ESO Santiago - December 2007

PHOTONIC ASTRONOMY & QUANTUM OPTICS

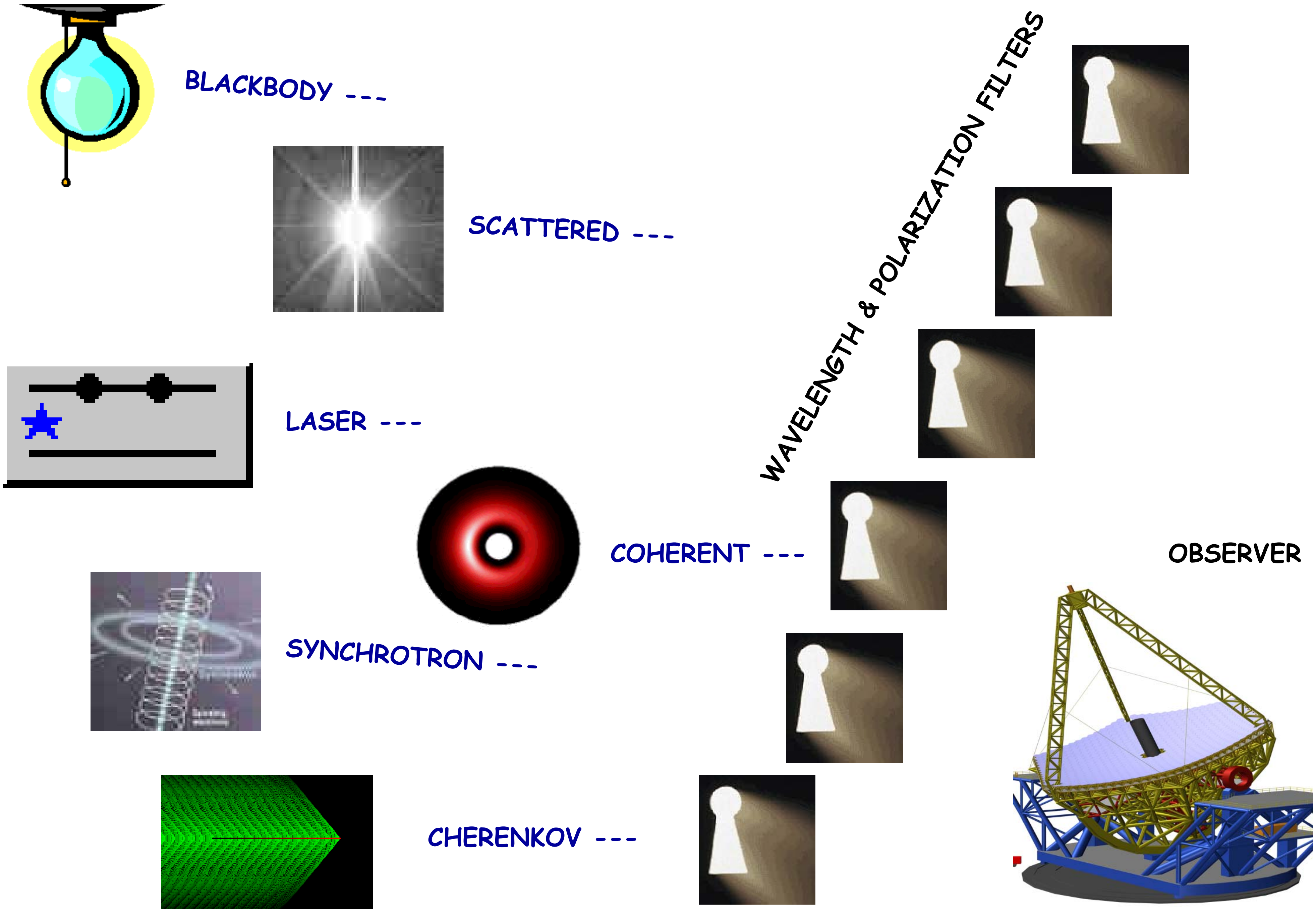
Dainis Dravins

Lund Observatory, Sweden

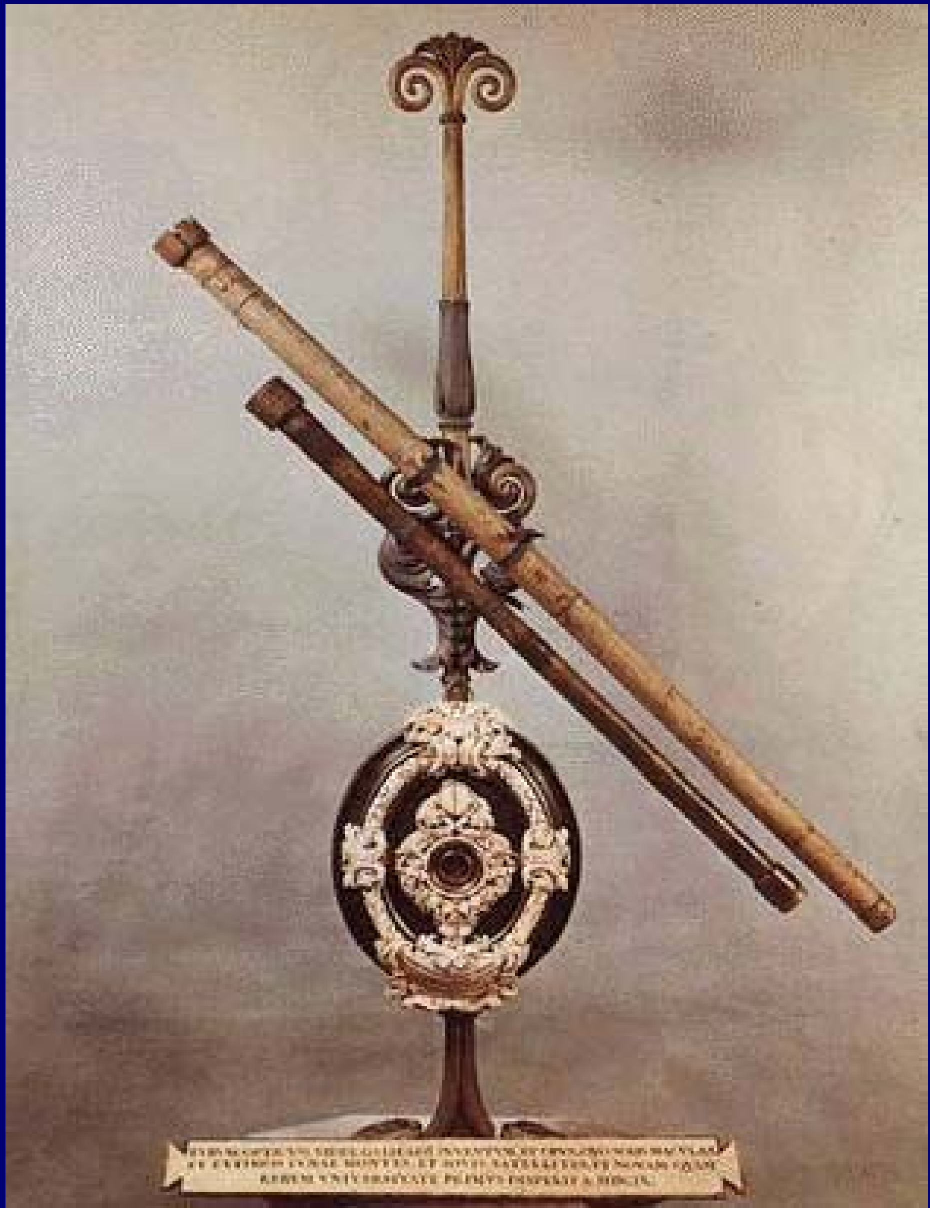
LUND UNIVERSITY

What information is contained in light?

What is being observed ? What is not ?

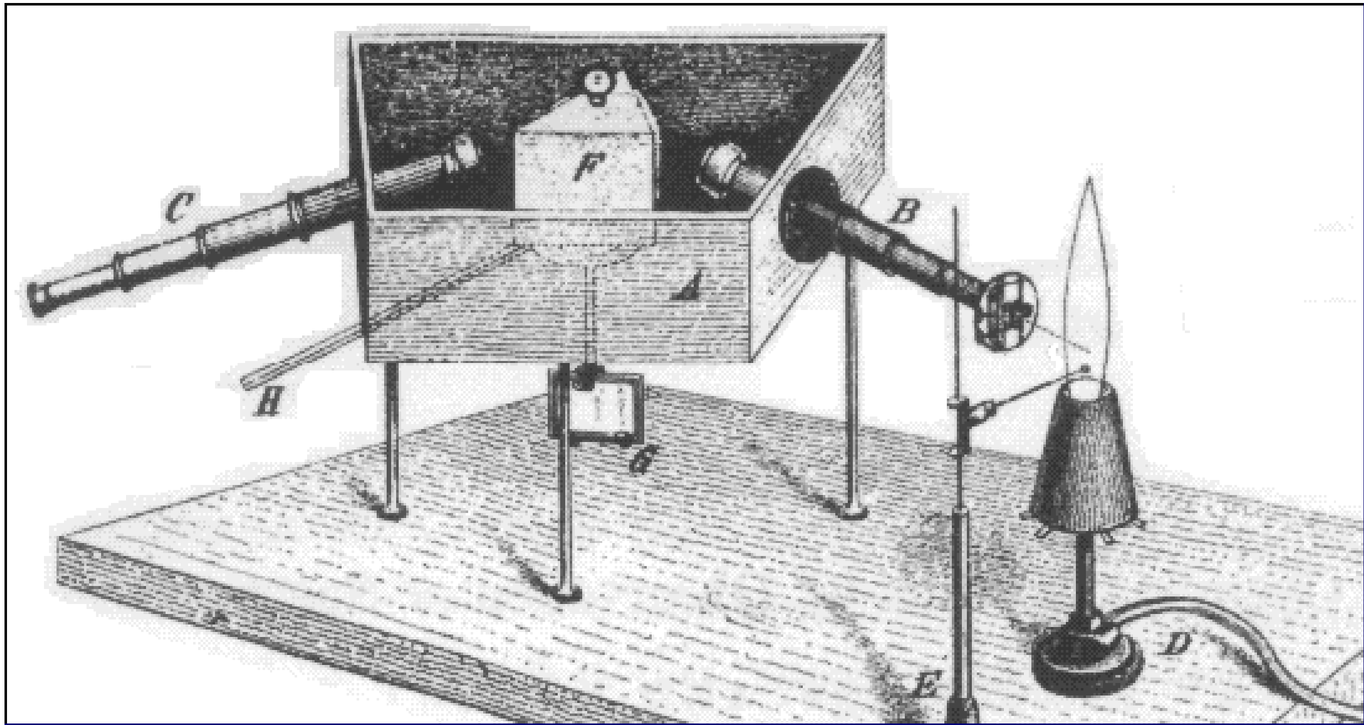

BLACKBODY ---
SCATTERED ---
LASER ---
COHERENT ---
SYNCHROTRON ---
CHERENKOV ---
WAVELENGTH & POLARIZATION FILTERS
OBSERVER

Instruments measuring first-order spatial coherence



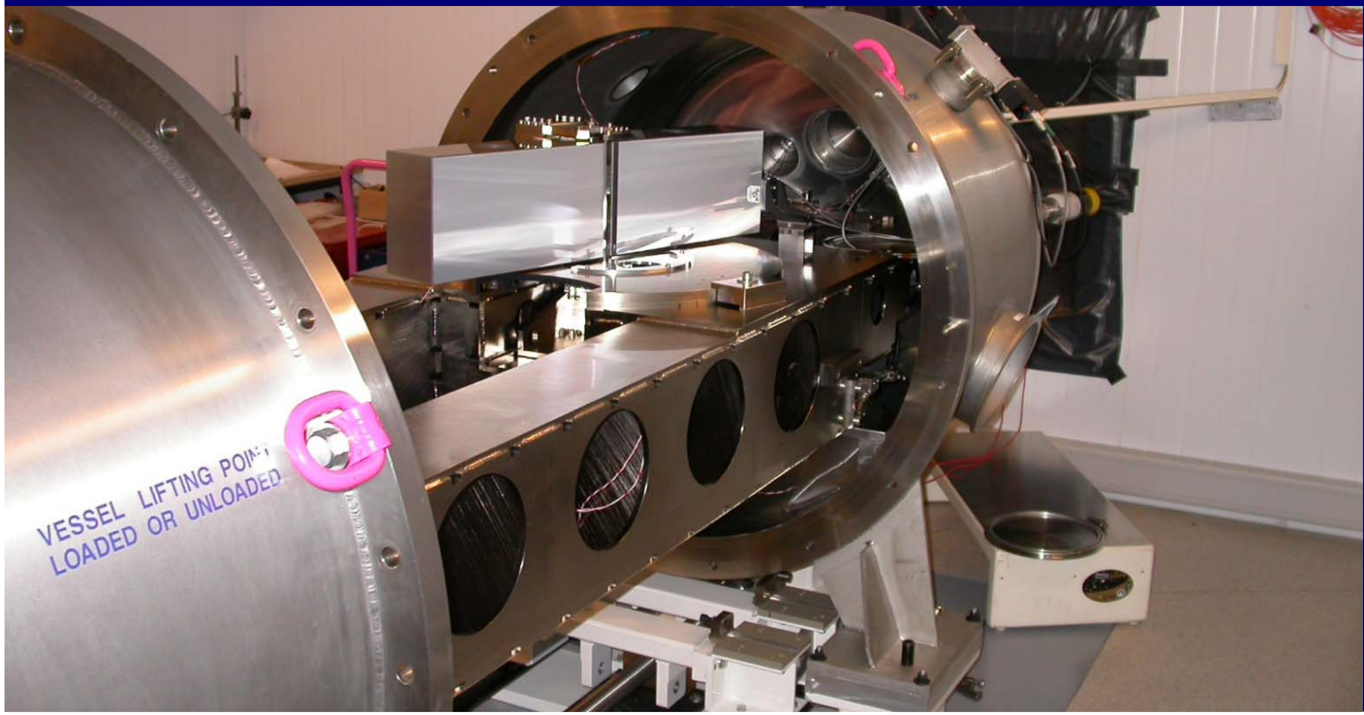
Galileo's telescopes (1609)

Hubble Space Telescope (1990)



Fraunhofer's spectroscope (1814)

Instruments measuring first-order temporal coherence



HARPS (2003)

Information content of light. I

ONE–PHOTON EXPERIMENTS

1:st order correlation function:

$$G^{(1)}[r_1,t_1; r_2,t_2] = \langle E^*(r_1,t_1)\, E(r_2,t_2) \rangle$$

Special case: $r_1 = r_2$, $t_1 = t_2$

$\langle E^*(0,0)\, E(0,0) \rangle$ – BOLOMETER

Special case: $r_1 \neq r_2$, $t_1 = t_2$

$\langle E^*(0,0)\, E(r,0) \rangle$ – [PHASE] INTERFEROMETER

Special case: $r_1 = r_2$, $t_1 \neq t_2$

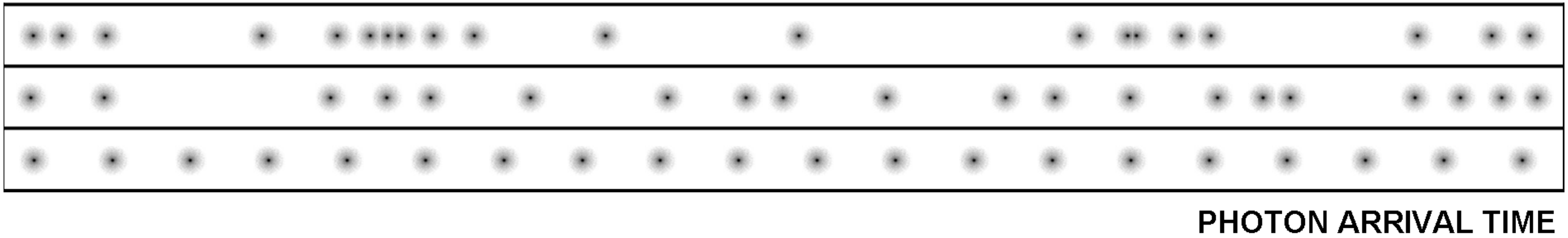
$\langle E^*(0,0)\, E(0,t) \rangle$ – SPECTROMETER

"COMPLEX" RADIATION SOURCES

What can a [radio] telescope detect?

What can it not?

PHOTON STATISTICS

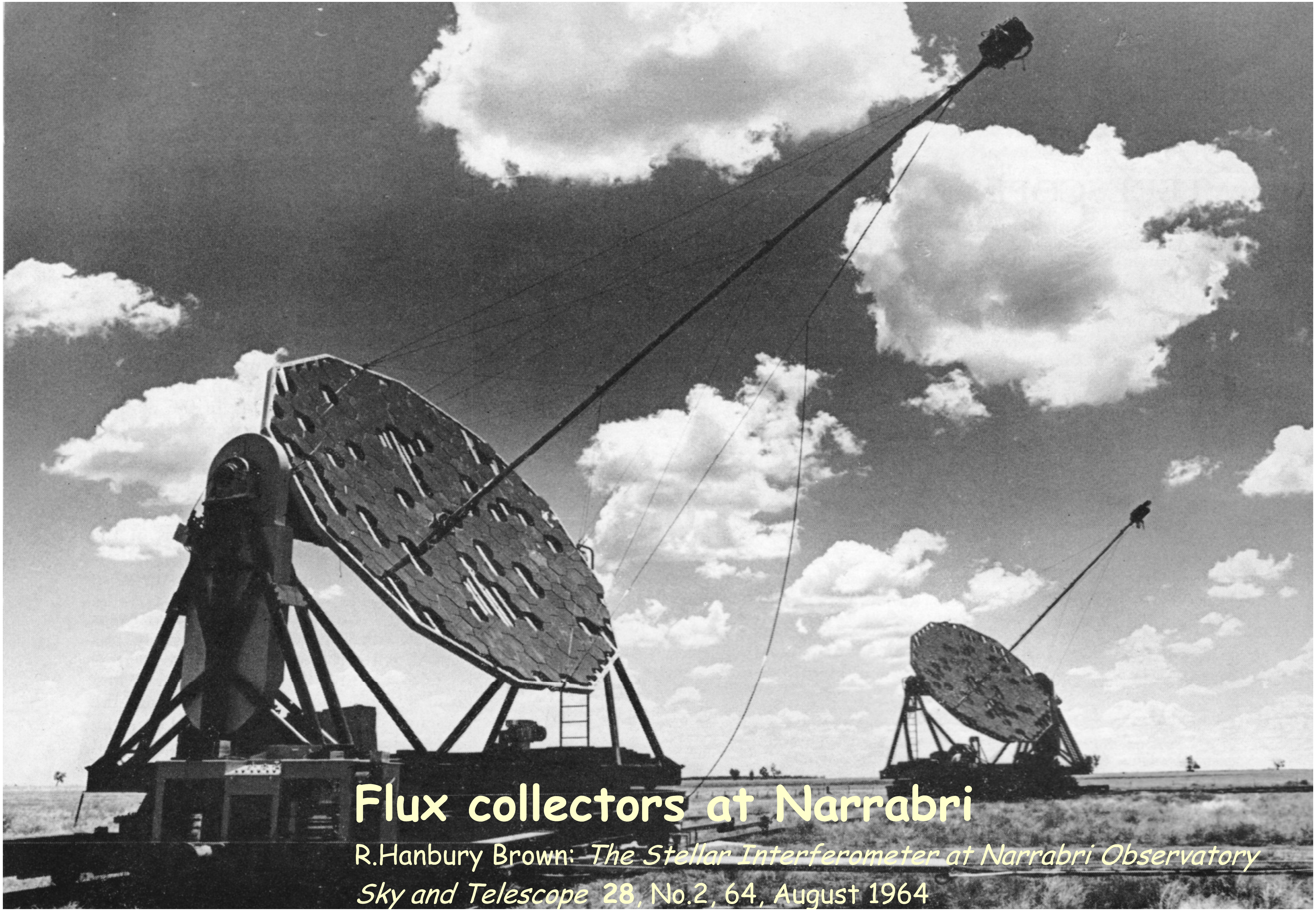


Top: Bunched photons (Bose-Einstein; 'quantum-random')

Center: Antibunched photons (like fermions)

Bottom: Coherent and uniformly spaced (like ideal laser)

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



Flux collectors at Narrabri

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

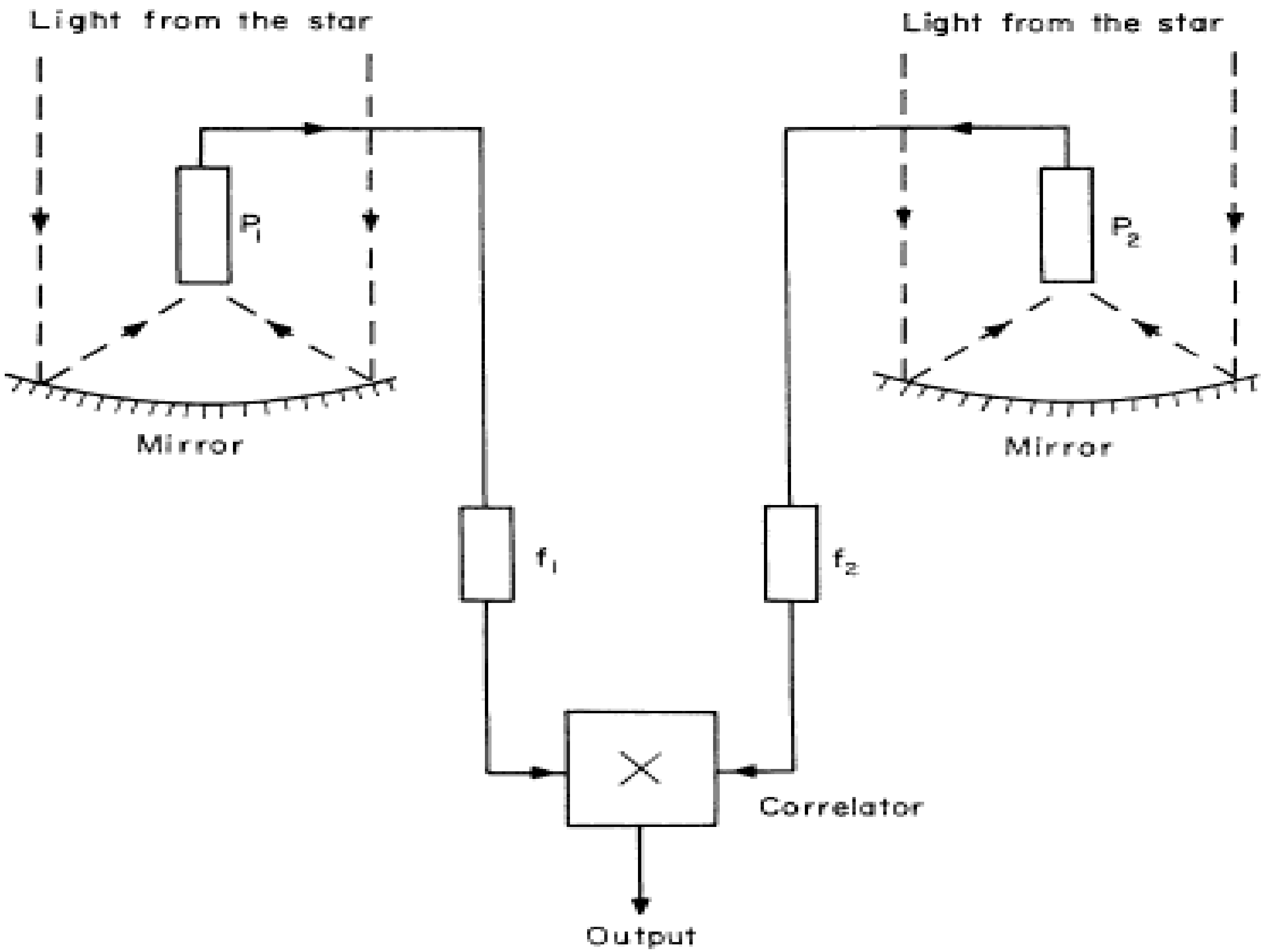
Sky and Telescope **28**, No.2, 64, August 1964

Narrabri observatory

with its circular railway track (188 m diameter)

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

Intensity interferometry



R.Hanbury Brown, J.Davis, L.R.Allen, MNRAS 137, 375

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

Information content of light. II

TWO-PHOTON EXPERIMENTS

2:nd order correlation function:

$$G^{(2)}[r_1,t_1;\ r_2,t_2] = \langle I(r_1,t_1)\ I(r_2,t_2) \rangle$$

Special case: $r_1 = r_2,\ t_1 = t_2$

$\langle I(0,0)\ I(0,0) \rangle$ – "QUANTUM SPECTROMETER"

Special case: $r_1 \neq r_2,\ t_1 = t_2$

$\langle I(0,0)\ I(r,0) \rangle$ – INTENSITY INTERFEROMETER

Special case: $r_1 = r_2,\ t_1 \neq t_2$

$\langle I(0,0)\ I(0,t) \rangle$ – CORRELATION SPECTROMETER

D.Dravins, ESO Messenger No. 78, 9

Roy Glauber

Nobel prize in physics

Stockholm, December 2005

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

Applications in astrophysics?

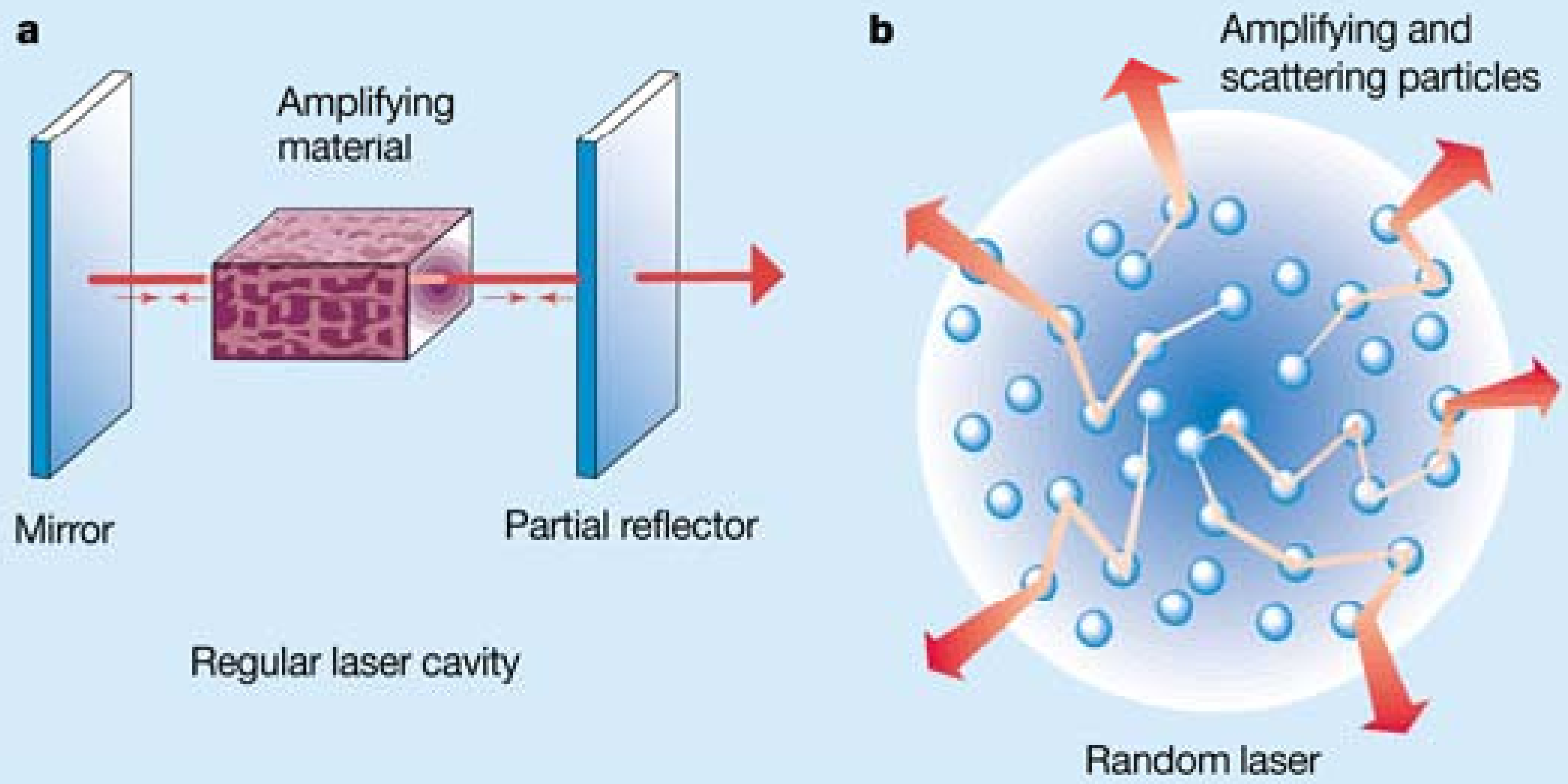
PHOTONIC

ASTRONOMY

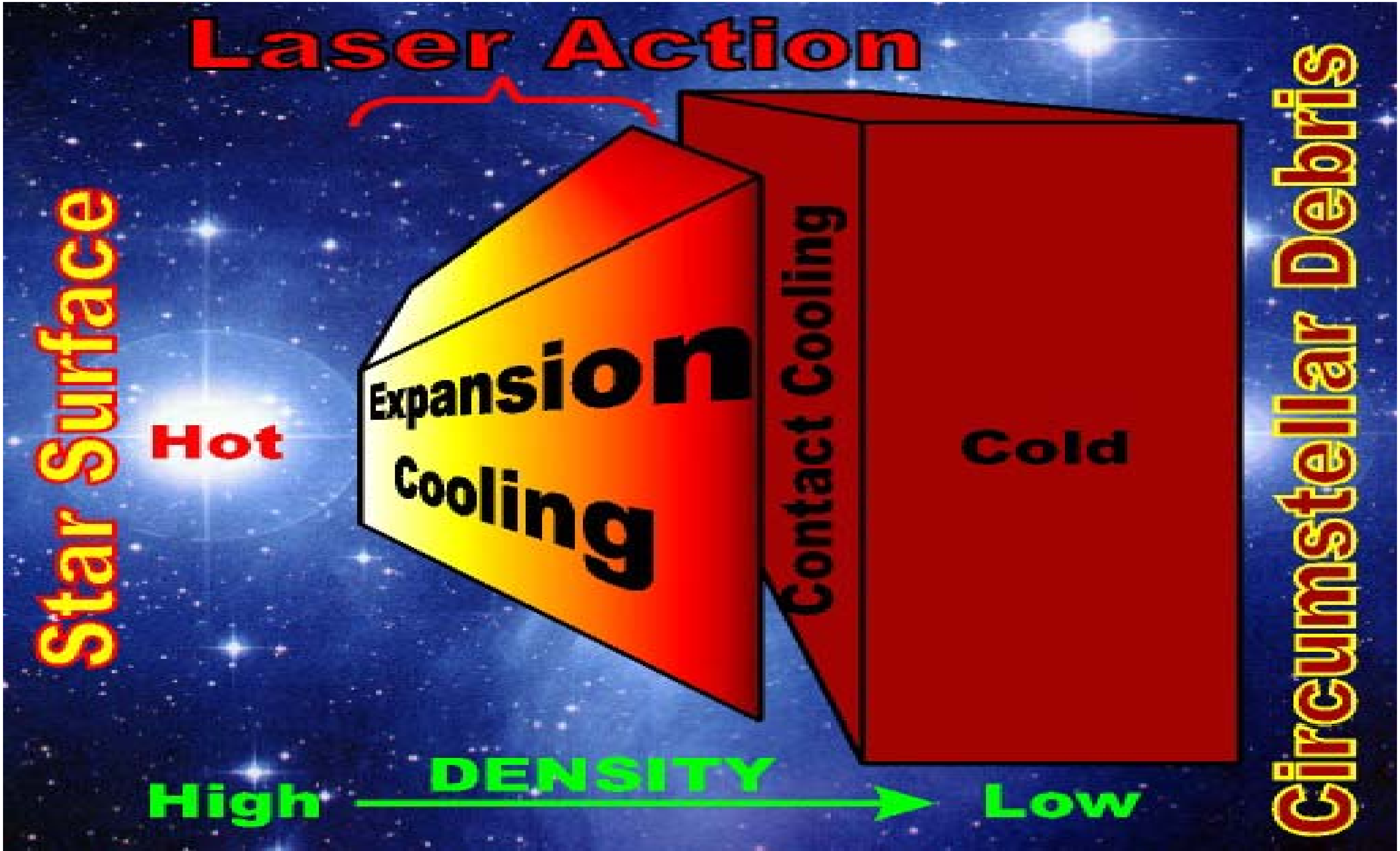
Natural lasers result when atomic energy levels become overpopulated

A known case is the ultraluminous star η Car; other sources might be symbiotic, Wolf-Rayet & Be stars

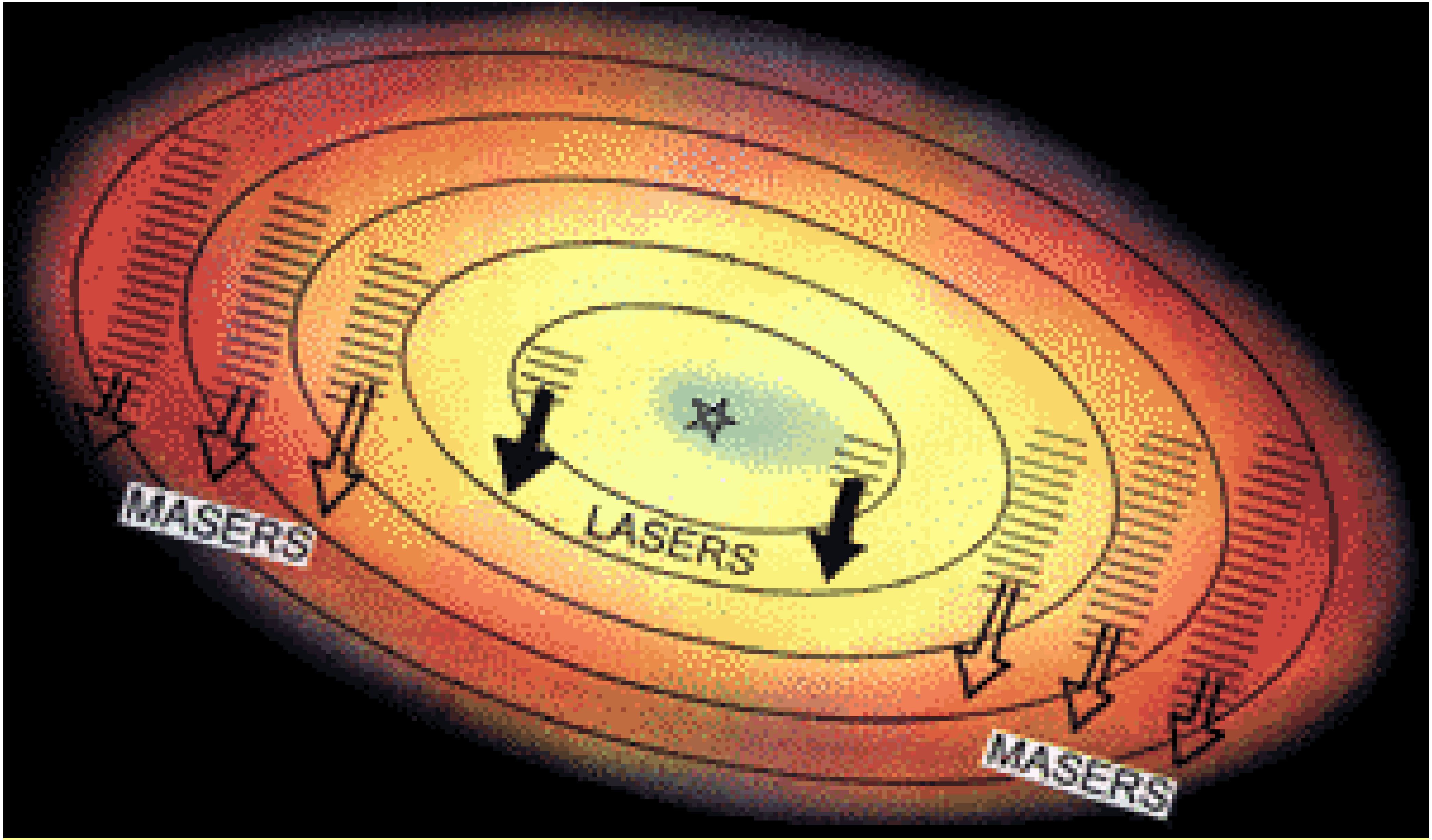
"Random-laser" emission



D.Wiersma, Nature,406, 132 (2000)



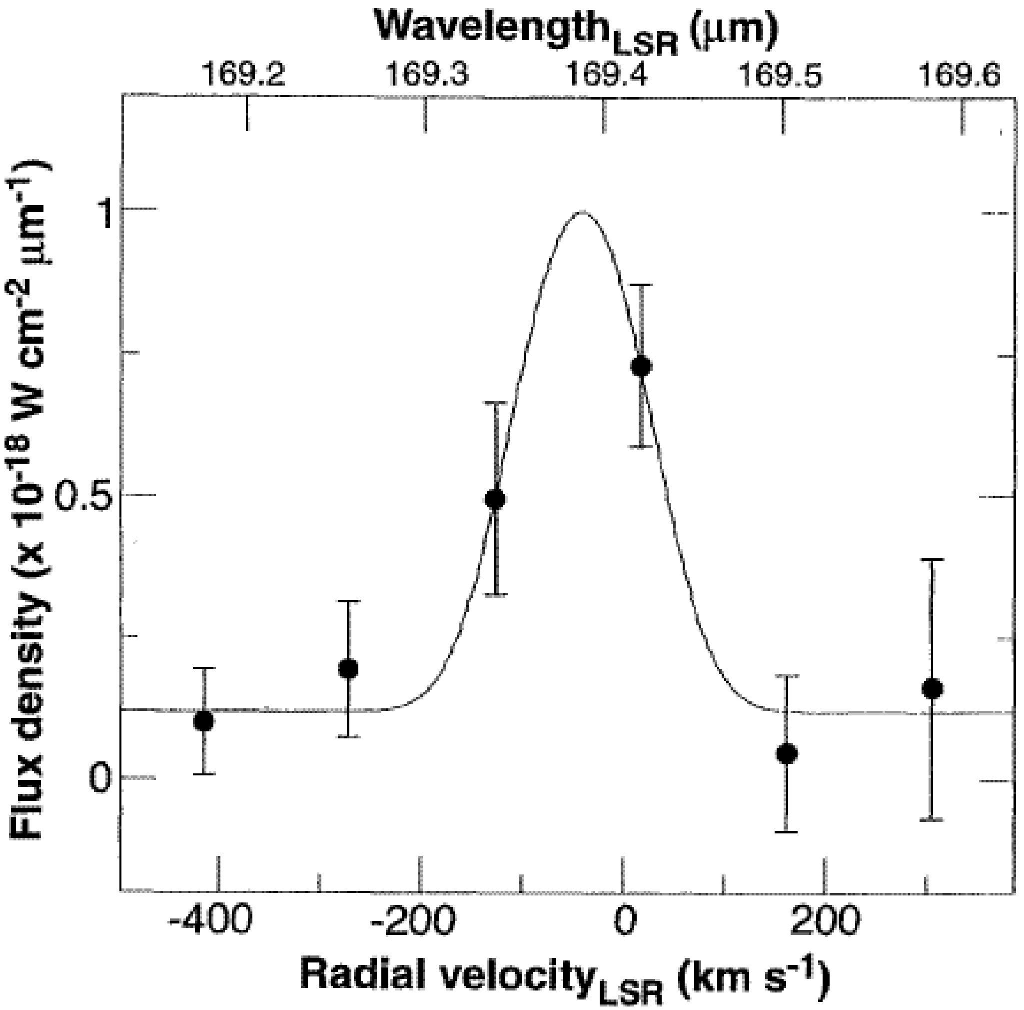
J. Talbot
Laser Action in Recombining Plasmas
M.Sc. thesis, University of Ottawa (1995)

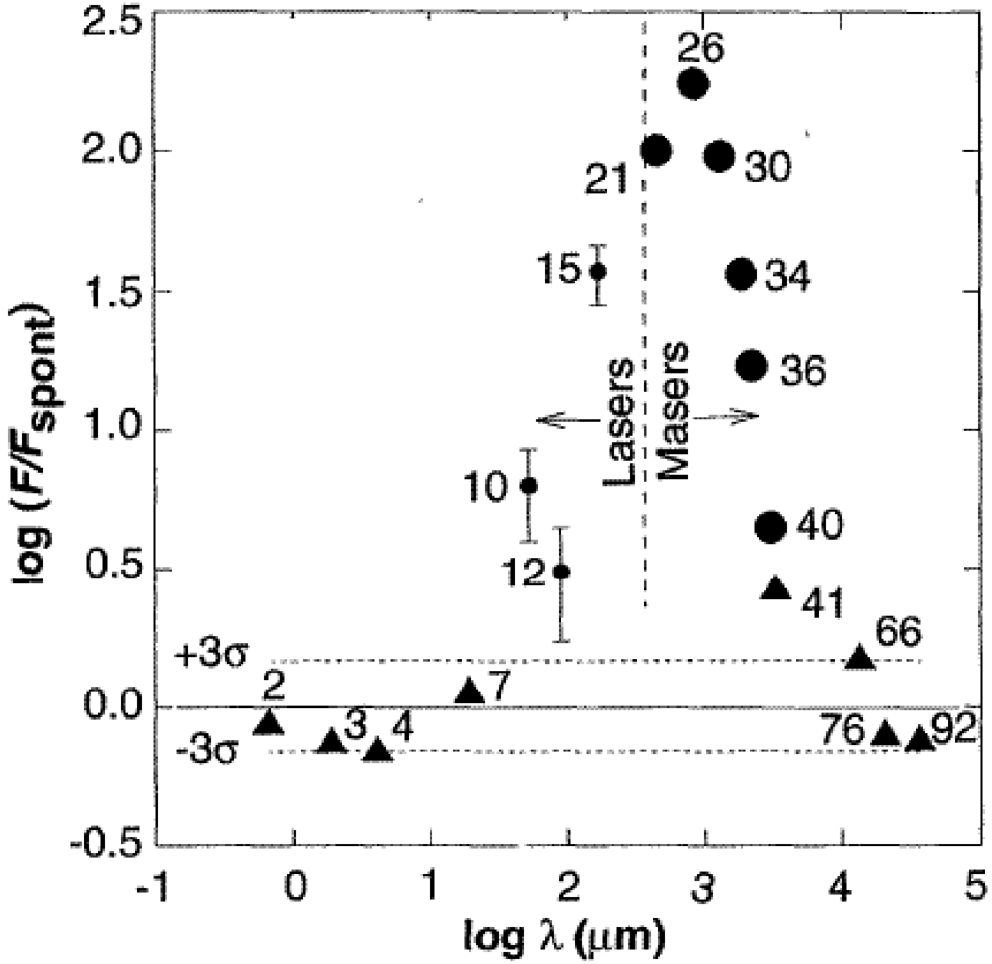


Hydrogen recombination lasers & masers in MWC 349A

Circumstellar disk surrounding the hot star.

Maser emissions occur in outer regions while lasers operate nearer to the central star.

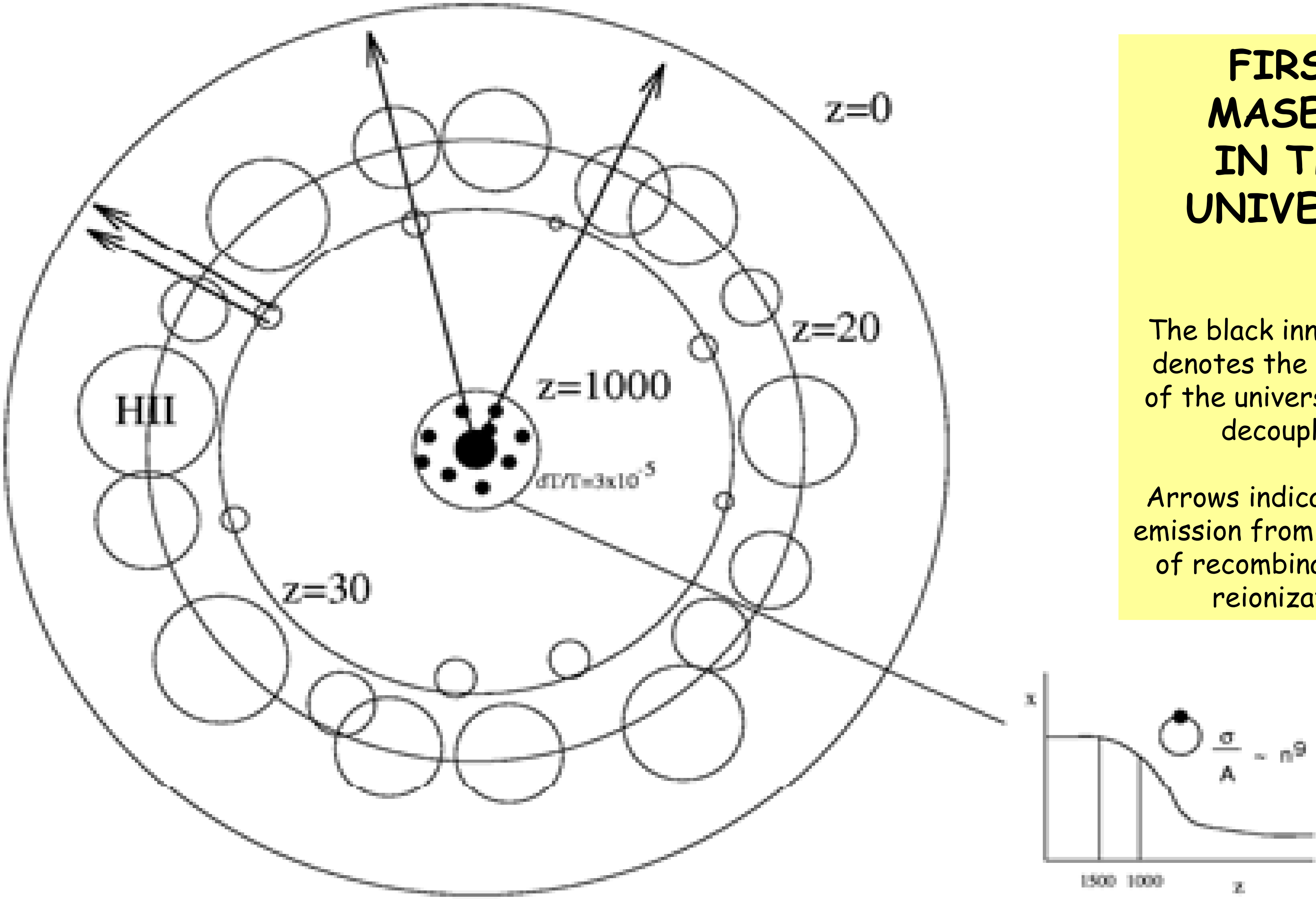




V. Strelnitski; M.R. Haas; H.A. Smith; E.F. Erickson; S.W. Colgan; D.J. Hollenbach

Far-Infrared Hydrogen Lasers in the Peculiar Star MWC 349A

Science **272**, 1459 (1996)

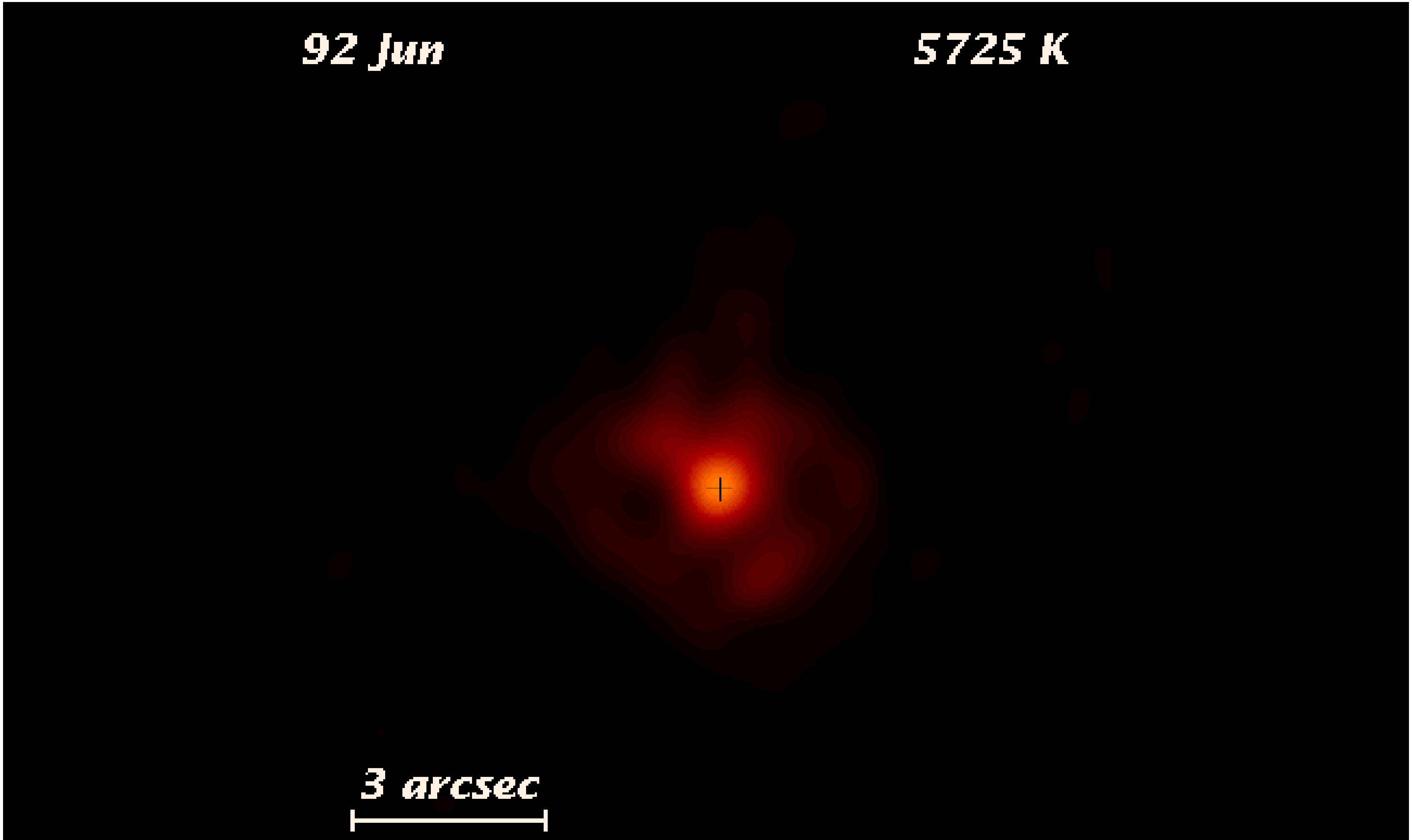


FIRST MASERS IN THE UNIVERSE

The black inner region denotes the evolution of the universe before decoupling.

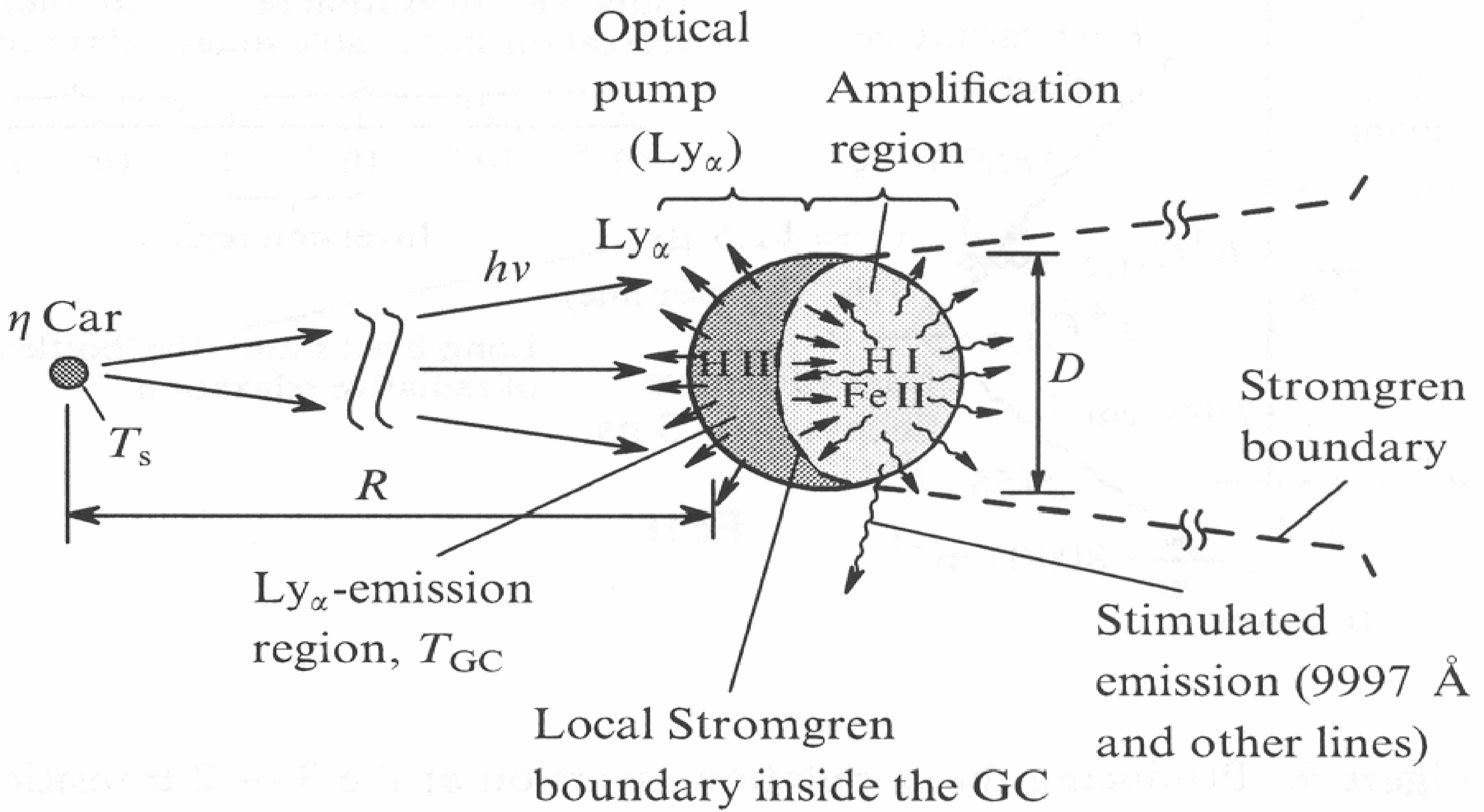
Arrows indicate maser emission from the epoch of recombination and reionization.

M. Spaans & C.A. Norman
Hydrogen Recombination Line Masers at the Epochs of Recombination and Reionization
ApJ **488**, 27 (1997)



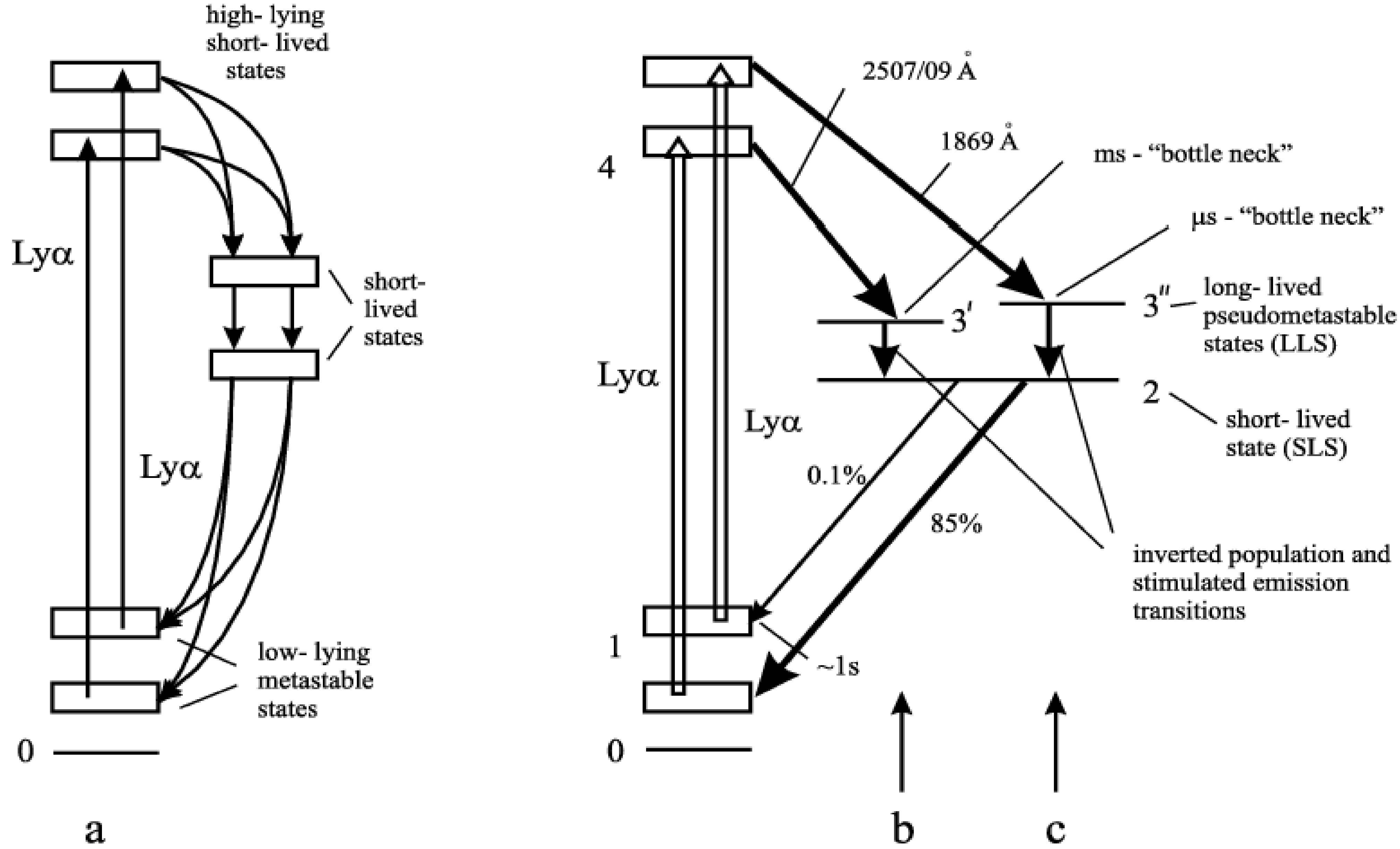
Eta Carinae

5.5 year cyclic variation at 6 cm (Stephen White, *ANTF*)

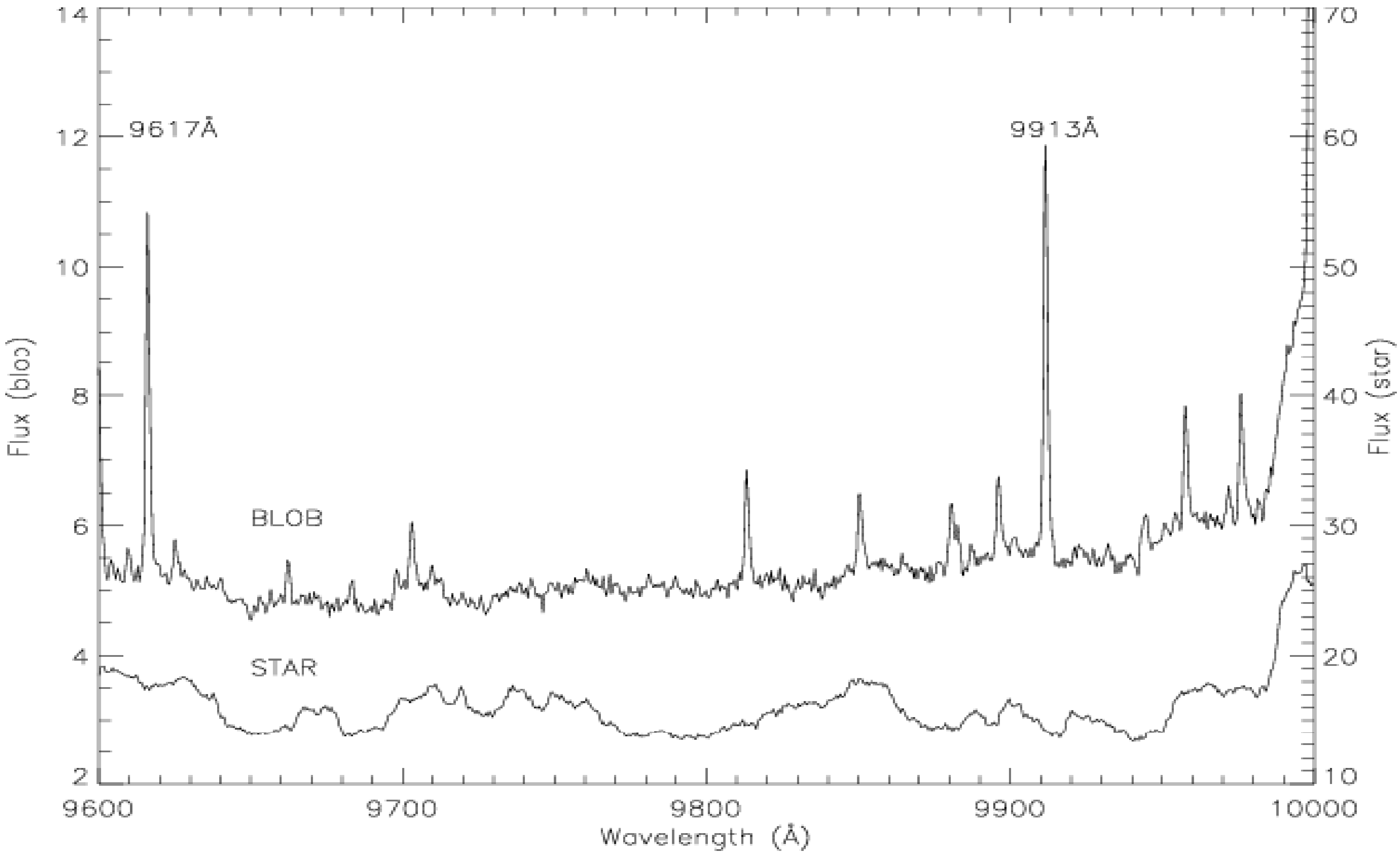


Model of a compact gas condensation near η Car with its Strömgren boundary between photoionized (H II) and neutral (H I) regions

S. Johansson & V. S. Letokhov
Laser Action in a Gas Condensation in the Vicinity of a Hot Star
JETP Lett. **75**, 495 (2002) = Pis'ma Zh.Eksp.Teor.Fiz. **75**, 591 (2002)



S. Johansson & V.S. Letokhov
Astrophysical lasers operating in optical Fe II lines in stellar ejecta of Eta Carinae
A&A **428**, 497 (2004)

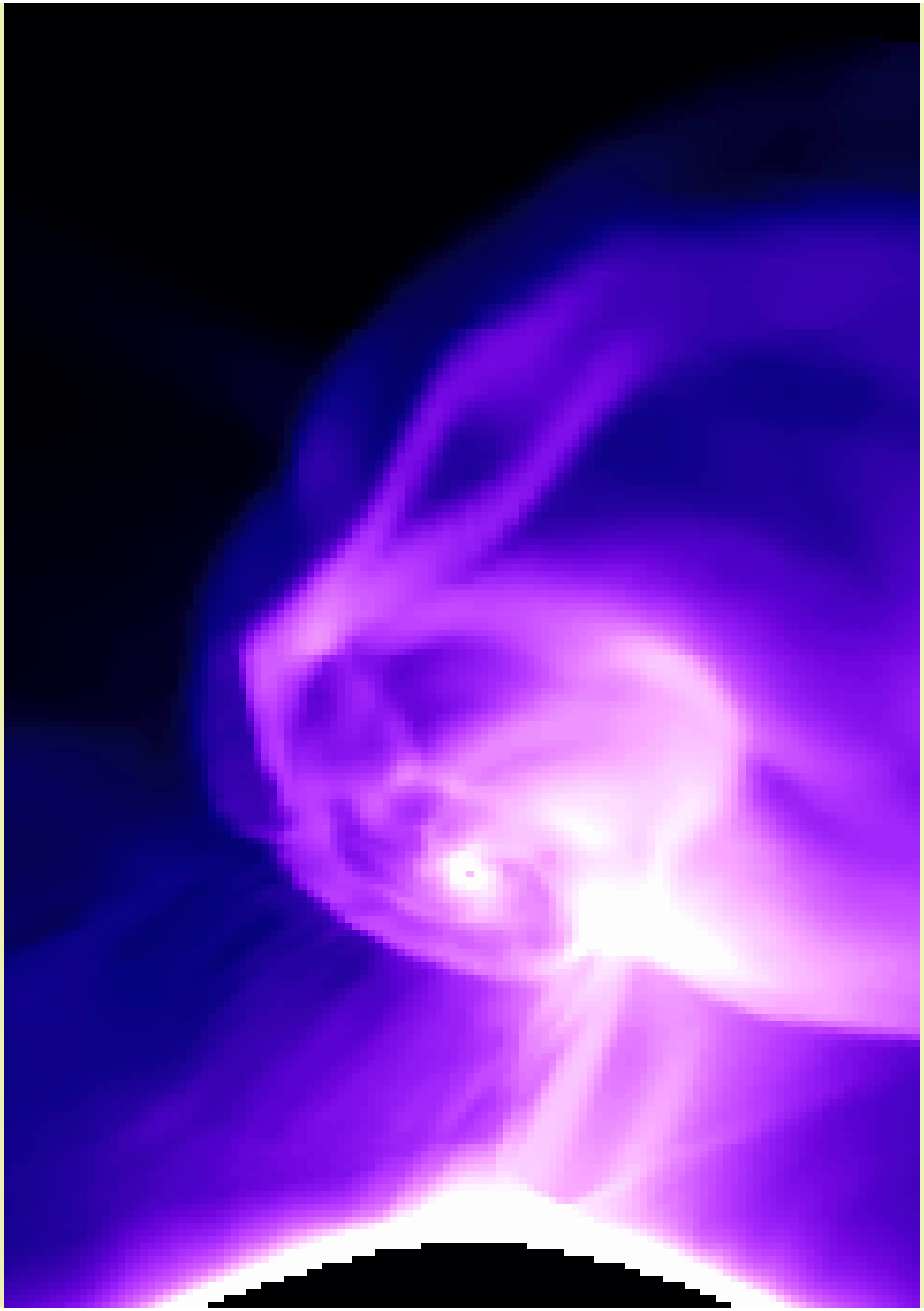


S. Johansson & V.S. Letokhov
Astrophysical lasers operating in optical Fe II lines in stellar ejecta of Eta Carinae
A&A **428**, 497 (2004)

John M. Blondin

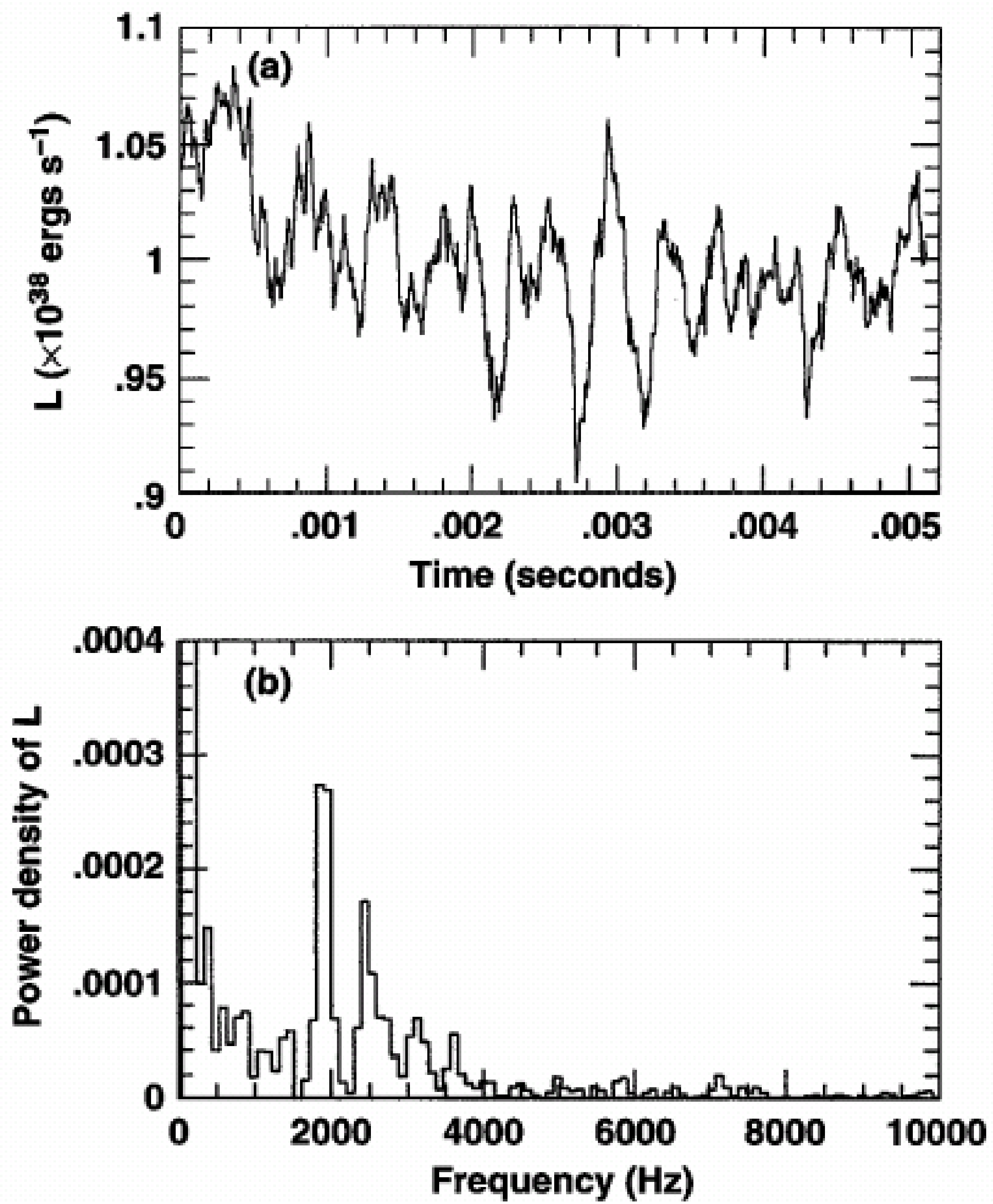
(North Carolina State University)

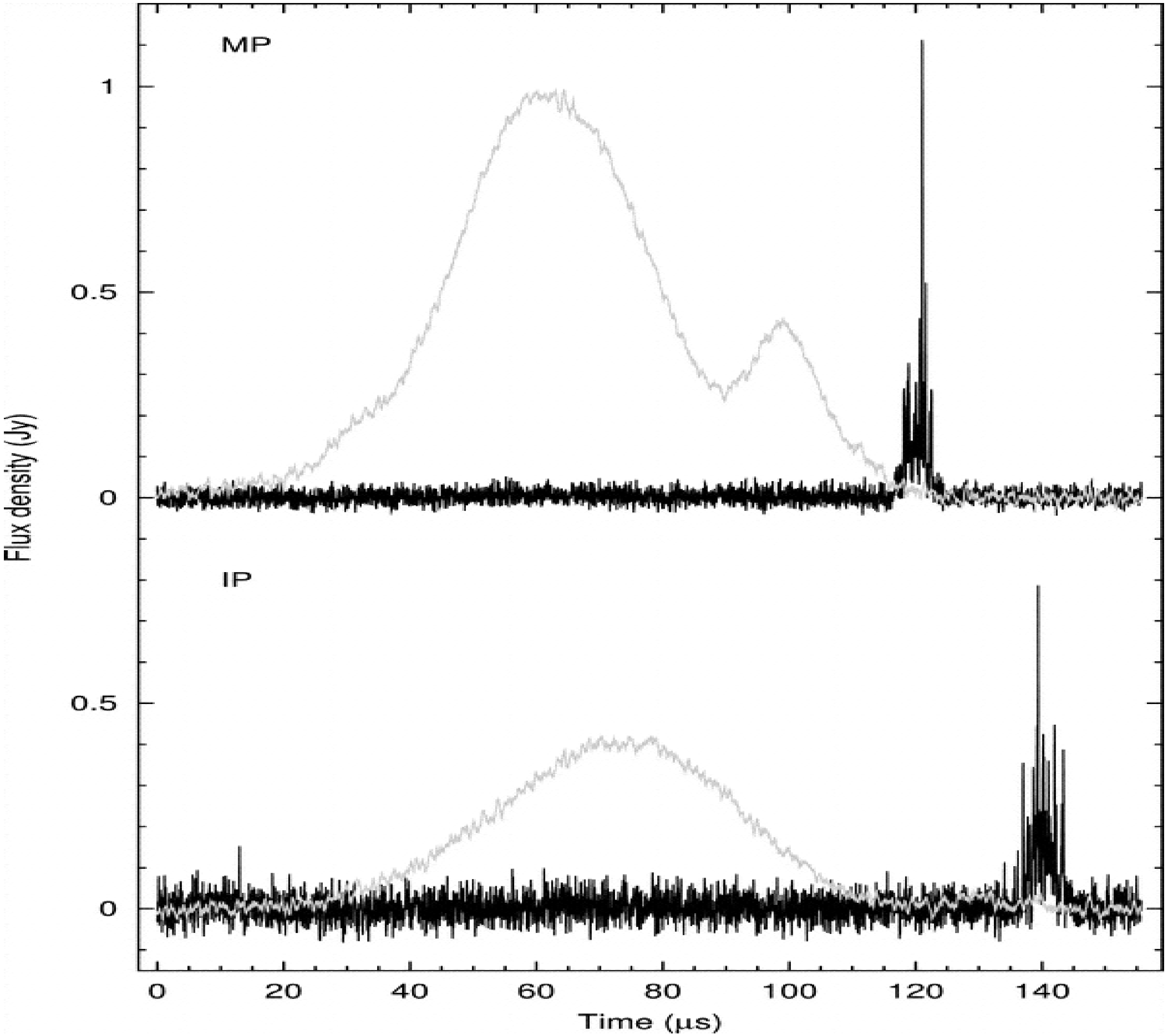
Hydrodynamics on supercomputers: Interacting Binary Stars



Photon Bubble Oscillations in Accretion

Klein, Arons, Jernigan & Hsu
ApJ **457**, L85





Longitudes of giant pulses compared to the average profile.
Main pulse (top);
Interpulse (bottom)

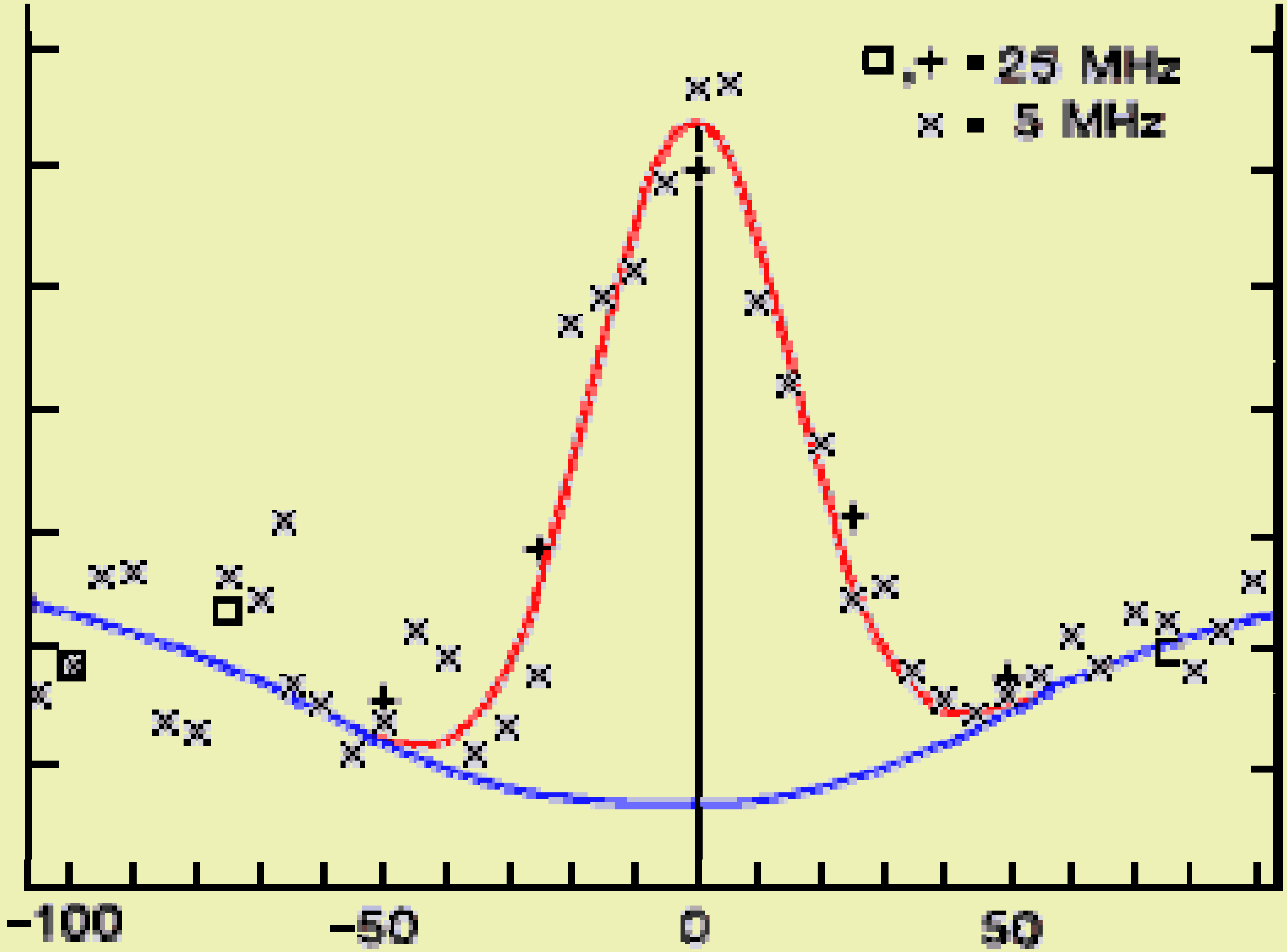
V.A. Soglasnov et al.
Giant Pulses from PSR B1937+21 with Widths ≤ 15 Nanoseconds and $T_b \geq 5\times10^{39}$ K, the Highest Brightness Temperature Observed in the Universe, ApJ **616**, 439 (2004)

Direct detection of astrophysical lasers?

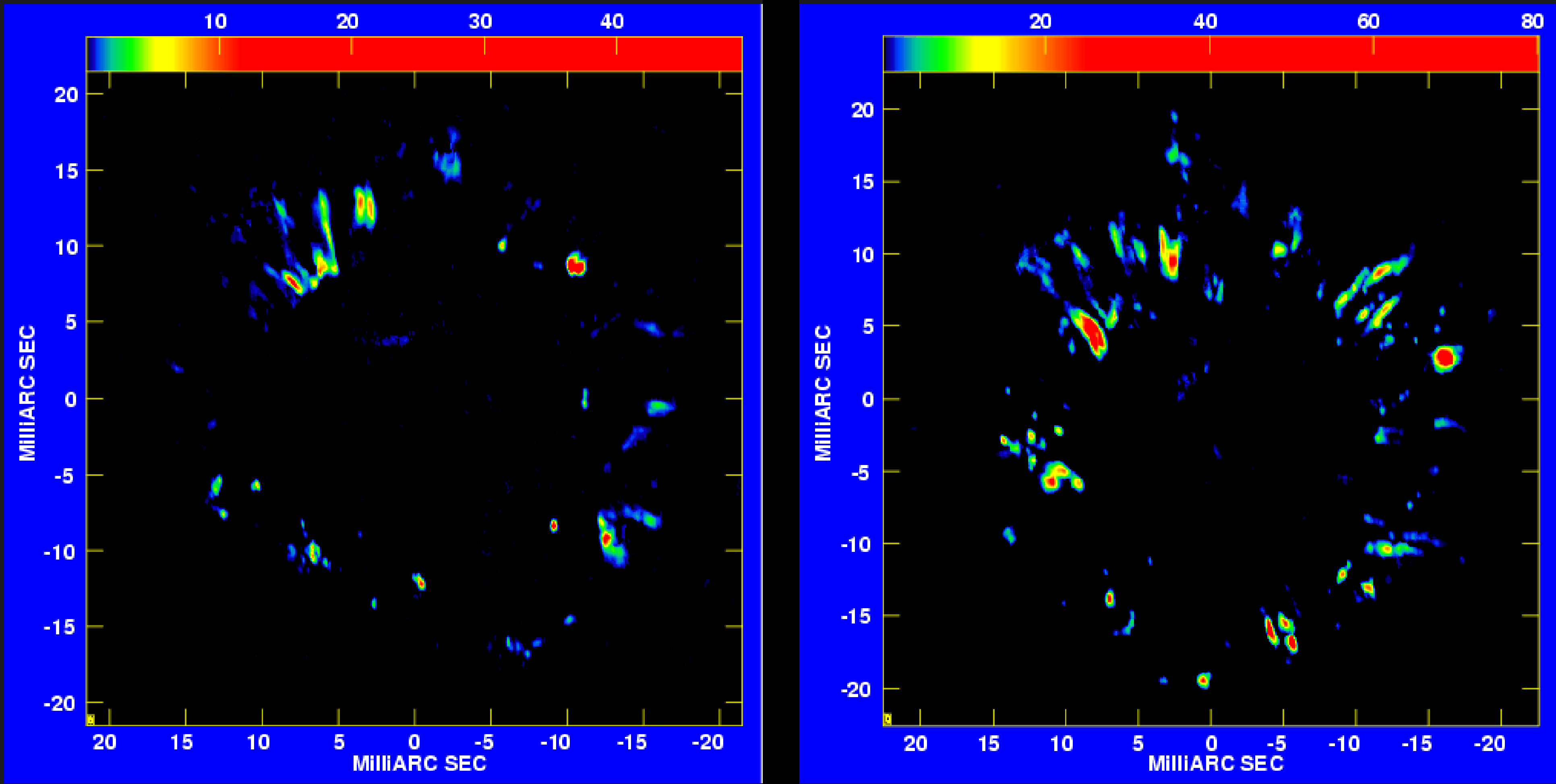
Spectral resolution $\lambda/\Delta\lambda \gtrsim 100{,}000{,}000$??

Flicker in location, frequency & intensity !!

CO_2 lasers on Mars

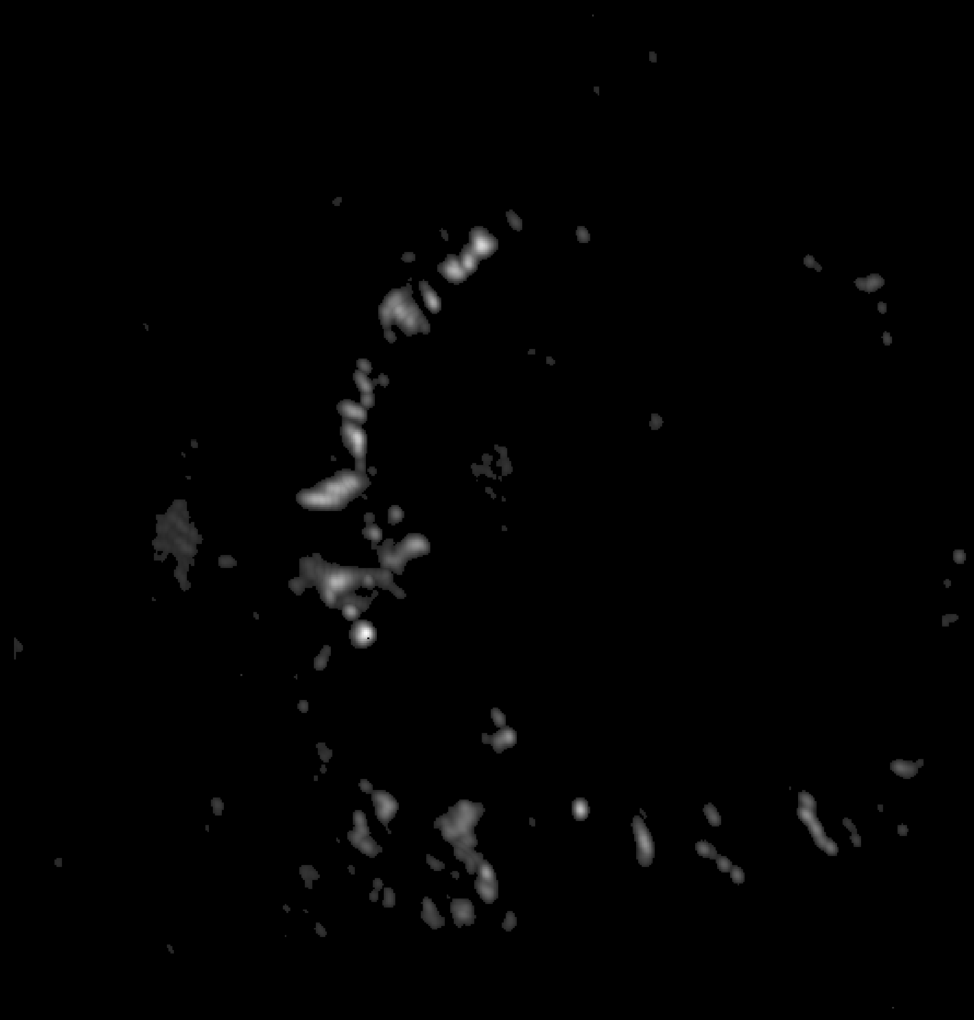


Spectra of Martian CO_2 emission line as a function of frequency difference from line center (in MHz). Blue profile is the total emergent intensity in the absence of laser emission. Red profile is Gaussian fit to laser emission line. Radiation is from a 1.7 arc second beam (half-power width) centered on Chryse Planitia. The emission peak is visible at resolutions R > 1,000,000. (Mumma et al., 1981)



VLBI maps at two epochs of SiO maser emission around TX Cam.
The color bar gives flux in Jy/beam.

J.Yi, R.S.Booth, J.E.Conway, P.J.Diamond:
SiO masers in TX Cam. Simultaneous VLBA observations of two 43 GHz masers at four epochs, A&A **432**, 531 (2005)



A Movie of a Star: Multiepoch Very Long Baseline Array Imaging of the SiO Masers toward the Mira Variable TX Cam [21 months; 43 GHz]

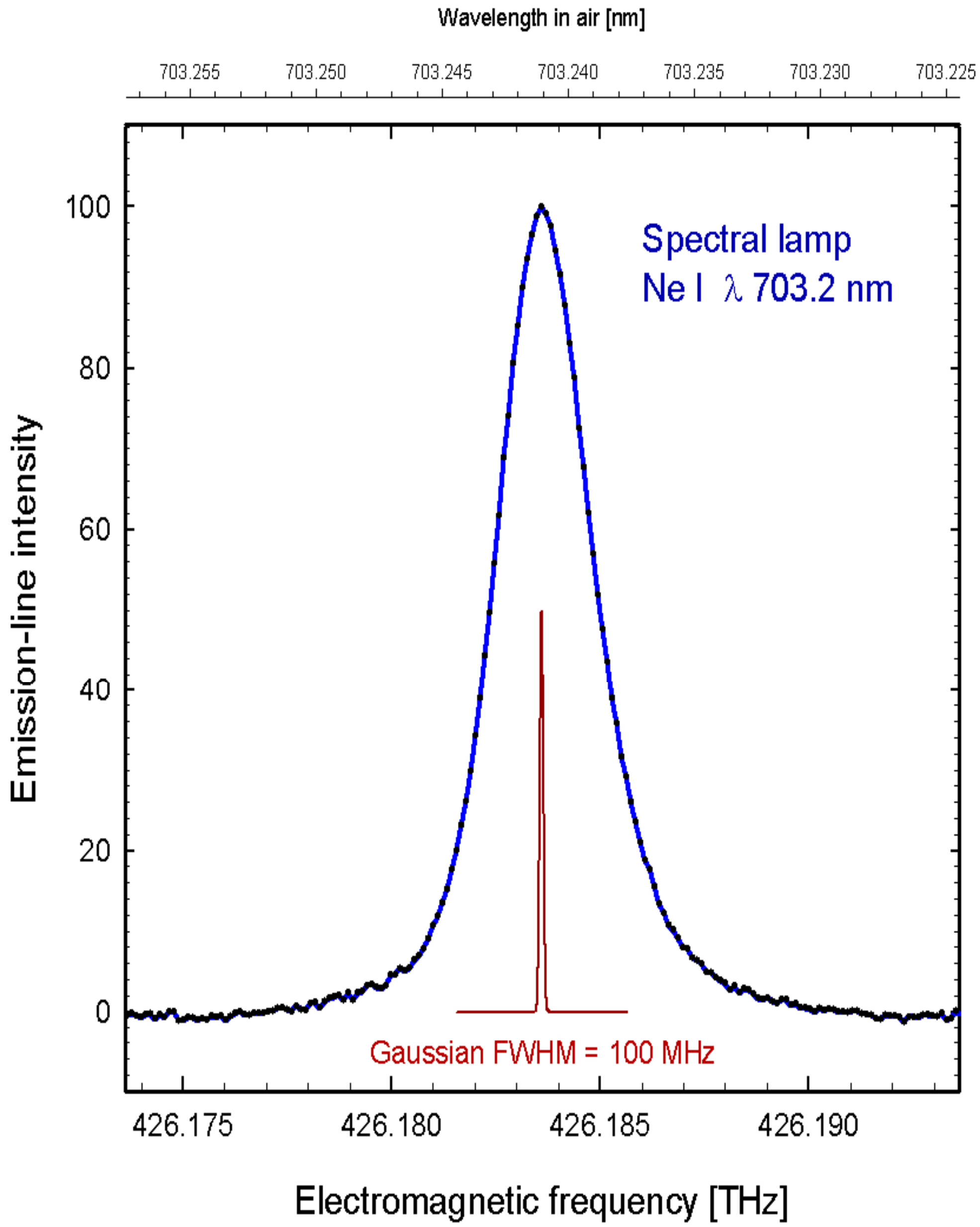
(P.Diamond & A.Kemball, Astrophys.J. **599**, 1372, 2003)

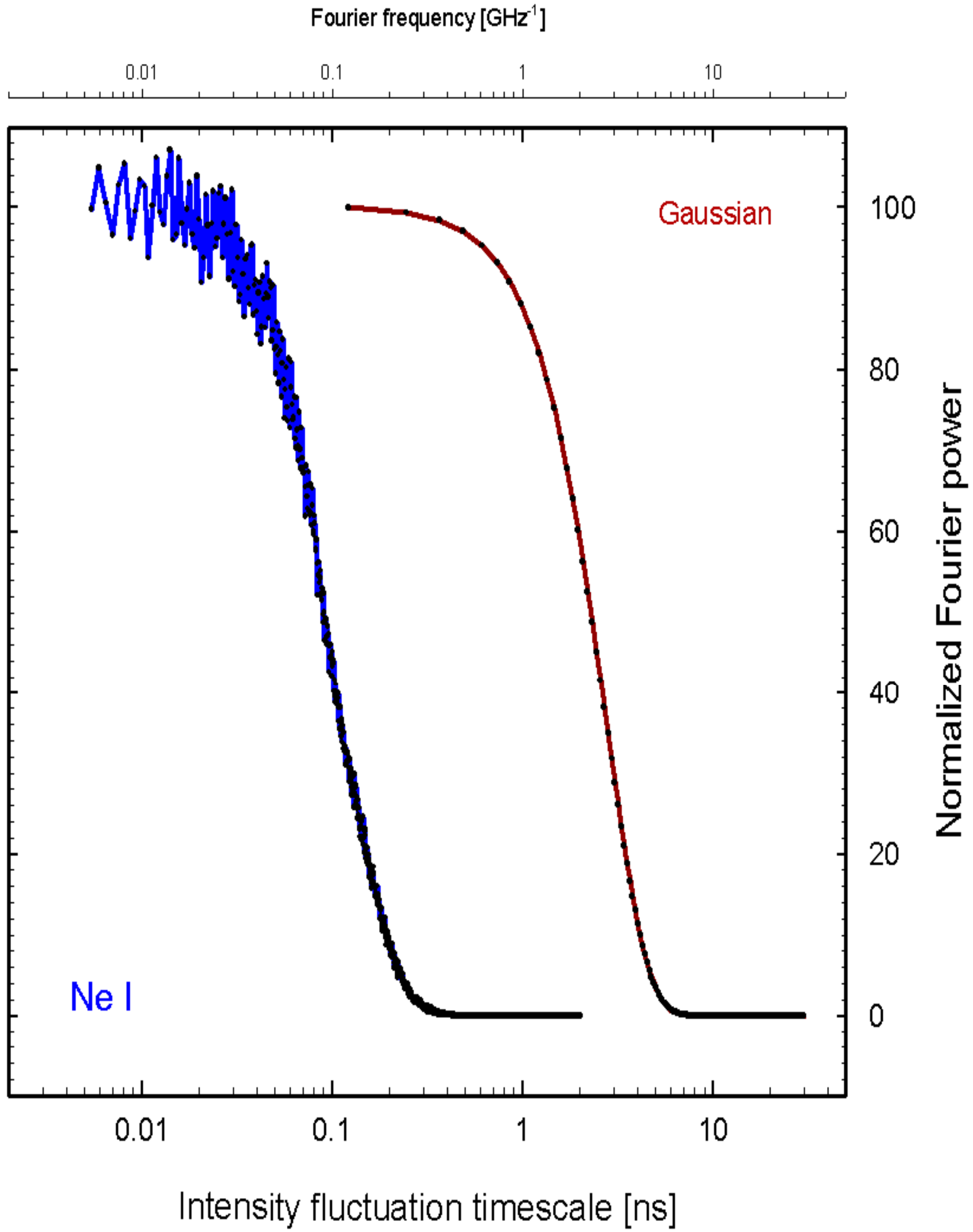
Spectral resolution = 100,000,000!

- To resolve narrow optical laser emission ($\Delta\nu \approx$ 10 MHz) requires spectral resolution $\lambda/\Delta\lambda \approx$ 100,000,000
- Achievable by photon-correlation ("self-beating") spectroscopy!
  Resolved at delay time $\Delta t \approx$ 100 ns
- Method assumes Gaussian (thermal) photon statistics

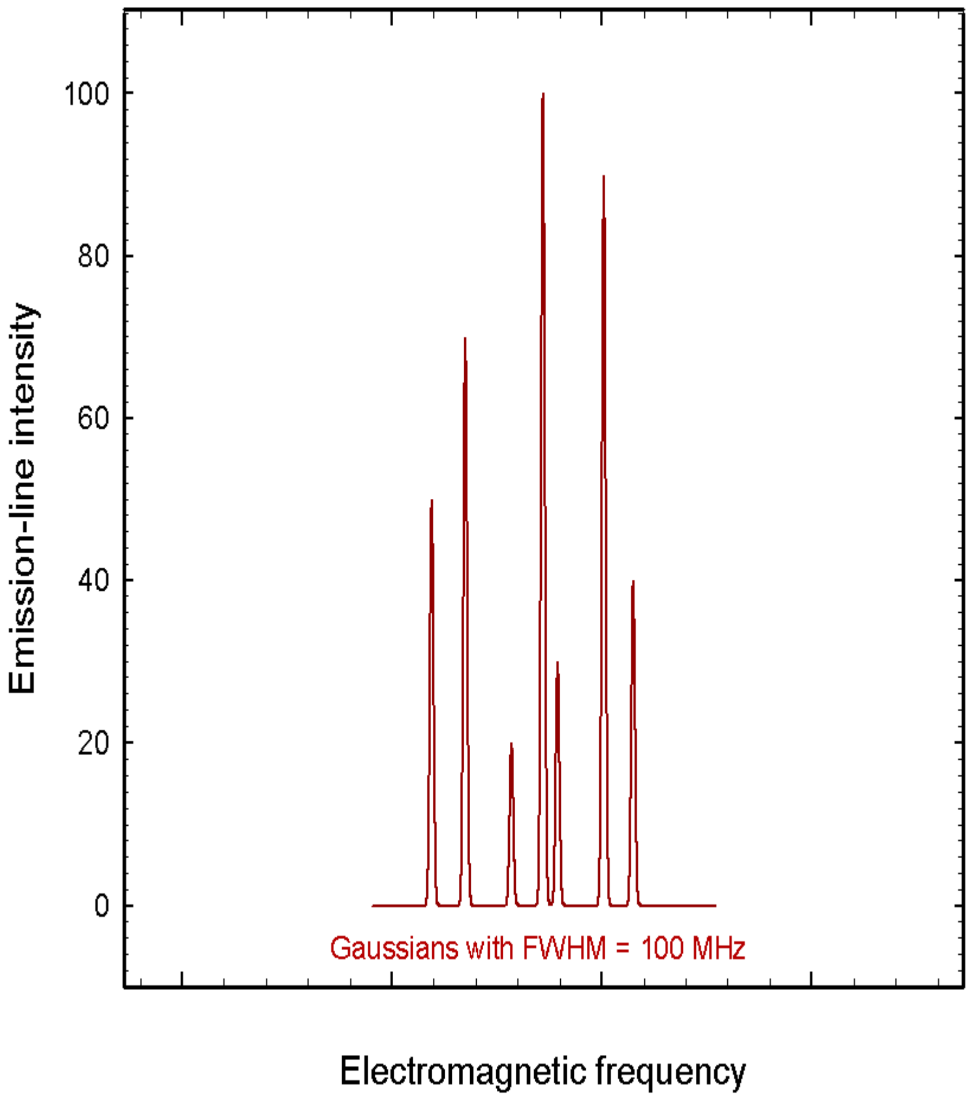
PHOTON CORRELATION SPECTROSCOPY: SPECTROMETER LENGTH AND EQUIVALENT LIGHT-TRAVEL-TIME REQUIREMENTS FOR DIFFERENT RESOLVING POWERS AT λ 600 nm

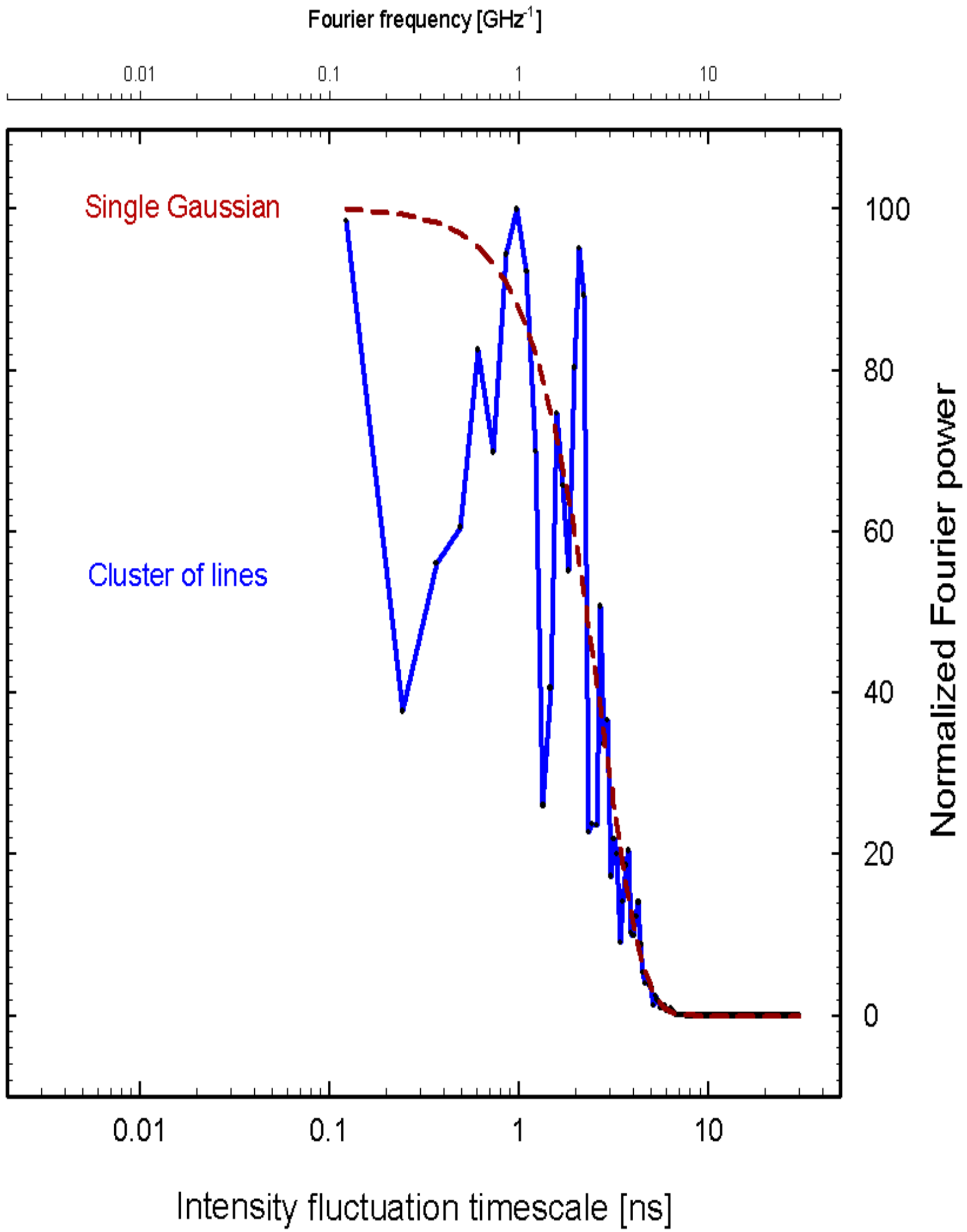
Spectral resolution R	Length	Time
100,000	6 cm	200 ps
1,000,000	60 cm	2 ns
10,000,000	6 m	20 ns
100,000,000	60 m	200 ns
1,000,000,000	600 m	2 μs



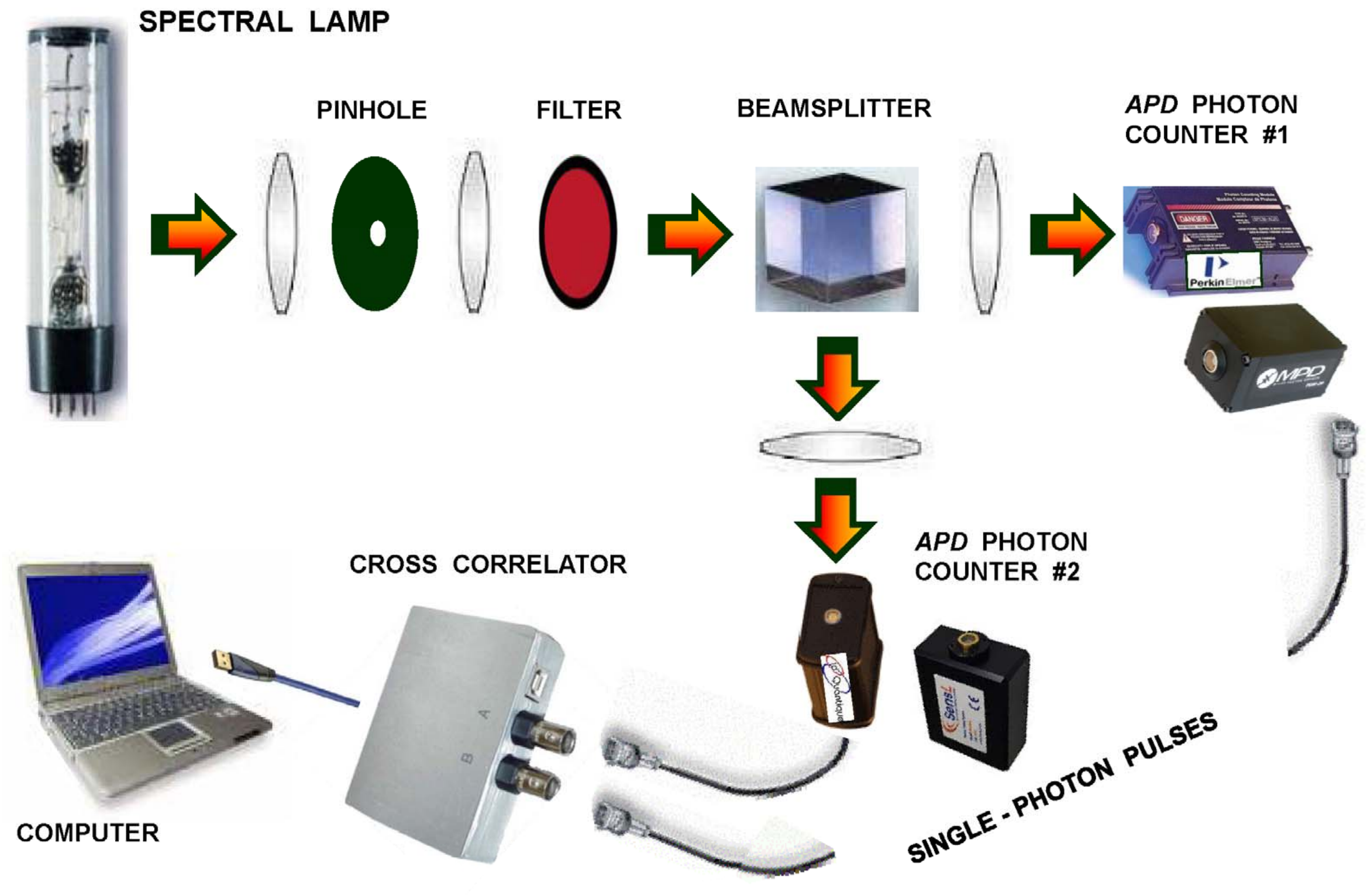


Narrow (4 pm = 40 mÅ) laboratory line profile & expected very narrow natural laser line (0.15 pm = 1.5 mÅ)



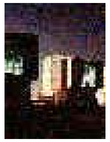
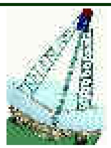
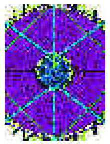


Multiple laser-line components generate similar fluctuation timescales as a single one.
Intensity correlations remain irrespective of flickering in instantaneous wavelength or intensity



Laboratory setup for photon-correlation spectroscopy under near-astrophysical conditions

Advantages of very large telescopes

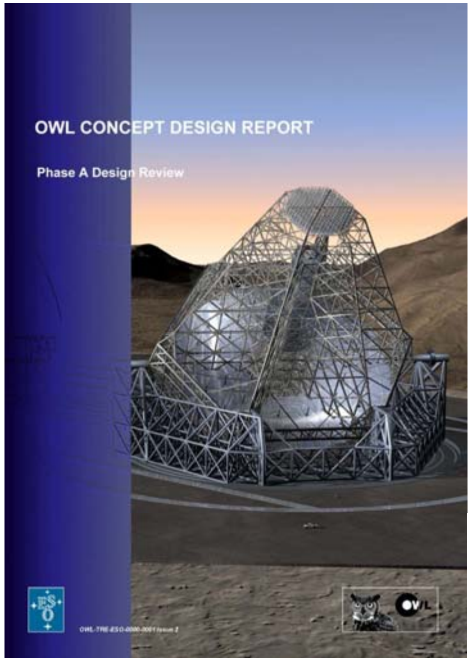
Telescope diameter	Intensity $\langle I \rangle$	Second-order correlation $\langle I^2 \rangle$	Fourth-order photon statistics $\langle I^4 \rangle$
 3.6 m	1	1	1
 8.2 m	5	27	720
 4 x 8.2 m	21	430	185,000
 50 m	193	37,000	1,385,000,000
 100 m	770	595,000	355,000,000,000

ESO Instrument Studies for 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 !



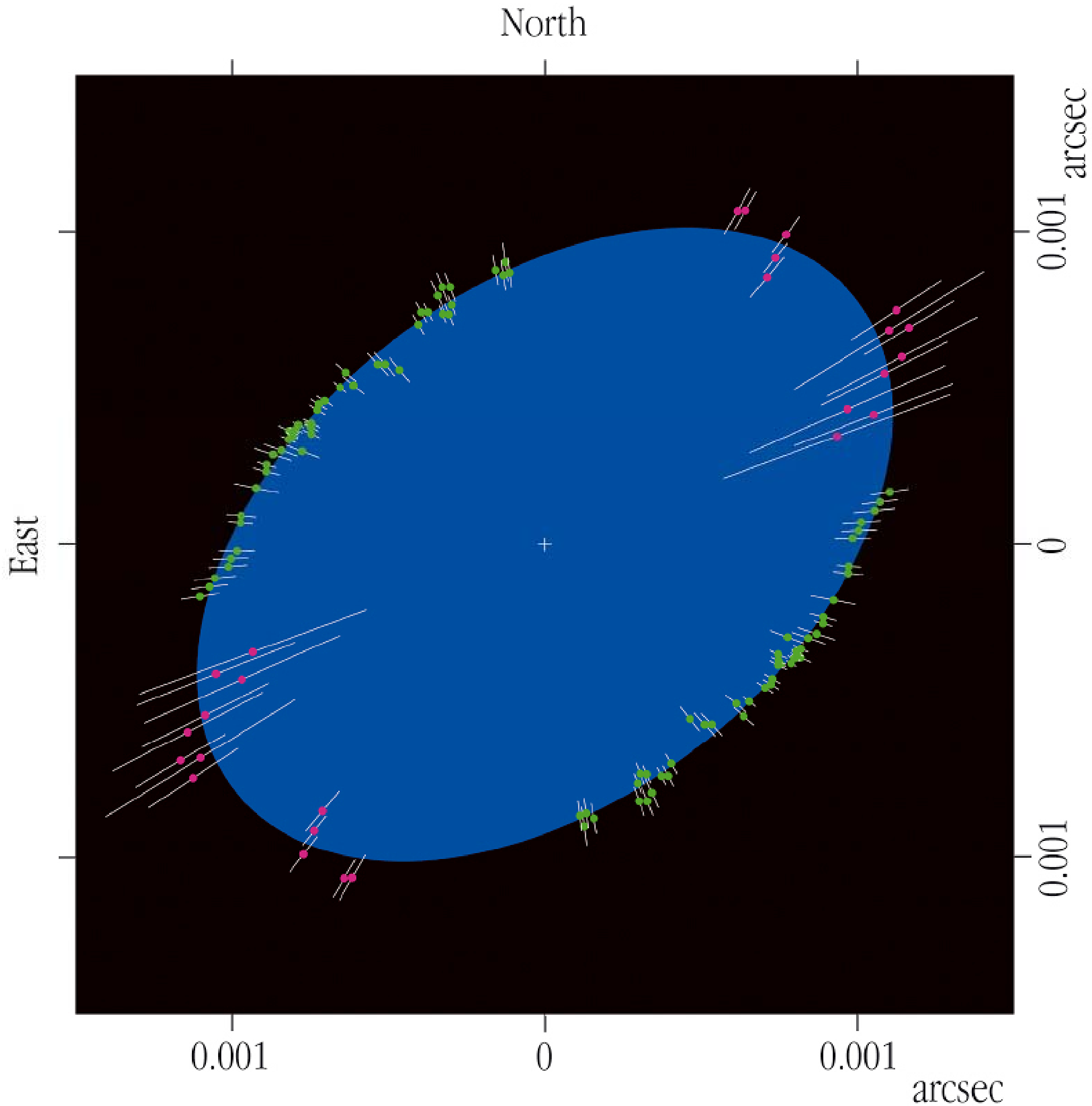
D. Dravins [1], C. Barbieri [2], V. Da Deppo [3], D. Faria [1], S. Fornasier [2], R. A. E. Fosbury [4], L. Lindegren [1], G. Naletto [3], R. Nilsson [1], T. Occhipinti [3], F. Tamburini [2], H. Uthas [1], L. Zampieri [5]

(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

LUND UNIVERSITY

Interferometry & aperture synthesis

ESO Paranal: Four auxiliary telescopes of the VLTI



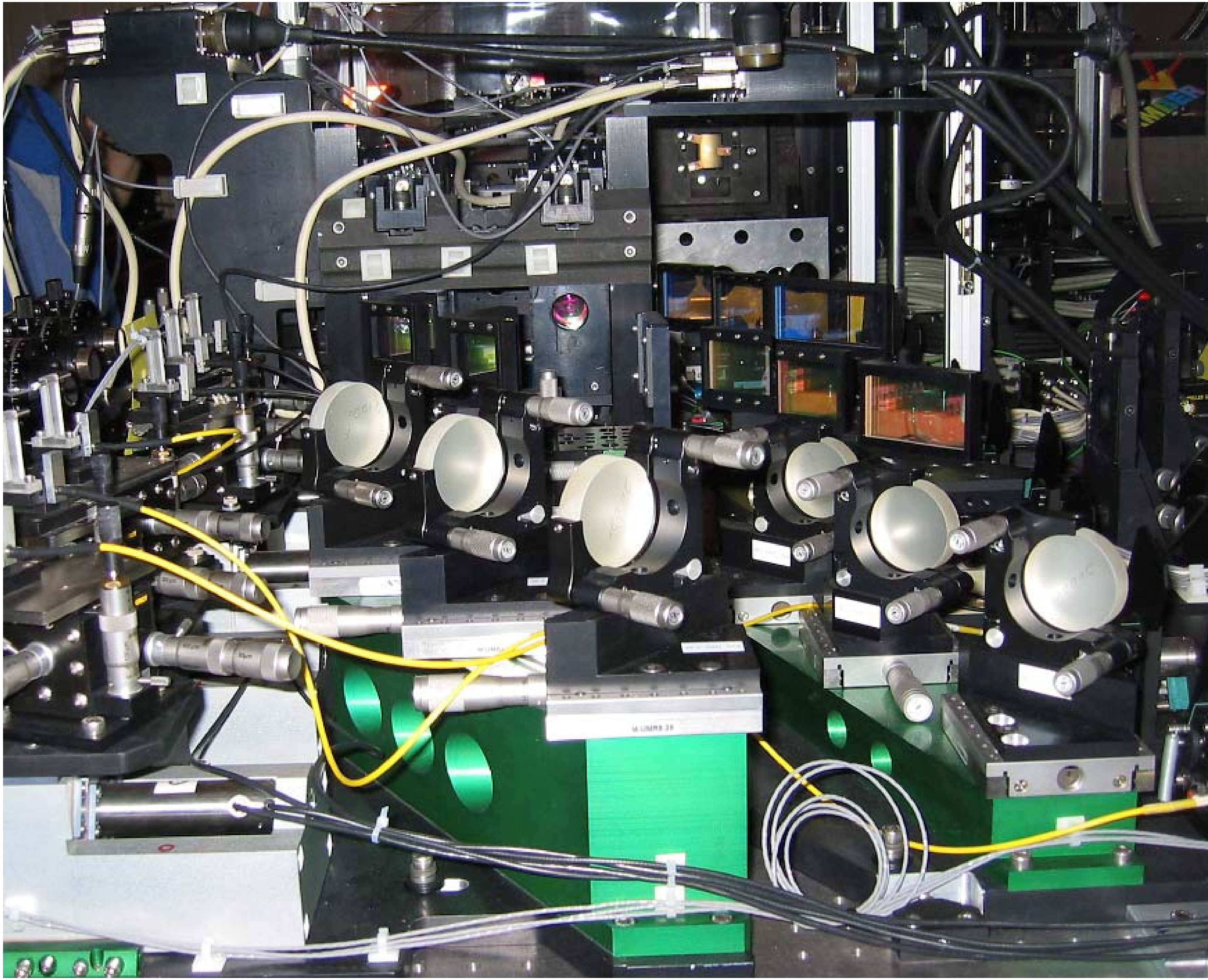
SHAPE OF ACHERNAR

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

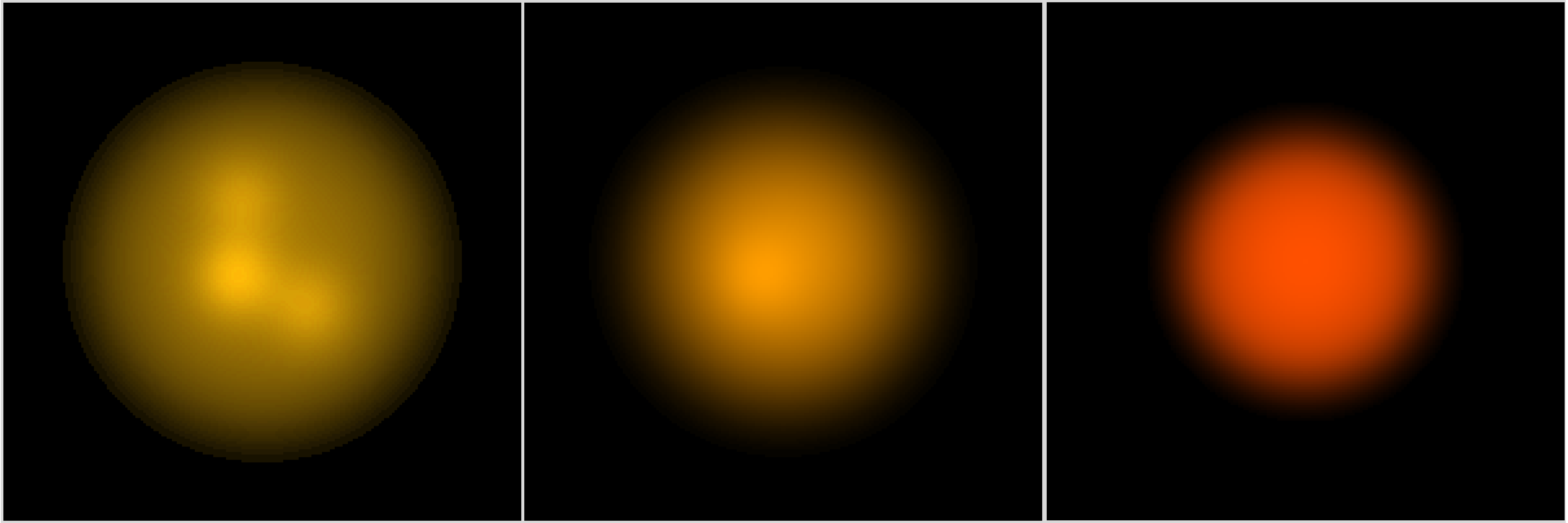
Axis ratio = 1.56, the most flattened star seen so far.

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.



Details of *AMBER (Astronomical Multiple Beam Recombiner)* instrument for VLTI



Surface imaging of Betelgeuse with COAST and the WHT
Left: 700 nm, center: 905 nm; right: 1290 nm

Two images were reconstructed using data from COAST, and the third from an aperture-masking experiment at the 4.2 m William Herschel Telescope on La Palma. The resolution of all images is 20-30 milliarcseconds, and each image shows an area 0.1 arcsecond square.

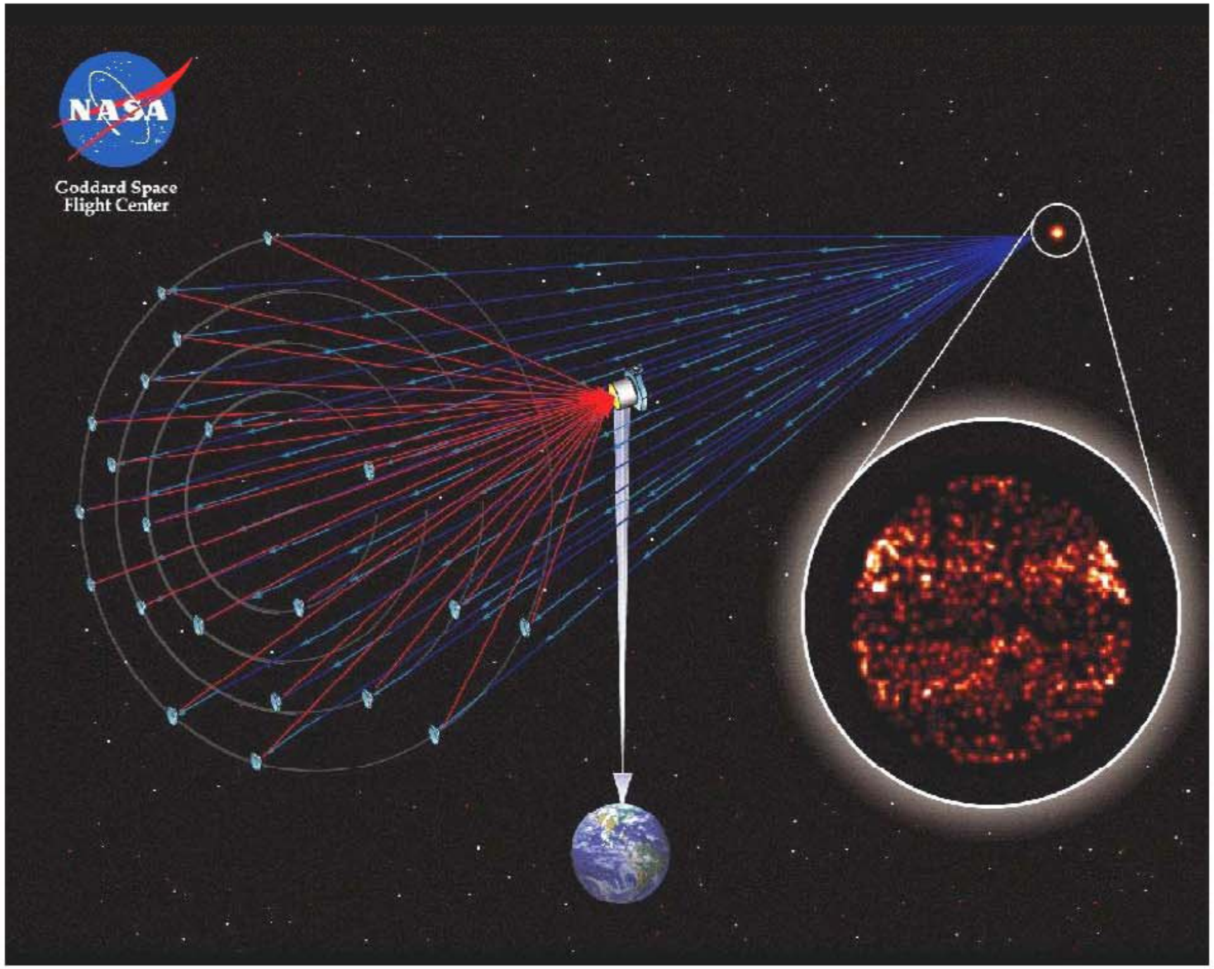
The (nearly simultaneous) images are strikingly different. Three bright features ("hotspots") are visible at 700 nm, but only one is discernible at 905 nm, and at 1290 nm the star presents a featureless disk. The disk is also smaller at 1290 nm, and its intensity falls off more sharply towards the edge. (COAST/ Cavendish optical interferometry)

Highest spatial resolution in astronomy?


Luciola* Hypertelescope
A.Labeyrie et al. – ESA Cosmic Vision 2015-2025 proposal (2007)
*Luciola = genus of fireflies

The Stellar Imager (*SI*) "Vision Mission":

Imaging the UV/Optical Universe with Sub-milliarcsecond Resolution

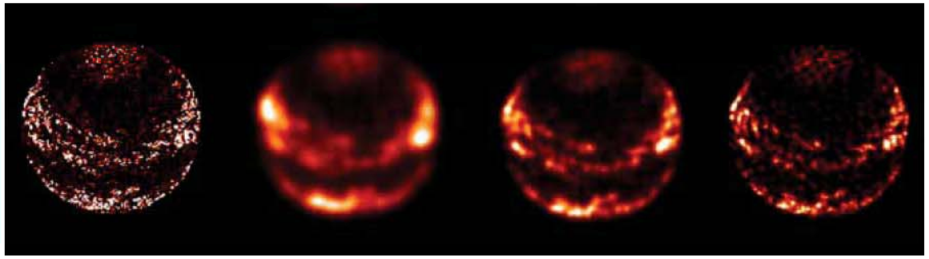


K. G. Carpenter (NASA/GSFC), C. J. Schrijver (LMATC), M. Karovska (SAO)
and the SI Mission Concept Development Team

What Will Stellar Imager See?

Solar-type star at *4 pc* in *CIV line*

Model *SIsim* images

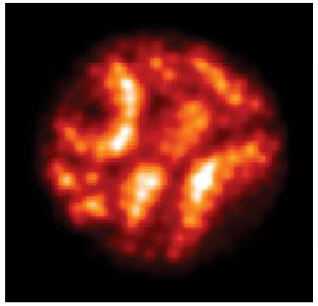


Baseline: 125m 250m 500 m

Evolved giant star at *2 Kpc* in *Mg H&K line*

Model

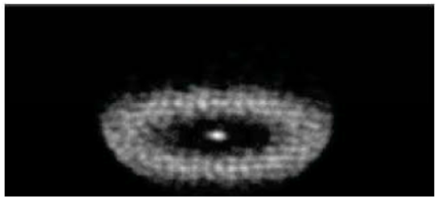
SIsim image (2mas dia)



Baseline: 500 m

SI imaging of planet forming environments: magnetosphere-disk interaction region

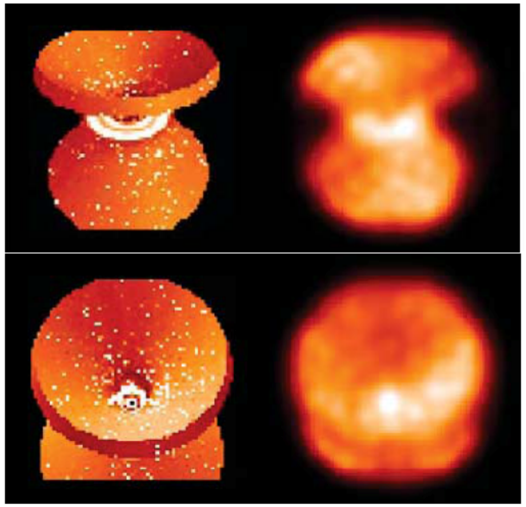
0.1 mas



SI simulation in
Ly α–fluoresced H2 lines

Baseline: 500 m

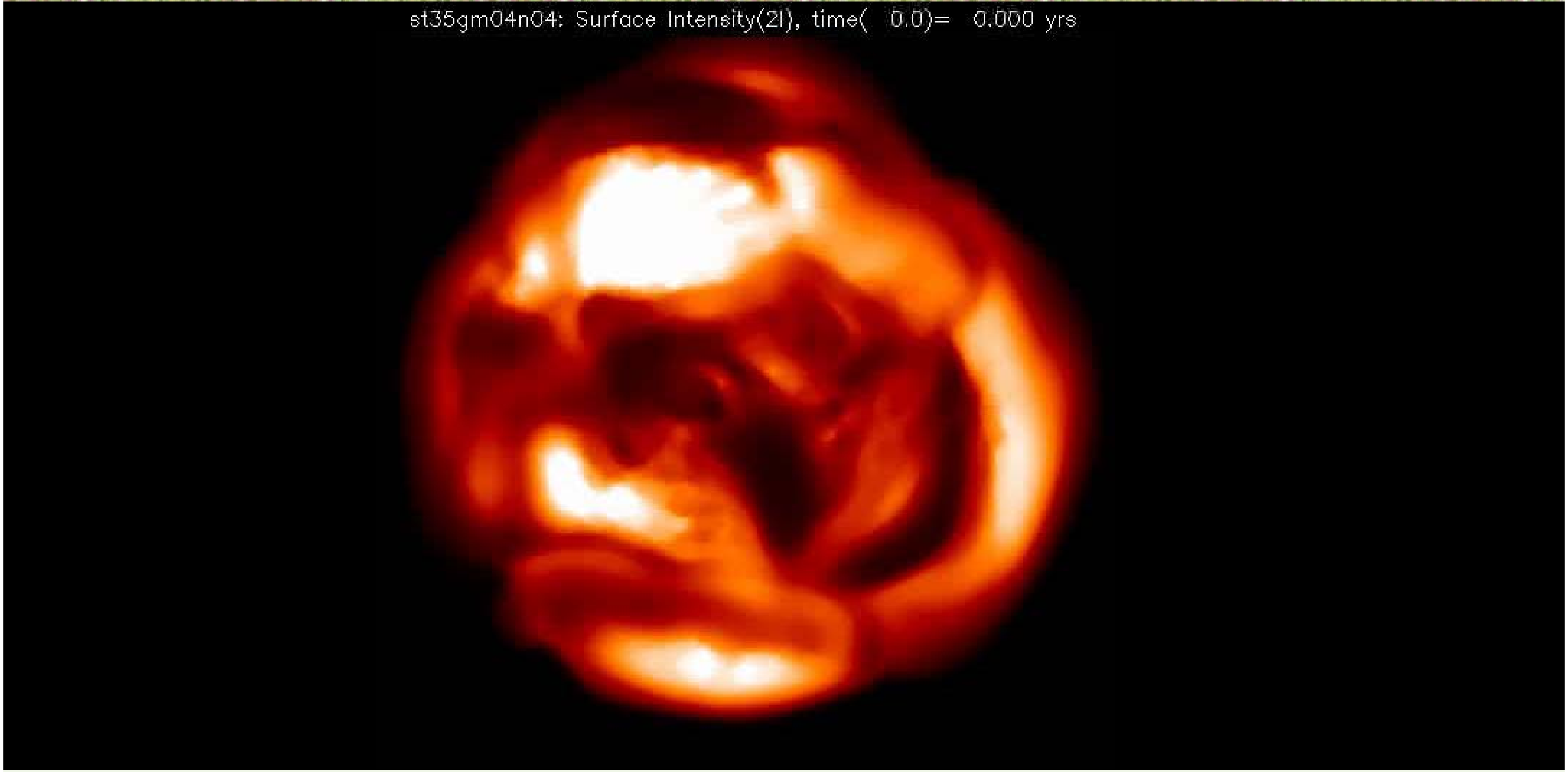
SI imaging of nearby AGN will differentiate between possible BELR geometries & inclinations



0.1 mas

model *SI* simulations in *CIV line*
(500 m baseline)

COOL SUPERGIANT SIMULATION



Bernd Freytag (Uppsala)

TOWARDS A DIFFRACTION-LIMITED SQUARE-KILOMETER OPTICAL TELESCOPE

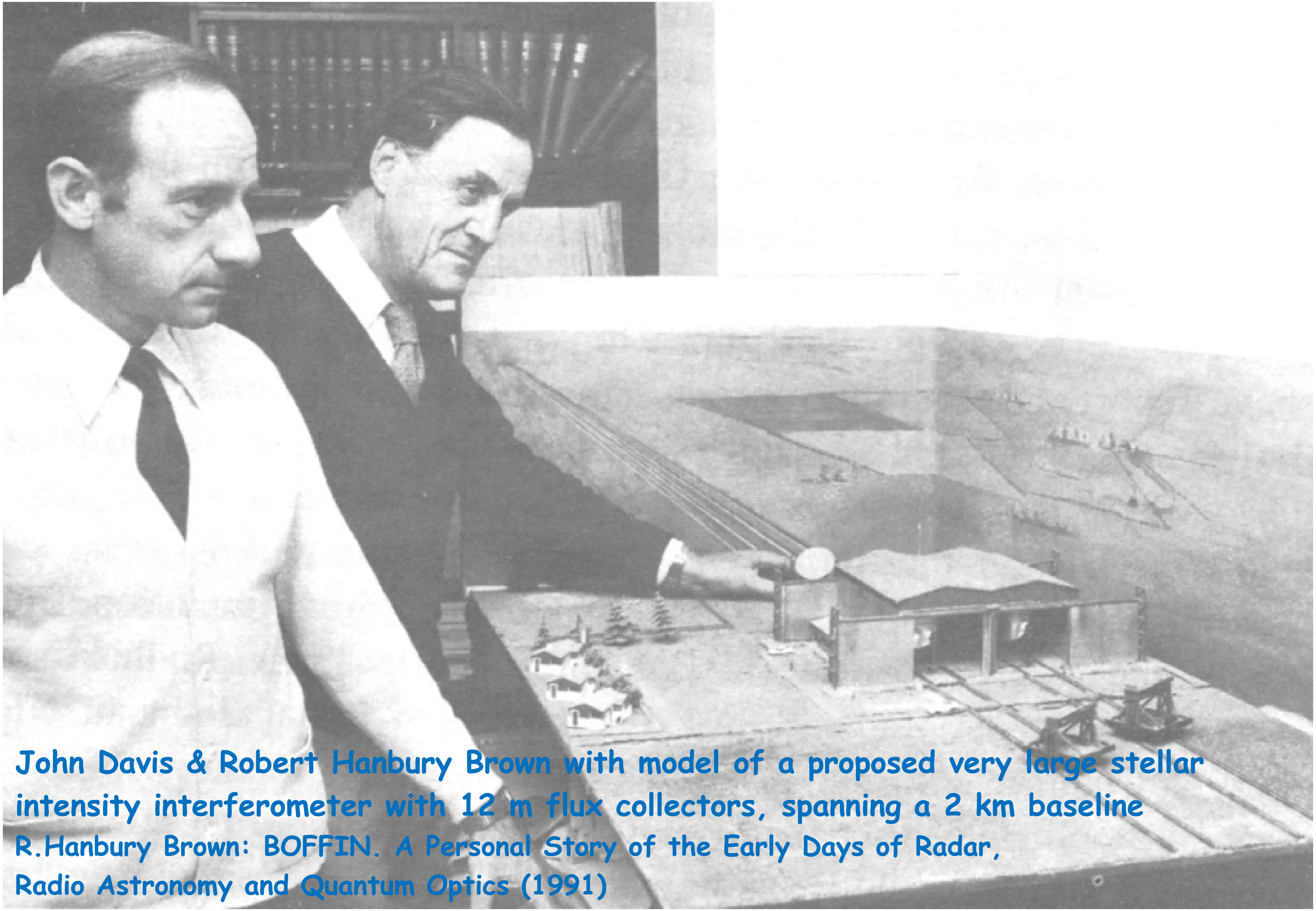
DIGITAL REVIVAL OF INTENSITY INTERFEROMETRY

Intensity interferometry

Pro: Time resolution of 1 ns, say, implies 30 cm light travel time; no need for any more accurate optics nor atmosphere.

Short wavelengths no problem; hot sources observable

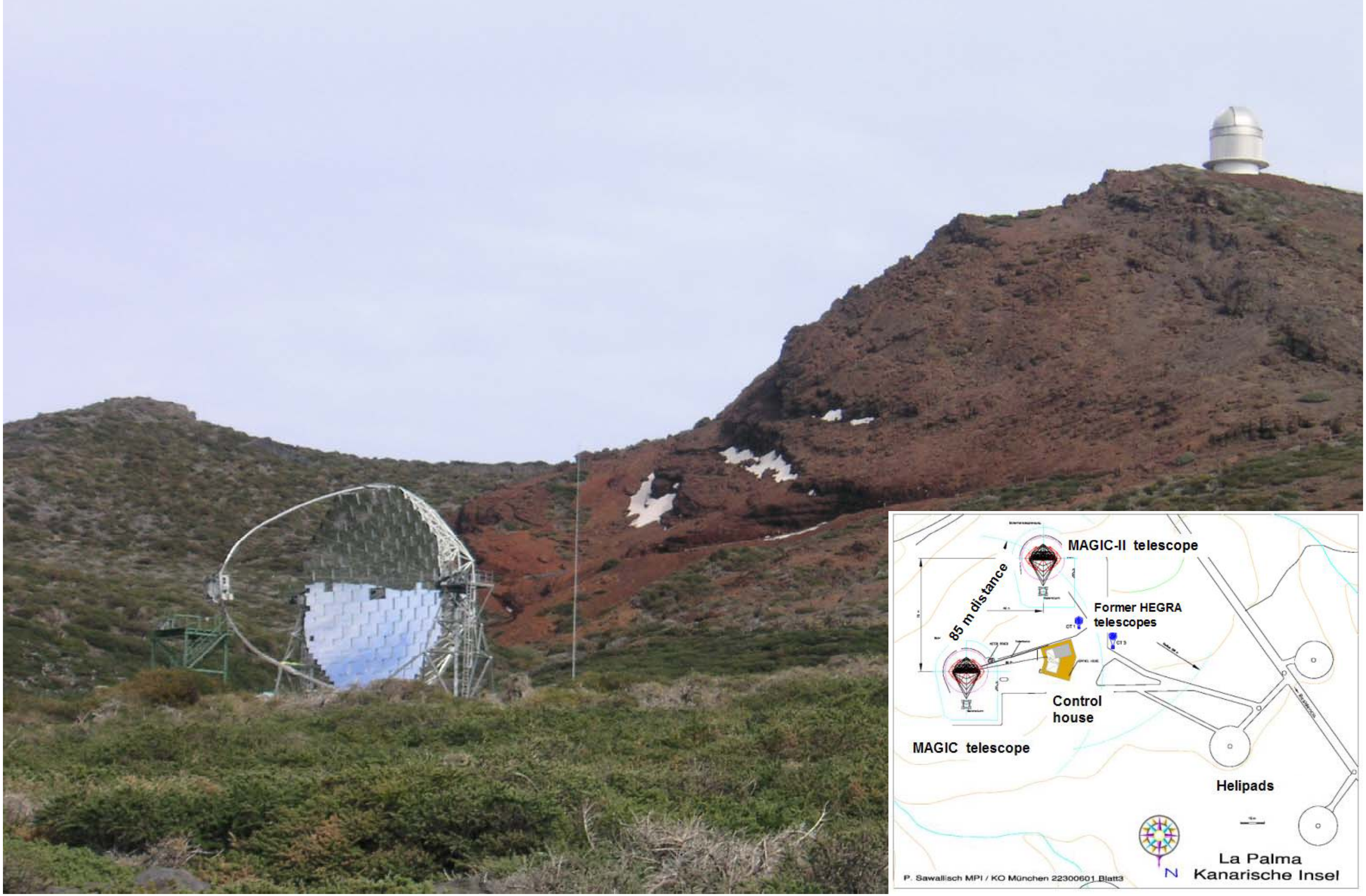
Con: Signal comes from two-photon correlations, increases as signal squared; requires large flux collectors



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)

MAGIC I, Roque de los Muchachos, La Palma

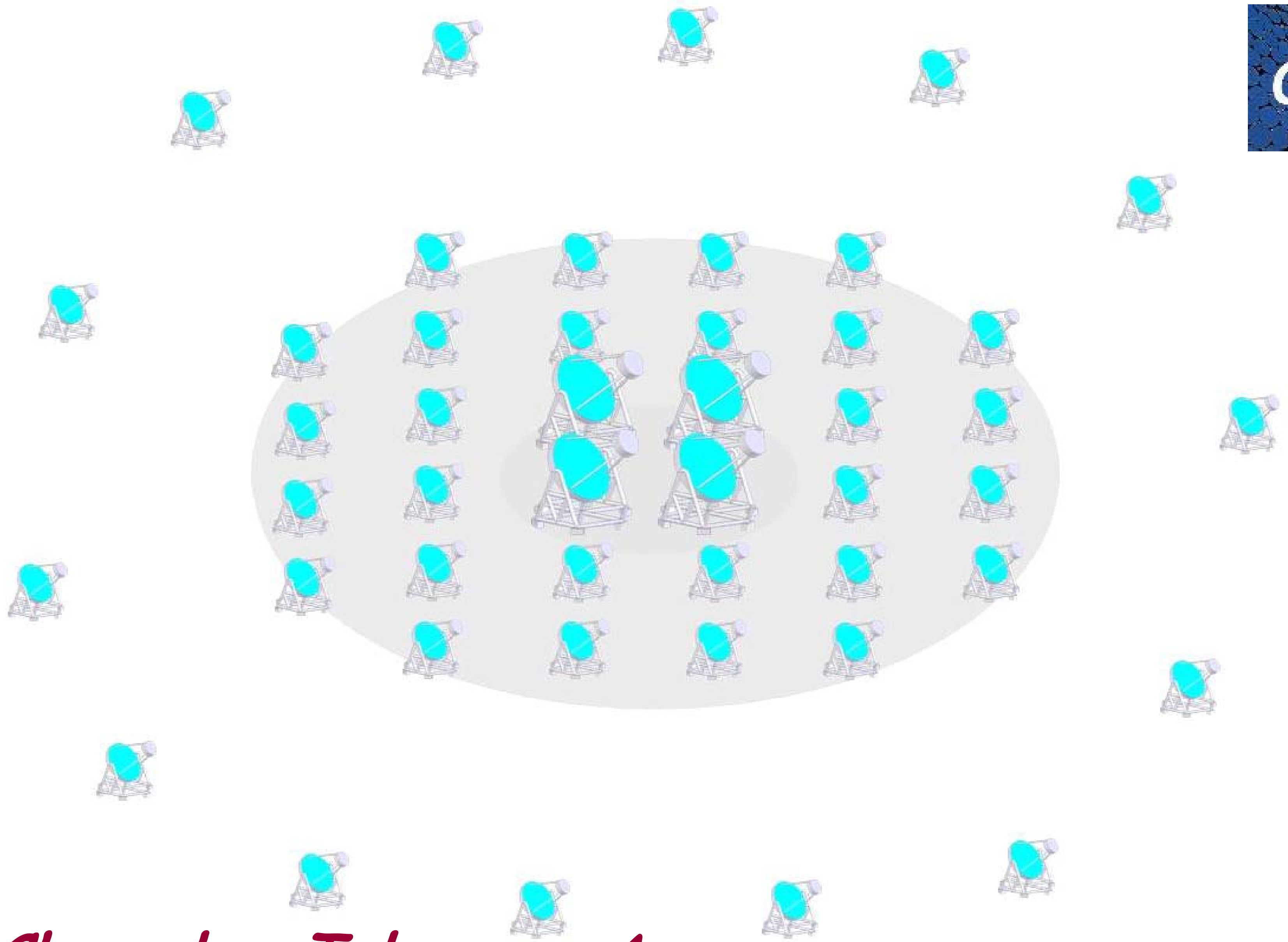


VERITAS telescopes at Basecamp, Mt.Hopkins, Arizona

(Very Energetic Radiation Imaging Telescope Array System)

AGIS (Advanced Gamma-ray Imaging System); U.S. project for a large array of 50-100 atmospheric Cherenkov telescopes (Figure by J.Buckley & V.Guarino)

S.LeBohec, M.Daniel, W.J.de Wit, J.A.Hinton, E.Jose, J.A.Holder, J.Smith, R.J.White
Stellar Intensity Interferometry with Air Cherenkov Telescope Arrays
in D.Phelan, O.Ryan & A.Shearer, eds., *The Universe at sub-second timescales*, AIP Conf.Proc. (2008)

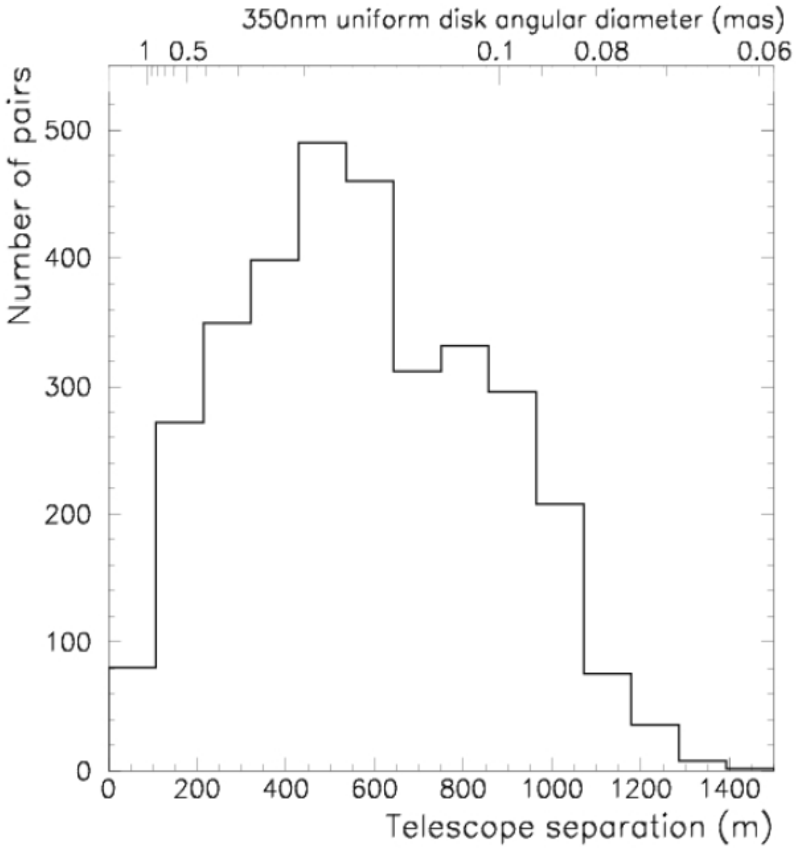


CTA, Cherenkov Telescope Array

An advanced facility for ground-based gamma-ray astronomy

Proposal in European Strategy Forum on Research Infrastructures (ESFRI);

***ASPERA* Astroparticle Physics Roadmap Phase I (2007)**



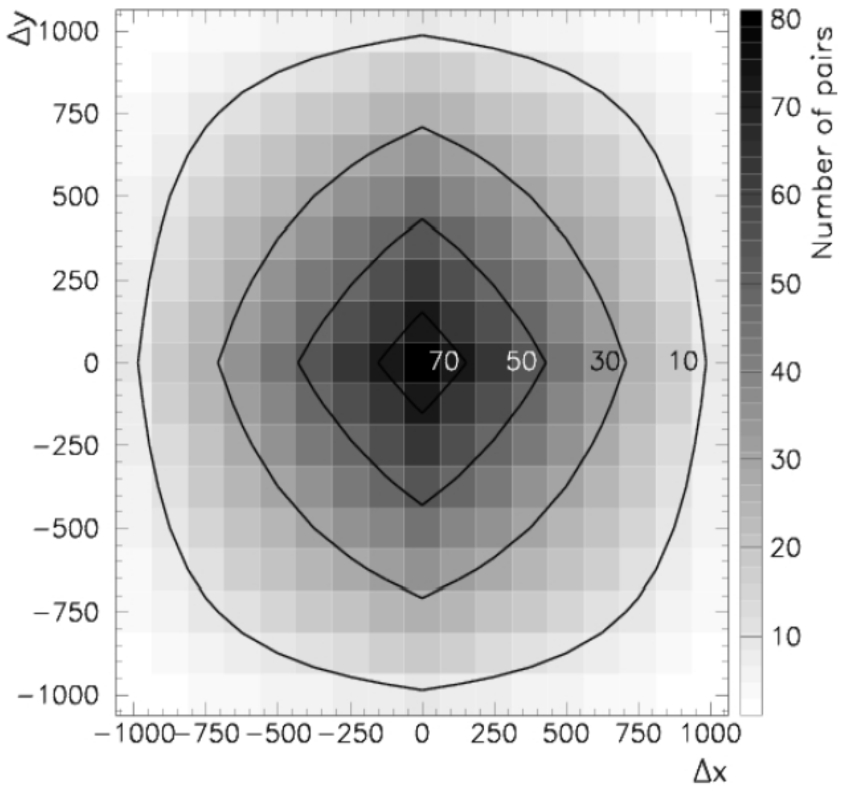


FIGURE 3. The distribution of baselines in a $1km^2$ square grid array of 81 125m spaced telescopes is shown on the left. The upper scale indicates the first cancellation base line for a uniform disk observed at 350nm. The two dimensional baseline distribution is shown on the right.

S.LeBohec, M.Daniel, W.J.de Wit, J.A.Hinton, E.Jose, J.A.Holder, J.Smith, R.J.White
Stellar Intensity Interferometry with Air Cherenkov Telescope Arrays
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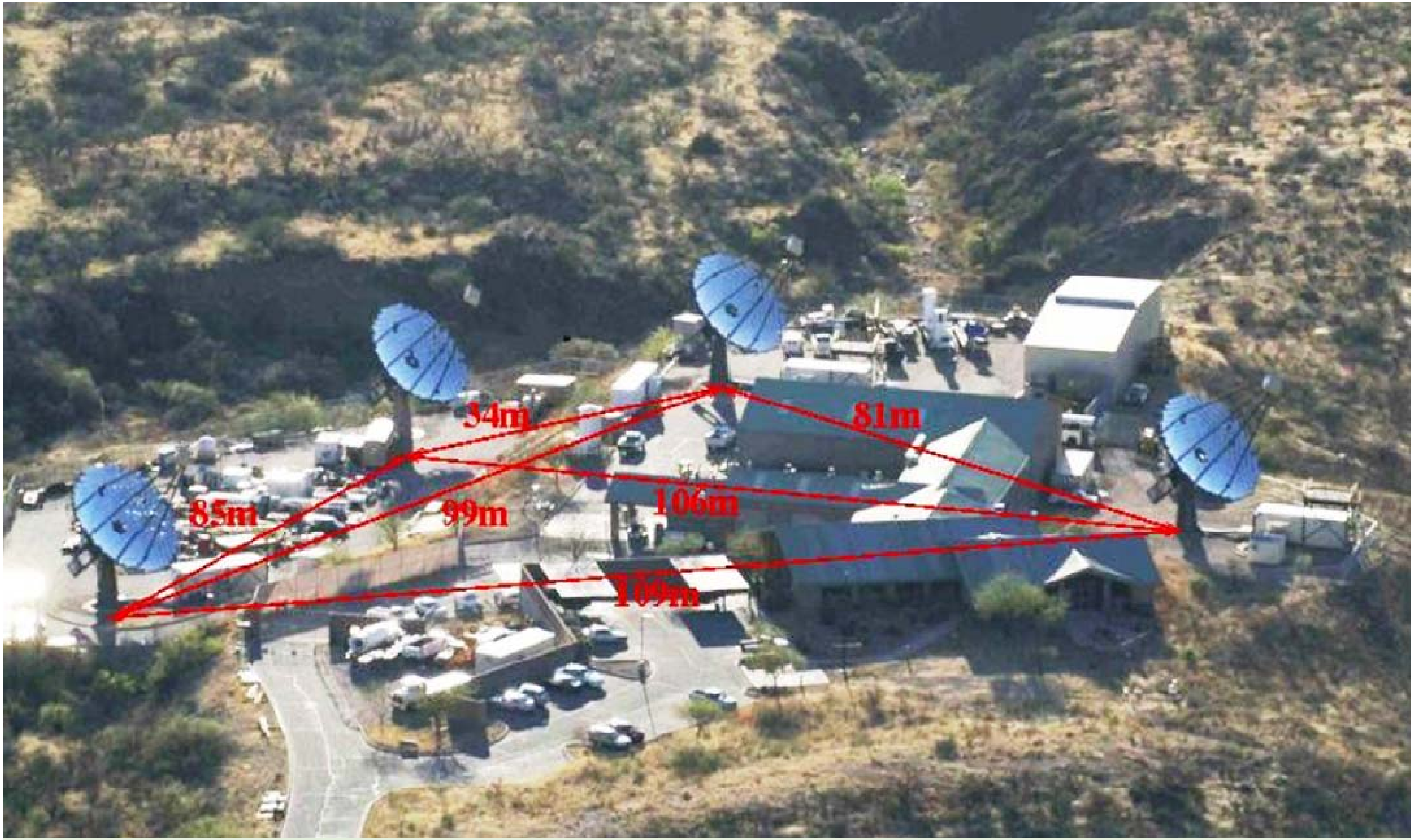
Digital intensity interferometry

Very fast digital detectors, very fast digital signal handling,
and the quantum-optical theory of optical coherence
now enable very-long-baseline optical interferometry
by combining distant telescopes in software

Observing with VERITAS, Oct. 2007

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

Digitally correlated pairs of 12-meter telescopes



The four 12-meter telescopes of the VERITAS array in Arizona offer baselines between 34-109 m

S.LeBohec, M.Daniel, W.J.de Wit, J.A.Hinton, E.Jose, J.A.Holder, J.Smith, R.J.White

Stellar Intensity Interferometry with Air Cherenkov Telescope Arrays

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VERITAS


VERITAS


VERITAS

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

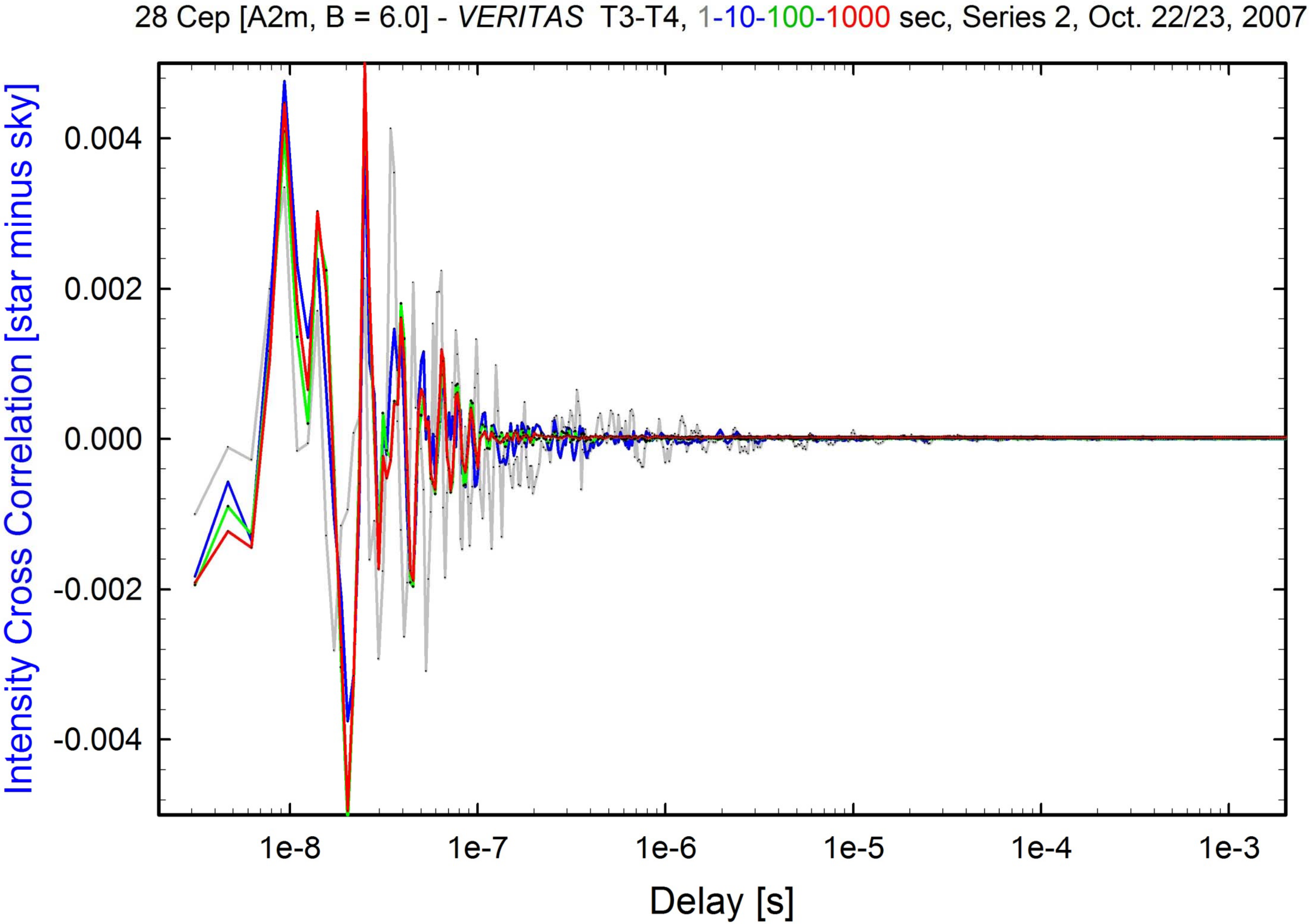
Current performance

VERITAS October 2007:

* Photon rates >30 MHz per telescope

* Real-time cross correlation, Δt = 1.6 ns

* Telescope pairs connected in software


28 Cep [A2m, B = 6.0] - VERITAS T3-T4, 1-10-100-1000 sec, Series 2, Oct. 22/23, 2007
Intensity Cross Correlation [star minus sky]
0.004
0.002
0.000
-0.002
-0.004
1e-8
1e-7
1e-6
1e-5
1e-4
1e-3
Delay [s]

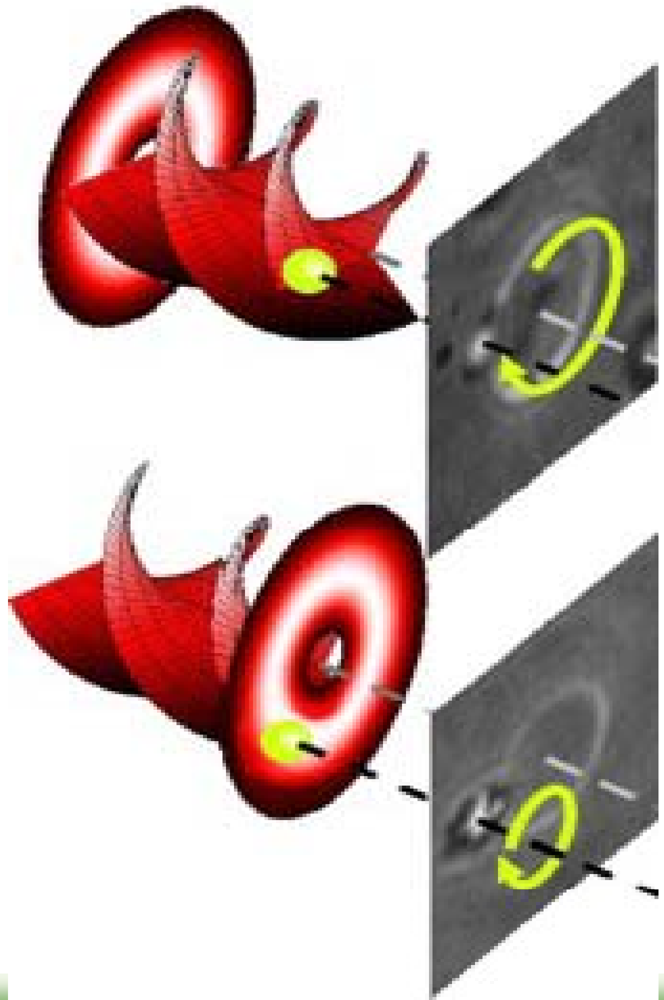
STAR BASE UTAH, A testbed for Air Cherenkov Telescope instrumentation and intensity interferometry

November 2007: Mount for first f/1 Davis-Cotton 3-m telescope is installed in the western building
Location is next to Bonneville SeaBase, some 80 km from Salt Lake City (Stephan LeBohec et al., University of Utah)

Photons have many properties…

PHOTON
ORBITAL
ANGULAR
MOMENTUM!

Photon Orbital Angular Momentum



At microscopic level, interactions have been observed with helical beams acting as optical tweezers.

A small transparent particle was confined away from the axis in the beam's annular ring of light.

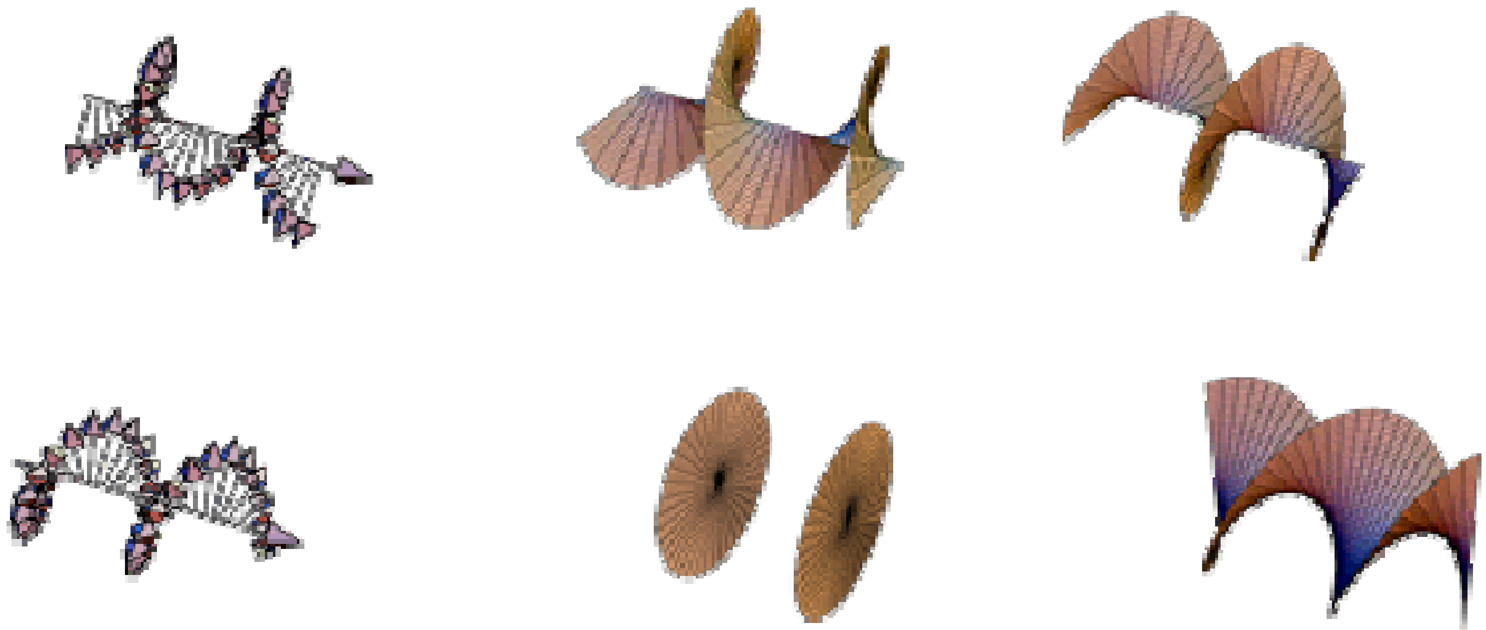
The particle's tangential recoil due to the helical phase fronts caused it to orbit around the beam axis.

At the same time, the beam's spin angular momentum caused the particle to rotate on its own axis.

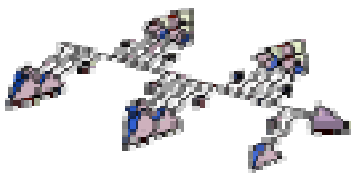
M.Padgett, J.Courtial, L.Allen, Phys.Today May 2004, p.25

Photon Orbital Angular Momentum

Spin

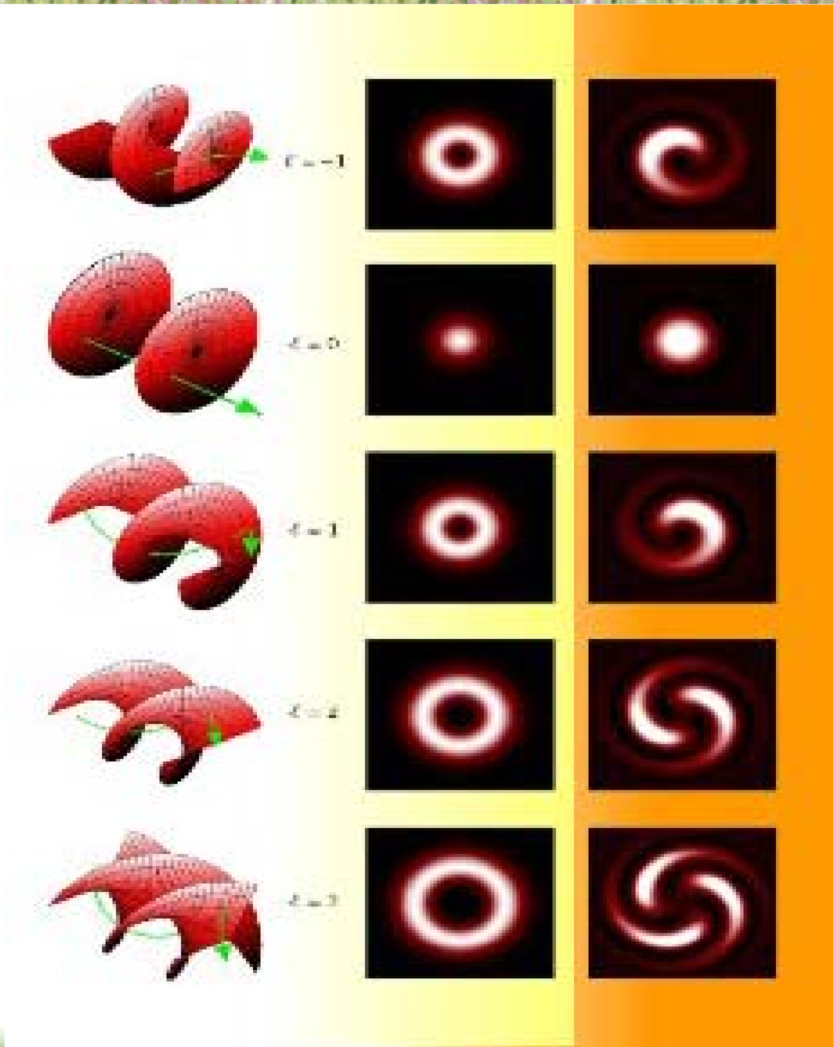


POAM



Although polarization enables only two photon-spin states, photons can have many orbital-angular-momentum eigenstates, allowing single photons to encode much more information.
Harwit, ApJ **597**, 1266 (2003)

Photon Orbital Angular Momentum

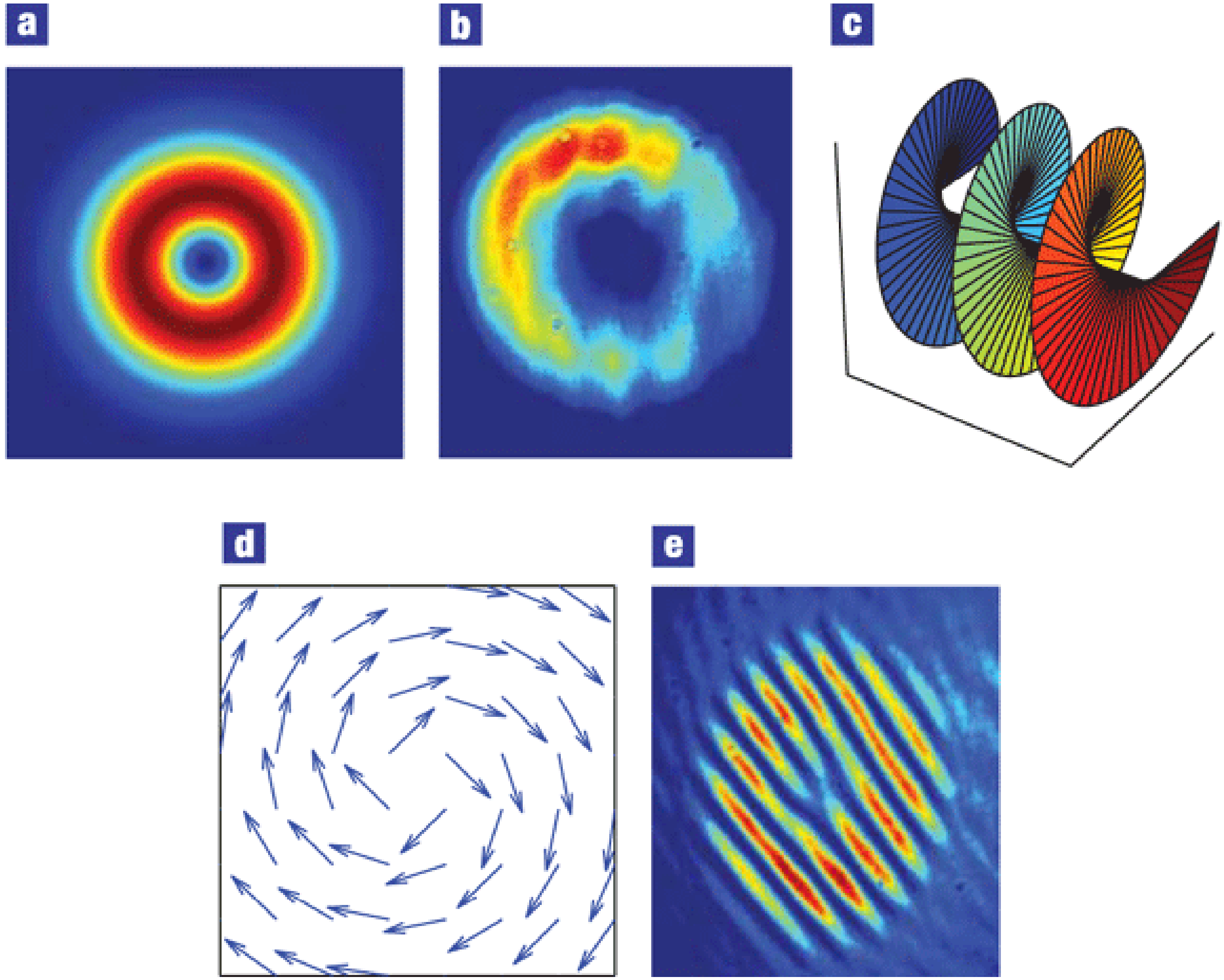


For any given ℓ, the beam has ℓ intertwined helical phase fronts.

For helically phased beams, the phase singularity on the axis dictates zero intensity there.

The cross-sectional intensity pattern of all such beams has an annular character that persists no matter how tightly the beam is focused.

M.Padgett, J.Courtial, L.Allen, Phys.Today May 2004, p.25



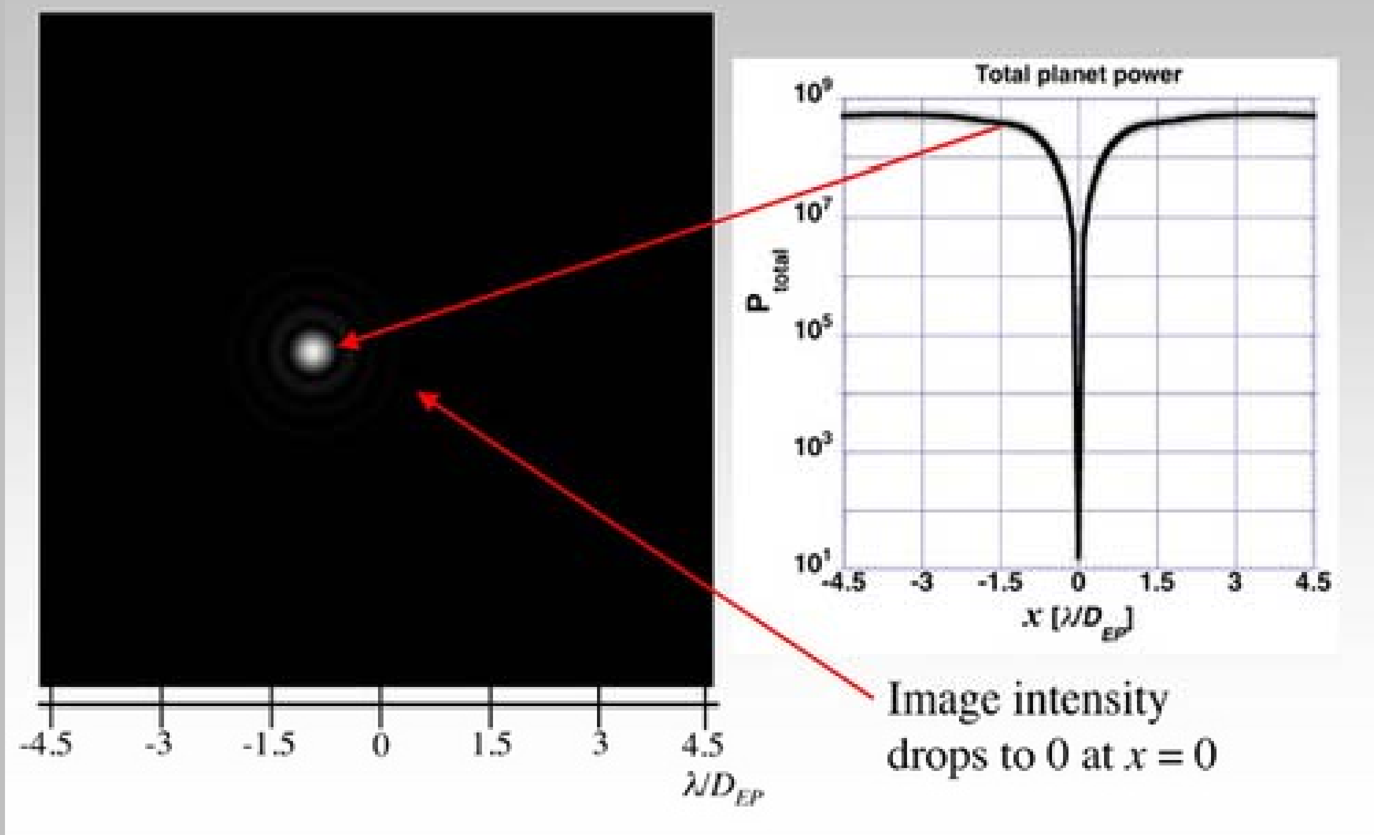
Light with photon orbital angular momentum

Transverse intensity patterns of a light beam; **a**: theoretical; **b**: experimental
c: Phase twists around the central dark spot, producing a staircase-like phase wavefront
d: Local momentum mimics a tornado or vortex fluid – "optical vortices"
e: Interference pattern for m = 1, revealed by the fork-like structure.

G.Molina-Terriza, J.P.Torres & Ll.Torner: *Twisted Photons*, Nature Physics **3**, 305 (2007)

Max Book: *Malstroem de Luxe* (Galleri Engström, Stockholm)

Perfect Nulling:
m=2 Vortex



Simulated images of a star-planet system observed through an ideal (achromatic, no aberrations) *POAM* imaging system (optical vortex coronagraph): Starlight is suppressed and *only* the exoplanet is seen!

Based on:
G.Foo, D.M.Palacios, G.A.Swartzlander:
Optical vortex coronagraph, Opt.Lett. **30**, 3308 (2005)

Utilization of Photon Orbital Angular Momentum in the Low-Frequency Radio Domain

B. Thidé,[1,*] H. Then,[2] J. Sjöholm,[3] K. Palmer,[3] J. Bergman,[1] T. D. Carozzi,[4] Ya. N. Istomin,[5] N. H. Ibragimov,[6] and R. Khamitova[6]

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[5]*I. E. Tamm Theory Department, P. N. Lebedev Physical Institute, 53 Leninsky Prospect, Moscow, 119991, Russia*
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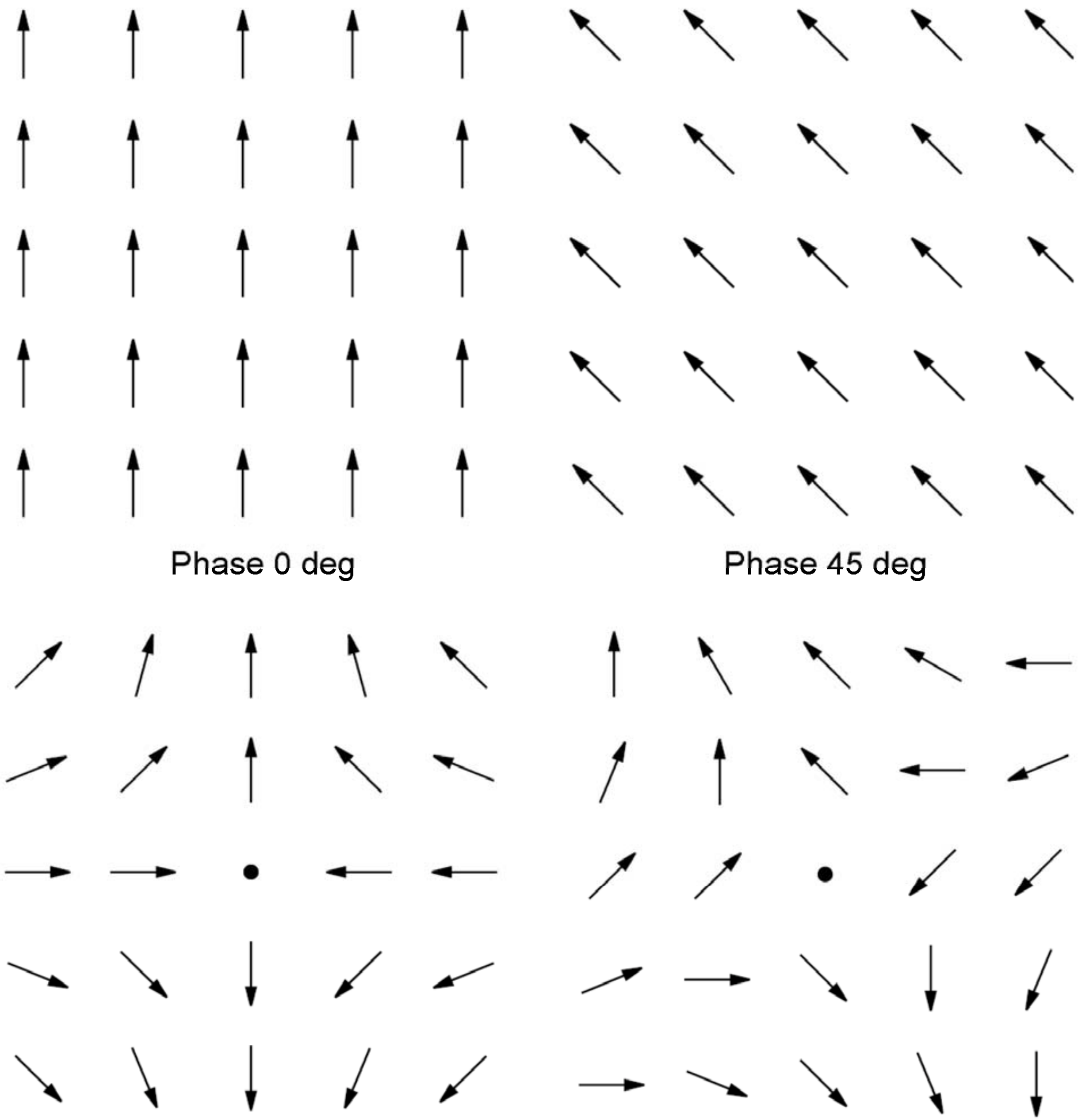
(Received 21 May 2007; published 22 August 2007)

We show numerically that vector antenna arrays can generate radio beams that exhibit spin and orbital angular momentum characteristics similar to those of helical Laguerre-Gauss laser beams in paraxial optics. For low frequencies ($\lesssim 1$ GHz), digital techniques can be used to coherently measure the instantaneous, local field vectors and to manipulate them in software. This enables new types of experiments that go beyond what is possible in optics. It allows information-rich radio astronomy and paves the way for novel wireless communication concepts.

DOI: 10.1103/PhysRevLett.99.087701 PACS numbers: 84.40.Ba, 07.57.−c, 42.25.Ja, 95.85.Bh

Three orthogonal loop antennas probe the 3D magnetic field pseudovectors

Figure from Bo Thidé (Swedish Institute of Space Physics, Uppsala & Växjö University)

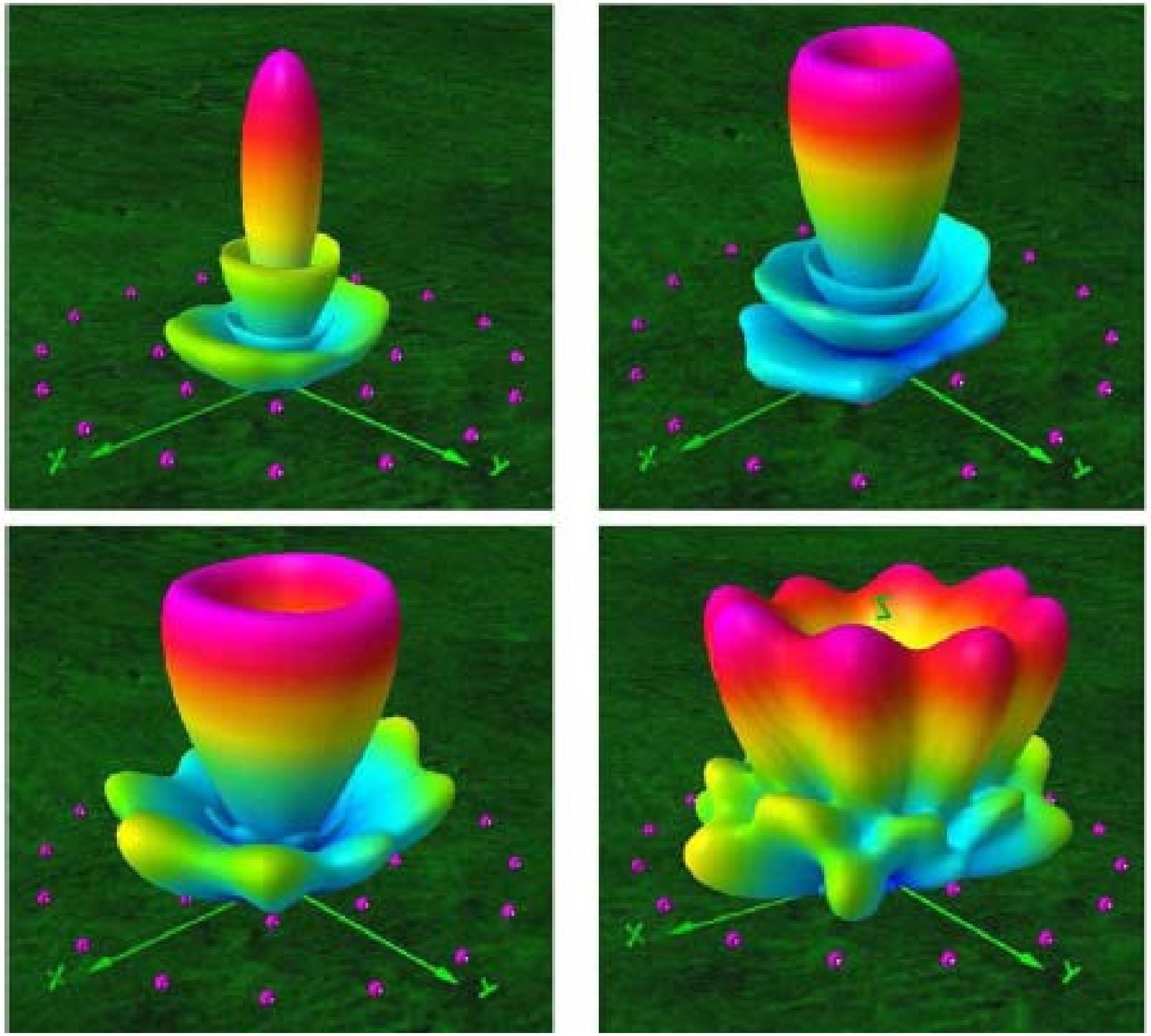


Field vectors across an antenna array for a radio beam with:

TOP: Spin
(circular polarization)

BOTTOM: Orbital angular momentum

Figure from Bo Thidé (Swedish Institute of Space Physics, Uppsala & Växjö University)



Radio-beam patterns generated by differently arranged circles of antennas

B.Thidé, H.Then, J.Sjöholm, K.Palmer, J.Bergman, T.D.Carozzi, Ya.N.Istomin, N.H.Ibragimov, R. Khamitova
Utilization of Photon Orbital Angular Momentum in the Low-Frequency Radio Domain
Phys. Rev. Lett. **99**, 087701 (2007)

Photon Orbital Angular Momentum

* Individual photons can have different POAM states

* Imaging with POAM-manipulated light might reveal exoplanets

* Possible natural POAM sources?
Rotating Kerr black holes??

Bottom line:

BOTH INDIVIDUAL PHOTONS
AND PHOTON STREAMS ARE
MUCH MORE COMPLEX
THAN GENERALLY RECOGNIZED

To be exploited also for astronomy!

PHOTONIC
ASTRONOMY

THE END