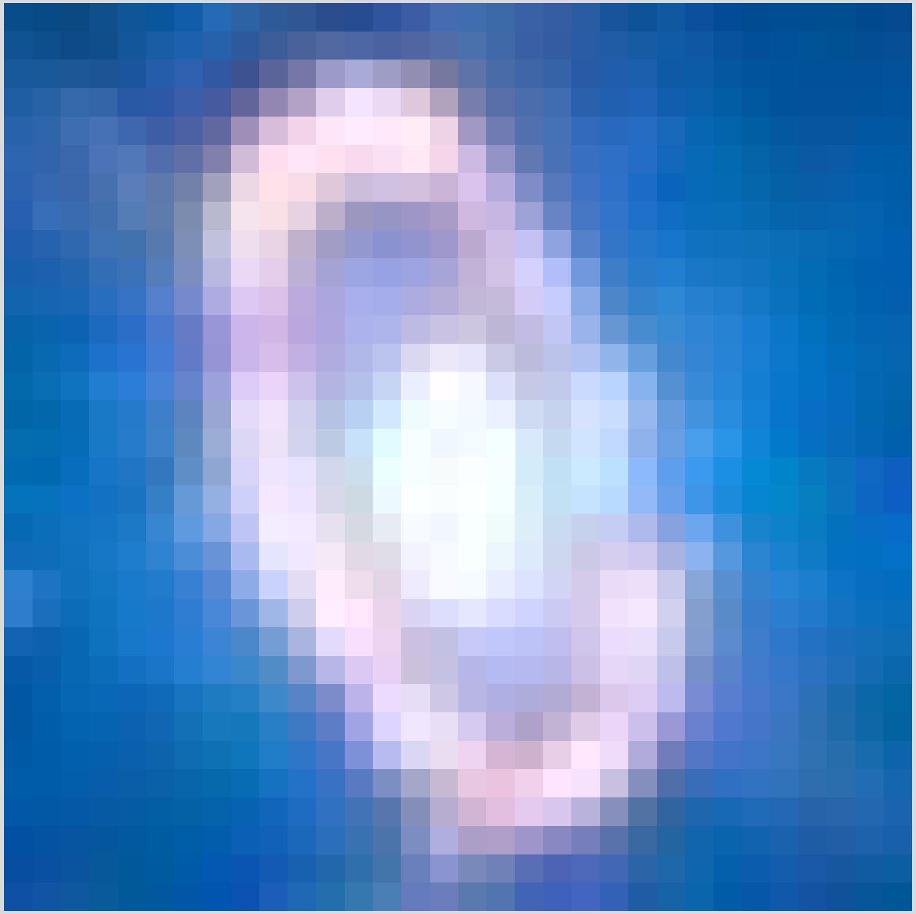
E-ELT

European Extremely Large Telescope

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



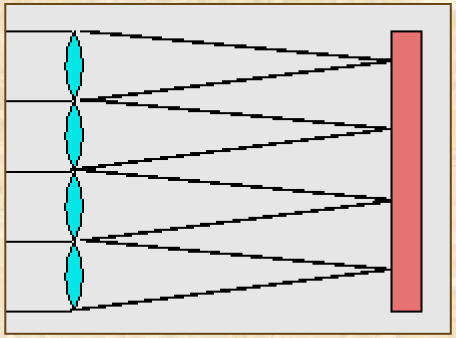


Artist's vision image from ESO press release eso1032

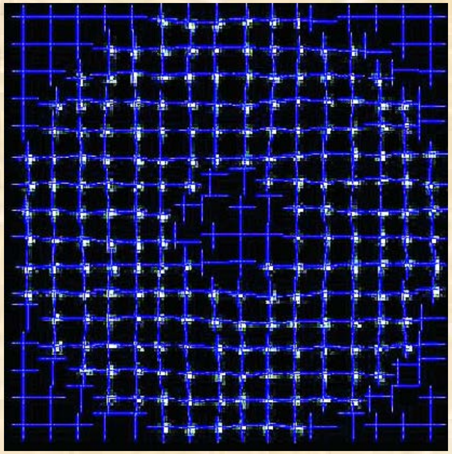
E-ELT

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

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

- ⋆ Optical aperture synthesis and diffraction-limited imaging by software!

THE

END