
Artist's view of a nova eruption (David A. Hardy & PPARC)

Diffraction-limited E-ELT imaging in the blue with intensity interferometry

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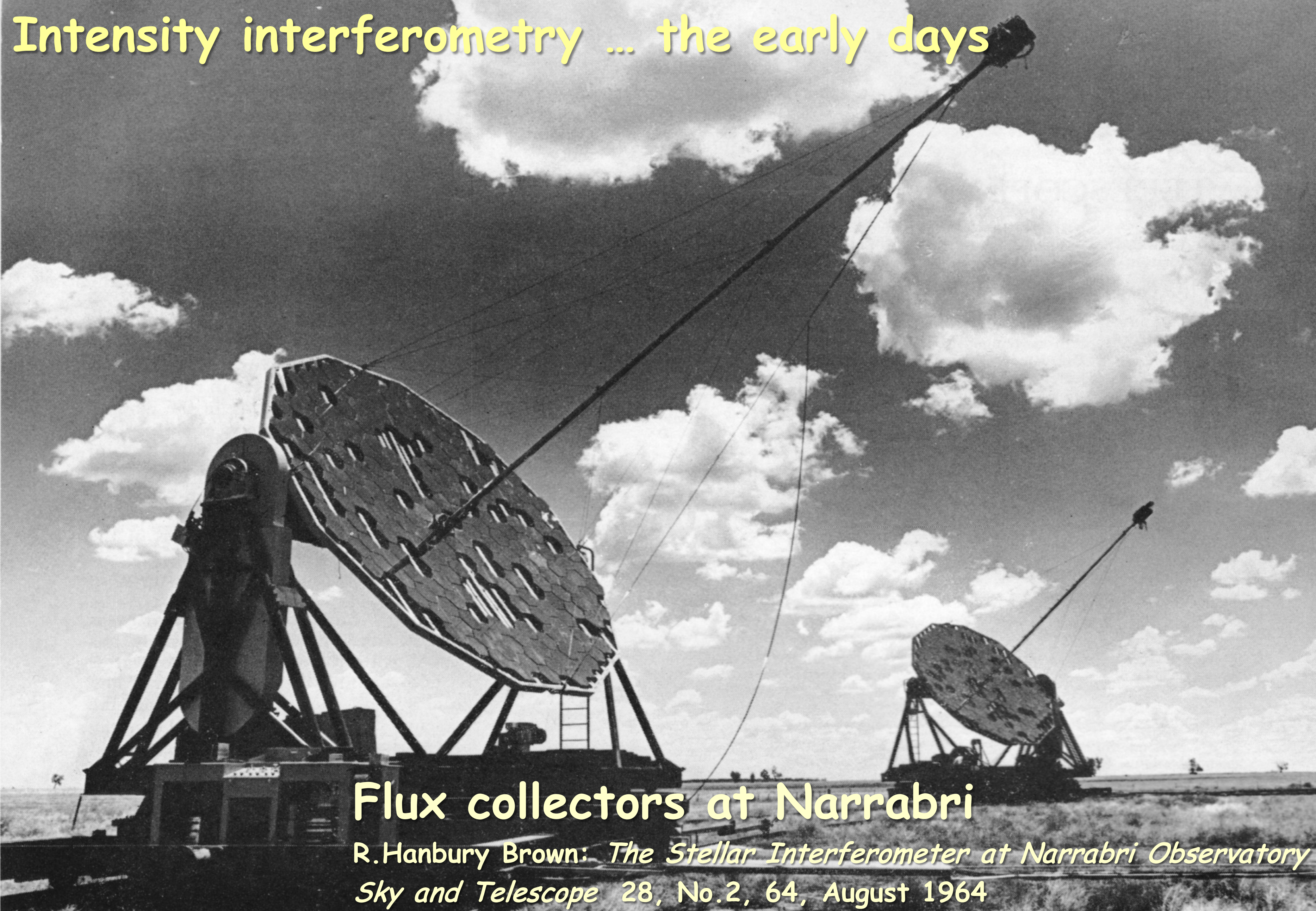
www.astro.lu.se/~dainis

Quantum Optics for Astronomical Imaging

- ★ *Intensity interferometry* first quantum-optical experiment
- ★ Measures two-photon properties, second-order coherence
- ★ Name is a misnomer: *Actually* nothing is interfering
- ★ Pro: Insensitive to atmospheric turbulence, optical errors
- ★ Con: Requires large flux collectors, fast electronics

Intensity interferometry … the early days



Flux collectors at Narrabri

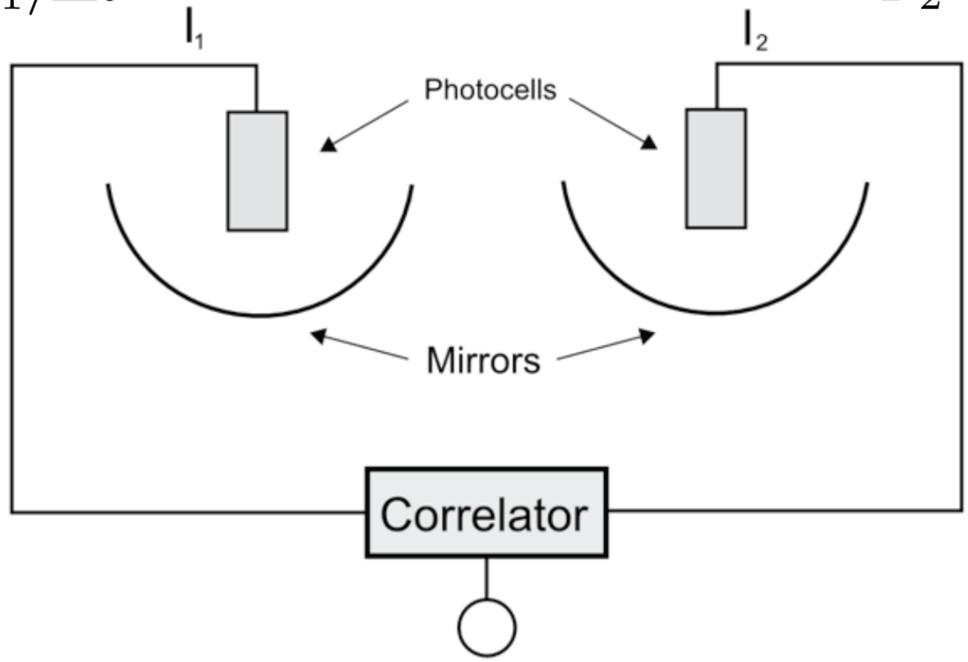
R.Hanbury Brown: *The Stellar Interferometer at Narrabri Observatory*

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

INTENSITY INTERFEROMETRY

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

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



$$P_{12} = \alpha_1 \alpha_2 \langle I_1 \rangle \langle I_2 \rangle (1 + \underset{\substack{\uparrow \\ \text{Photon clumping}}}{|\gamma_{12}|^2}) \Delta t^2$$

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.

Software telescopes in radio and the optical

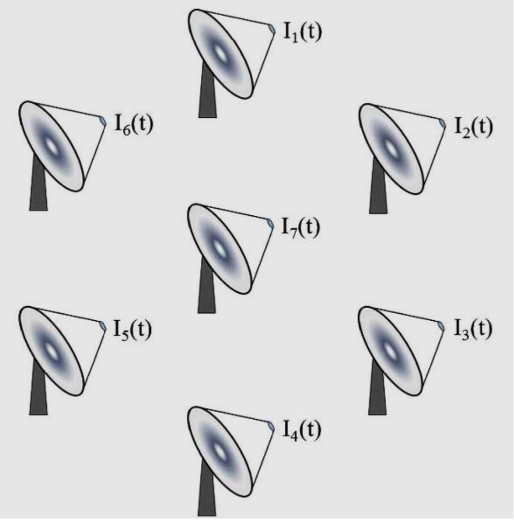
LOFAR

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.
Moderate 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., in press (2013)

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

Digital intensity interferometry

- ★ Observe with numerous telescopes or subapertures
- ★ Fast digital detectors & high-speed signal handling
- ★ Combine optical apertures in software
- ★ Huge number of baselines, no loss of digital signal
- ★ With 100 subapertures: $N\times(N-1)/2 \sim 5000$ baselines
- ★ Filled (u,v)-plane enables 2-dimensional imaging

S/N in intensity interferometry

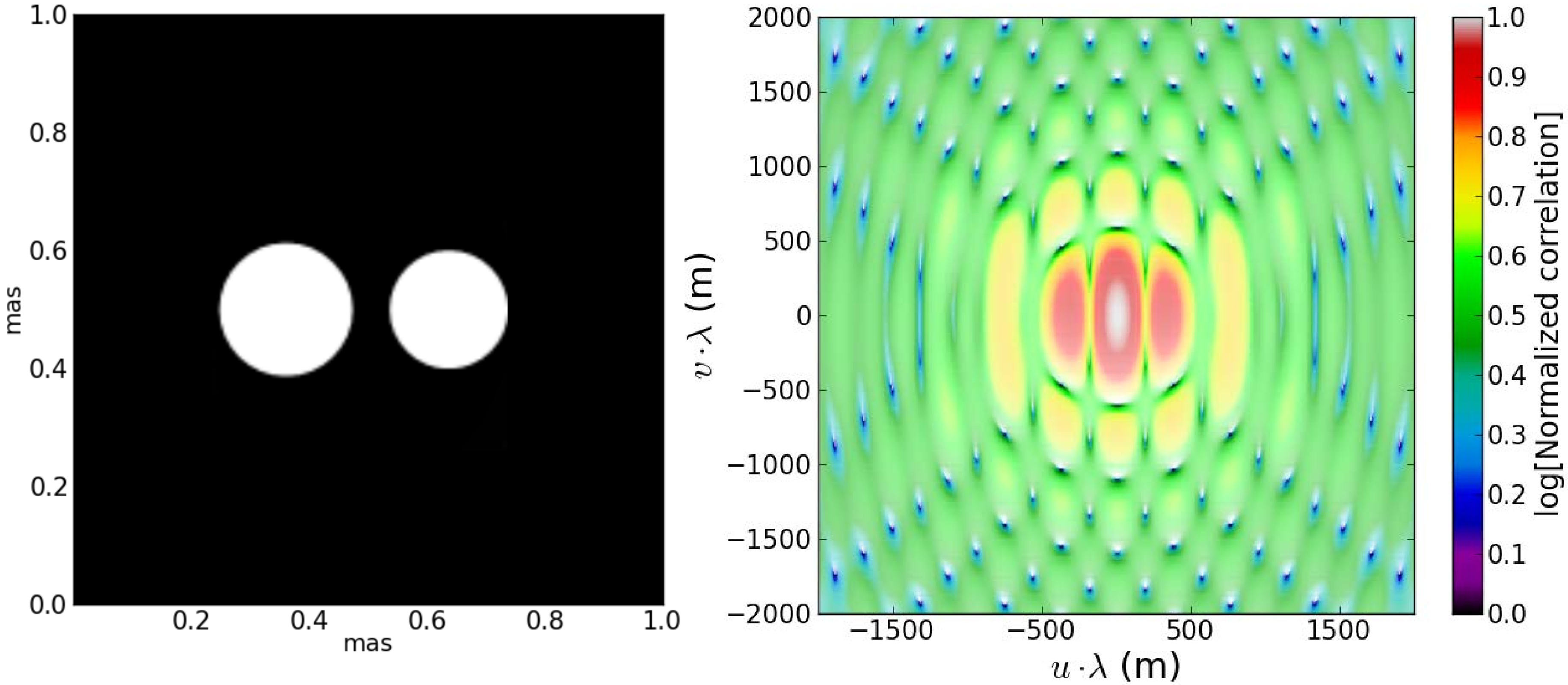
PROPORTIONAL TO:

- ★ 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



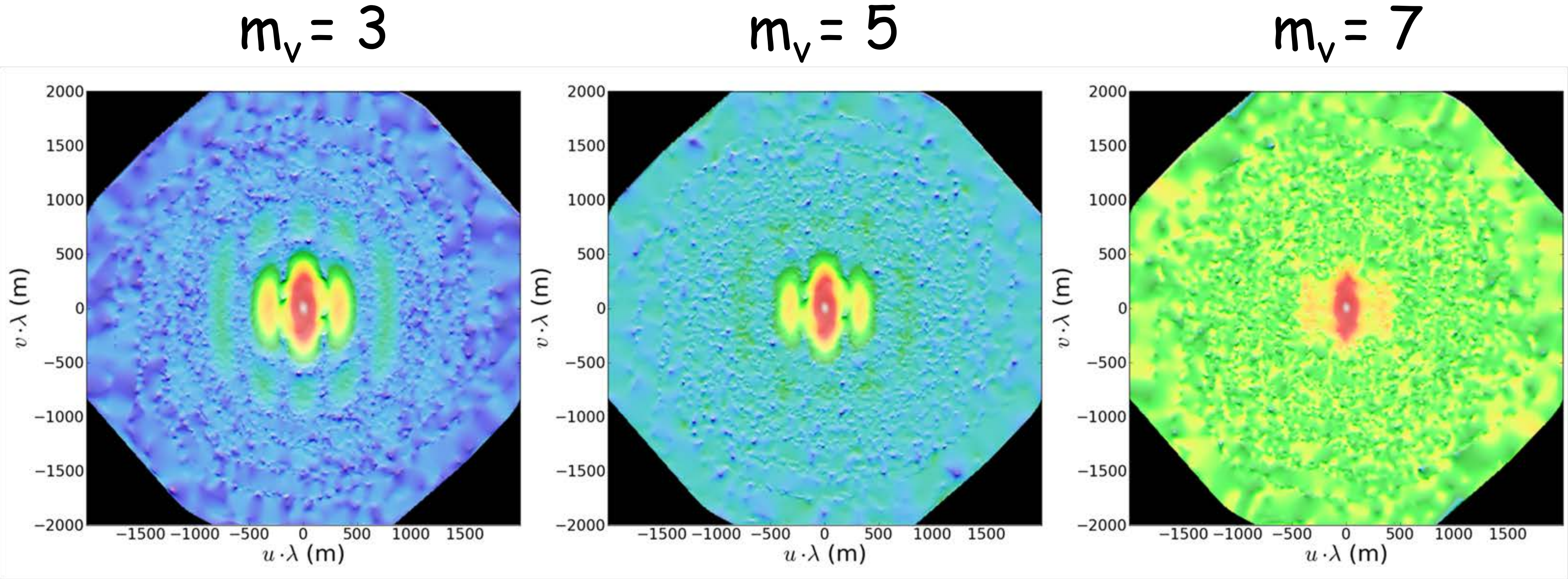
Squared visibility from a close binary star.

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 layout: 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)

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 $m_v \sim 8$	★ Limiting magnitude might reach extragalactic sources

Image reconstruction

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

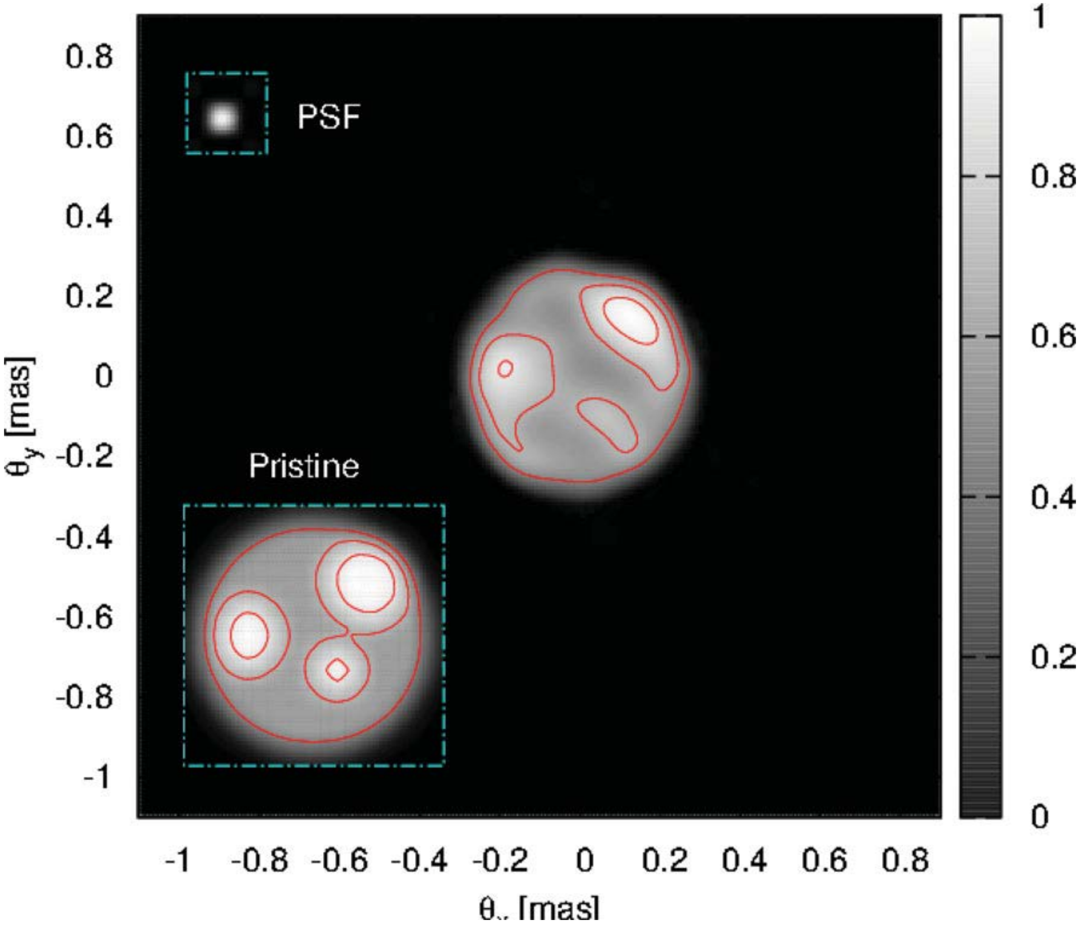
$$g^{(2)}(\tau) = 1 + |g^{(1)}(\tau)|^2$$

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



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.

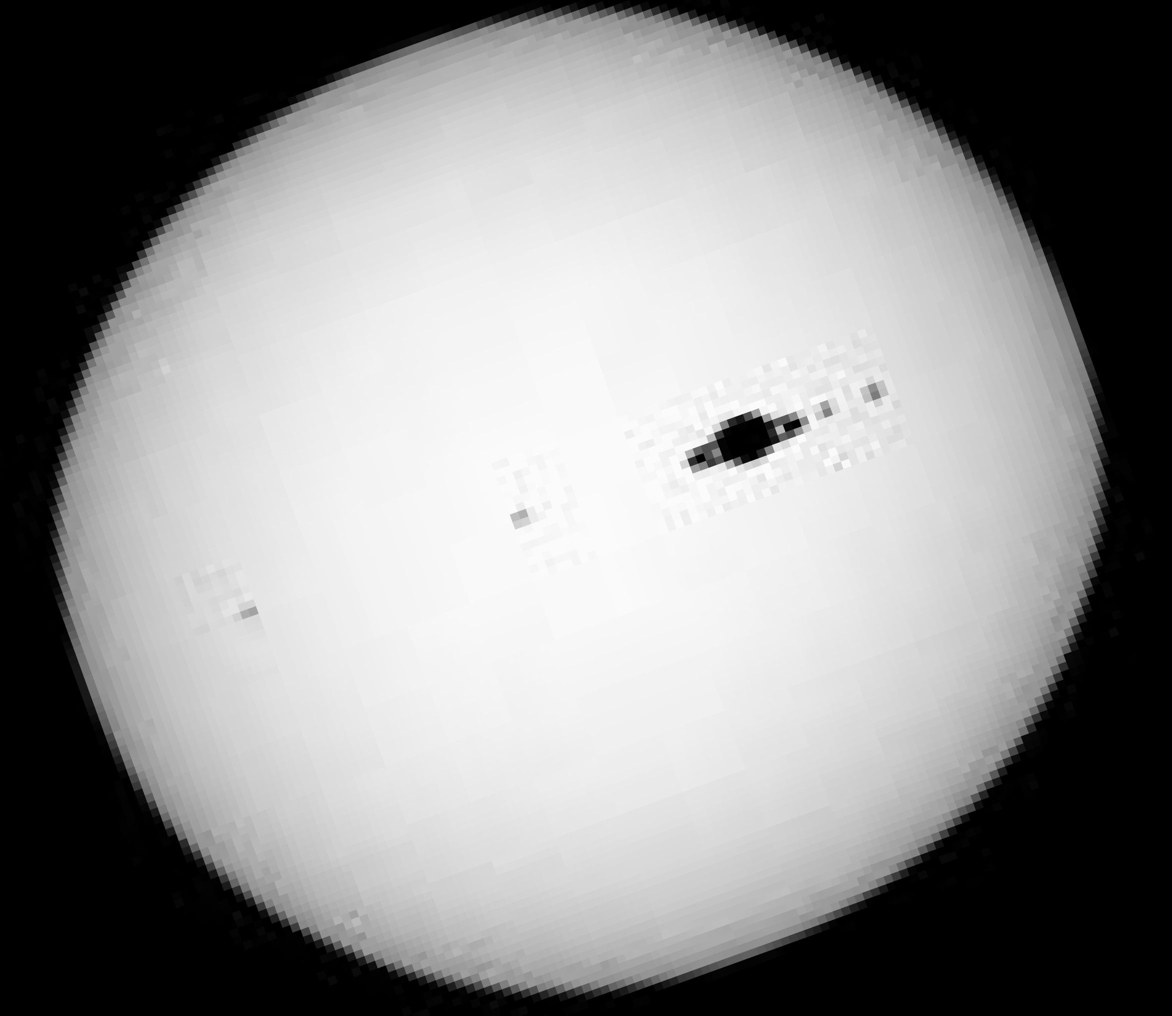
Simulated data correspond to visual magnitude m_V = 3, and 10 hours of observation.

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)

Kilometer-scale diffraction-limited optical imager:

Cherenkov Telescope Array as an Intensity Interferometer

Expected resolution for assumed exoplanet transit across the disk of Sirius



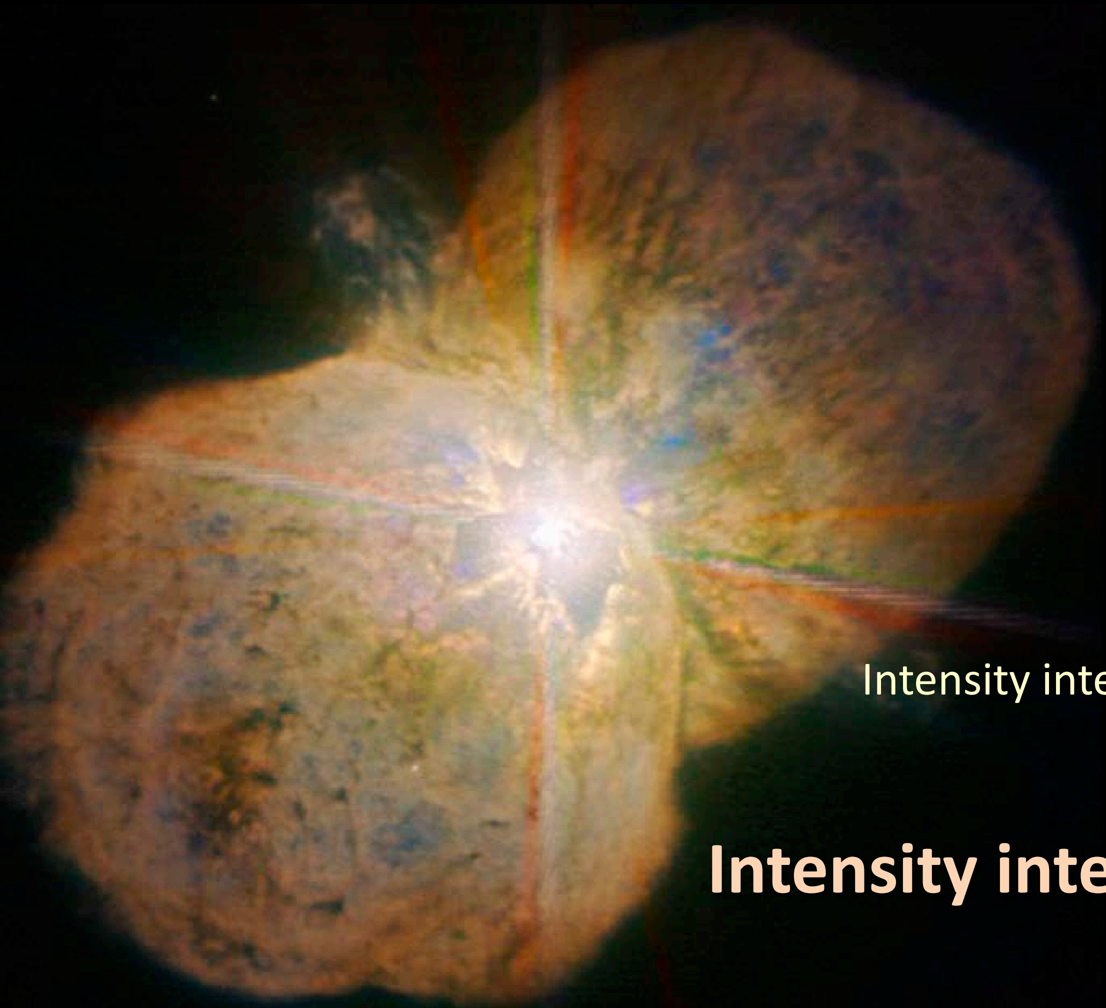
Stellar diameter = 1.7 solar
Distance = 2.6 pc
Angular diameter = 6 mas

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

Eta Carinae

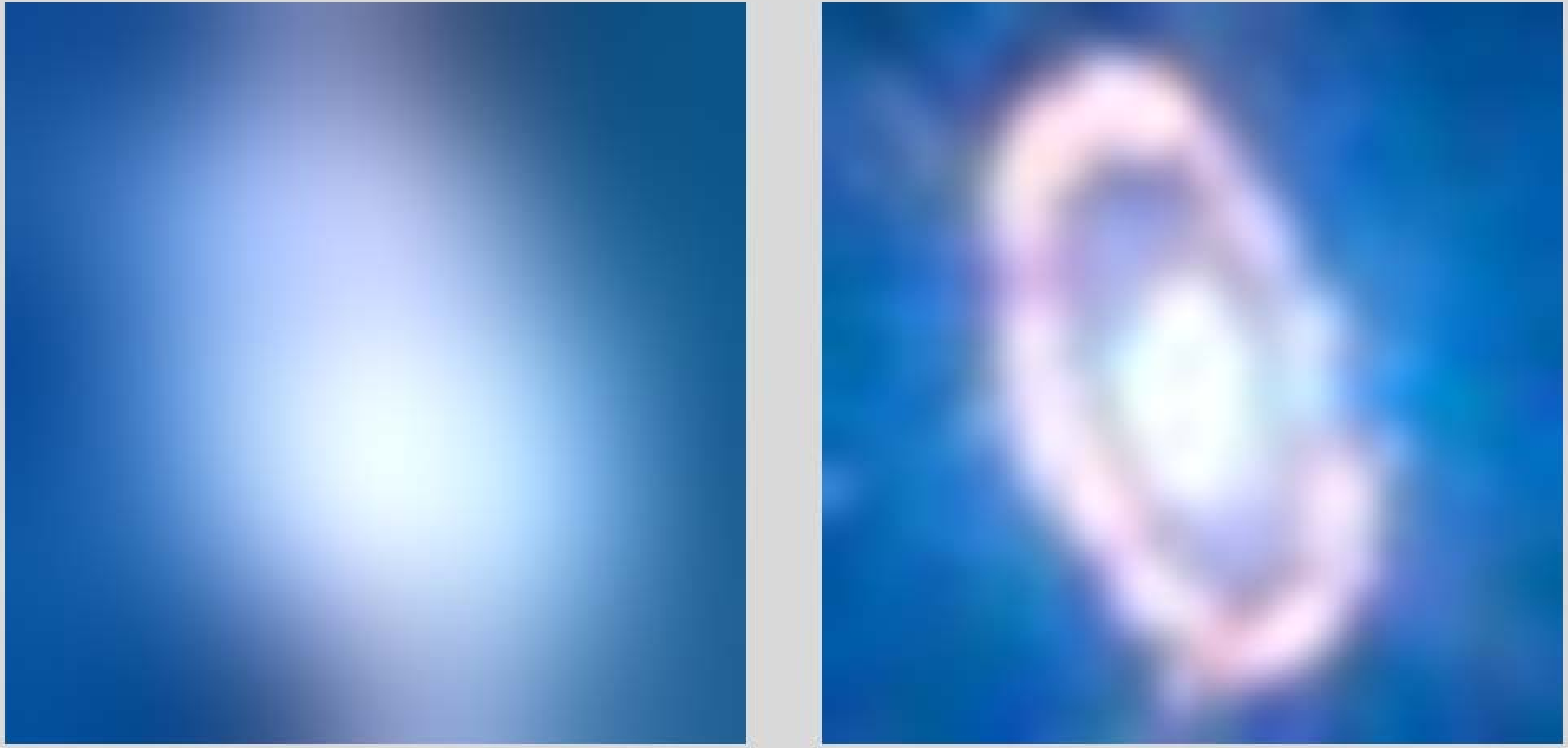
NACO near-IR adaptive optics image from ESO VLT *Yepun*
Composite image: J, H, K bands & narrow-band filters @ 1.64, 2.12, 2.17 μm
(ESO Press release eso0817)



Diffraction in 8 m telescope @ λ 2 μm ~ 60 mas

E-ELT: 5 × larger diameter
Intensity interferometry @ λ 400 nm: 5 × shorter wavelength

Intensity interferometry @ E-ELT: ~ 2 mas



Artist's vision image from ESO press release eso1032

E-ELT

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

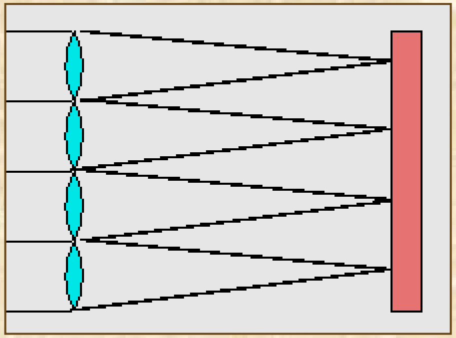
Practical realization?

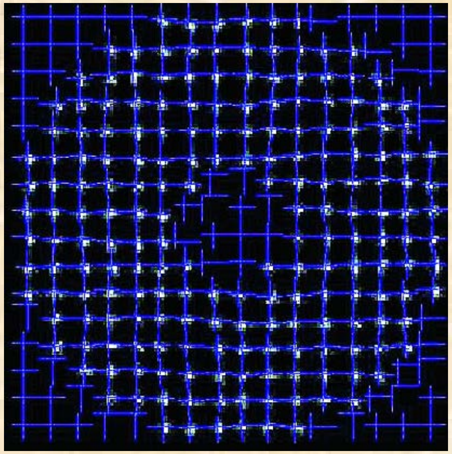
"A segmented telescope looks like a fully densified stellar interferometer."

(Isabelle Surdej, E-ELT Active Phasing Experiment, 2008)

Small 'technical' instrument

(already during E-ELT construction phase?)





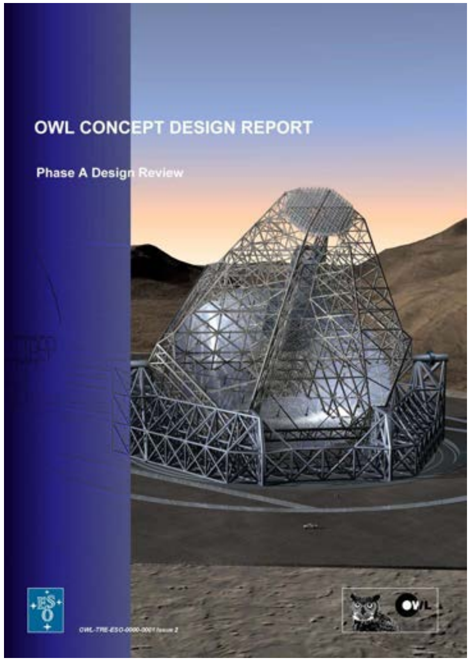
- ★ Lenslet array images E-ELT subapertures onto fast photon-counting detectors
- ★ Basically a Shack-Hartmann wavefront sensor
- ★ Electronic signal of photon streams is handled by on-line firmware or off-line software
- ★ Can use incompletely filled aperture, unadjusted mirror segments, poor seeing
- ★ Optical aperture synthesis and diffraction-limited imaging by software!

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 !

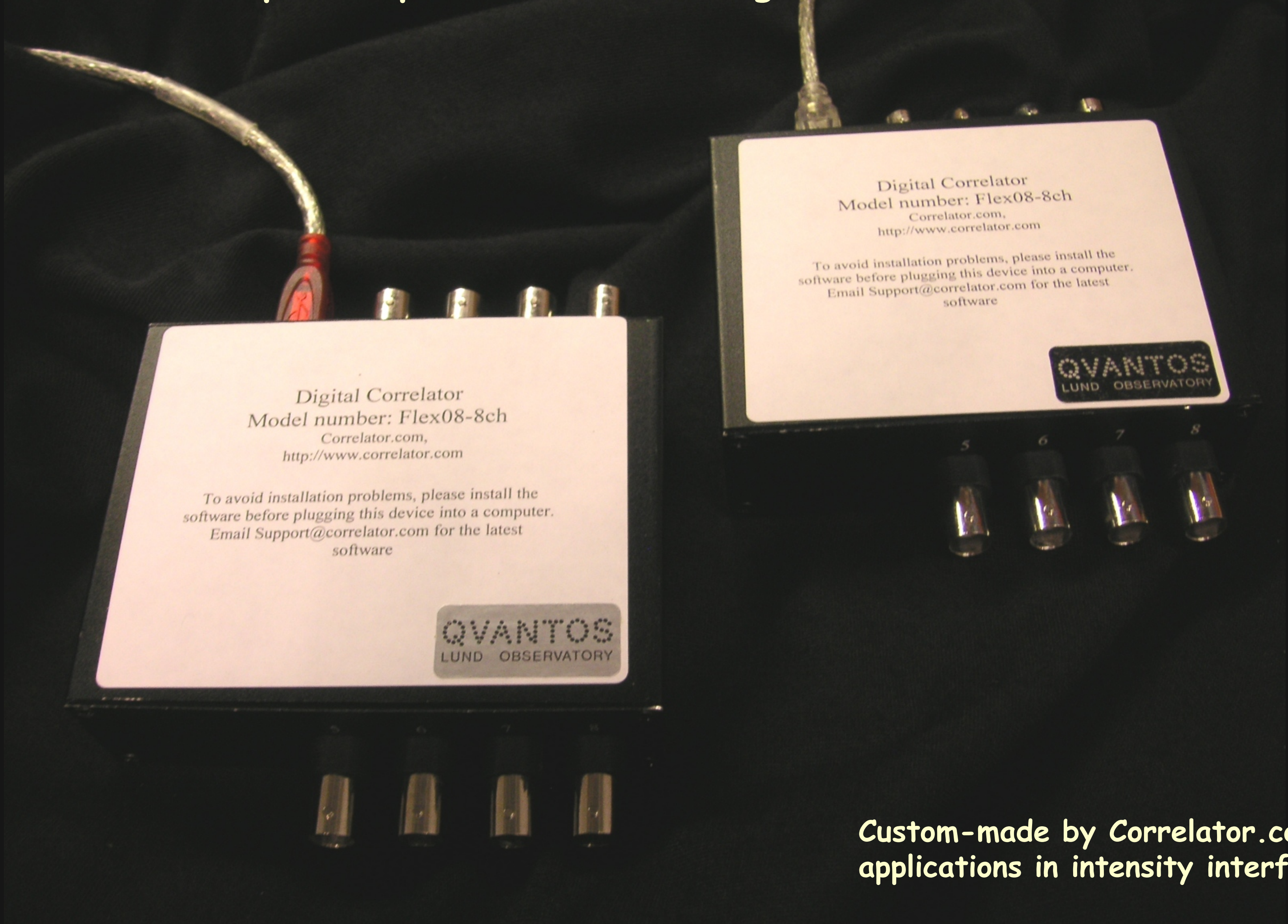

OWL CONCEPT DESIGN REPORT

Phase A Design Review

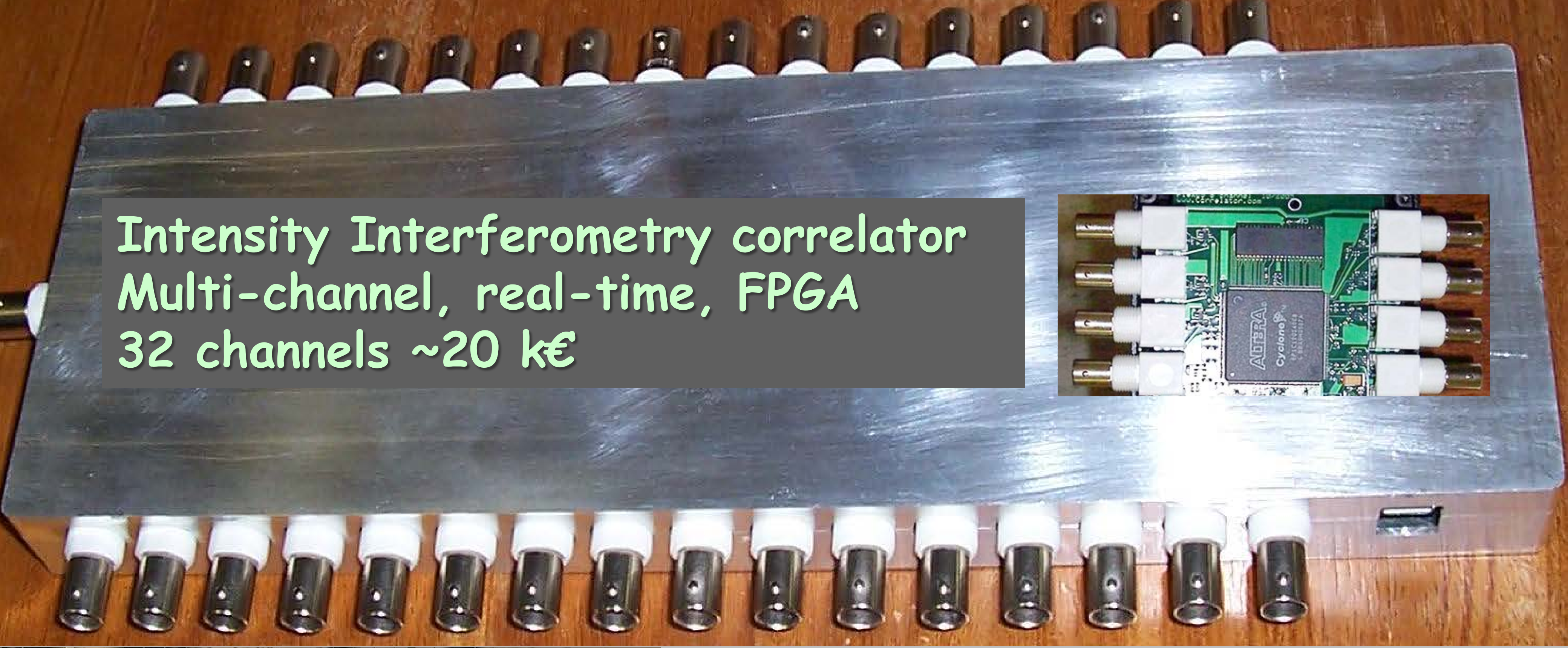
D. Dravins[1], C. Barbieri[2], V. Da Deppo[3], D. Faria[1], S. Fornasier[2], R. A. E. Fosbury[4], L. Lindegren[1], G. Naletto[3], R. Nilsson[1], T. Occhipinti[3], F. Tamburini[2], H. Uthas[1], L. Zampieri[5]

(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

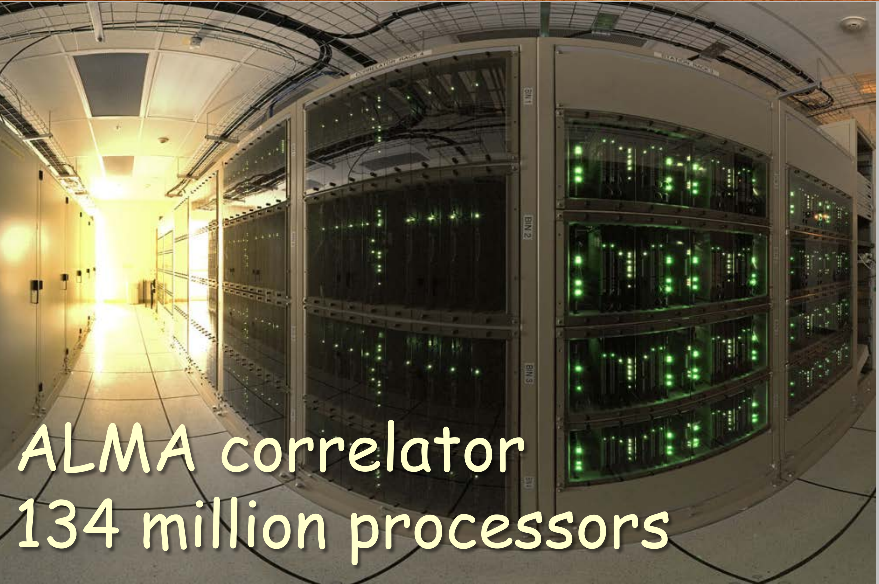
DIGITAL PHOTON CORRELATORS @ Lund Observatory
700 MHz clock rate (1.4 ns time resolution)
200 MHz maximum photon count rates per channel (pulse-pair resolution 5 ns)
8 input channels for photon pulses at TTL voltages



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



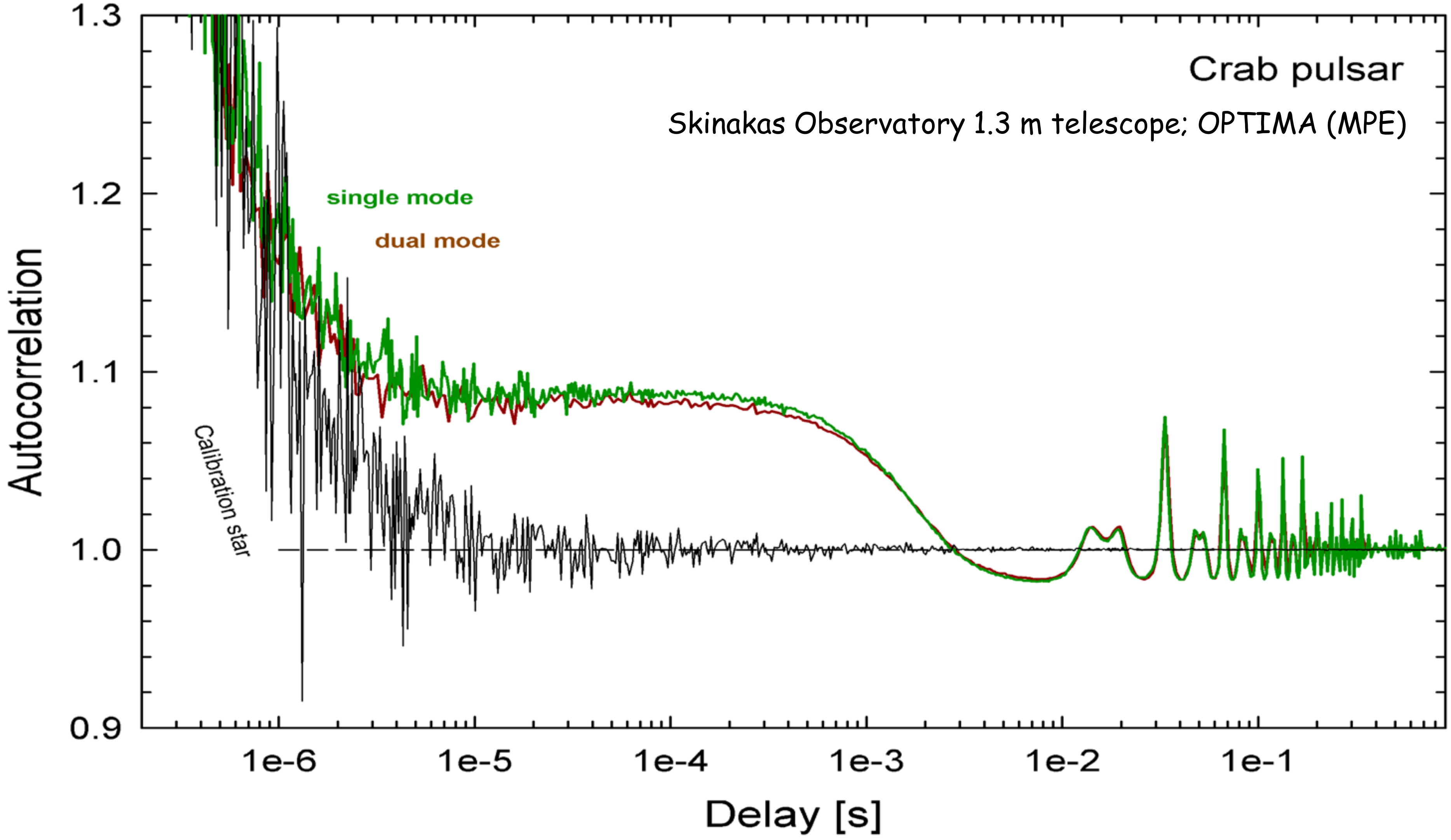
Intensity Interferometry correlator
Multi-channel, real-time, FPGA
32 channels ~20 k€



ALMA correlator
134 million processors

Very much more modest computations than in radio interferometry!

Photon correlation to [also] search for high-speed phenomena



Autocorrelation functions of the Crab pulsar, measured by photon-counting avalanche photodiodes in the *OPTIMA* instrument, computed by a real-time digital signal correlator of *QVANTOS Mark II* (Lund Observatory). The rise below 1 μs is due to detector afterpulsing.

Analyzing photon-counting detectors

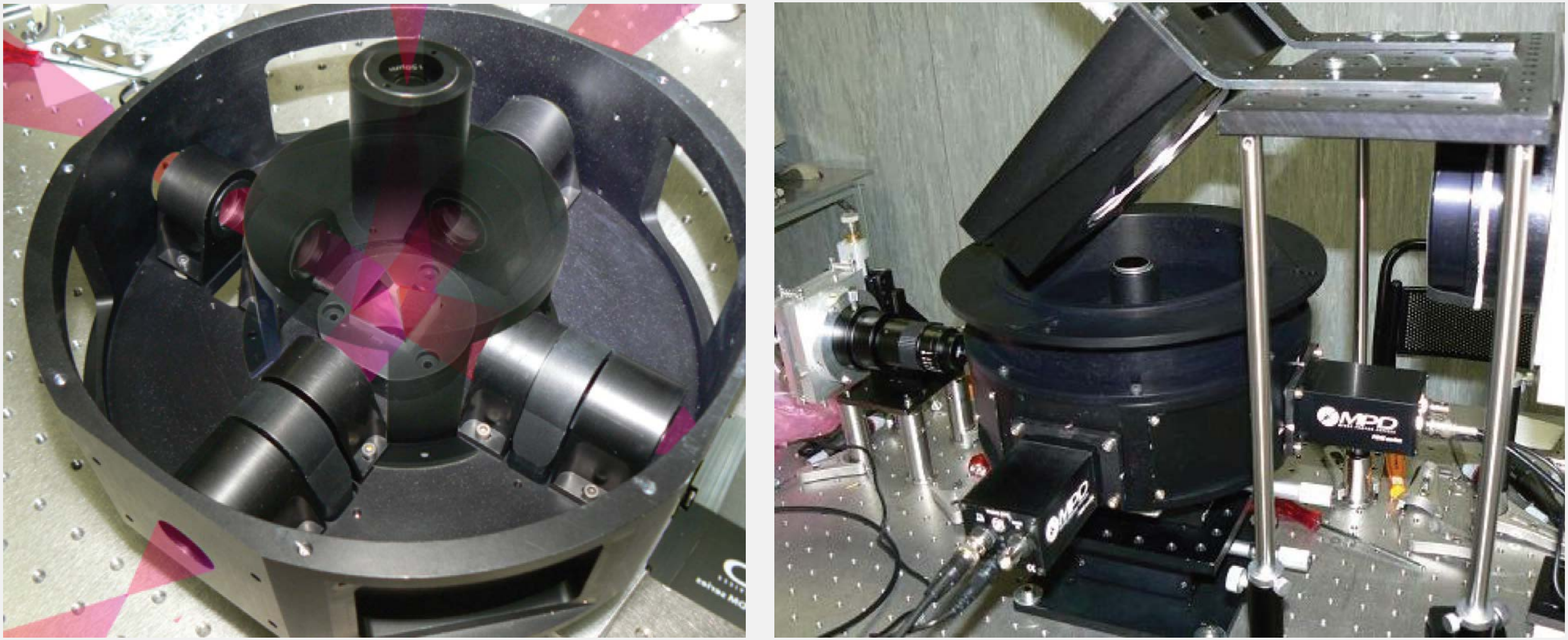
Afterpulsing, afterglow and other signatures could mimic intensity correlations

Single-photon-counting avalanche photodiode detectors being evaluated @ Lund Observatory for digital intensity interferometry
(made by: ***ID Quantique; Micro Photon Devices; PerkinElmer; SensL*****)**

AQuEYE
Asiago

C.Barbieri et al.:
AquEYE, a single photon counting photometer for astronomy, J. Mod. Optics **56**, 261 (2009)

G. Naletto et al.: *Iqueye, a single photon-counting photometer applied to the ESO New Technology Telescope,* Astron.Astrophys. **508**, 531 (2009)

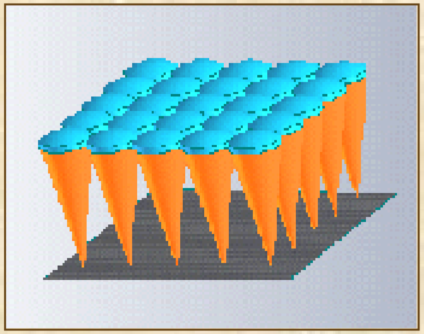


Left: AquEYE mechanics. Above the pyramid is the pinhole defining the aperture on the sky and used also for the mechanical alignment on the optical bench.
Right: AquEYE optomechanical assembly during alignment. Two of the four MPD SPADs are visible. The mirror above AquEYE feeds the reference beam from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

SUMMARY

Proposed small 'technical' instrument

- ★ E-ELT science already during years of construction phase
- ★ Photon-counting Shack-Hartmann wavefront sensor
- ★ Shack-Hartmann function for telescope optical diagnostics; Photon correlation signal for its mechanical diagnostics
- ★ Software access to signal enables aperture synthesis imaging with intensity interferometry, also high-speed photometry



THE
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