Aqueye and Iqueye: the fastest astronomical photometers

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Main Collaborators

The instruments here described and their results have been obtained thanks to a large National and International collaboration. Main Actors:

- C. Barbieri, G. Naletto, M. Barbieri, F. Tamburini, E. Verroi, E. Mari, A. Sponselli (University of Padova)
- T. Occhipinti (formerly University of Padova and now Adaptica srl)
- M. Calvani, L. Zampieri, C. Germanà (INAF OA Padova)
- D. Dravins (Lund Observatory, Sweden)
- A. Čadez (University of Ljubljana, Slovenia)
- A. Shearer (University Galway, Ireland)
- R. Mignani (UCL London, UK)
- P. Zoccarato (formerly University of Padova and now Australia)
- A. Richichi (ESO, Thailand)

Summary - 1

I'll describe experiments in very high time and space resolution by means of novel utilizations of the properties of light.

1 –time: we have conceived a photometer capable to time tag the arrival time of each photon with a resolution and accuracy of ***few hundred picoseconds***, for hours of continuous acquisition and with a dynamic range of more than 6 orders of magnitude. The final goal is a 'quantum' photometer for the E-ELT capable to detect and measure ***second order correlation effects*** (according to Glauber's description of the EM field) in the photon stream from celestial sources.

Two prototype units have been built and operated, one for the Asiago 1.8m telescope (Aqueye) and one for the 3.5m NTT (Iqueye). Results obtained on ***optical pulsars*** will be presented in detail, but the photometers have been used also for ***lunar occultations***, ***exo-planet transits*** and ***fast variable stars***.

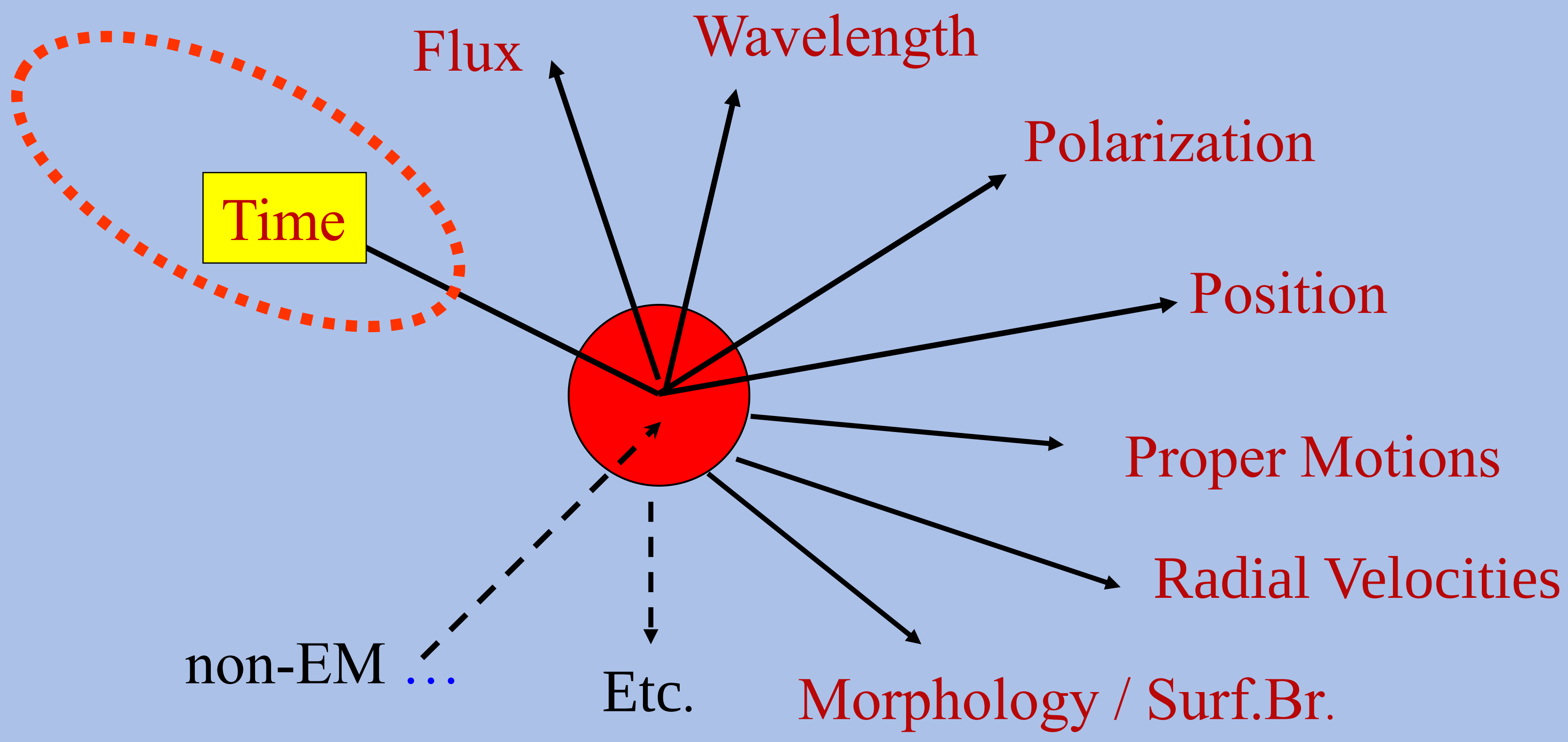
Summary - 2

2 - Among the second order effects in Glauber’s formalism, ***Hanbury Brown - Twiss Intensity Interferometry*** has been already successfully tested at the NTT, giving hopes to perform very high spatial resolution observations ***among telescopes not optically linked***, e.g. the E-ELT at Cerro Armazones and the VLT at Cerro Paranal, or Cerenkov light telescopes such as Magic or CTA.

A second avenue for high space resolution is being explored using the ***Orbital Angular Momentum*** of the light beam and associated ***Optical Vorticity***. The classical Rayleigh criterion of resolution can be ameliorated by an order of magnitude. Promising tests have been made with ***a coronagraph*** at the 122cm telescope in Asiago. Extension to the radio domain has been demonstrated. ***I’ll talk about that in a second presentation***.

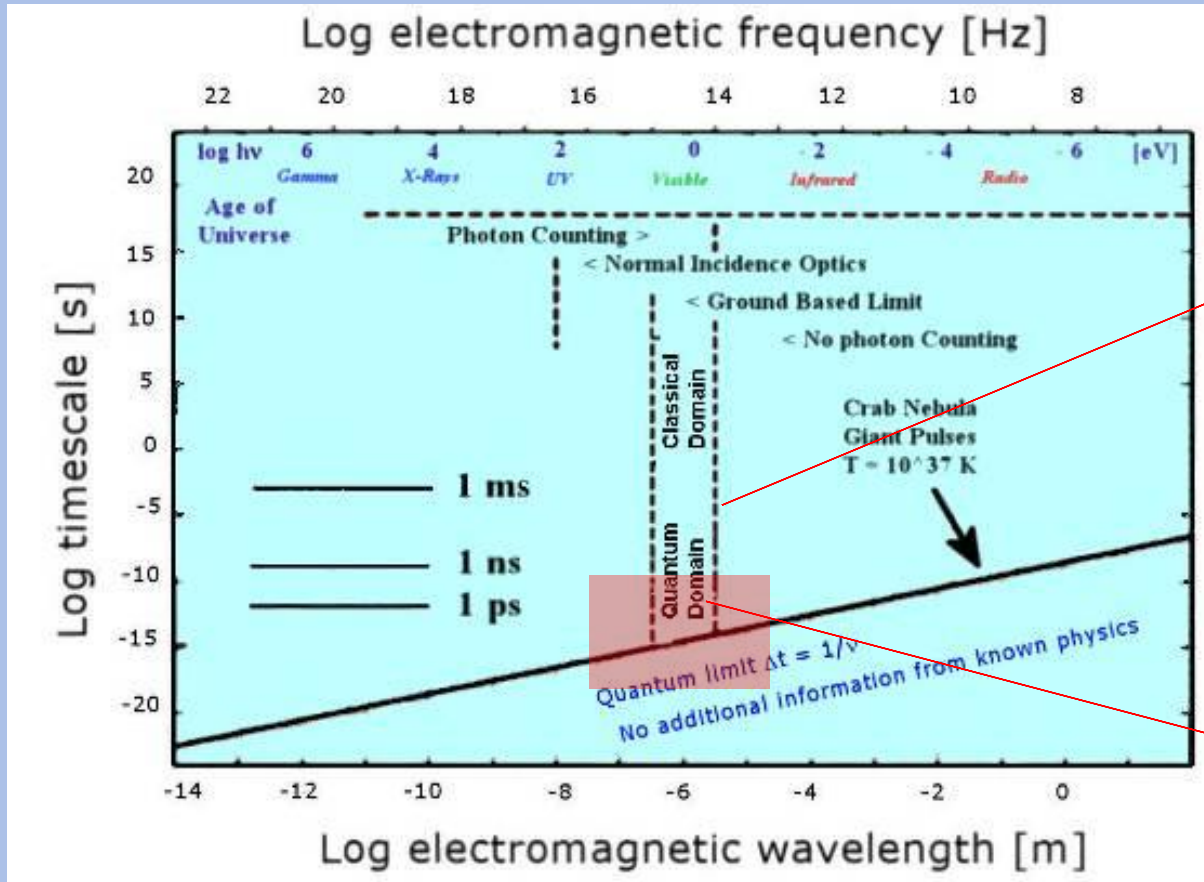
Time in the astronomical parameters space

Time is one of the many parameters in the space of astronomical variables.



All of Astronomy in Time and Frequency

This slide conveys the idea of all of Astronomy in a time – frequency domain, and of the *lower limit imposed by Heisenberg principle*.



L3 CCDs
MCP
STJ
TES
PM
SiPM
HPD
APD
SPAD
SSPD
…

Pushing the time resolution *towards the limits imposed by Heisenberg's principle* might have the same scientific impact of opening a new window. This new Astronomy can be designated as *Quantum Astronomy, or Photonics Astronomy*.

Some thoughts on quantum optics and astronomy

Photons are very complex entities, carrying more information than extracted in astronomical applications with conventional techniques of imaging, spectroscopy and polarimetry.

According to Glauber, Arecchi, Mandel, etc. seminal papers (from 1963 onwards), arbitrary states of light can be specified as first, second, and higher order ***correlation functions*** $\mathbf{G^{(1)}}$, $\mathbf{G^{(2)}}$, **…,** with respect to position ***r*** and time *t*.

VOLUME 10, NUMBER 3 PHYSICAL REVIEW LETTERS 1 FEBRUARY 1963

PHOTON CORRELATIONS*

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

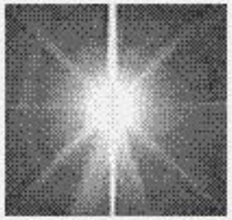
In 1956 Hanbury Brown and Twiss[1] reported that the photons of a light beam of narrow spectral width have a tendency to arrive in correlated pairs. We have developed general quantum mechanical methods for the investigation of such correlation effects and shall present here results for the distribution 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

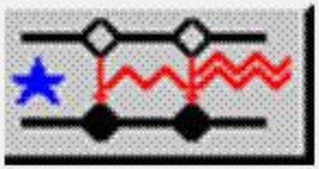
The first paper by Glauber made reference to the HBT experiment, whose application to the astronomical field as ***Intensity Interferometer*** (HBTII) will be described in later slides.

What is NOT observed in Astronomy - 1

blackbody



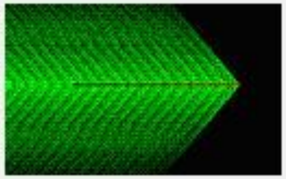
scattered



laser

coherent

synchrotron



cerenkov

Conventional measurements ***cannot distinguish*** sources with different emission mechanisms but characterized by the same $G^{(1)}$. In other words**,** light from various sources can be created through different (and typically ***unknown***) physical processes: thermal radiation, stimulated emission, synchrotron radiation, etc.

wavelength and polarizer filters

observer

Now, assume one is observing these sources through “filters”, adjusted so that all sources have the same size, shape, intensity, spectrum, and polarization.
How can one tell the difference when observing from a great distance?

What is NOT observed in Astronomy - 2

For the different sources as defined in the previous slide, it is actually not possible, ***not even in principle***, to segregate them using ***any*** classical astronomical instrument:

telescopes with imaging devices (cameras or interferometers) would record the same spatial image

any spectrometer would find the same spectrum.

With such classical devices, ***two- or multiple photon processes*** in the source cannot be discriminated, not even in principle, from thermal processes.

Further properties of the photon stream

Still, the light from those sources can be physically different, since ***photons have more degrees of freedom*** than those relevant for mere imaging or spectroscopy, such as the ***temporal statistics of photon arrival times***, giving a measure of ordering (**entropy**) within the photon-stream, and its possible deviations from randomness.

Such properties are ***reflected in the second- (and higher-) order coherence of light***, ***observable as correlations between pairs (or a greater number) of photons***.

The differences lie in ***collective properties of groups of photons***, and cannot be ascribed to any one individual photon. The information content lies in the ***correlation in time (or space) between successive photon***s in the arriving photon stream (***or the volume of a "photon gas"***), and may be significant if the photon emission process has involved more than one photon at a time.

Two photon experiments

Realistically, in astronomical applications we might have some hope to detect two-photon correlation effects:

Two-photon measurements can be ascribed to quantities of type *I* **I*, i.e. intensity multiplied by itself, which in the quantum limit means observations of pairs of photons, or of statistical two-photon properties.

Second Order Correlation Function

$$g^{(2)}(d,\tau) = \frac{\langle I(\mathbf{r}_1,t_1) I(\mathbf{r}_2,t_2)\rangle}{\langle I(\mathbf{r}_1,t_1)\rangle \langle I(\mathbf{r}_2,t_2)\rangle}$$

(R. Glauber, 1965, Nobel Prize 2005)

with $\mathbf{r}_2$-$\mathbf{r}_1$=$\boldsymbol{d}$ and $\boldsymbol{t}_2$-$\boldsymbol{t}_1$=τ

1 - If $\tau \neq 0$ and $\boldsymbol{d}$=0 one gets photon correlation spectroscopy (R = 10^9- 10^{10} necessary to resolve ***lased*** spectral lines) .

2 - If τ=0 and $\boldsymbol{d}\neq$0 one gets Hanbury Brown - Twiss Intensity Inteferometry (Narrabri) .

PHOTON STATISTICS

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

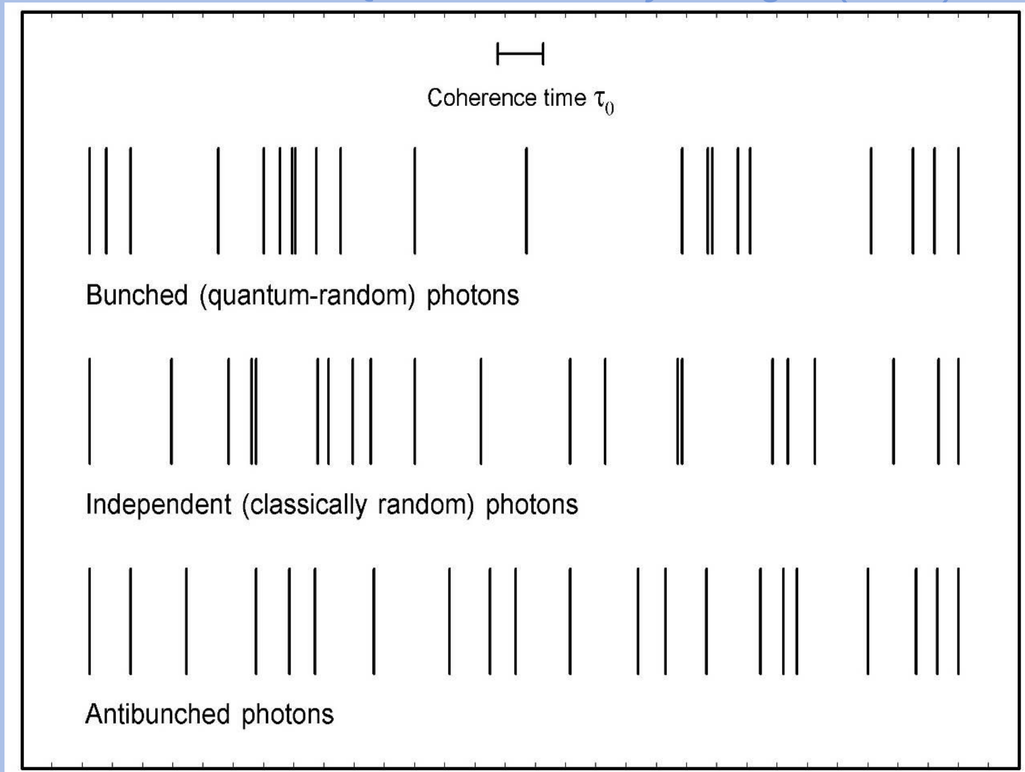
Statistics of photon arrival times in light beams with different entropies (different degrees of "ordering").

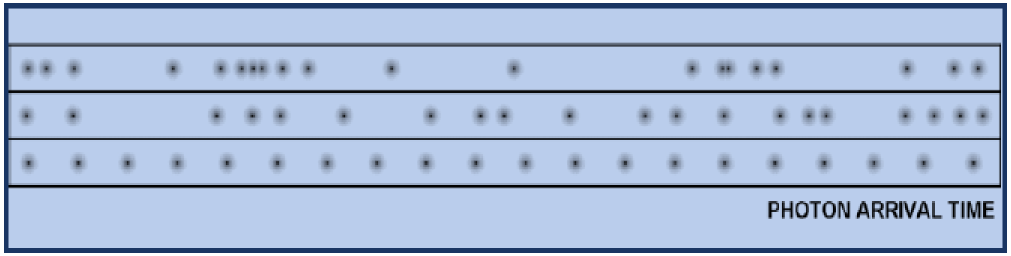
The statistics can be:

"quantum-random", as in maximum-entropy black-body radiation (following a Bose-Einstein distribution with a characteristic "bunching" in time; top),

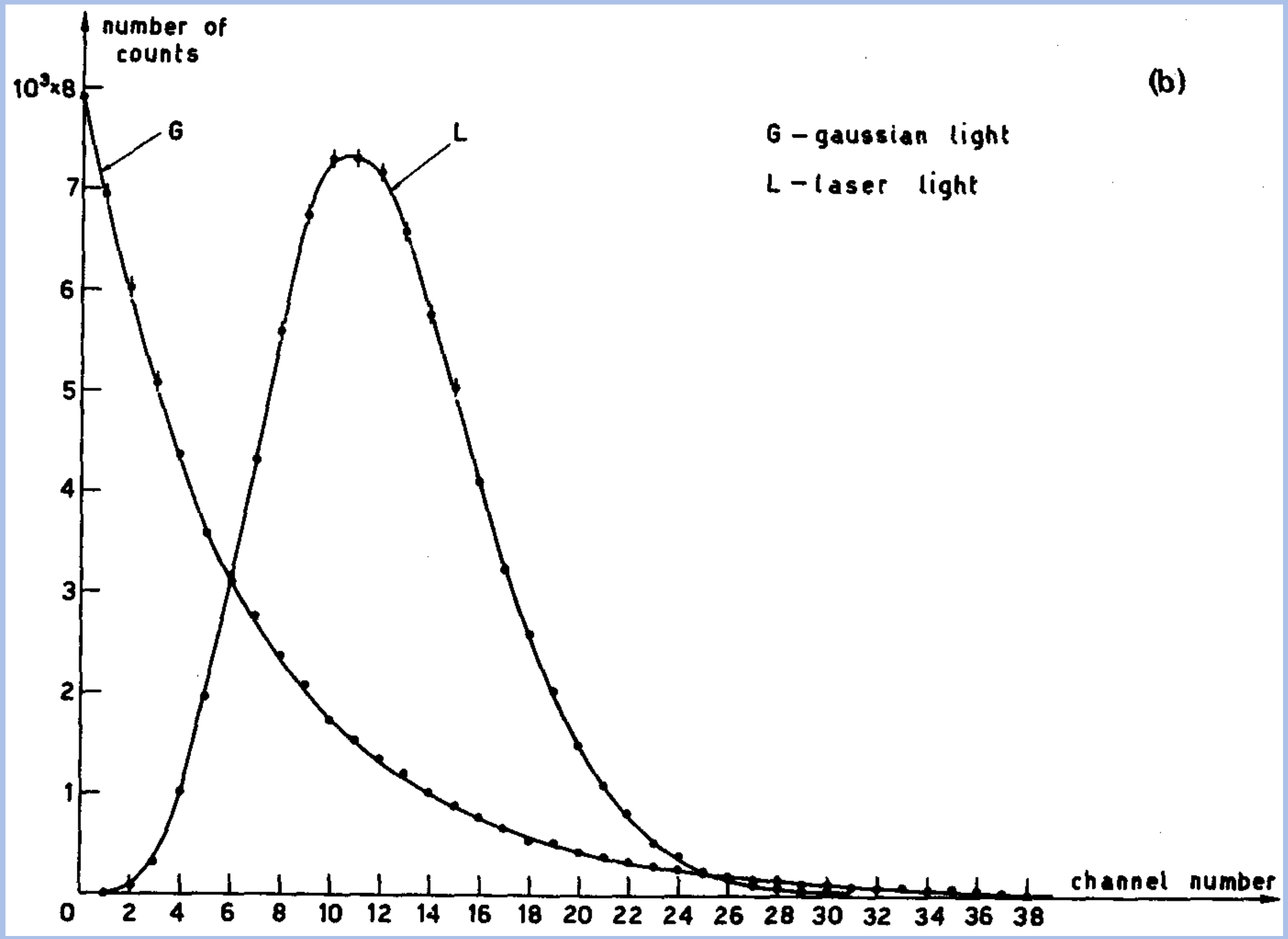
- or may be quite different if the radiation deviates from thermodynamic equilibrium, e.g. for anti-bunched photons (where photons tend to avoid one another; center),

-or a uniform photon density as in stimulated emission from an idealized laser (bottom).



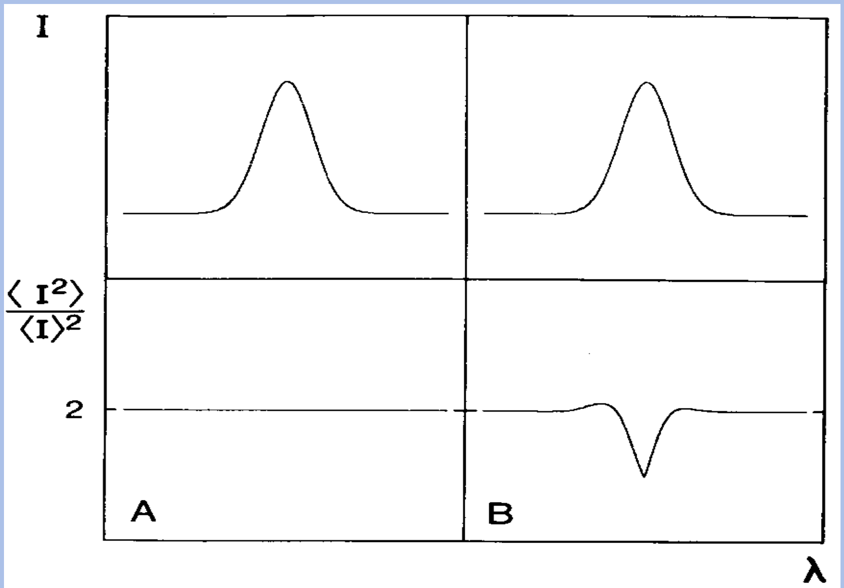


Examples of different Photon Statistics



PHOTON STATISTICS IN GAUSSIAN AND LASER SOURCES
F.T.Arecchi, Phys.Rev.Lett. 15, 912 (1965)

Photon correlation spectroscopy



Resolution	L	T
$1:10^5$	5 cm	200 psec
$1:10^6$	50 cm	2 nsec
$1:10^7$	5 m	20 nsec
$1:10^8$	50 m	0.2 μsec

Apparently identical spectral lines might instead have entirely different quantum statistics.

To resolve narrow optical laser emission ($\Delta\nu \approx 10$ MHz) requires spectral resolution $\lambda/\Delta\lambda \approx 10^8$ achievable by photon-correlation spectroscopy (delay time $\Delta t \approx 100$ ns, 20m delay line).

E.R.Pike, in R.A.Smith, ed. Very High Resolution Spectroscopy, p.51 (1976)

Advantages of photon correlation spectroscopy

Analogous to spatial information from intensity interferometry, photon correlation spectroscopy does not reconstruct the *shape* of the source spectrum, but “only” gives linewidth information

Advantage #1: Photon correlations are insensitive to wavelength shifts due to local velocities in the laser source

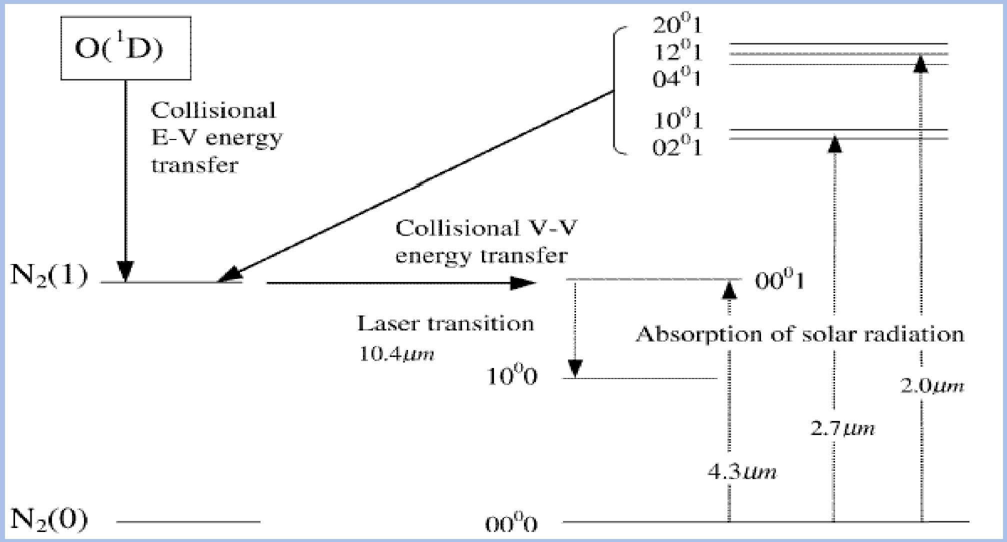
Advantage #2: Narrow emission components have high brightness temperatures, giving higher S/N ratios in intensity interferometry

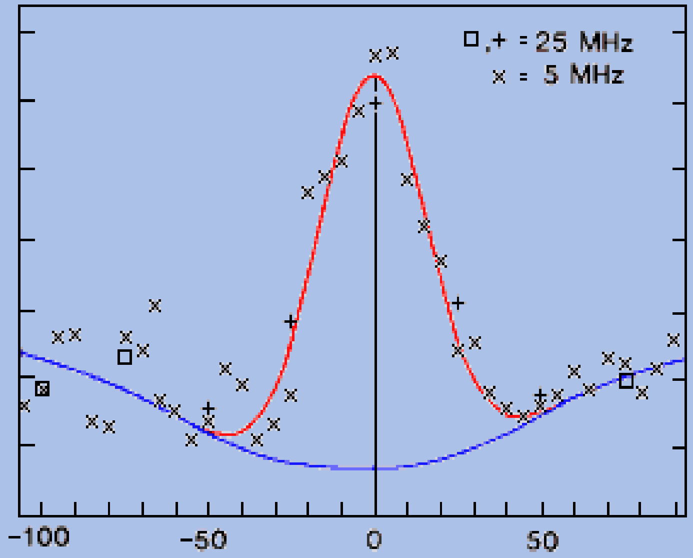
Quantum effects expected in cosmic light

Astrophysical Masers and Lasers are well known in the radio and far infrared domains.

Few examples of possible Lasers in the near IR and optical bands are provided in the following.

10-μm CO2 Laser in Venus, Mars and Earth atmospheres





Vibrational energy states of CO2 and N2 associated with the natural 10.4 μm CO2 laser**.**

G.M. Shved, V. P. Ogibalov, *Natural population inversion for the CO_2 vibrational states in Earth's atmosphere*, J. Atmos. Solar-Terrestrial Phys. **62**, 993 (2000)

D. Deming, F. Espenak, D. Jennings, T. Kostiuk, M. Mumma and D. Zipoy, *Observations of the 10-μm natural laser emission from the mesospheres of Mars and Venus***,** Icarus, 55, 1983, Pages 347-355 and 356-358

Early thoughts about lasers in stellar spectra

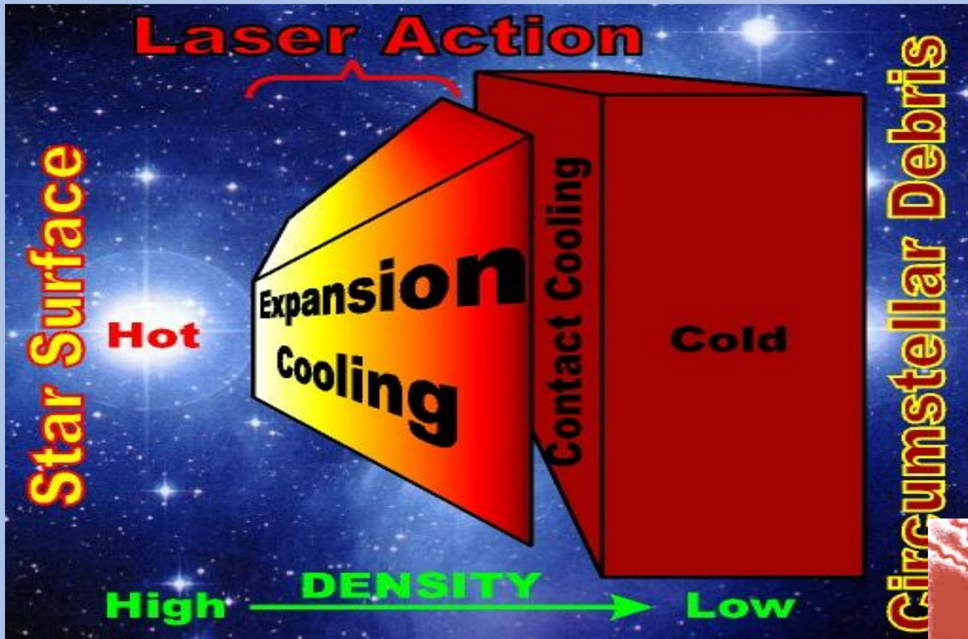
D. Menzel: *Physical Processes in Gaseous Nebulae. I* , Ap.J 85, 330 (1937) !

Outside of thermodynamic equilibrium, the condition may conceivably arise when the value of the integral turns out to be negative. The physical significance of such a result is that energy is emitted rather than absorbed. This energy must be distinguished, however, from that arising in random emissions. The process merely puts energy back into the original beam, as if the atmosphere had a negative opacity. This extreme will probably never occur in practice.

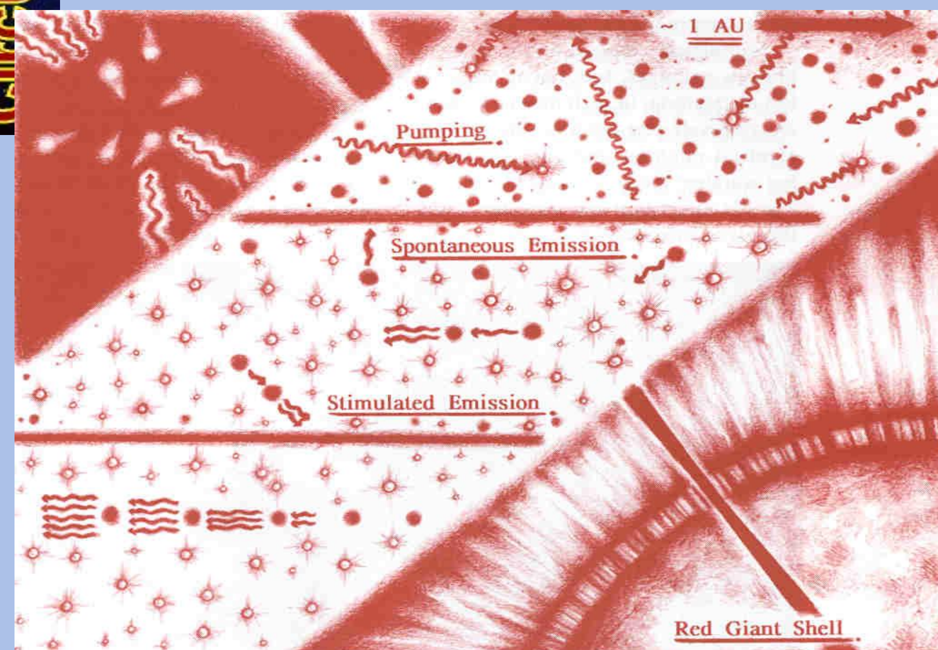
D. Menzel: *Laser Action in Non-LTE Atmospheres* (in Spectrum Formation in Stars with Steady-State Extended Atmospheres, IAU Colloq. 2, 16-19 April, **1969**, Munich, Germany, H. G. Groth and P. Wellmann eds., National Bureau of Standards Special Publication 332).

Abstract: The radiative transfer equation is written in microscopic form, and from some simplifications on the ratio of occupation numbers for upper and lower level, ***a laser action is suggested***.

More refined models

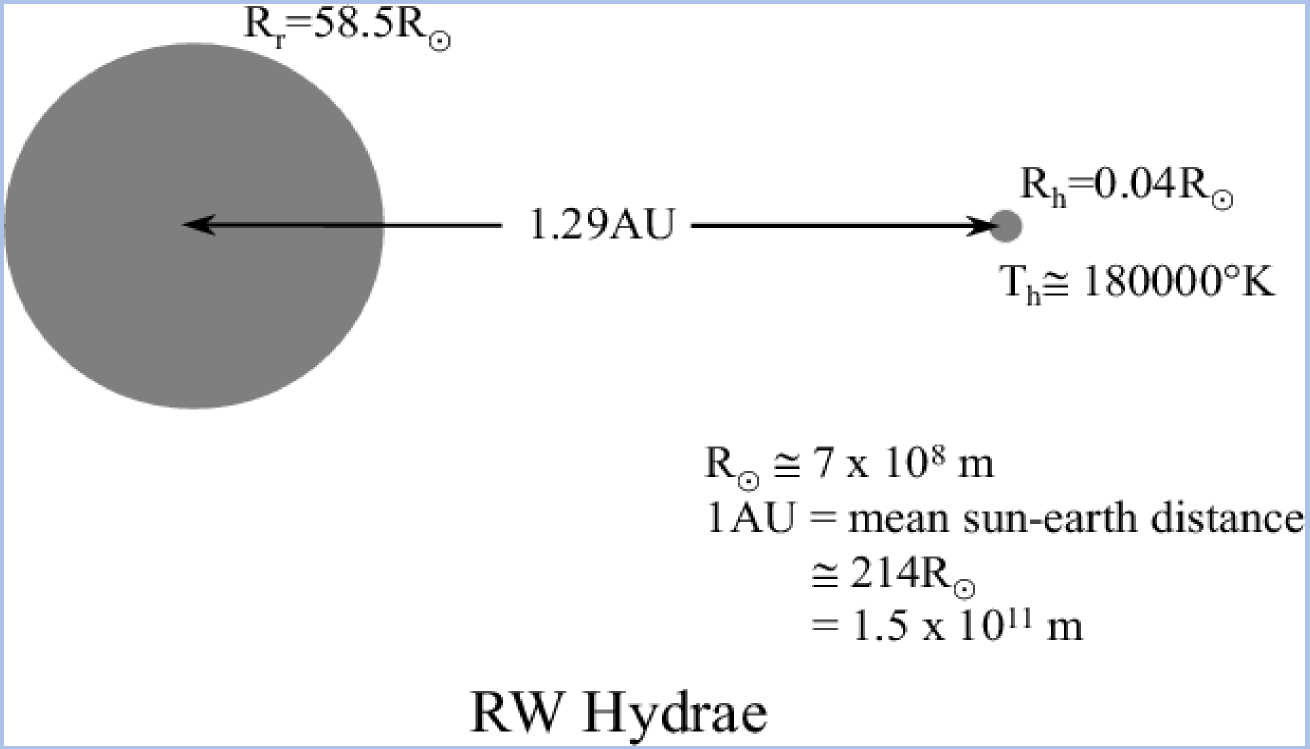


J. Talbot, *Laser Action in Recombining Plasmas*
M.Sc. thesis, University of Ottawa (1995)



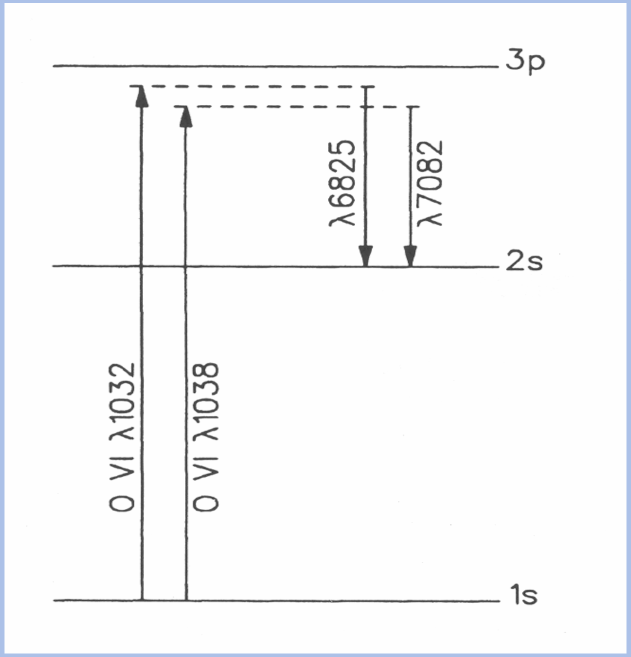
S.W.J.Colgan, Mercury, 26, No.4, 18 (1997)

Laser effects in Wolf-Rayet, symbiotic stars, and novae

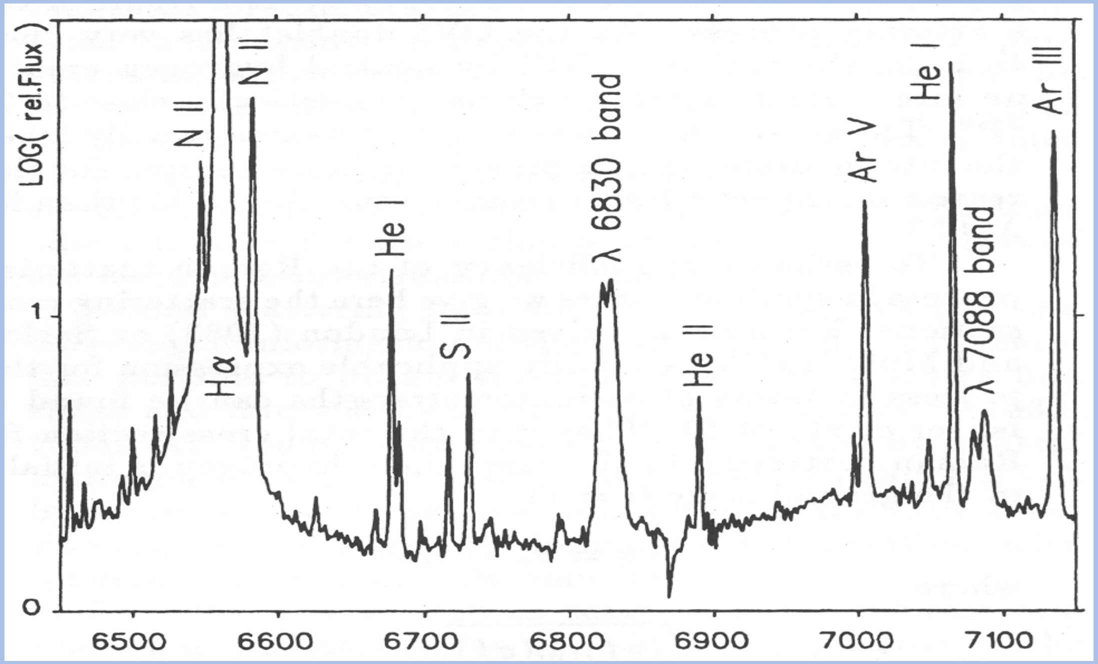


P. P. Sorokin & J. H. Glownia, ***Lasers without inversion (LWI) in Space: A possible explanation for intense, narrow-band, emissions that dominate the visible and/or far-UV (FUV) spectra of certain astronomical objects,*** **A&A 384, 350 (2002)**

Raman scattered emission bands in the symbiotic star V1016 Cyg



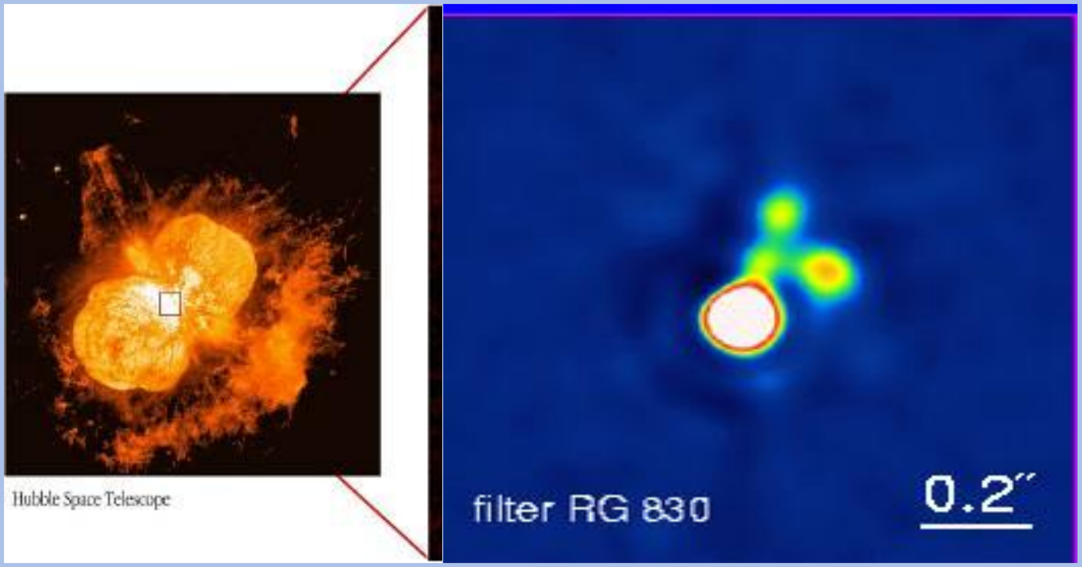
Energy-level diagram for Raman scattering of O VI photons by neutral hydrogen

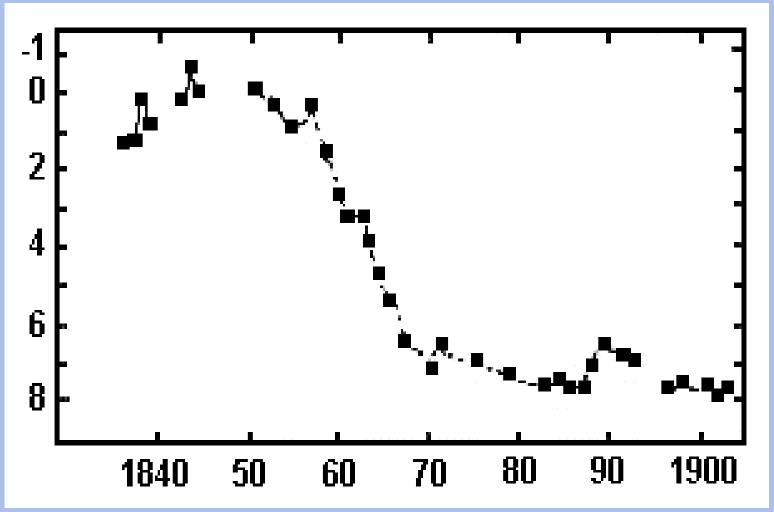


Raman scattered emission bands

H. M. Schmid, *Identification of the emission bands at λλ 6830, 7088*, A&A **211**, L31 (1989)

Laser emission in Eta Carinae - 1



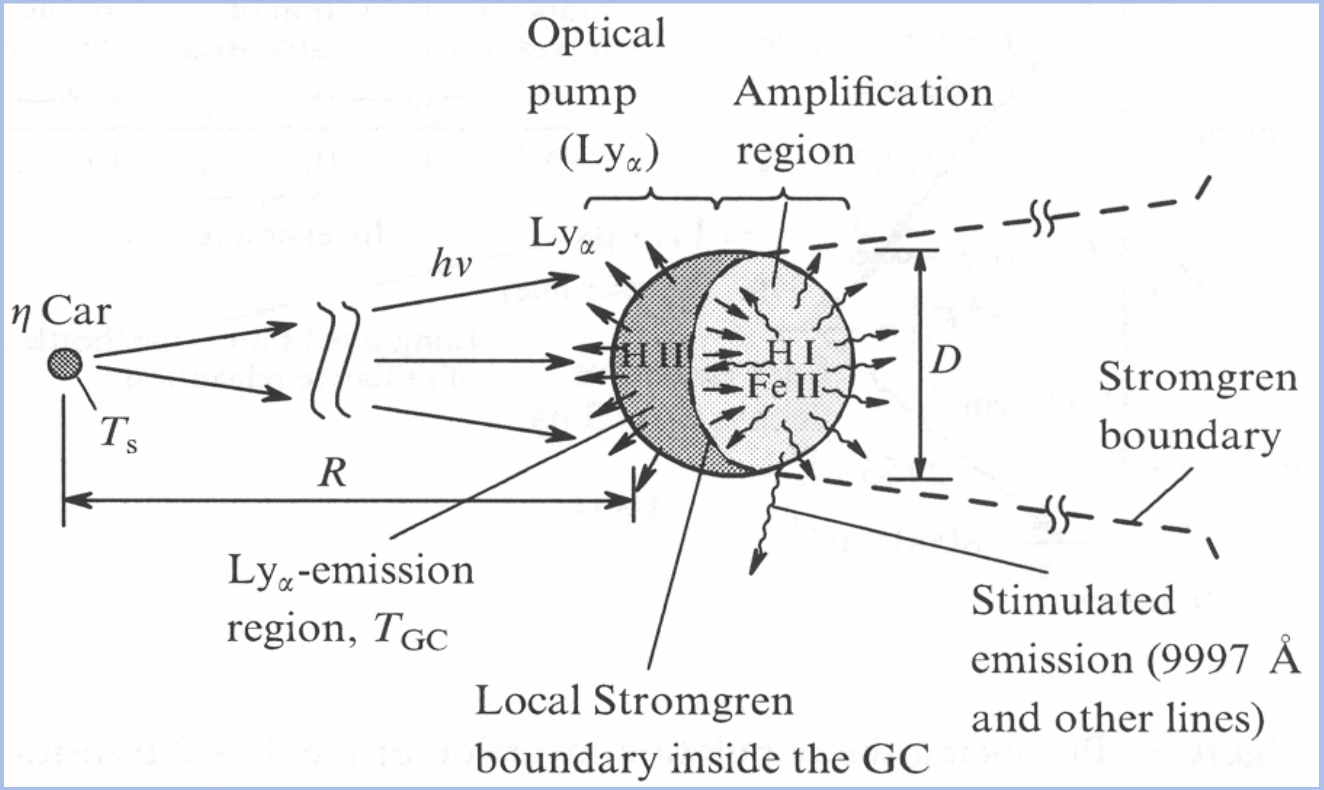


Eta Carinae is one of the most peculiar objects in the southern sky, with an enormous mass loss (10^{-3} $M_{\odot}$/y). Circa 1830, the so called Homunculus nebula was ejected by the star. Observations with HST have identified a gas cloud that acts ***as a natural ultraviolet laser pumped by UV radiation.*** The interstellar laser may result from Eta Carinae's violently chaotic eruptions, in which it blasts parts of itself out into space, like an interstellar geyser

The inset on the HST WFC is by;

K.-H. Hofmann; G. Weigelt, *Speckle masking observations of Eta Carinae*, A&A **203**, L21 (1988)

Laser Emission in Eta Car - 2

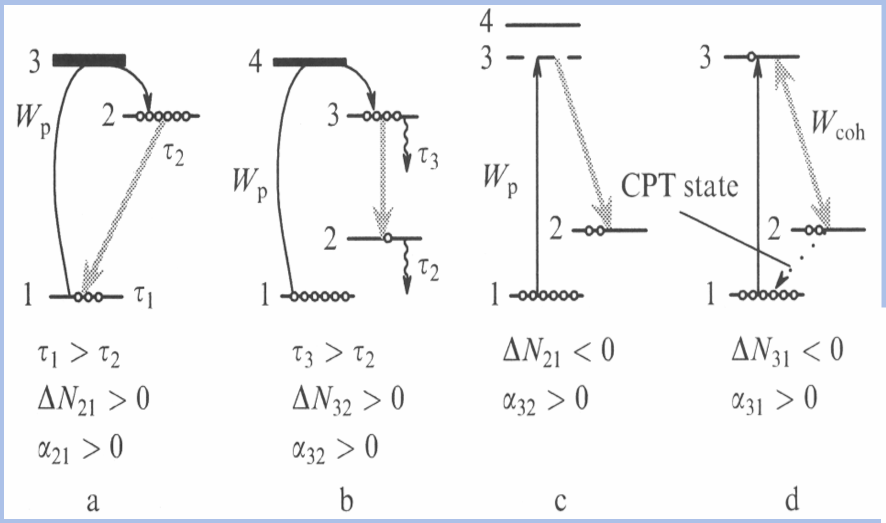


Model of a compact gas condensation near η Car with its Strömgren boundary between photoionized (H II) and neutral (H I) regions

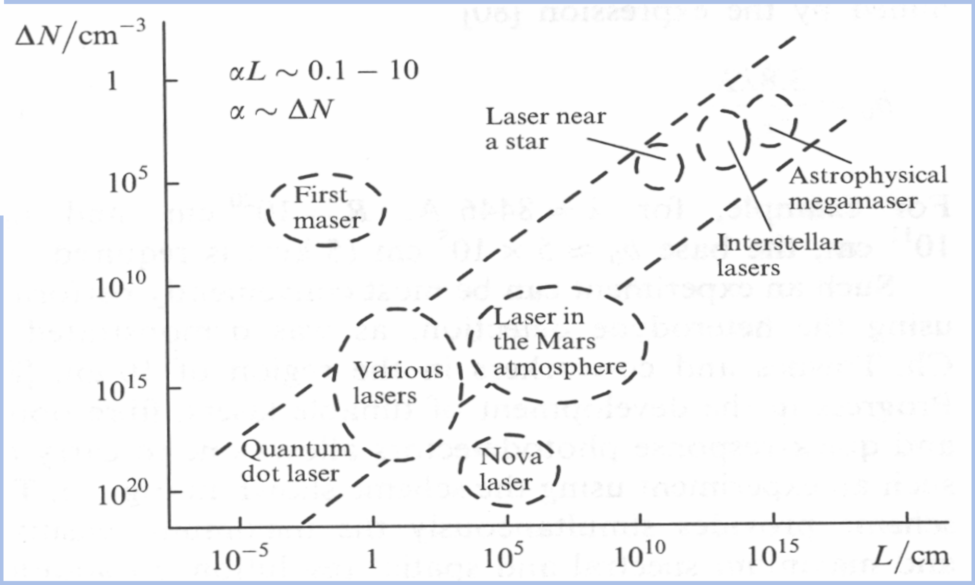
S. Johansson & V. S. Letokhov
Laser Action in a Gas Condensation in the Vicinity of a Hot Star
JETP Lett. **75**, 495 (2002) = Pis'ma Zh.Eksp.Teor.Fiz. **75**, 591 (2002)

A summary of astrophysical lasers

Letokhov, V. S., *Astrophysical Lasers,* Quant. Electr. **32**, 1065 (2002)



Methods for amplification in 3- & 4-level astrophysical lasers
(a, b) Raman scattering; (c, d) Pumping light



Masers and lasers in the active medium particle-density vs. medium-dimension diagram.

SETI Lasers??

One might even conceive enourmous atmospheric CO_2 lasers built by alien (very) intelligent civilizations (SETI) …

The HBT Intensity Interferometer (HBTII)

The correlation or *intensity* interferometer was invented around 1954 by R. Hanbury Brown and R. Q. Twiss.
A large stellar interferometer was completed in 1965 at Narrabri, Australia, and by the end of the decade it had measured the angular diameters of more than 30 stars, including Main Sequence blue stars.

The light-gathering power of the 6.5 m diameter mirrors, the detectors (photomultipliers), analog electronics etc. allowed the Narrabri interferometer to operate down to magnitude +2.0, a fairly bright limit indeed.
The intrinsically low efficiency of the system made the HBTII essentially forgotten, in favor of Michelson type (amplitude and phase) interferometers, e.g. the ESO VLTI.

Mutual coherence function

Normalized correlation between two electromagnetic waves at different positions and times (Michelson interferometer):

$$\gamma(\mathbf{r}_1,\mathbf{r}_2,\tau) \equiv \frac{\left\langle f(\mathbf{r}_1,t)\, f^*(\mathbf{r}_2,t+\tau)\right\rangle}{\sqrt{\left\langle f(\mathbf{r}_1,t)\, f^*(\mathbf{r}_1,t+\tau)\right\rangle \left\langle f(\mathbf{r}_2,t)\, f^*(\mathbf{r}_2,t+\tau)\right\rangle}}$$

Radio to Visible

$$\equiv \frac{\left\langle f(\mathbf{r}_1,t)\, f^*(\mathbf{r}_2,t+\tau)\right\rangle}{\sqrt{I_1\ I_2}} \le 1$$

Second order correlation (HBT intensity interferometry):

$$\gamma^{(2)}(\mathbf{r}_1,\mathbf{r}_2,\tau) \equiv \frac{\left\langle I(\mathbf{r}_1,t)\, I(\mathbf{r}_2,t+\tau)\right\rangle}{\left\langle I(\mathbf{r}_1,t)\right\rangle \left\langle I(\mathbf{r}_2,t+\tau)\right\rangle} = 1 + |\gamma|^2 \le 2$$

Blue to UV

Such correlation is proportional to $|\gamma_{12}|^2$, namely to the square of the ***fringe visibility in the Michelson interferometer.***

Van Cittert - Zernike theorem

In Michelson interferometry, each pair of telescopes measure $\gamma(\mathbf{r})$: fringe contrast and phase of complex EM wave. This yields one Fourier component of the light distribution of the star, $I(\mathbf{k})$

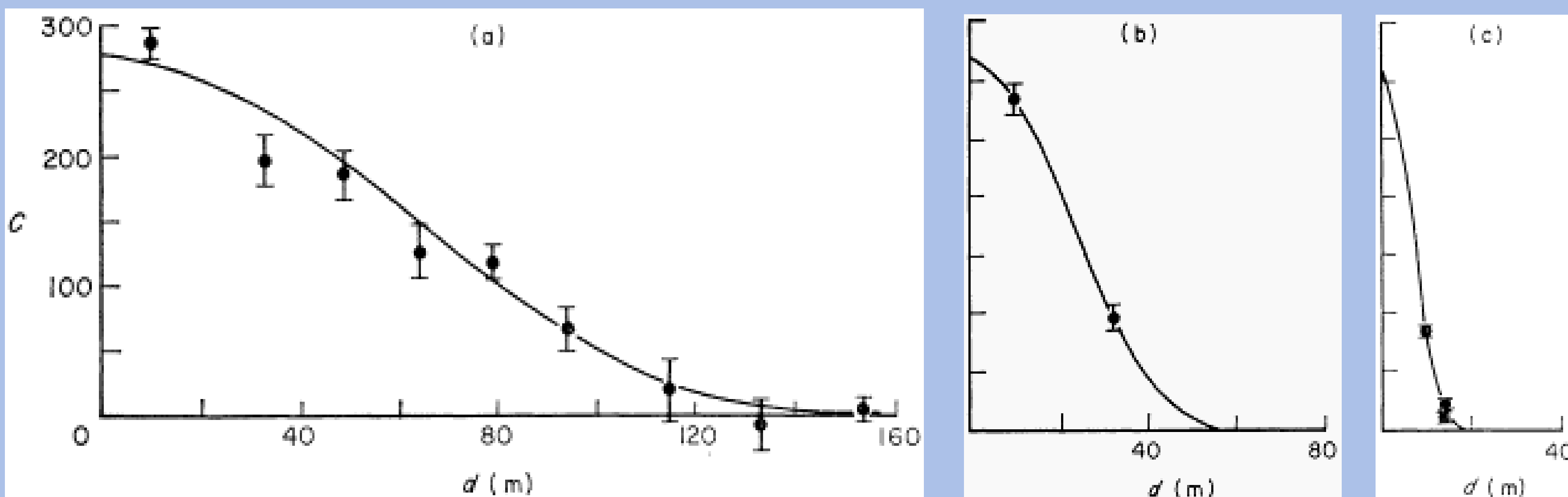
In *intensity* interferometry every two collectors are correlated to give $\gamma^{(2)}(\mathbf{r})$:

Sensitivity grows with ***area*** and with square root of ***electrical bandwidth***

Accuracy only required for ***electronic bandwidth***, a few centimeters, ***not fractions of a wavelength***.

Original results of HBTII

The measured correlation is proportional to $<\Delta I_1 \Delta I_2>$, where $\Delta I = I - I_{av}$ is the fluctuation of I (Bose Einstein statistics). ***Therefore the diameter*** of the star can be obtained, and if one had sufficient S/N also the ***limb darkening*** from the second lobe.



CHANGE OF CORRELATION WITH BASELINE (a) Beta Cru (B0 IV); (b) Alpha Eri (B5 IV); (c) Alpha Car (F0 II).

Future of HBTII?

•Quite recently, HBTII has been resurrected for a variety of reasons:

• ease of adjusting the time delays of the channels to equality within few centimeters (***electronic instead of optical*** path compensation);

• immunity to seeing: ***adaptive optics is not required;***

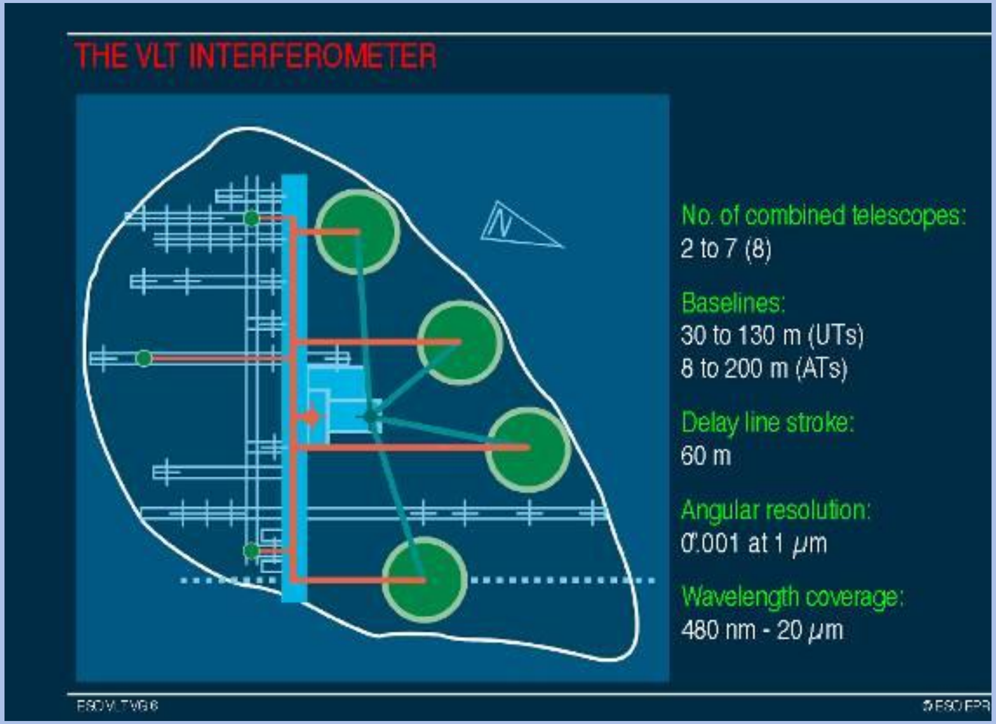
• ***blue sensitivity*, **with the possibility to utilize the large body of data obtained in the Near-IR from Michelson-type interferometers and to supplement their data with observations in this spectral region**;**

• ***Main Sequence blue stars can be reached***, and not only the red Giants and SuperGiants commonly studied with Michelson interferometers.

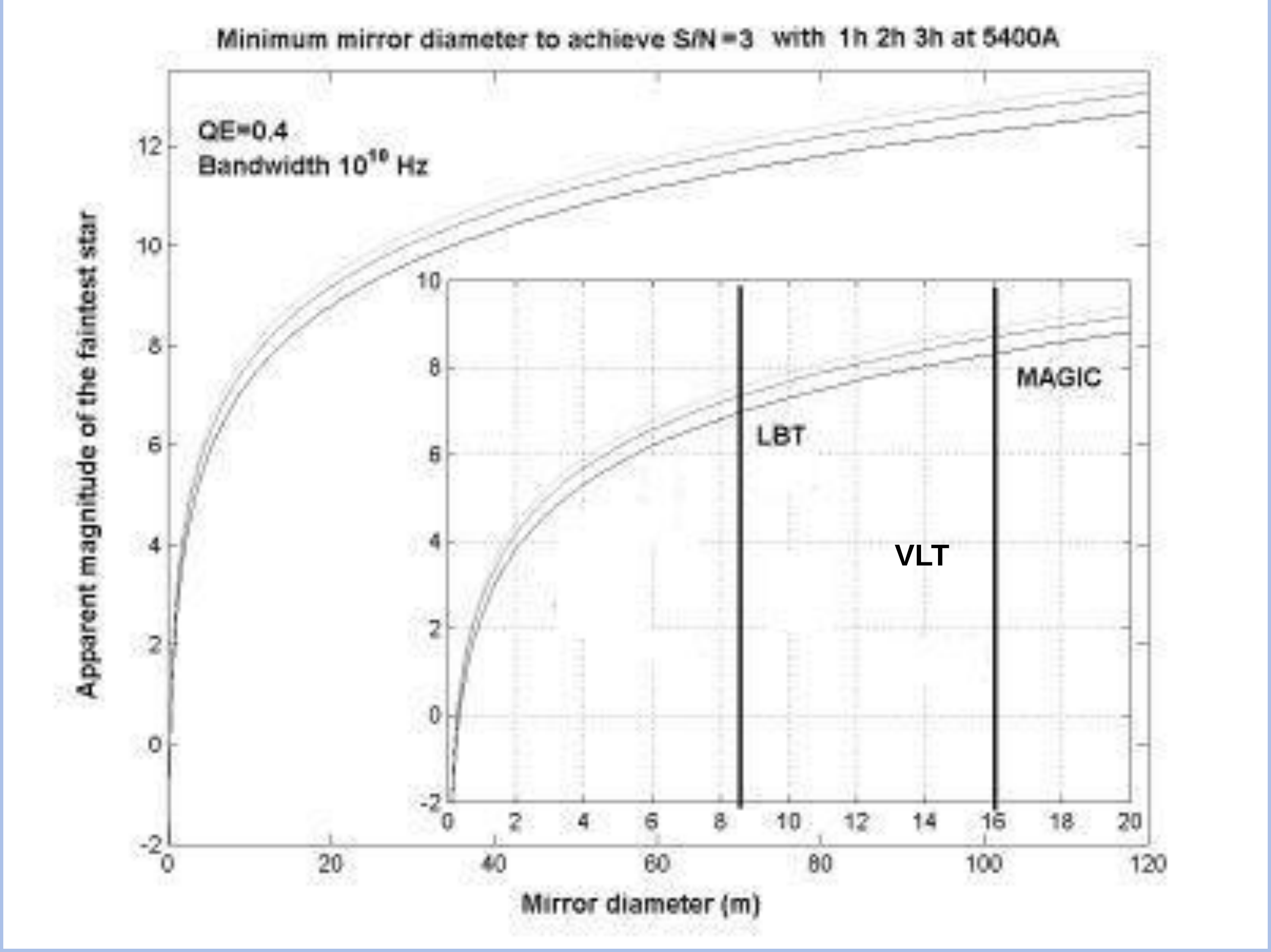
Very Long Baseline Optical Interferometry

A further advantage of HBTII is that ***no optical link is needed***: it can be performed with *two distant* telescopes not in direct view. Only time tagging to better than say 1ns and proper account of atmospheric refraction and delays..

With little effort it could be tested also with two telescopes of the ESO VLT.



HBTII with Cherenkov Light Telescopes



The concept is currently being tested by D. Dravins and collaborators with ***VERITAS Cherenkov light telescopes in Arizona***

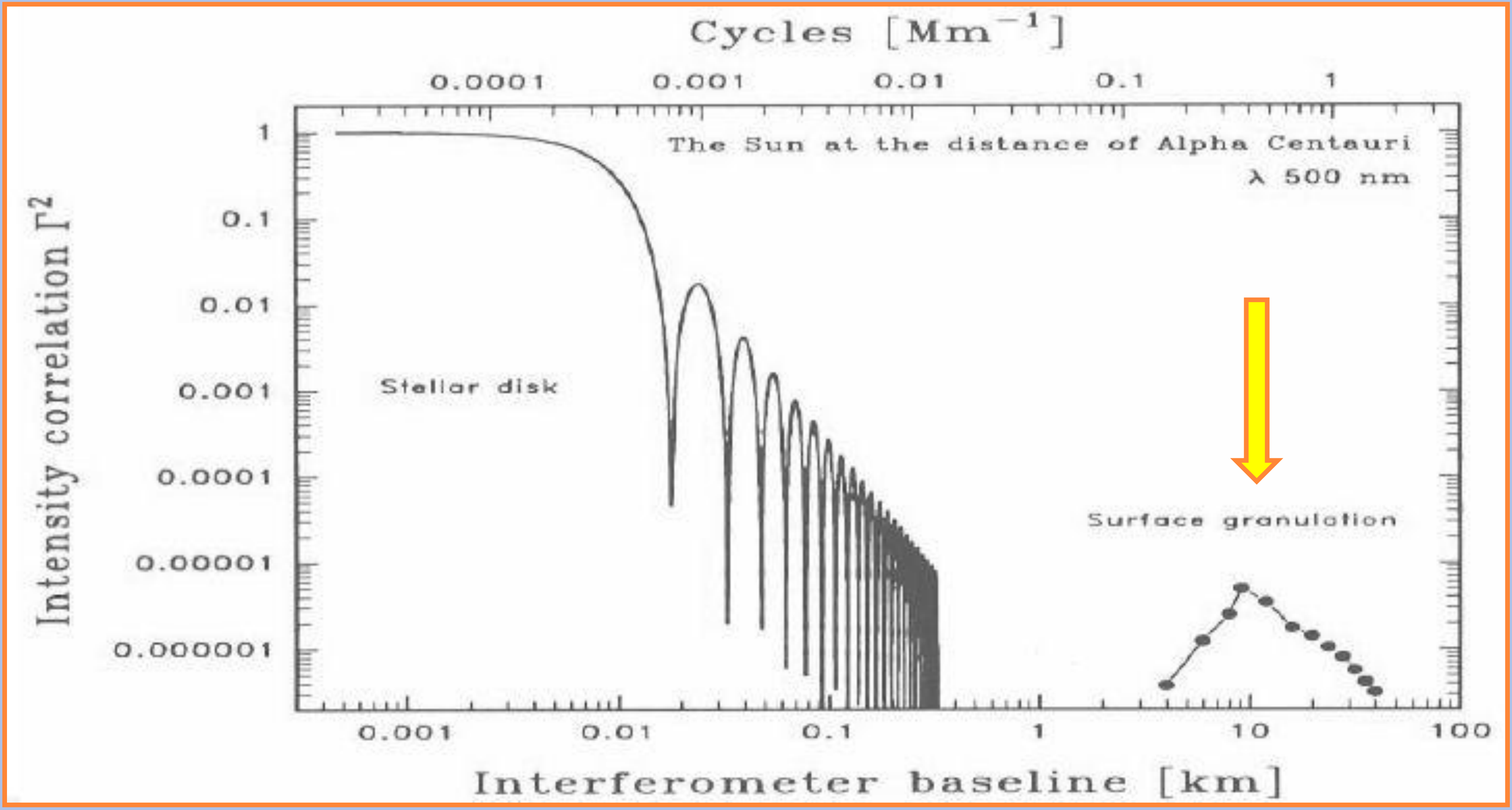
Futuristic: HBTII VLT - E-ELT?

2020? E-ELT: Quantum Astronomy

E-ELT – VLT: an exciting realization of HBTII

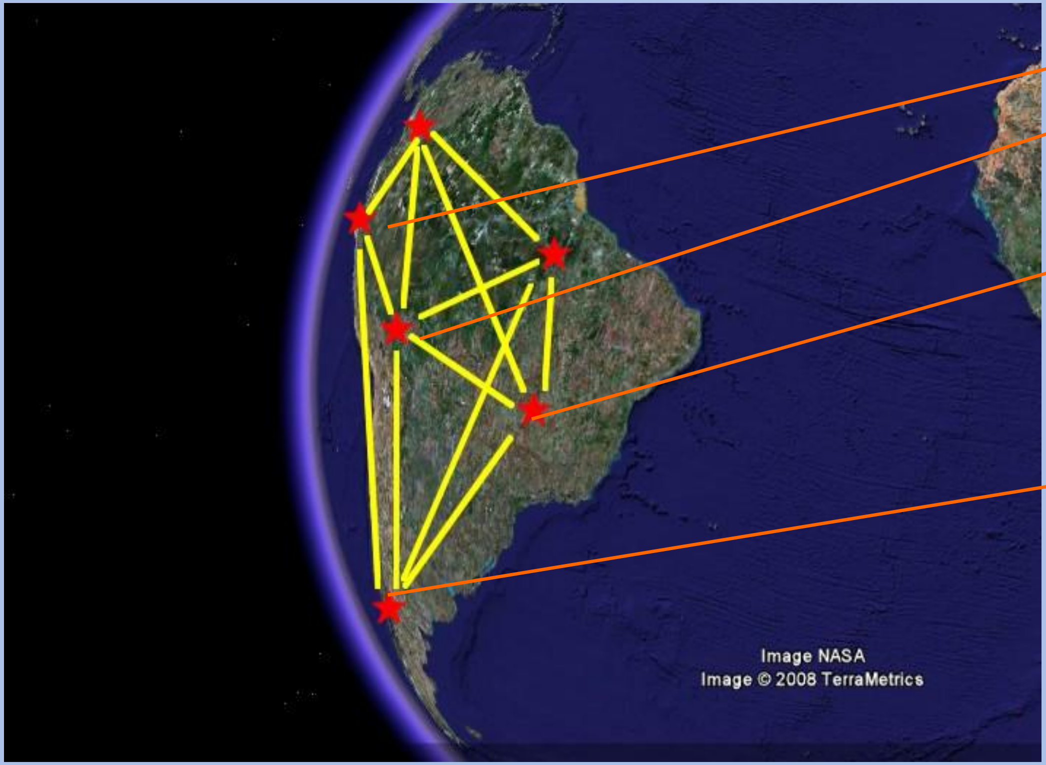
Paranal and Armazones are 22km apart, in an almost E-W configuration. The rotation of the Earth will perform the synthesis, pushing the angular scale by 100x from VLTI (200m).

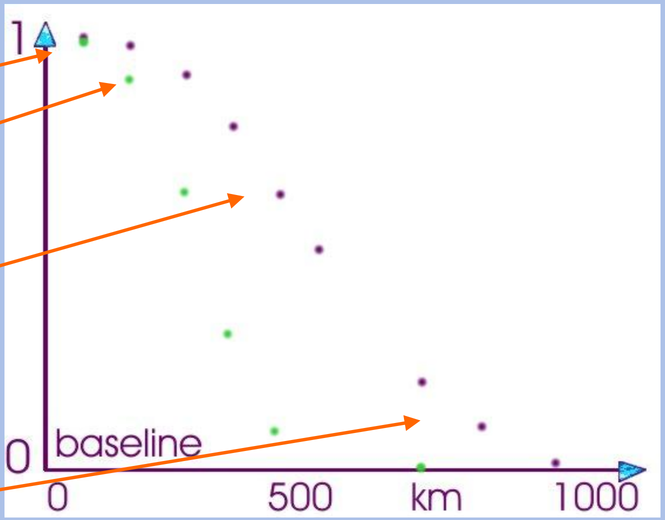
A possible result E-ELT – VLT HBTII



Dreaming a bit

A network of telescopes, allowing multi-dimensional HBTII performed by means of post-process data analysis.





Sub-microarcsec resolution!

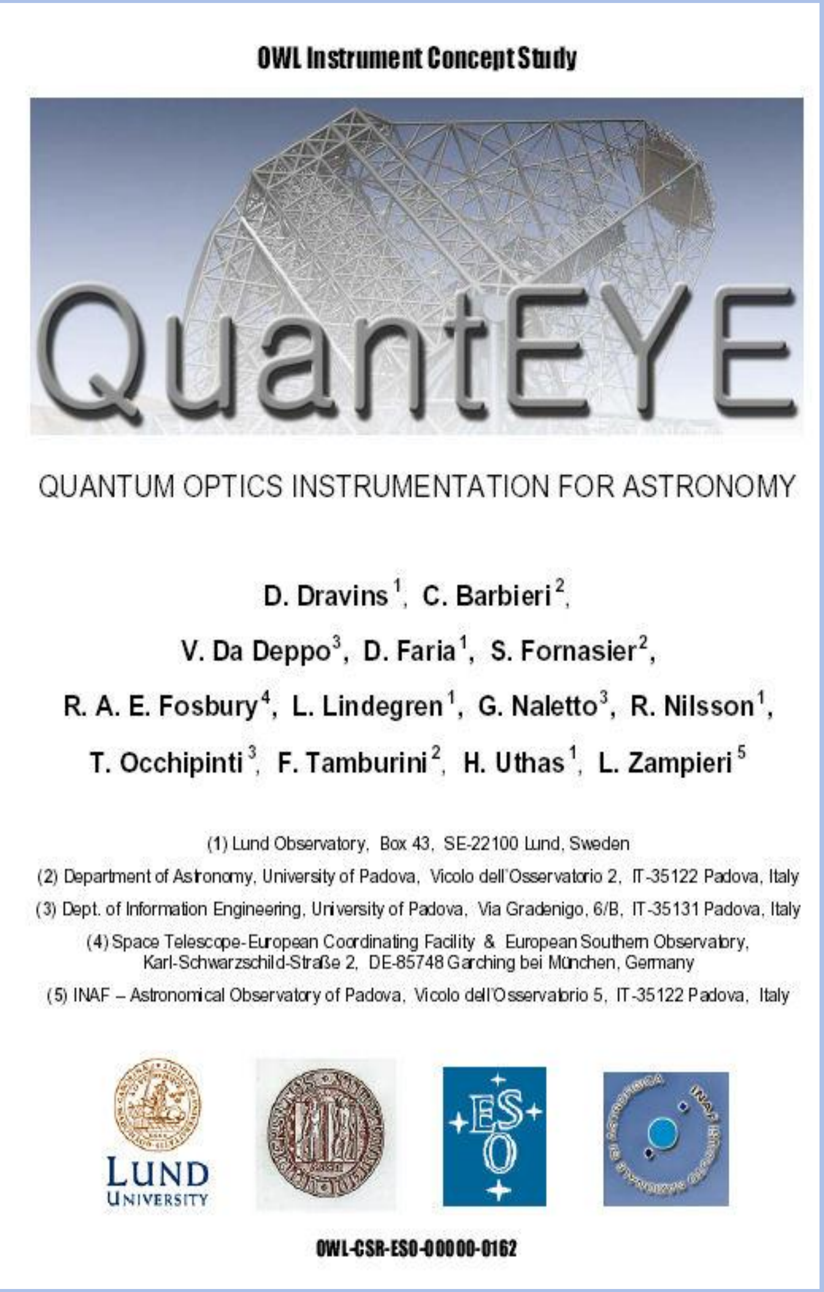
Why Extremely Large Telescopes?

The above mentioned quantum correlations are fully developed on time scales of the order of the *inverse optical bandwidth*. For instance, with the very narrow band pass of 1 A (0.1 nm) in the visible, through a definite polarization state, typical time scales are $\approx 10^{-11}$ seconds (10 picoseconds).

However, the photon flux is very weak even from bright stars, so that only Extremely Large Telescopes (ELTs) can bring Quantum Optical effects in the astronomical reaches.

Telescope diameter	Intensity $\langle I \rangle$	Second-order correlation $\langle I^2 \rangle$
 3.6 m	1	1
 8.2 m	5	27
 4 × 8.2 m	21	430
 50 m	193	37,000

***The amplitude of second order functions increases with the square of the telescope area* (not diameter!), so that a 40m telescope will be 256 times more sensitive to such correlations than the existing 8-10m telescopes.**


OWL Instrument Concept Study

QuantEYE

QUANTUM OPTICS INSTRUMENTATION FOR ASTRONOMY

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V. Da Deppo[3], D. Faria[1], S. Fornasier[2],
R. A. E. Fosbury[4], L. Lindegren[1], G. Naletto[3], R. Nilsson[1],
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LUND UNIVERSITY

ESO

OWL-CSR-ESO-00000-0162

In Sept. 2005, we completed a study (***QuantEYE***, the ESO Quantum Eye) in the frame of the studies for the (then) 100m Overwhelmingly Large (OWL) telescope**.**

The main goal of the study was to demonstrate the possibility to reach the picosecond time resolution (***Heisenberg limit***) needed to bring quantum optics concepts into the astronomical domain, with two main scientific aims in mind:

- ***Measure the entropy of the light beam through the statistics of the photon arrival time.***
- ***Demonstrate the feasibility of astronomical photon correlation spectroscopy and of a modern version of the Hanbury Brown Twiss Intensity Interferometry.***

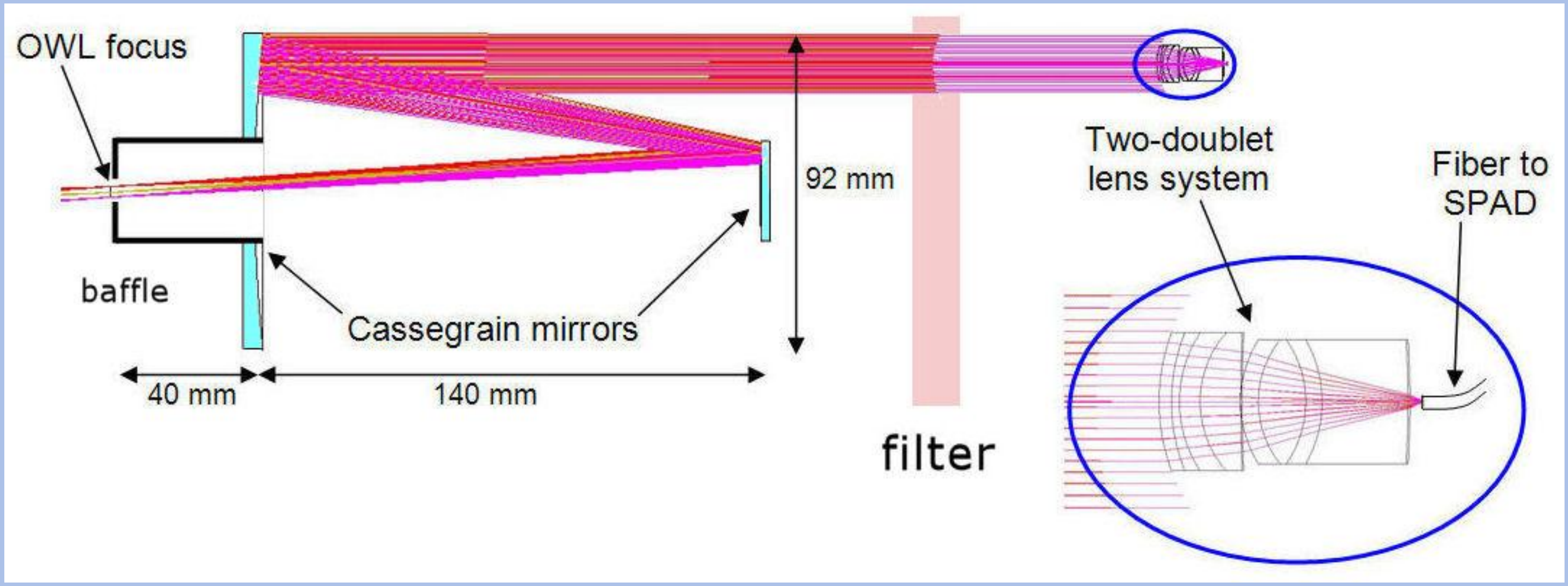
From theory to reality: the key technological limitation is the detector

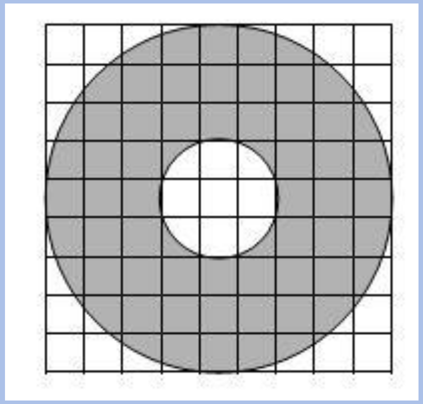
The most critical point, and driver for the design of Quanteye, was the selection of very fast, efficient and accurate ***photon counting detectors***.

No detector on the market had all needed capabilities: In order to proceed, we choose ***SPADs operating in Geiger mode***. They give ≈35 ps time resolution with count rates as high as 15 MHz, and a fair QE. The main drawback of SPADs was the lack of CCD-like arrays.

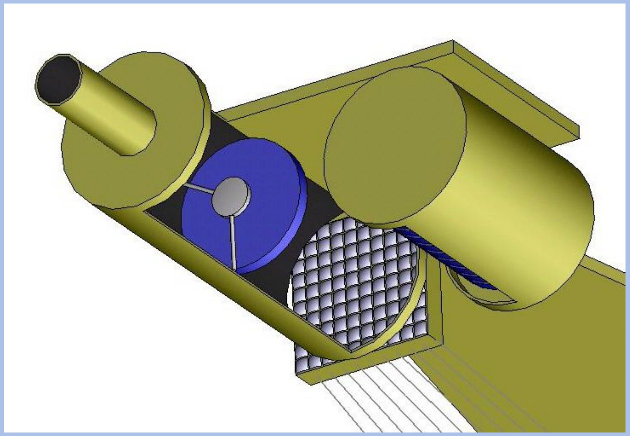
To overcome both the SPAD limitations and the difficulties of a reasonable optical design (coupling the pupil of large telescope to a single 50 - 100 μm detector), we decided to ***split the problem***: we designed QuantEYE by subdividing the pupil into **10 × 10 sub-pupils**, each of them focused on a single SPAD, giving a total of ***100 distributed*** SPAD's. In such a way, a "sparse" SPAD array ***collecting all light and coping with the required very high count rate*** could be obtained. The distributes array samples the telescope pupil, so that a system of ***100* parallel smaller** telescopes is realized, ***each one acting as a fast photometer.***

QuantEYE optical design





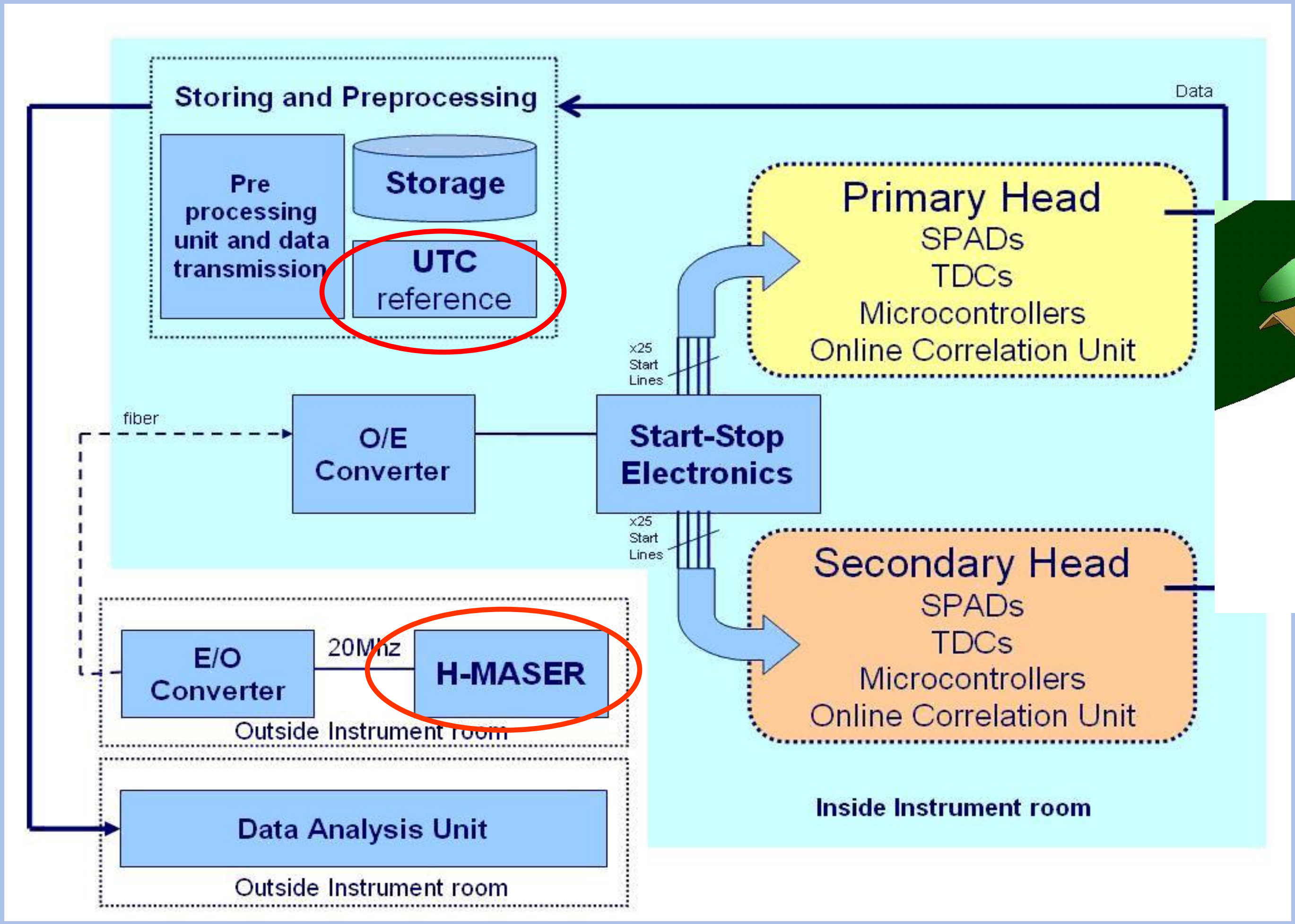
telescope pupil subdivision

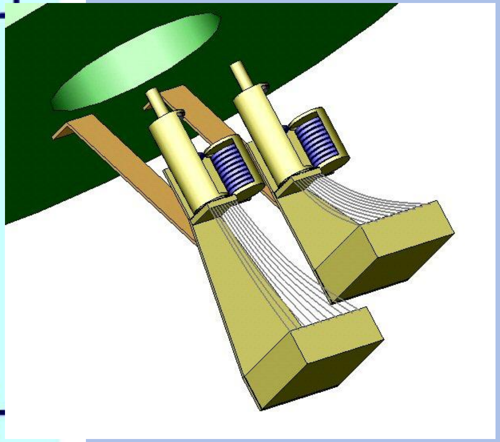


Advantages of this optical design

- The global count rate is statistically increased by a factor N^2 with respect to the maximum count rate of a single SPAD. In the assumption of having $N = 10$ (100 SPAD's), the global count rate becomes 1 GHz (one photon every 100 ns on each SPAD);
- Simpler optical design;
- Detector redundancy;
- By suitable cross-correlations of the detected signal, a digital HBT intensity interferometer is realized among a large number of different sub-apertures across the full ELT pupil.

Overall QuantEYE block diagram

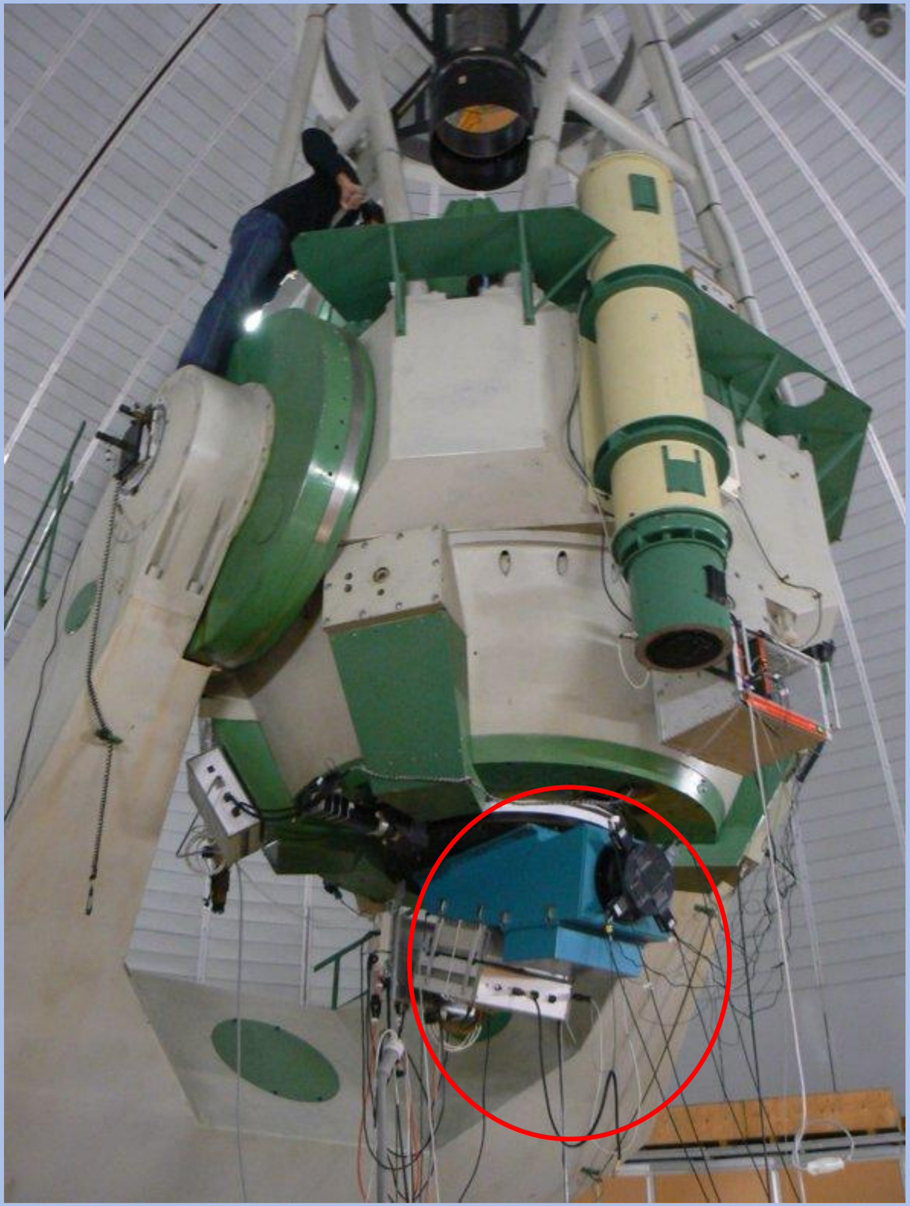




The overall system: two heads, controls, storage, time unit.

AquEYE

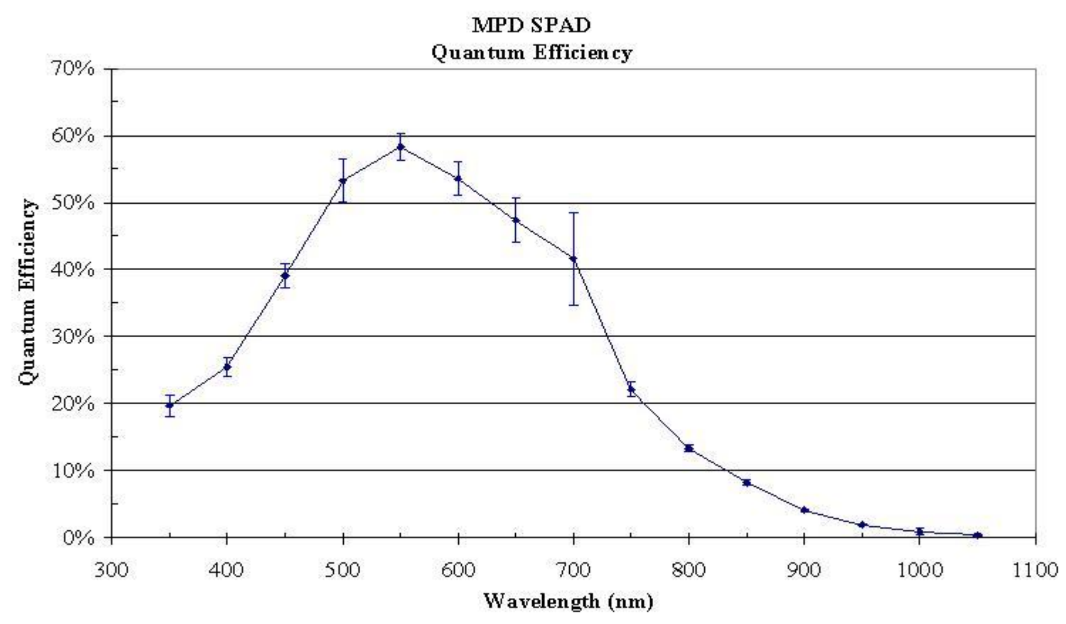
The Quanteye concepts was tested with a much smaller version of the instrument, named AquEYE, the Asiago Quantum Eye.
It is mounted on the AFOSC camera of the Asiago-Cima Ekar (Italy) 182 cm telescope (AFOSC plays the role of a 1:3 focal reducer).



MPD’s SPADs

The selected detectors are Geiger mode SPADs produced by MPD (Italy). They are operated in continuous mode, the timing circuit and cooling stage are integrated in a ruggedized box. The timing accuracy out of the NIM connector is around **35 ps**.

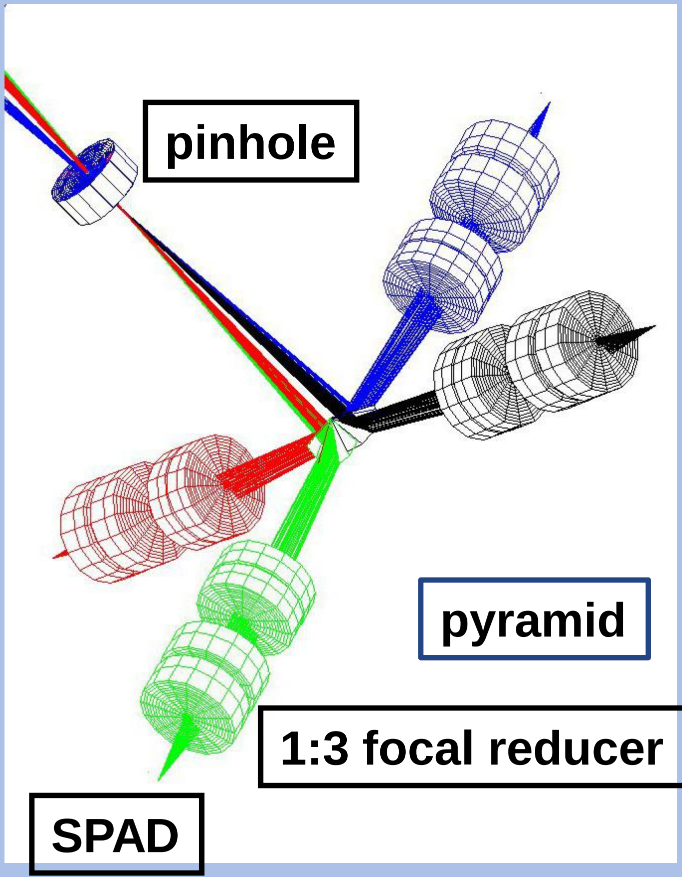
Their main drawbacks are the small sensitive area (50 – 100 μm diameter), a ≈77 ns dead time and a 1.5% afterpulsing probability.

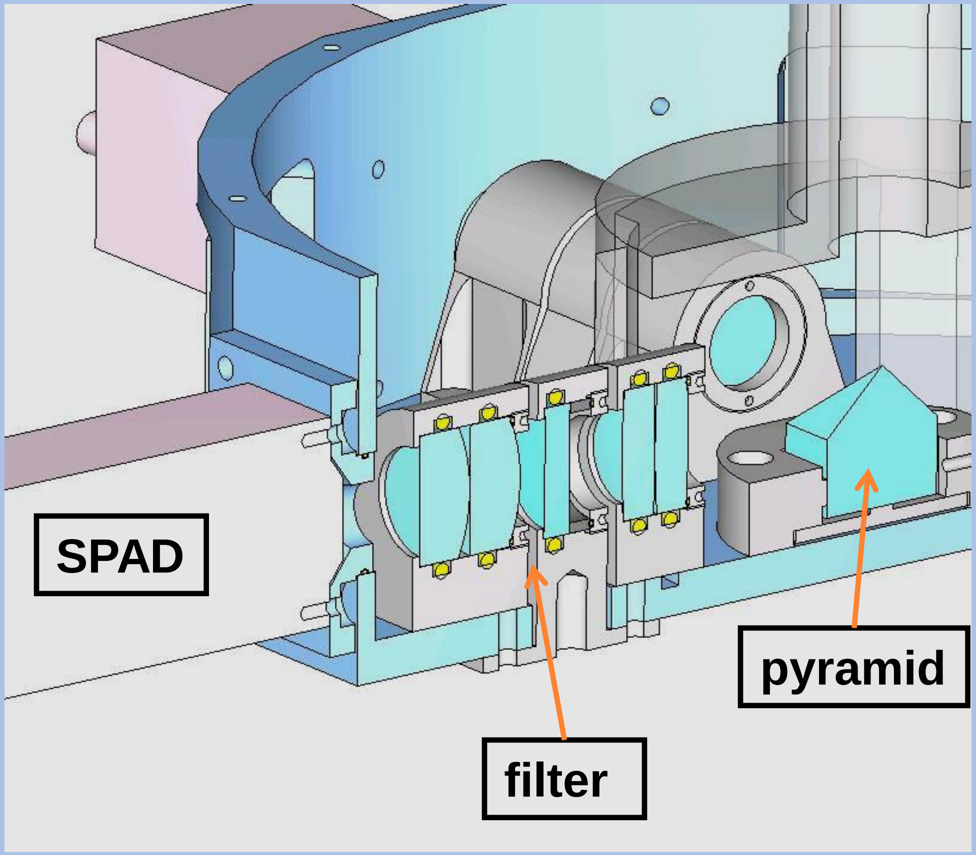


Measured at Catania Observatory

AquEYE optomechanical design

The light beam from AFOSC is divided in ***four parts*** by means of a pyramidal mirror. Each beam is then focused on its own SPAD by another 1:3 focal reducer made by a pair of doublets.

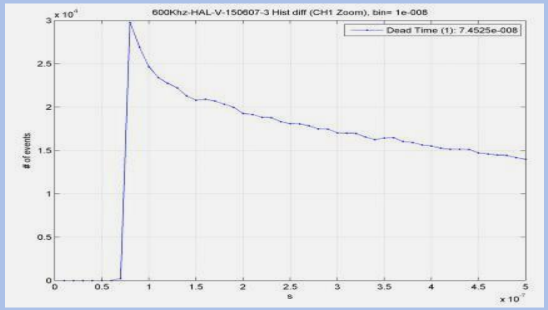


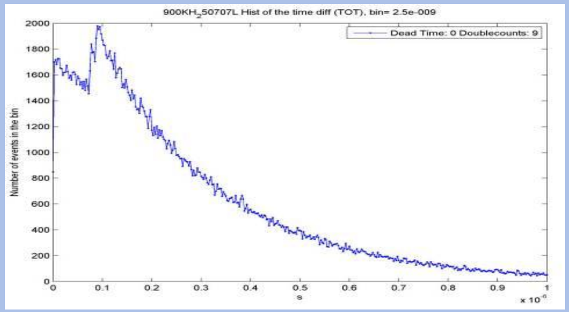


Advantages of multiple pupils

1 - In conjunction with the pupil splitting concept, by separately recording the counts, multiple detectors give the possibility of ***simultaneous multicolor photometry*** and to perform ***cross correlation of the 4 sub-apertures (HBTII experiment)***.

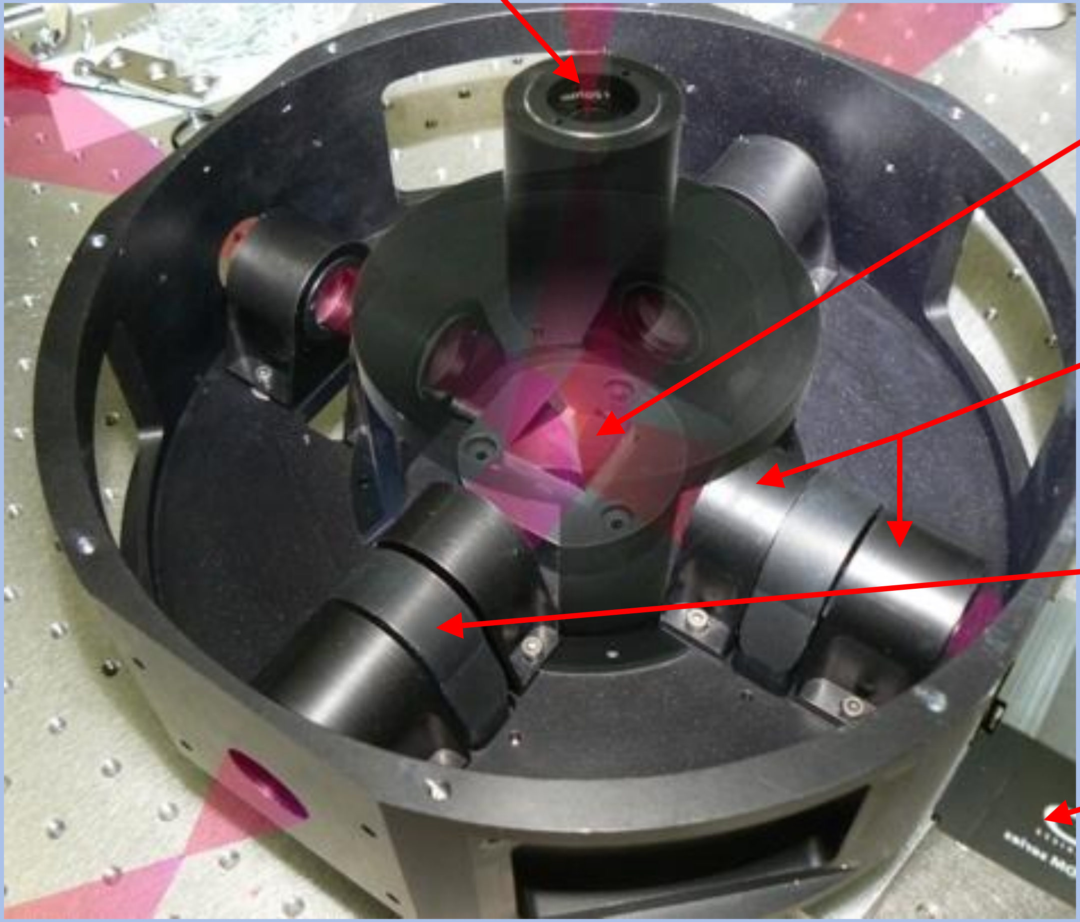
2 – when summing together the 4 outputs, we obtain a ***partial recovery of the dead time***.

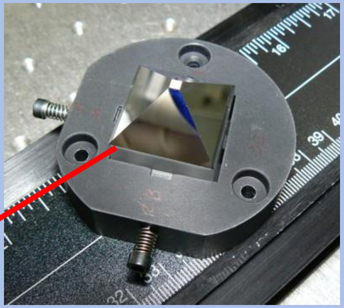




AquEYE Optomechanics

AFOSC focus





Pyramid

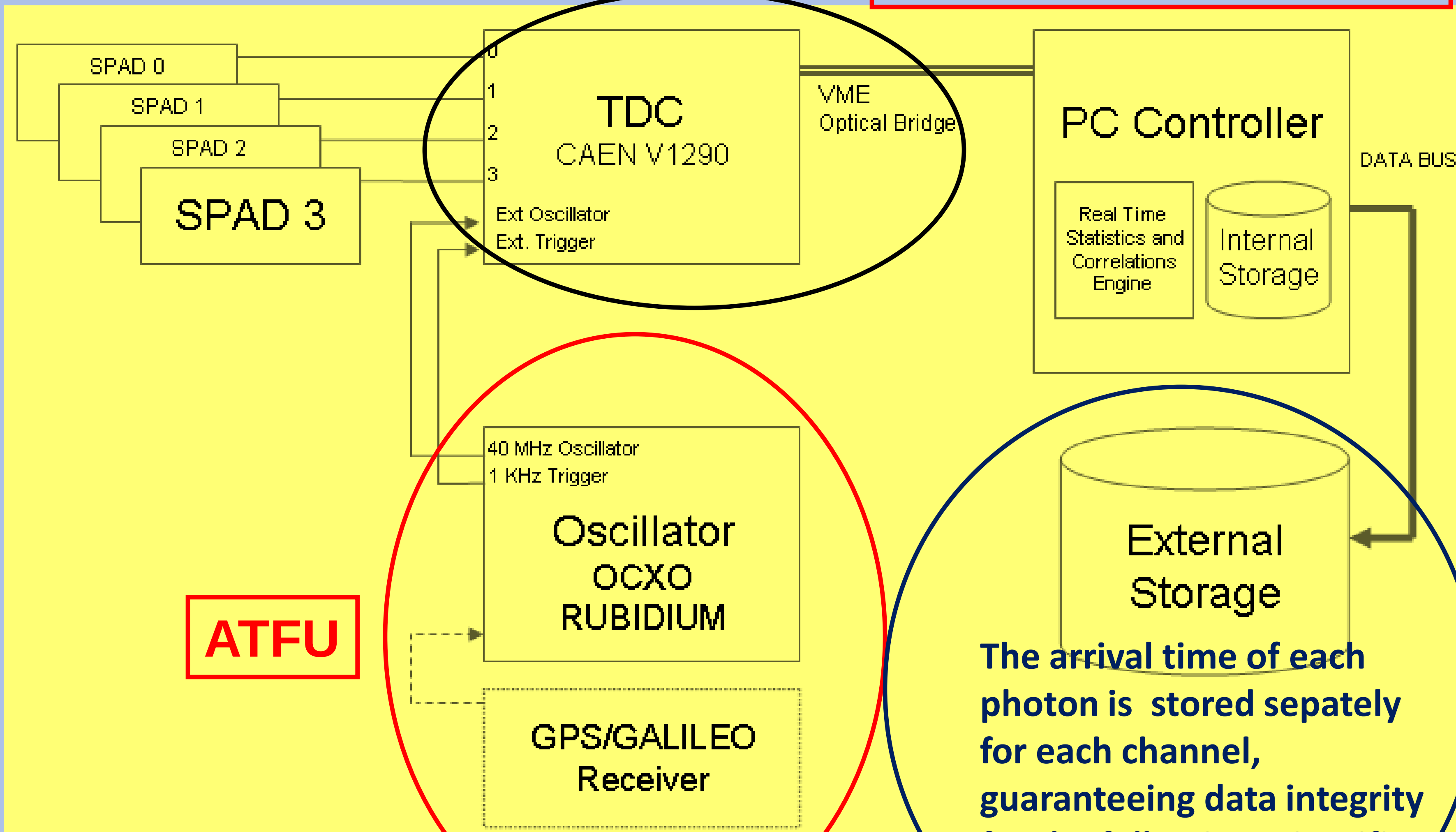
Focusing lenses

Filters

SPAD

AquEYE Electronics

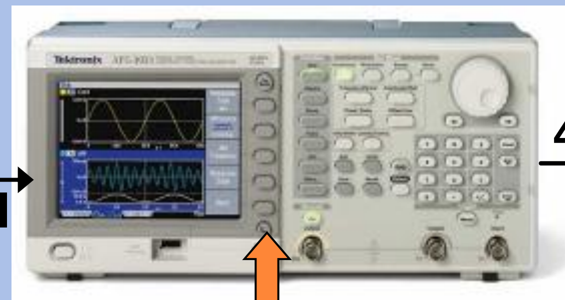
A Time To Digital Converter board originally made for CERN.



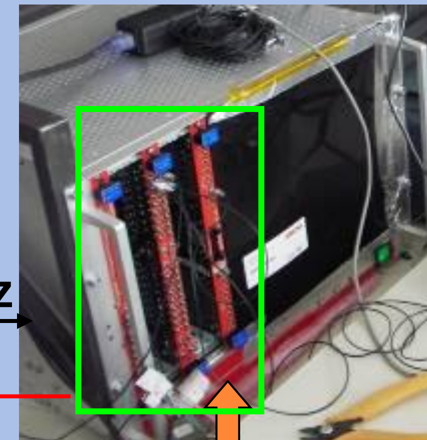
The arrival time of each photon is stored sepately for each channel, guaranteeing data integrity for the following scientific investigations.

Acquisition and Time System

10 MHz
Sinusoidal



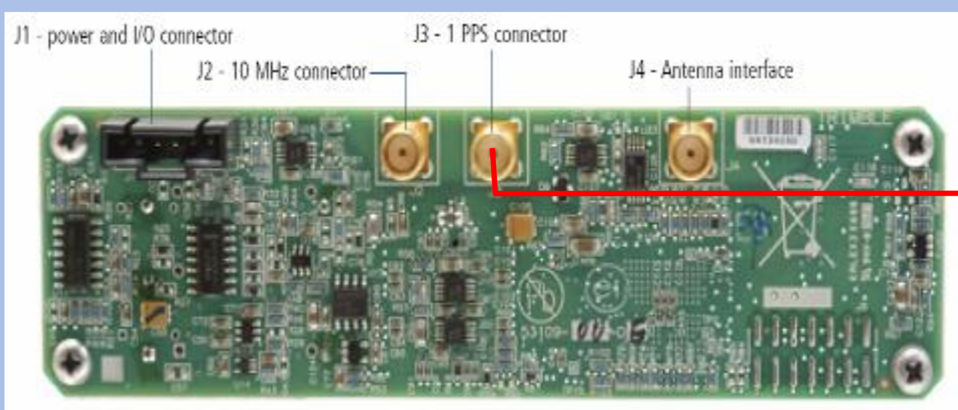
40 MHz
TTL



SRS FS725 Rubidium Frequency Standard

Tektronix AFG3251 Signal Generator

CAEN VME CRATE with V2718, V976 and V1290N

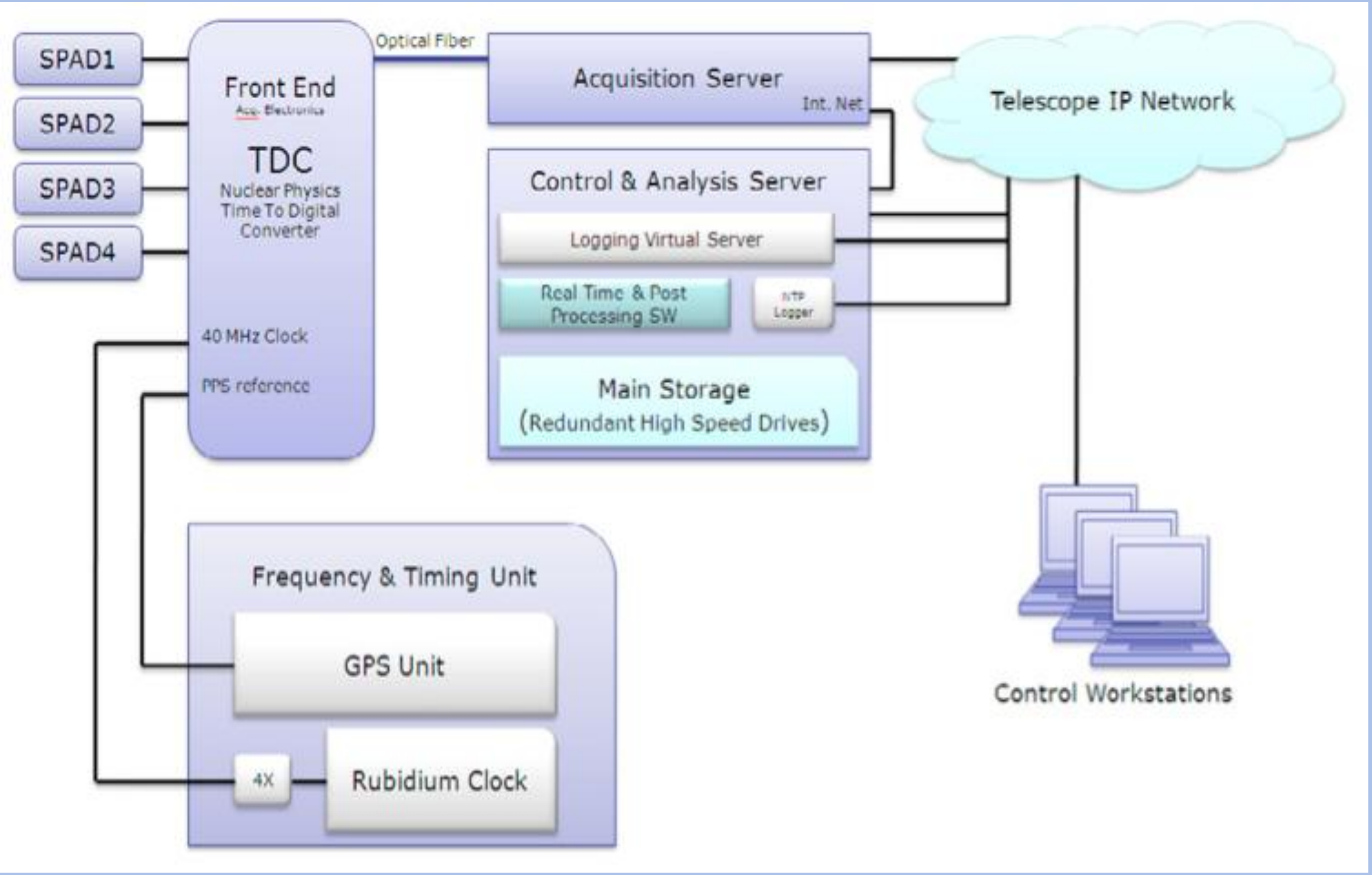


1 PPS
TTL

1 PPS
NIM

GPS receiver

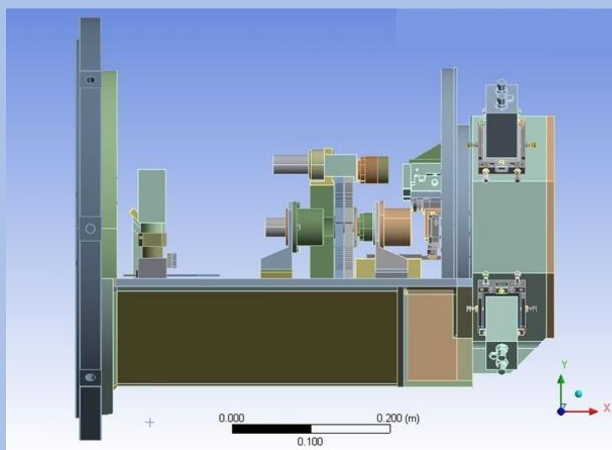
The overall system



Forthcoming improvements

We have undertaken a major refurbishment of Aqueye, to be completed in early 2013:
- AFOSC will be eliminated as entrance stage. A dedicated focal reducer is being designed
- a simple adaptive optics module will be added between the focal reducer and Aqueye, whose deformable mirror will be driven by the 4 spads
- a fifth spad will continuously monitor the adjacent sky background

From Asiago to La Silla



Thanks to the positive experience of AquEYE, it was decided to realize IquEYE, a more complex instrument for applications to a larger telescope, namely the ESO 3.5m NTT in La Silla (Chile). The same basic optical solution of pupil splitting in 4 was maintained.

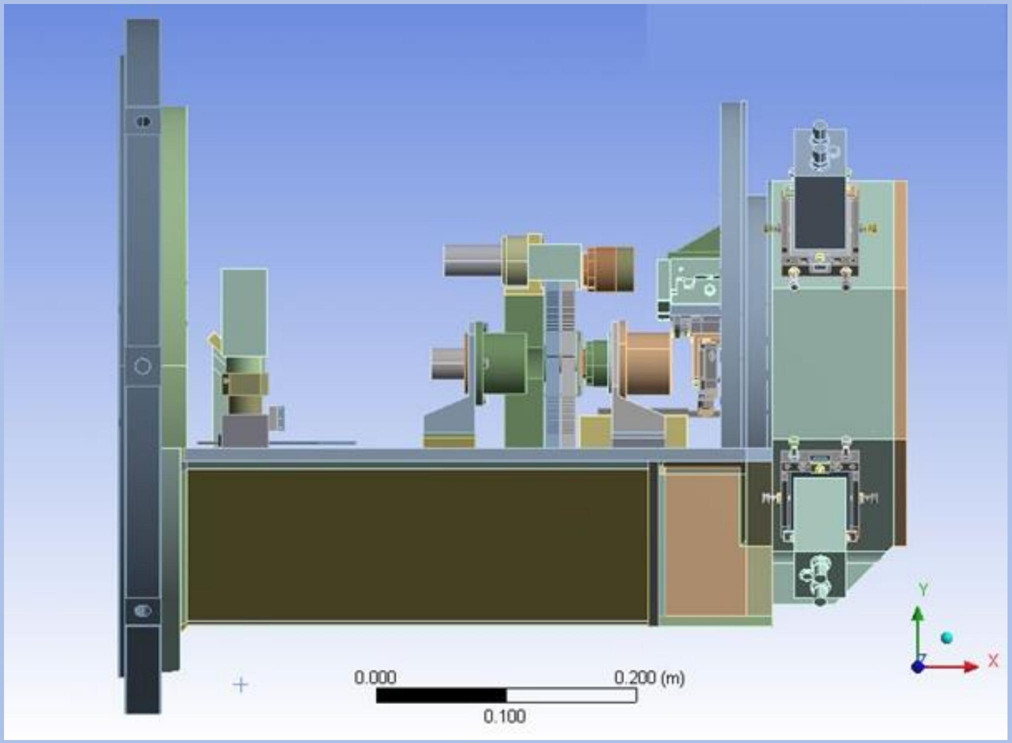
The main modification was the utilization of a new production batch of MPD SPADs, with ***100 micrometer effective area diameter, lower dark counts and better engineering***.
After a first run in Jan 2009, some improvements were introduced in Dec. 2010.

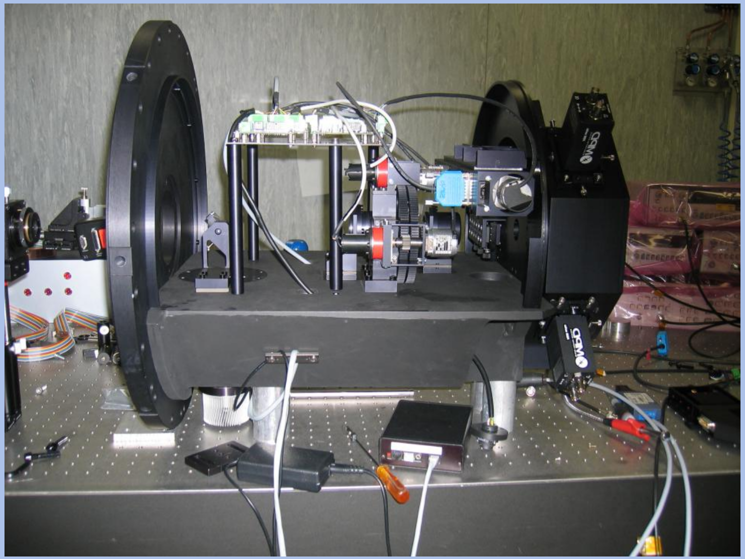
Iqueye1 SPADs data

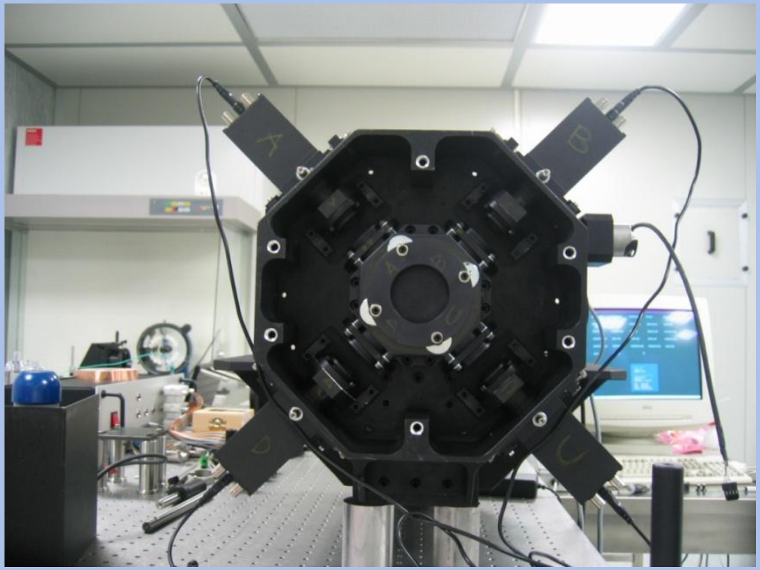
Module nr.	QE @550nm	Dark c/s	Dead time (ns)	Afterpulsing %	NIM Timing resolution (ps)
00553	0.54	18.7 +/- 4.4	77.3	1.4	29-50
00554	0.53	19.6 +/- 5.2	78.2	1.4	27-40
00556	0.52	15.8 +/- 4.1	78.0	0.9	26-50
00557	0.53	17.6 +/- 4.5	77.2	1.5	27-50

Active area: 100 micrometer diameter

IquEYE1 opto-mechanics







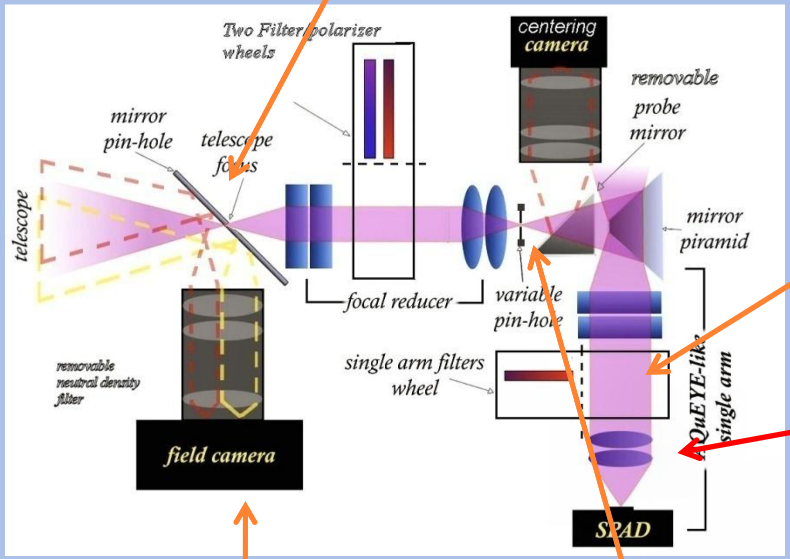
From Iqueye 1 to Iqueye 2

The run of Jan. 2009 was extremely successful, both on scientific and technical aspects.

The desirability of some improvements was also revealed, which we implemented for the second unit (Iqueye2) which was brought to the telescope in Dec. 2009, and operated again very well. Actually, the system was so reliable that operation was moved to the ‘new’ control room 2 km away from the telescope.

Iqueye - 2

A fiber fed fifth spad on the NTT focal plane to measure the sky brightness



Filter wheel in each SPAD: simultaneous multicolour photometry

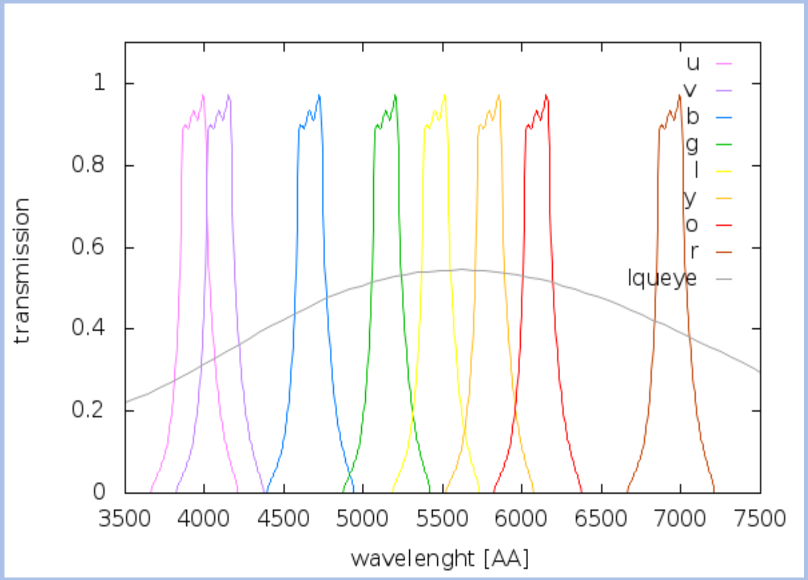
Custom made lenses for better light concentration on the SPAD (more than 99.9%)

Improved entrance pinhole and viewing camera

Control of back-scattered light

Hardware and software for data acquistion and control have been streamlined.

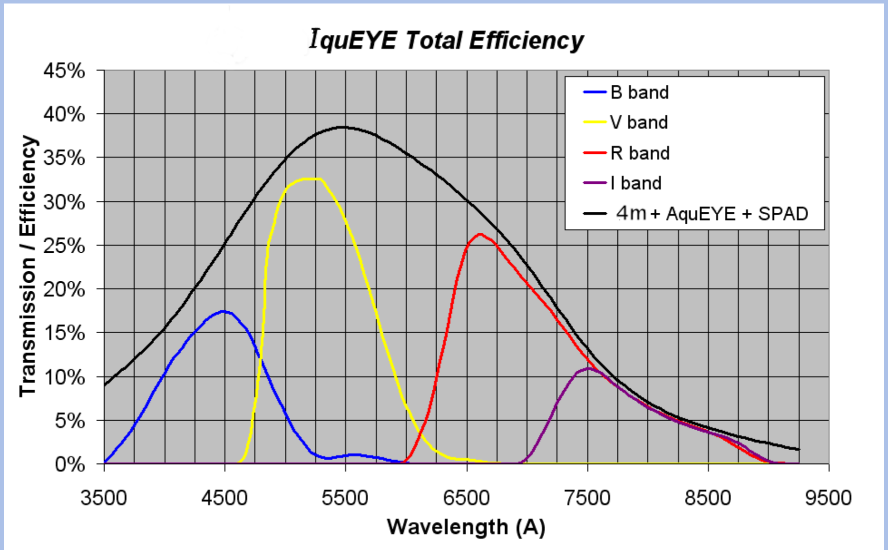
Response of Iqueye

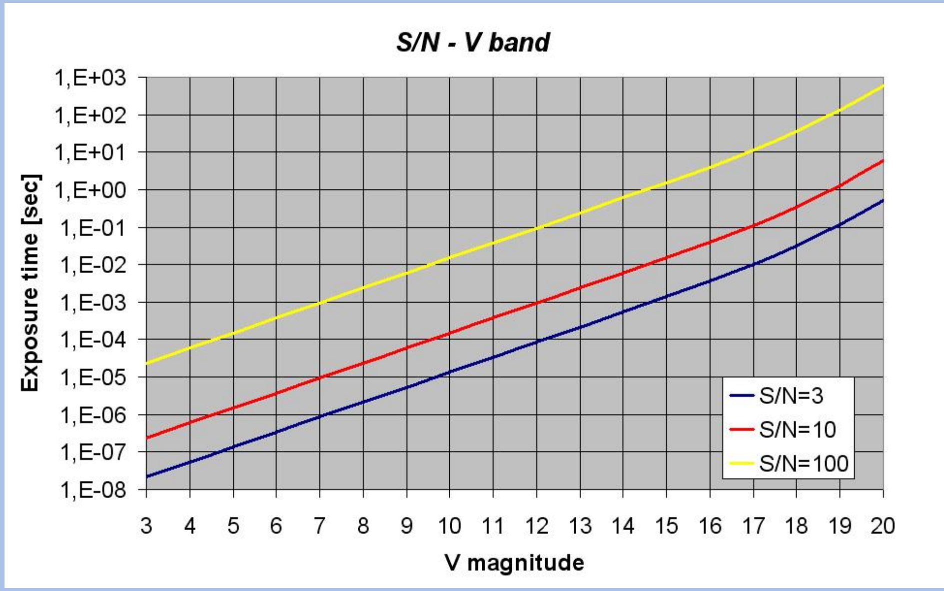


Broadband filters FWHM=100nm, central wavelenghts 450,550,650 nm

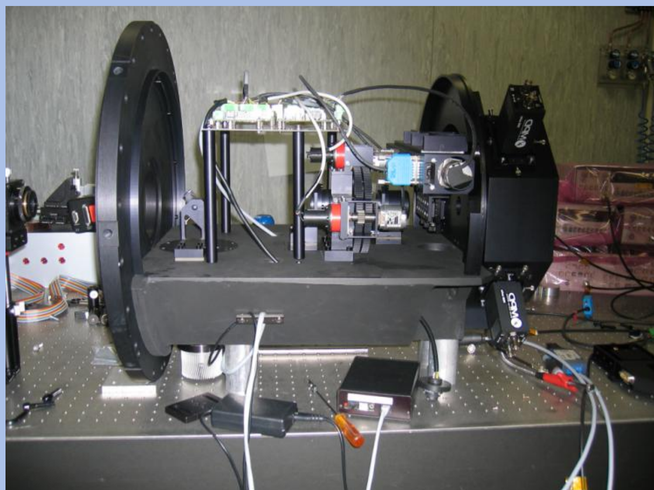
Intermediate filters, FWHM=10nm, central wavelengths: 394, 410, 467, 515, 546, 580, 610, 694 nm.

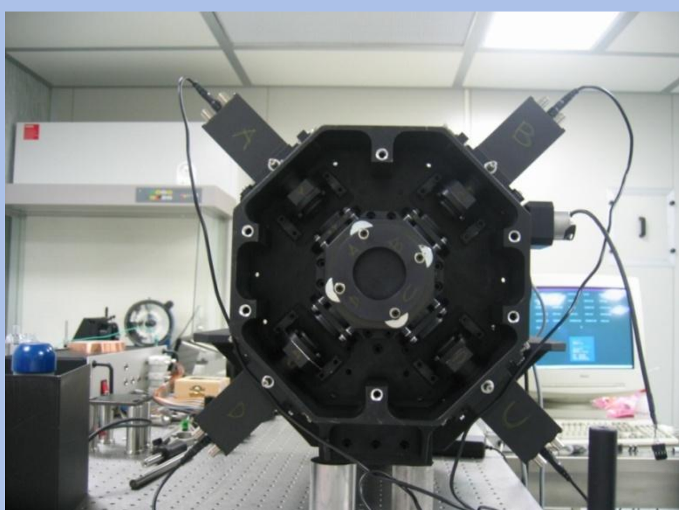
Narrow band filters: Hα (656/3 nm), O [III] (501/1 nm), He II (468/2 nm), O I(630/2 nm).

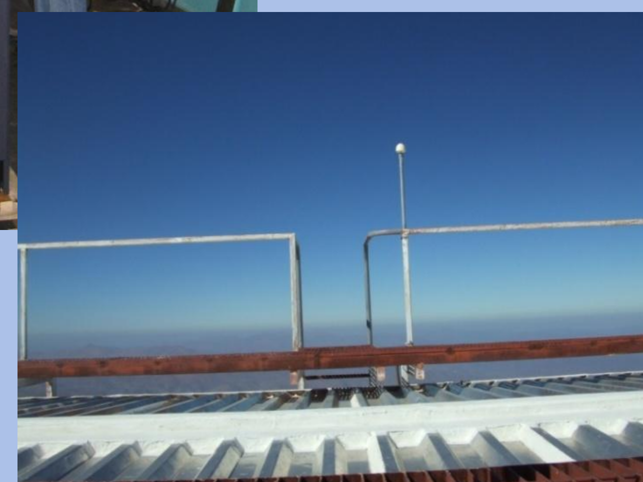




Photos of Iqueye







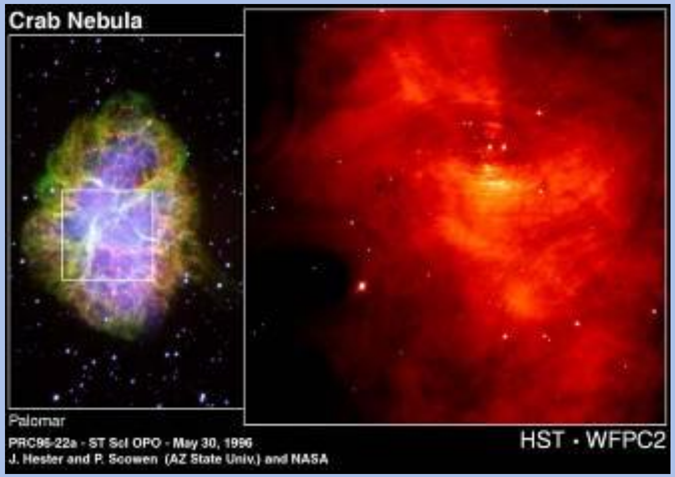
Forthcoming developments

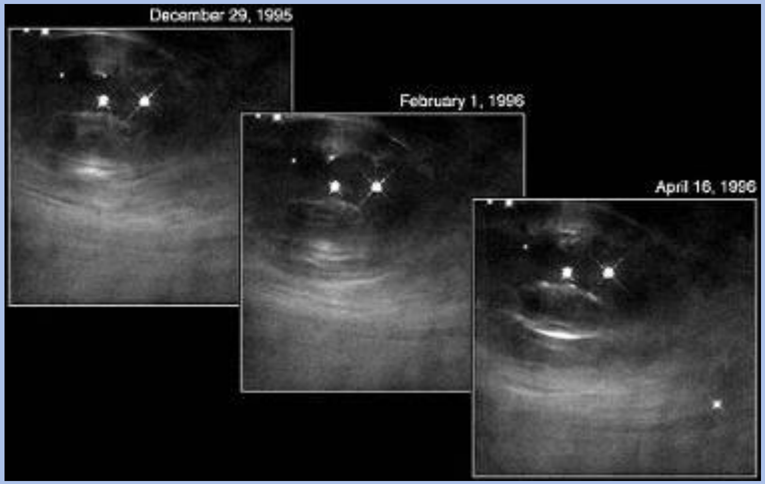
We have undertaken the study to adapt Iqueye to the Cassegrain focus of the 4.2m William Herschel Telescope on the Roque de los Muchachos.

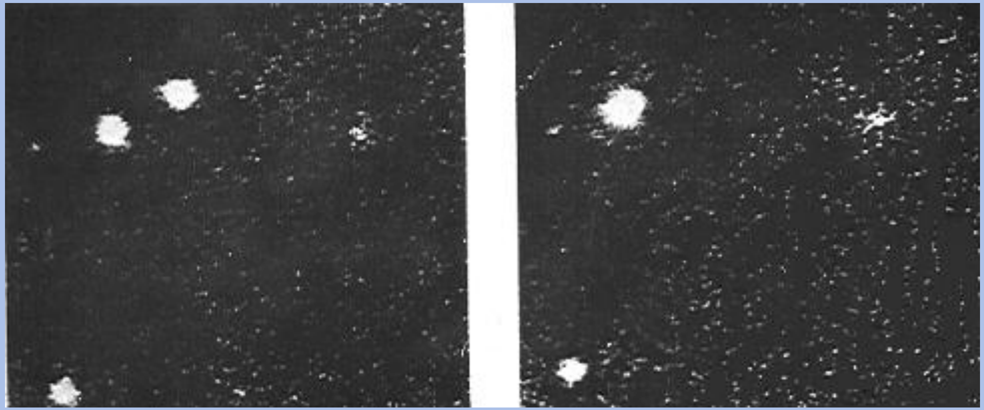
We hope to be ready for spring 2013.

Some results on optical pulsars

The pulsar in the Crab Nebula

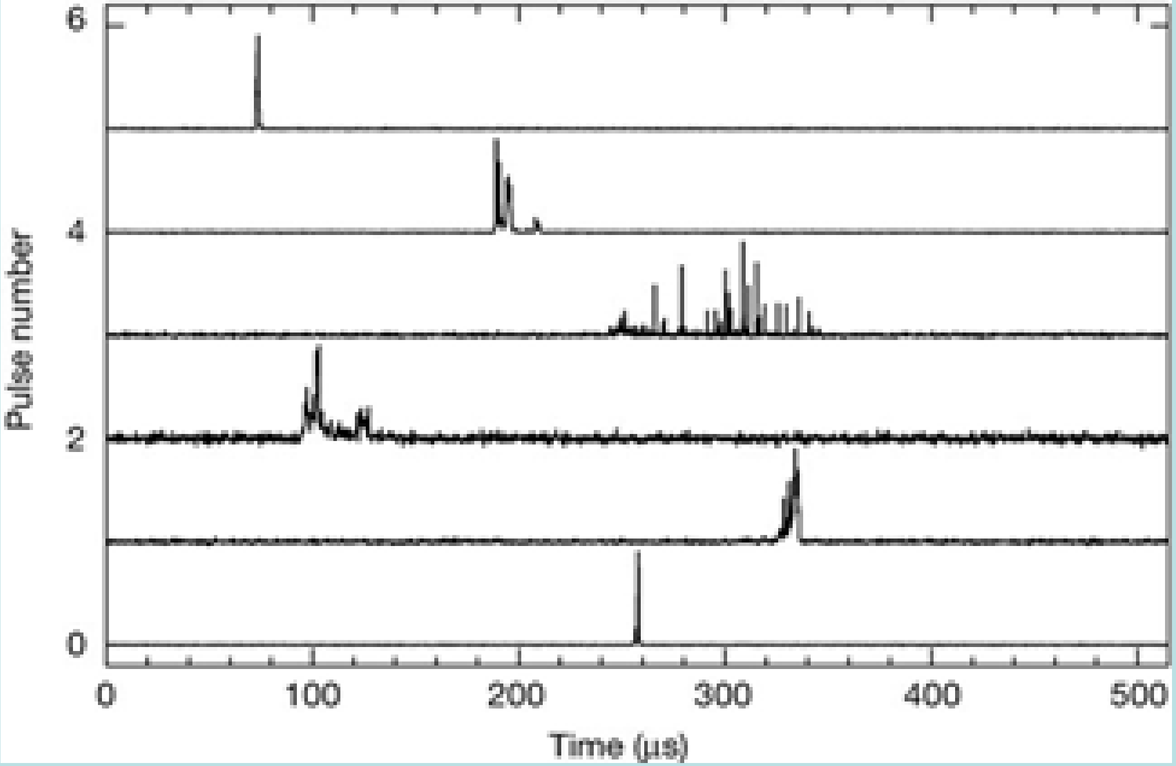






The remnant of the Supernova detected inAD 1054 by Chinese astronomers.
The Crab pulsar, with a period of 33 ms, is slowing at the rate of about 10^{-8} sec per day.
Several phenomena remain to be explained, like **the nanosecond giant radio bursts**

The ‘giant pulses’ in the Crab pulsar

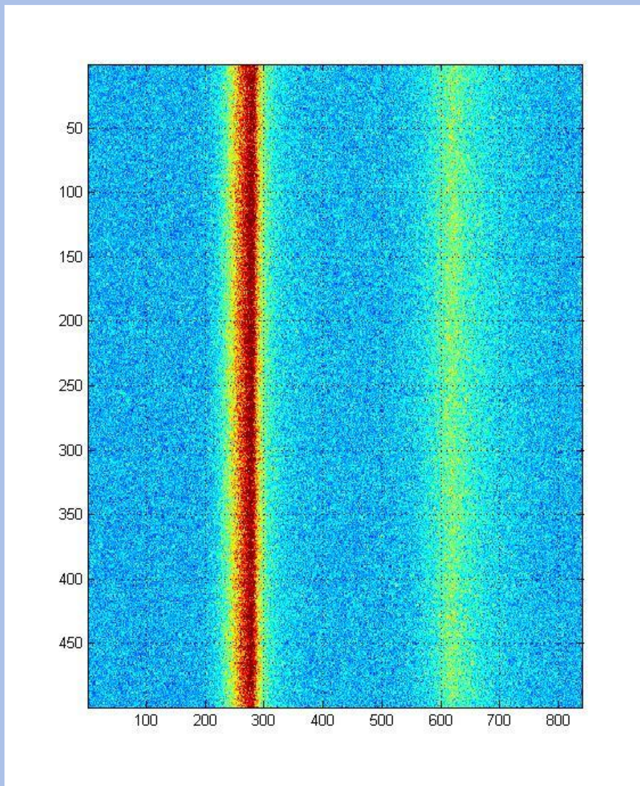


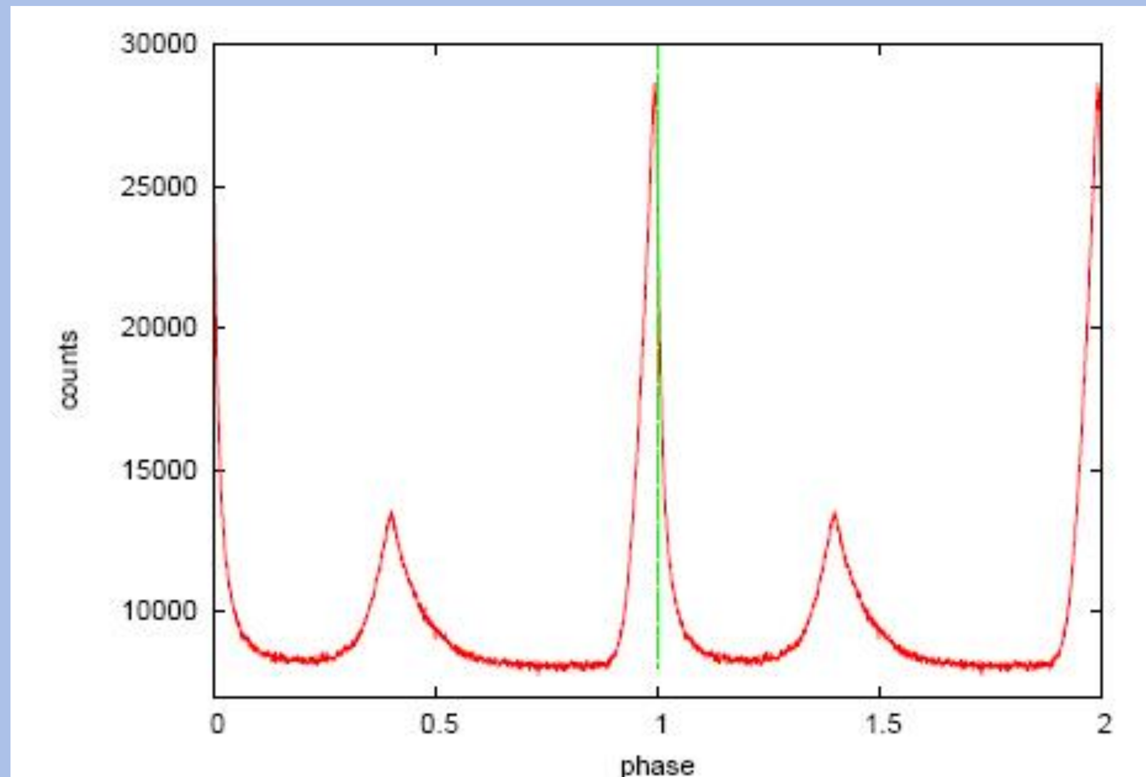
$T_b \geq 5\times10^{37}$ K, the highest brightness temperature observed in the Universe.
The dimension of the emitting region cannot be much greater than one meter.

T.H. Hankins, J.S. Kern, J.C. Weatherall, J.A. Eilek
Nanosecond radio bursts from strong plasma turbulence in the Crab pulsar, Nature **422**, 141 (2003)

Timing of the CRAB pulsar

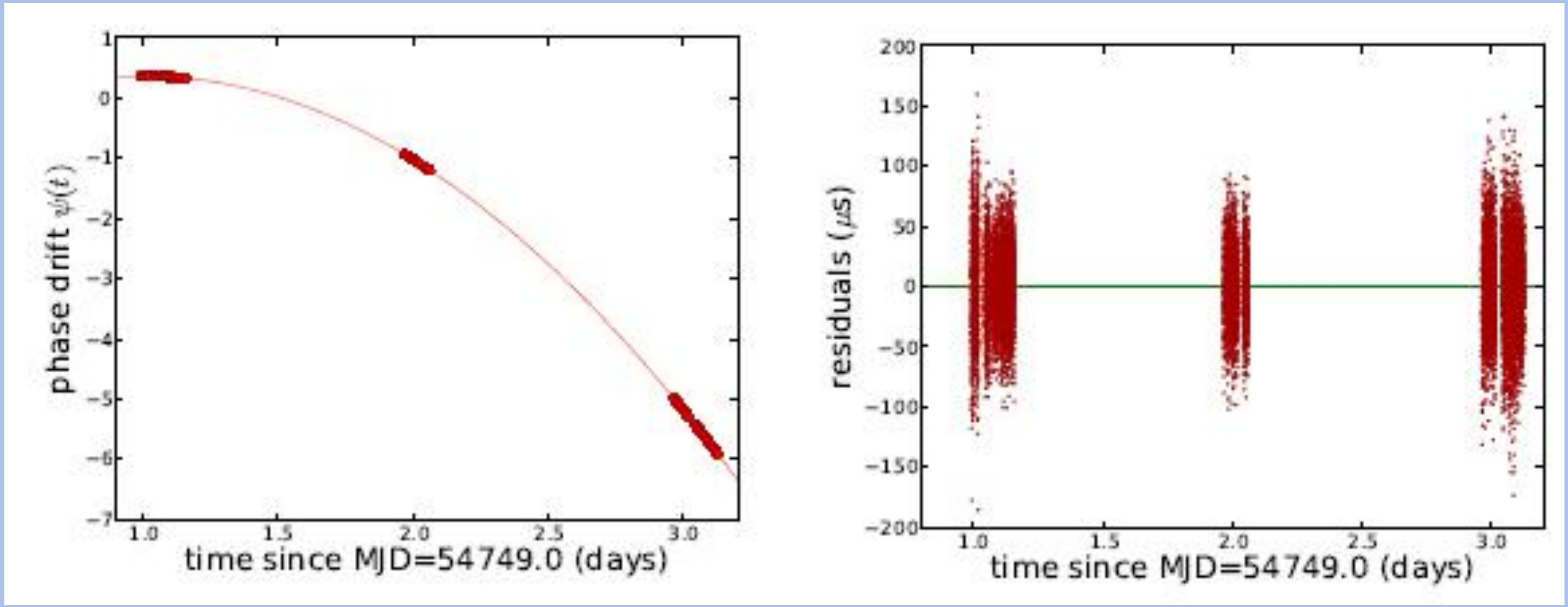
Aqueye - Two days in Oct. 2008





Folded light curve of the Crab pulsar. The folding period and the bin time are 0.0336216417 s and 33.6 μs, respectively..For sake of clarity two rotations of the neutron star are shown.
Phase zero/one corresponds to the position of the main peak in the radio band and is marked with a vertical *green dashed line.*

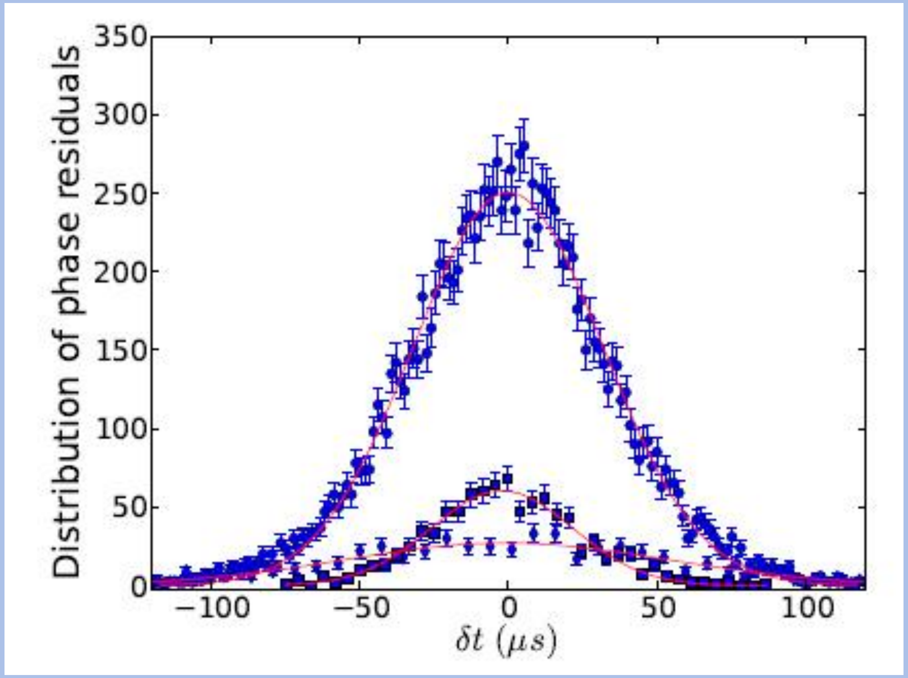
Phase drift and phase residuals

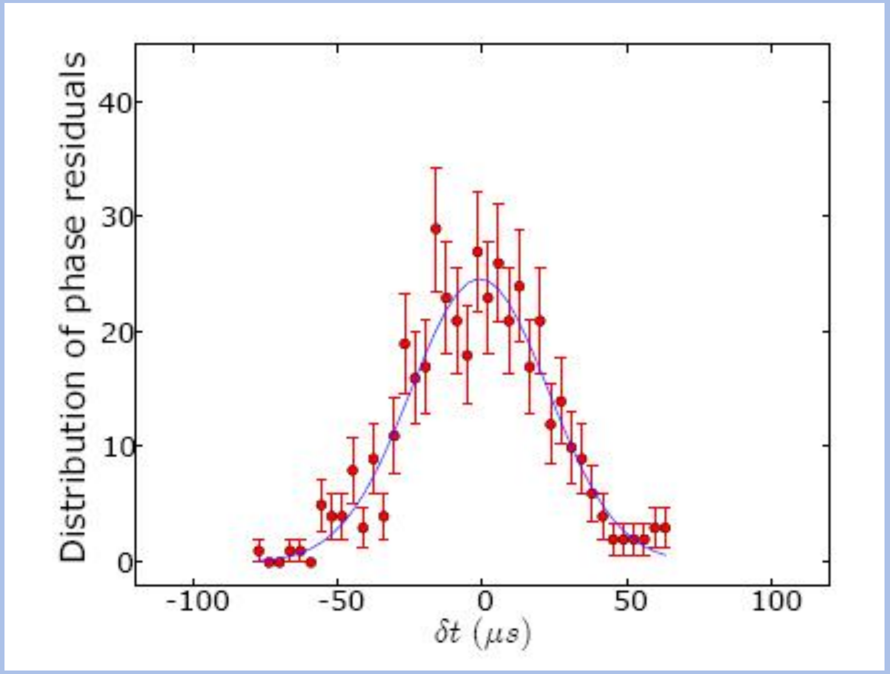


Left panel: **Phase-drift of the main peak of the Crab pulsar measured during the observing run in Asiago in October 2008. The (red) curve is the best-fitting parabola (eq[2]). The reference epoch t_0 is *MJD=54749.0,* while the reference rotational period is P_{init} *= 0.0336216386529 s.***

Right panel: **Phase residuals (in μs) after subtracting the best-fitting parabola to the phase-drift.**

Phase noise of Aqueye data





Left panel: observed phase noise; right panel: simulated phase noise. The measured width of the phase residuals distribution appears to approach the theoretical expectations for phase noise induced by *pure photon statistics*. However, more data would be welcome.

Comparison with Jodrell Bank (radio)

Rotational periods of the Crab pulsar measured by Aqueye in 2008 compared to those reported in the Jodrell Bank radio ephemerides. The time-tags were barycentered in Tempo1 emulation mode.

MJD[a]	P(Aqueye)[b] (s)	P (JB) (s)
54750.0	0.033621638649	0.033621638653
54751.0	0.033621674970	0.033621674973
54752.0	0.033621711290	0.033621711292

[a] MJD at the solar system barycenter (Tempo1 mode).

[b] σ_P=1.7 ps (68% statistical error)

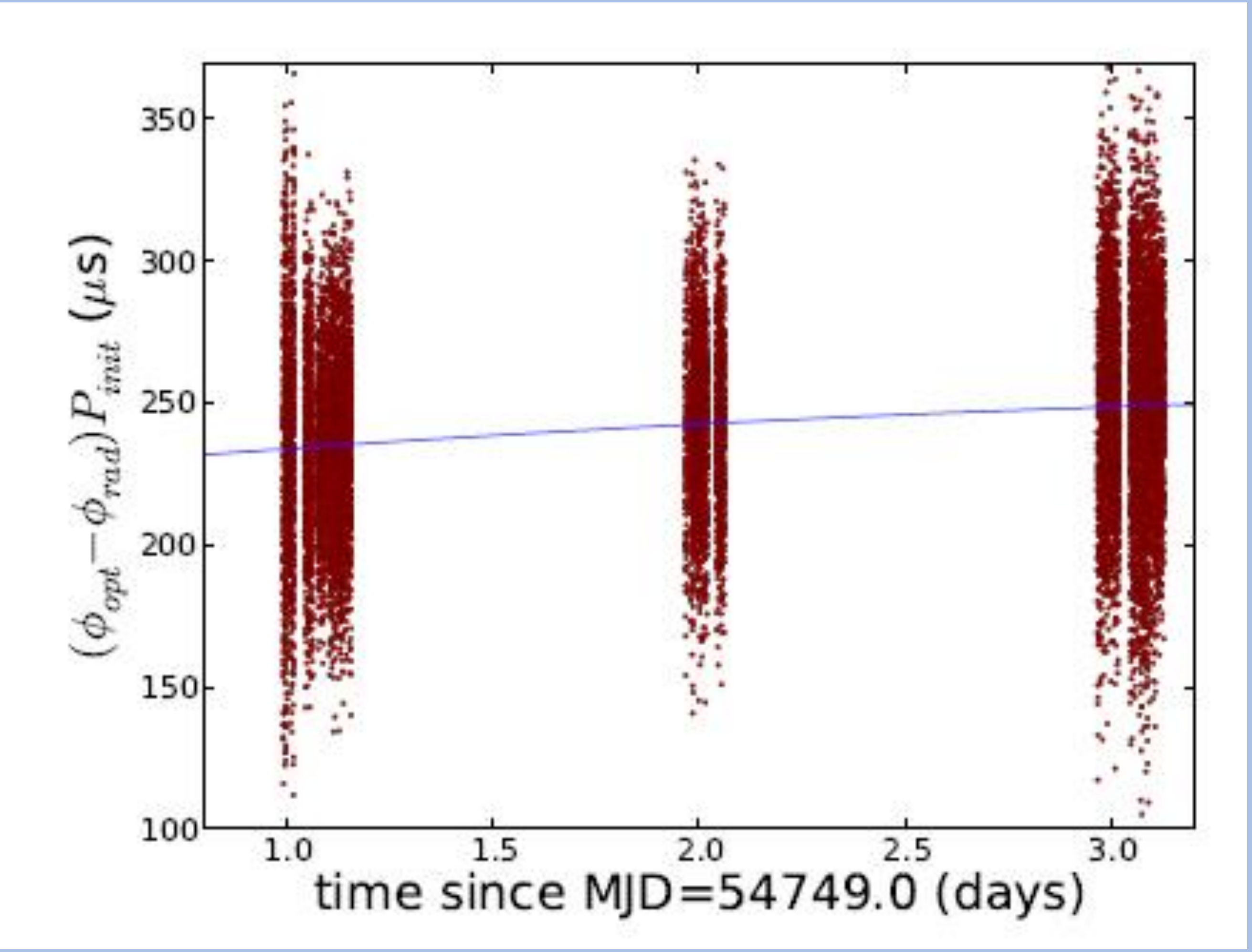
The statistical error on the optical rotational periods is 1.7 ps (1σ error).

The differences between optical and radio ranges from ~ 2 to 4 ps.

Also the measurements of the first derivative of the rotational frequency $\dot{\nu}$ **are in agreement**

$\dot{\nu}_{Aqueye}$ = $3.71876\times 10^{-10} \pm 6\times 10^{-15}$ s^{-2} **and** $\dot{\nu}_{JB} = 3.718655\times 10^{-10} \pm 2\times 10^{-16}$ s^{-2}.

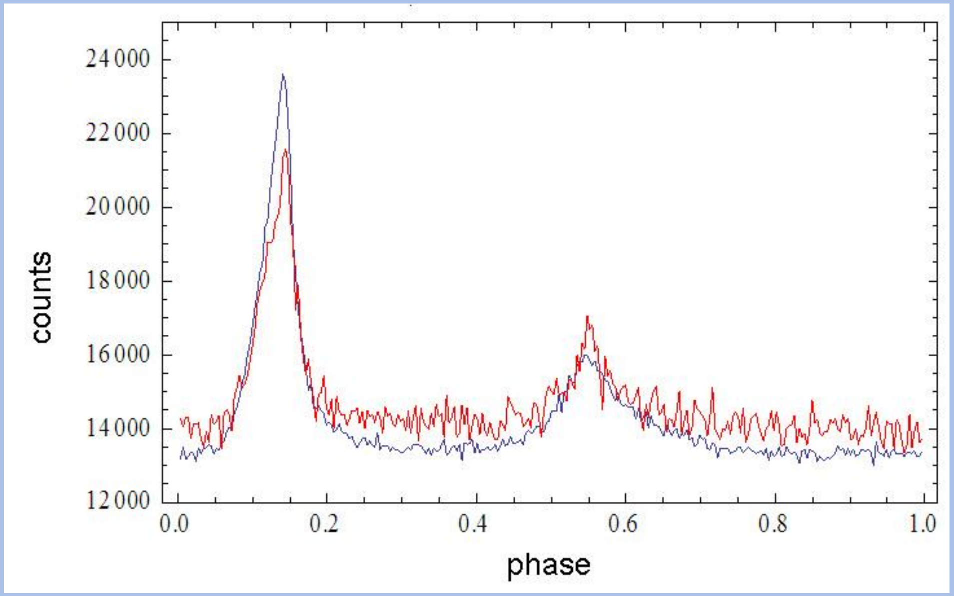
Radio – Optical Delay



Difference between the optical and radio time of arrival of the main peak. The optical peak leads the radio one by ~ 230 μs (at MJD=54750, epoch of the first observation). The (blue) line is the optical-radio drift, which is consistent with zero within the errors.

Oct 2008: Asiago AND Ljubljana

in Oct. 2008, ***simultaneous*** data were taken with the 80-cm Vega telescope of the Ljubljana Observatory, equipped with a similar photon counter and a common reference time system provided by a GPS and GALILEO-GNSS receiver.

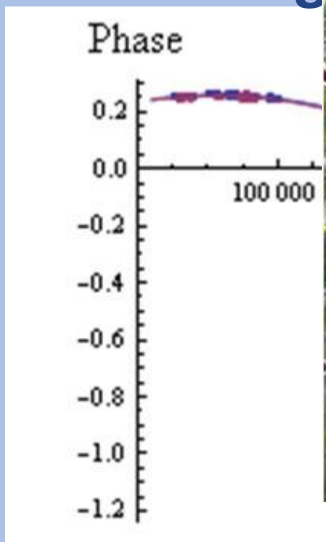


blue = Asiago
Red = Ljubljana x10

Excellent co-phasing

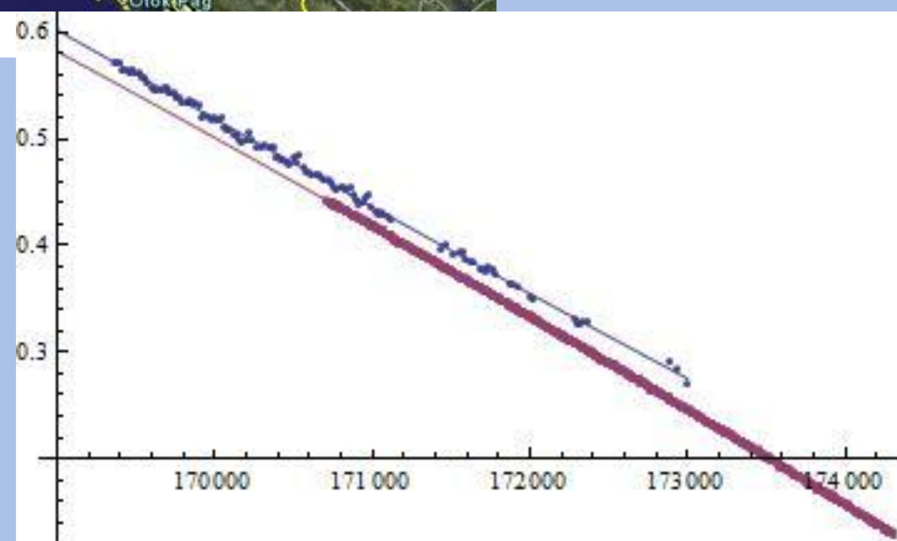
of the op ... ***ur***

knowledg



It would be very useful to repeat such experiment, any volunteer?

Just for fun:
distance Asiago – Ljubljana
(Copernicus – Vega)
Cartesian distance: 230. 4 km
Google Earth: 230.2 Km
From phase residuals: 229.2 Km
(preliminary, to be refined)

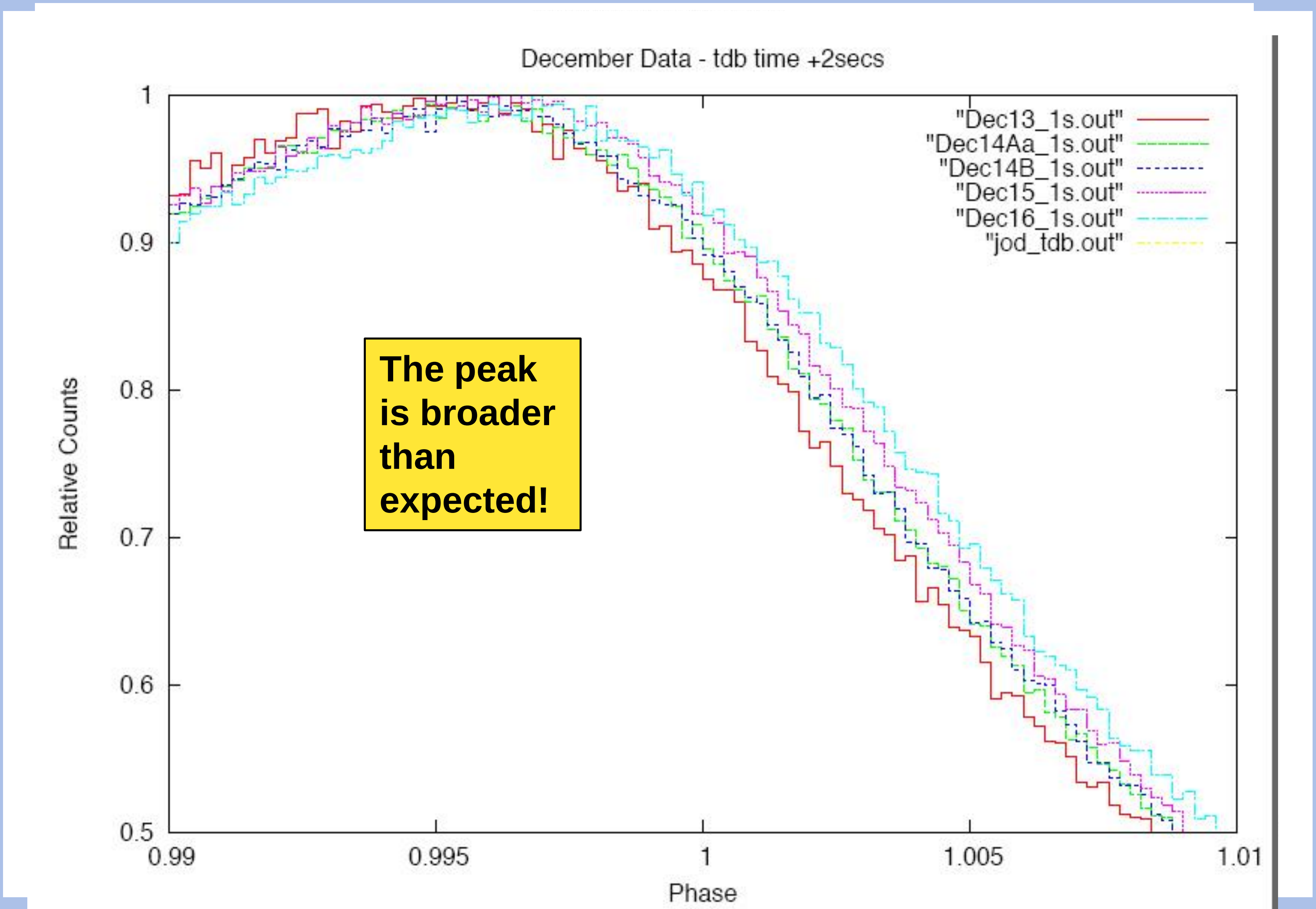


Iqueye at the NTT - 2009

The Crab pulsar was observed in January 2009 and again in December 2009.

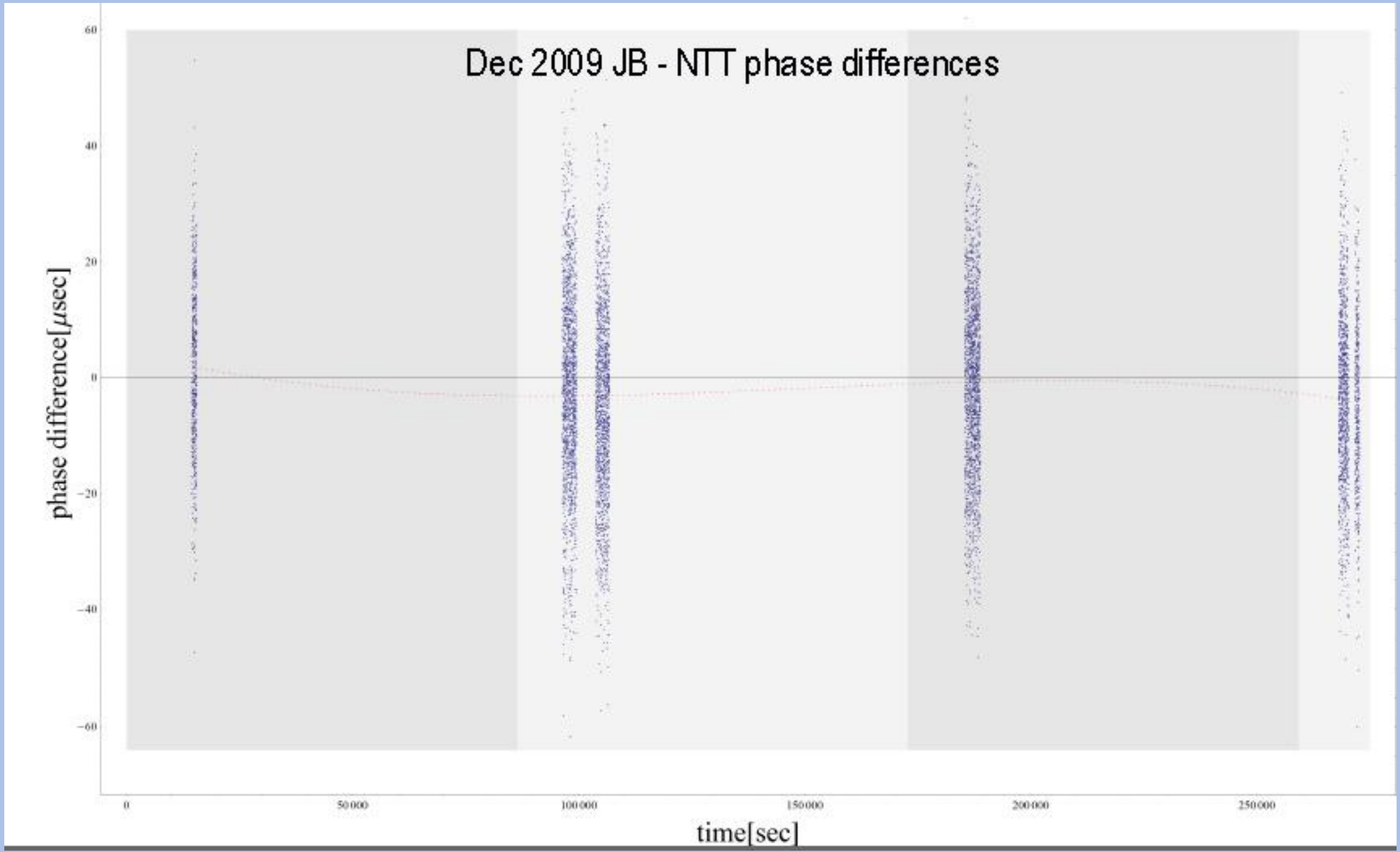
In the last occasion simultaneous data were obtained with Jodrell Bank, which detected hundreds of Giant Radio Bursts during the Iqueye observations.

The CRAB pulsar at the NTT



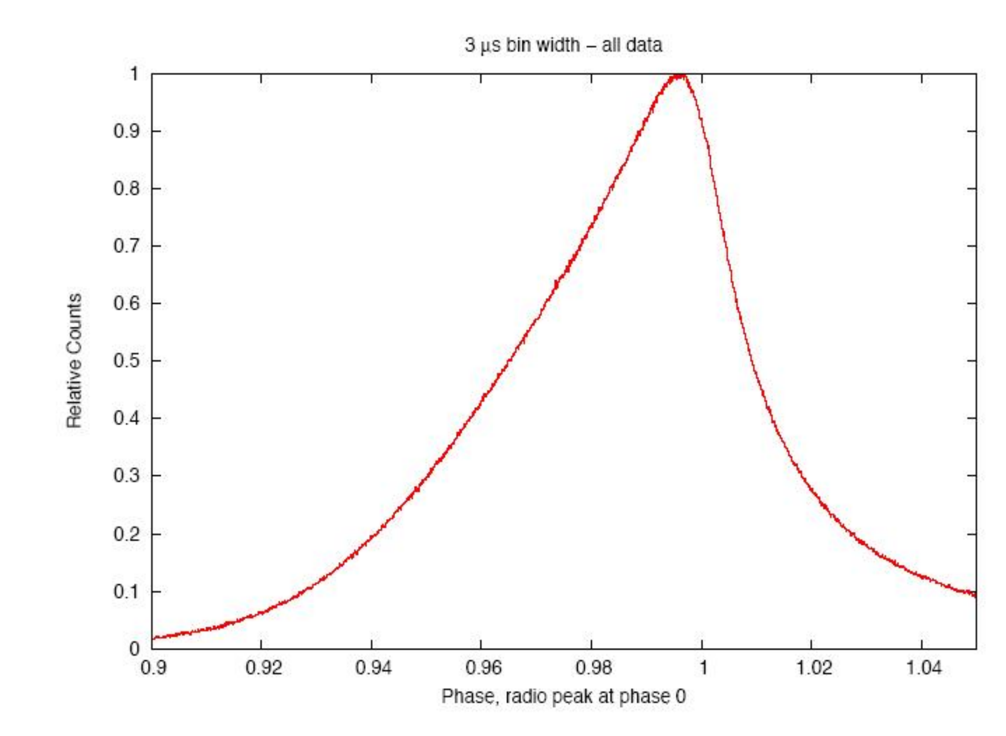
Accuracy of periods and phase residuals

A comparison with JB shows agreement to the picosecond level.
Phase differences are within 20 microseconds or so (with an offset still TDB).



Accuracy of period and phase difference

A comparison with JB ephemeris shows agreement in period to *1 picosecond* level. Regarding phases:

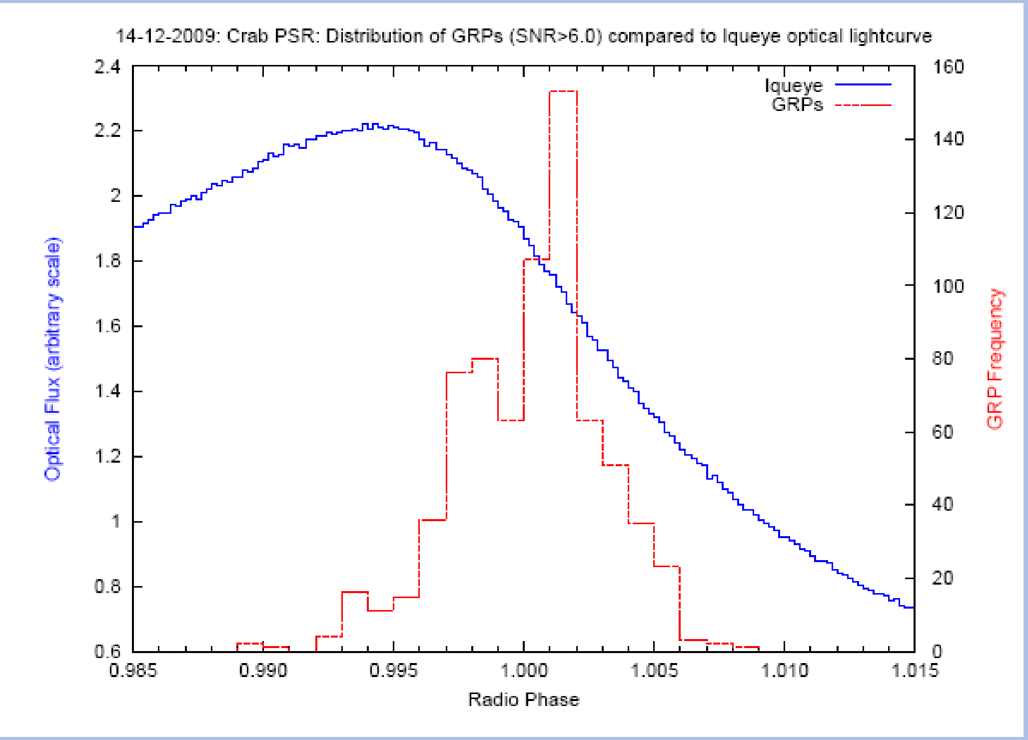


NTT – JB average phase difference

The NTT data confirm the systematic phase difference already found at Asiago, *with the optical pulse preceding the radio one by (178 $\pm$ 33, 1 sigma) microseconds*.

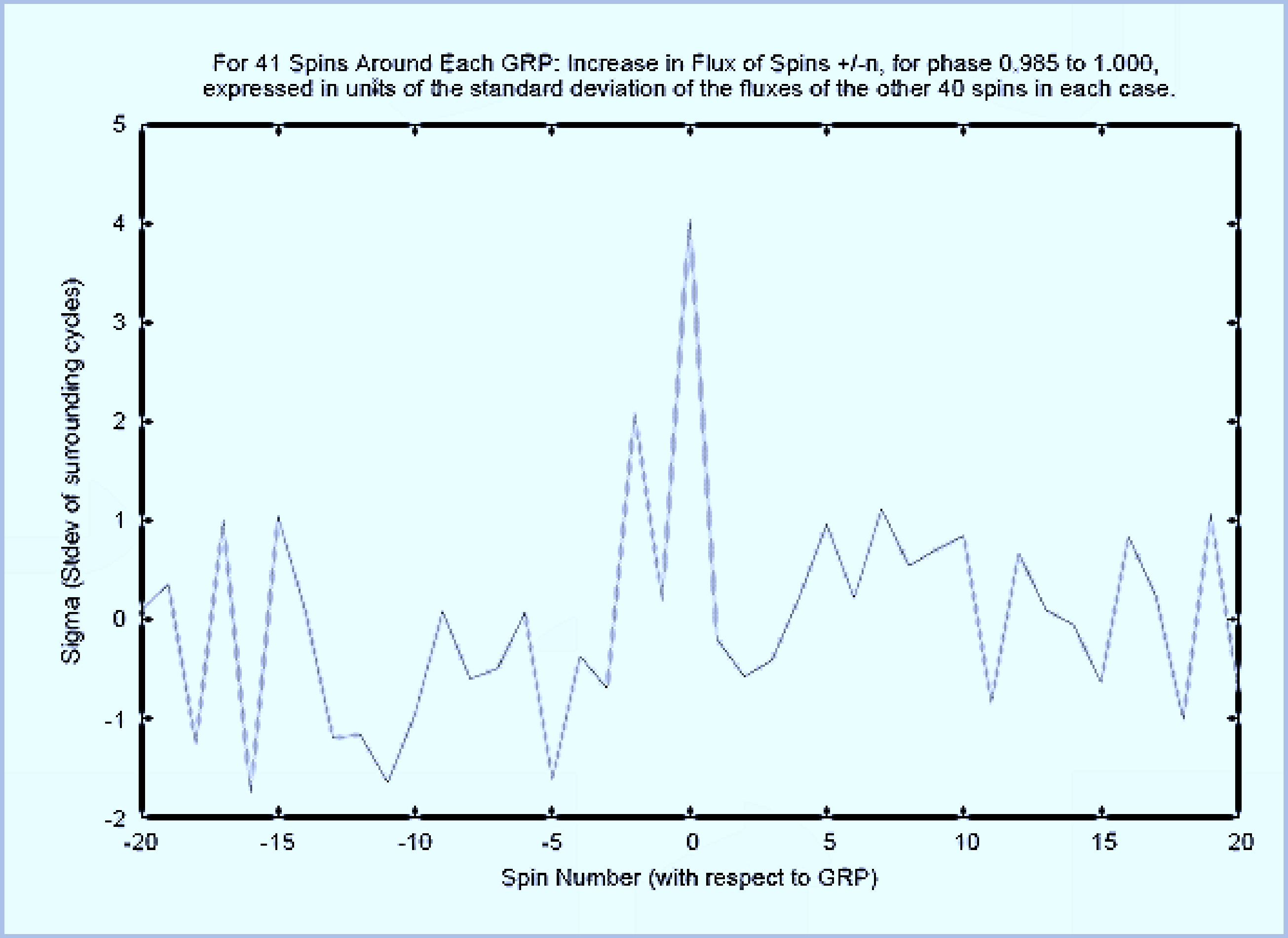
The observations in December 2009 had concurrent radio observations taken at Jodrell Bank. The radio data were de-dispersed, cleaned and analysed to find so-called ‘giant radio pulses’ (GRPs), occasionally emitted with an intensity of up to 1000 times that of a typical pulse.

The GRPs identified for the night of December 14th 2009 are approximately normally distributed about the nominal peak radio phase. 737 GRPs were identified above a 6.0-σ cutoff, of which 663 GRPs had concurrent optical observations.

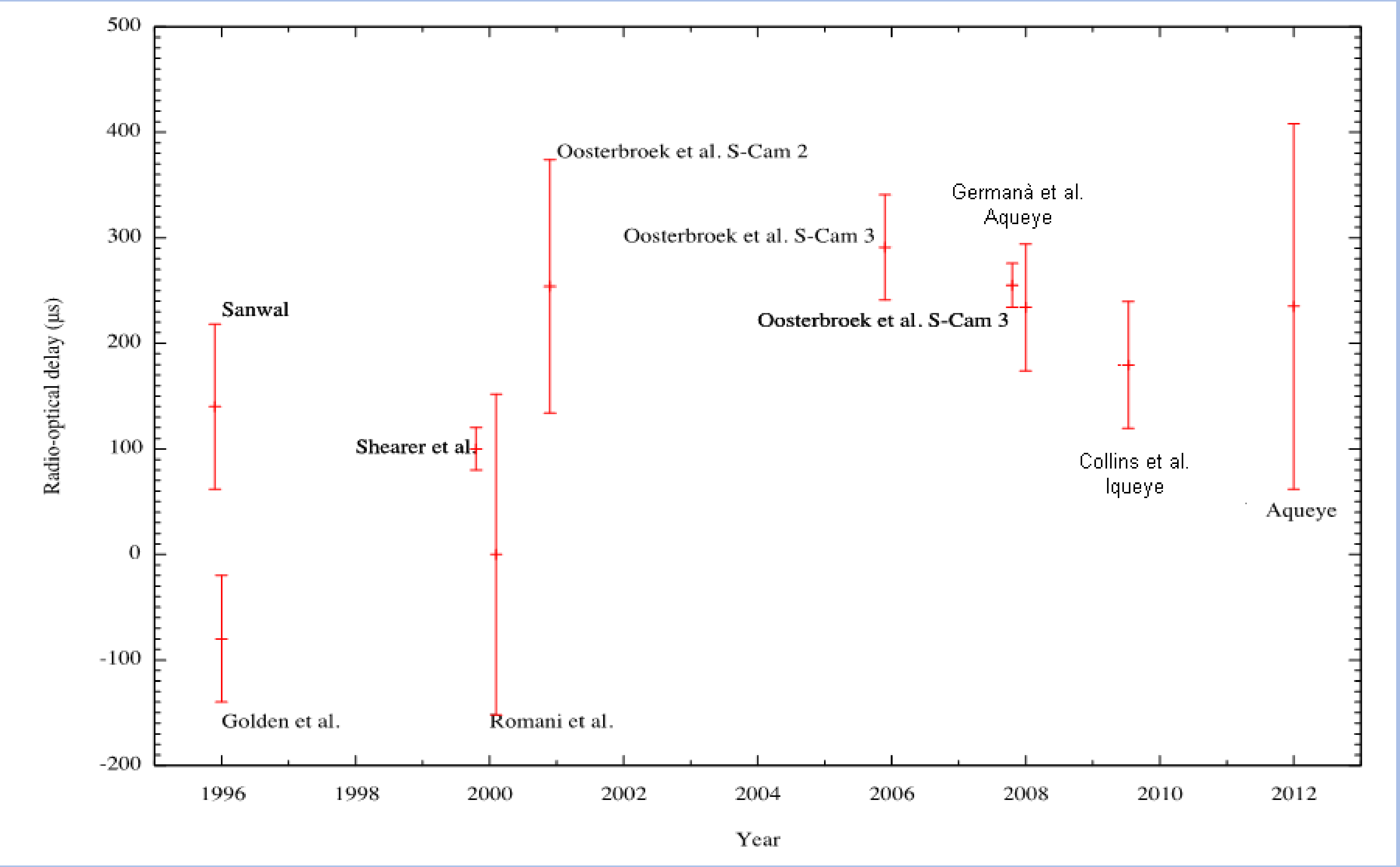


Distribution of the phases of those 663 GRPs with respect to the optical light curve.
Red: Frequency distribution of Crab pulsar Main-Pulse GRPs, with SNR >6.0 σ.
Blue: Iqueye optical lightcurve for the same observing period, showing how the optical peak precedes the radio peak.

The plot shows ***a noticeable increase in optical flux*** up to a 4-σ level in correspondence with the radio GRP, in qualitative agreement with previous findings (Shearer *et al., 2003)*



Values of the radio – optical delay of the main peak



Some conclusions from Crab pulsar

Aqueye and Iqueye provide the best timing of photon arrival times of all optical instruments.
In a few hours we reproduce to the picosecond level the JB ephemerides *averaged over decades*.

Concurrent observations with JB radiotelescopes have confirmed to a 4-σ level the increase of the optical flux when in phase with Giant Radio Pulses.

Barycentering is trickier than expected. The barycenter of the Solar System is probably not defined to better than 10 nanoseconds (3 m) or so.

Atmospheric delay models for visible light are desirable and are being implemented.

Atmospheric delay

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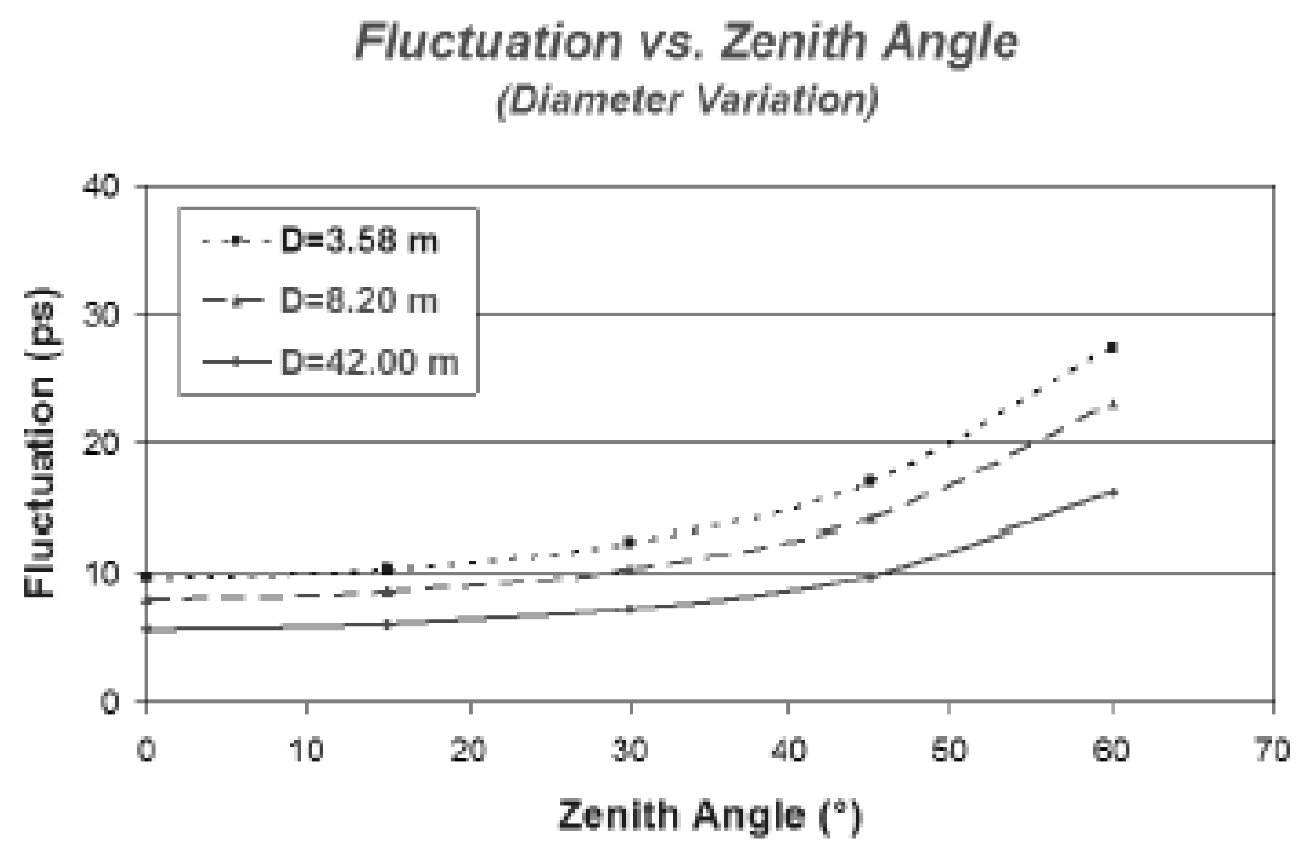
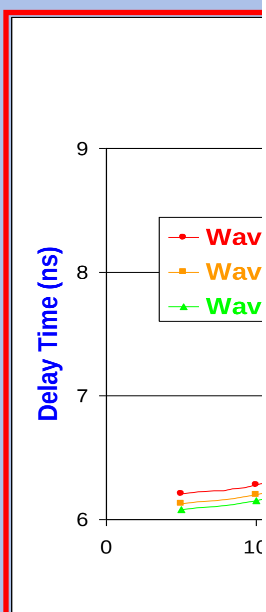
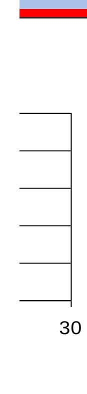
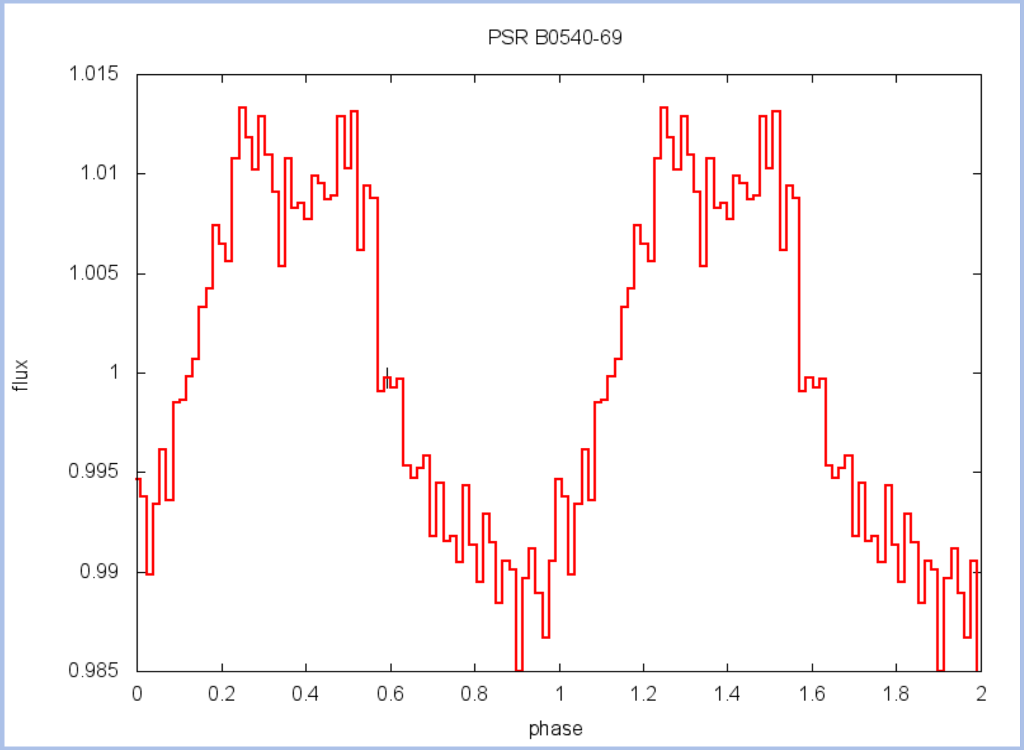


Figure 4. Delay time fluctuation as a function of the telescope diameter and the Zenith angle variation ($\lambda = 0.632\mu m$, $r_0 = 15cm$). The simulation compares La Silla (NTT), Paranal (VLT) and Armazones (ELT).





The second brightest pulsar: B0540-69 in the Large Magellanic Cloud

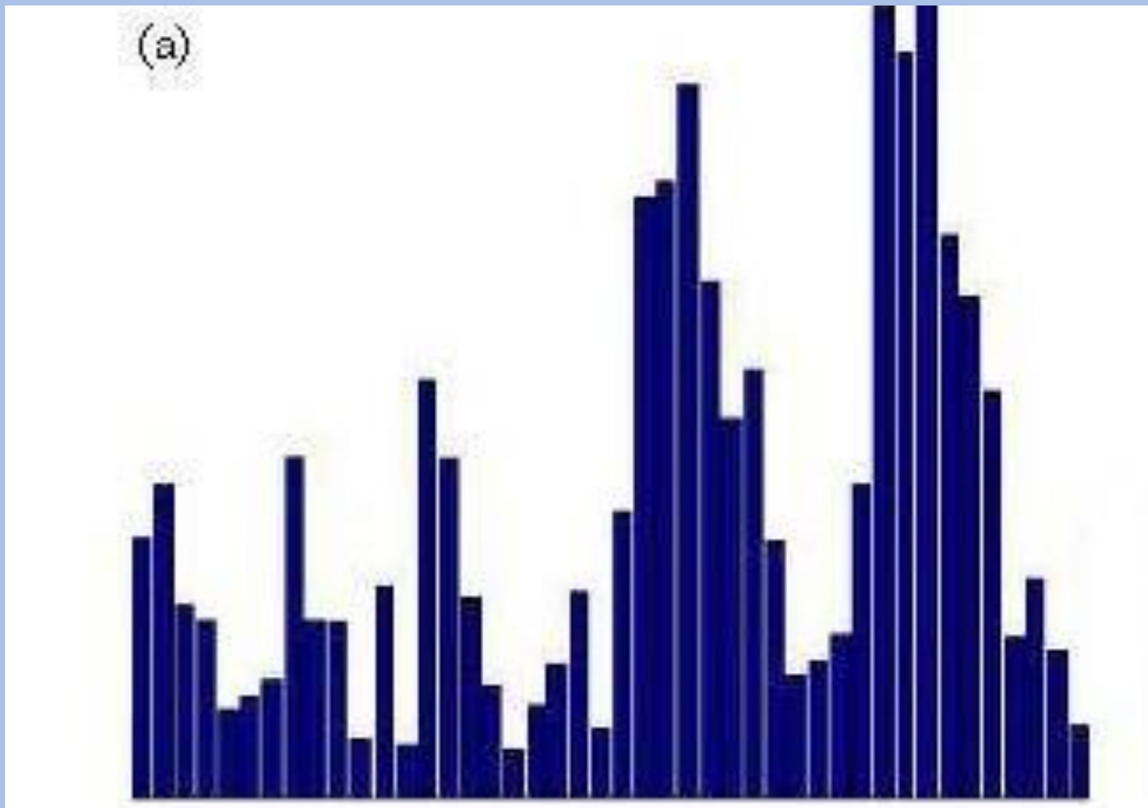


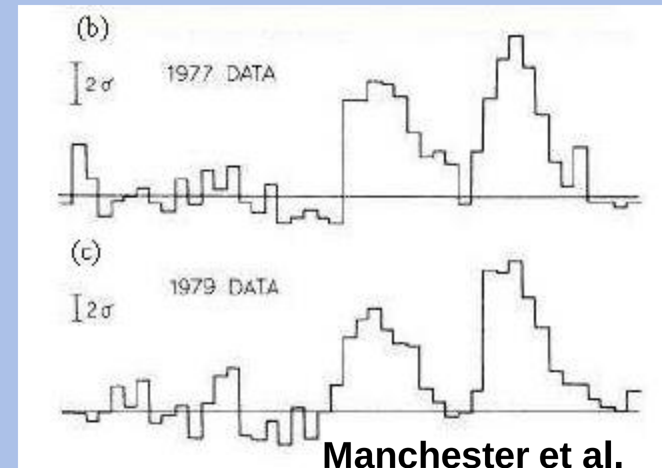
The braking index over 27 years of observations is *n* = 2.087 +/- 0.013, decidedly lower than the magnetic dipole value.

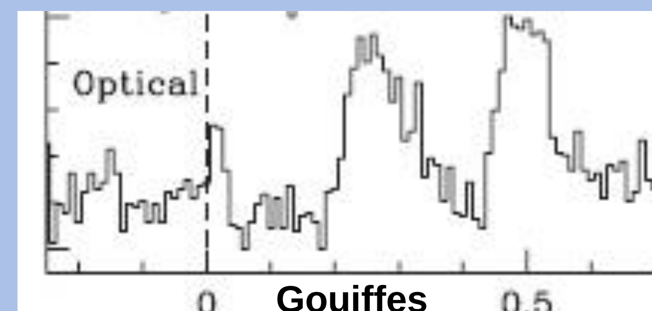
This pulsar is approximately 100 time fainter than Crab's, therefore individual pulses cannot be detected.

In 2 hours of photon counting we extended by 9 years the time span over which optical data have been obtained and derived **the best light curve available in the literature.**

The faintest pulsar: Vela







Vela's pulsar (period around 80 ms) is 10 times fainter than B0540-69.
The periodic signal is plainly evident from the Fourier transform.

The light curve (1 cycle shown), again one of the best in the literature, has a very complex shape.

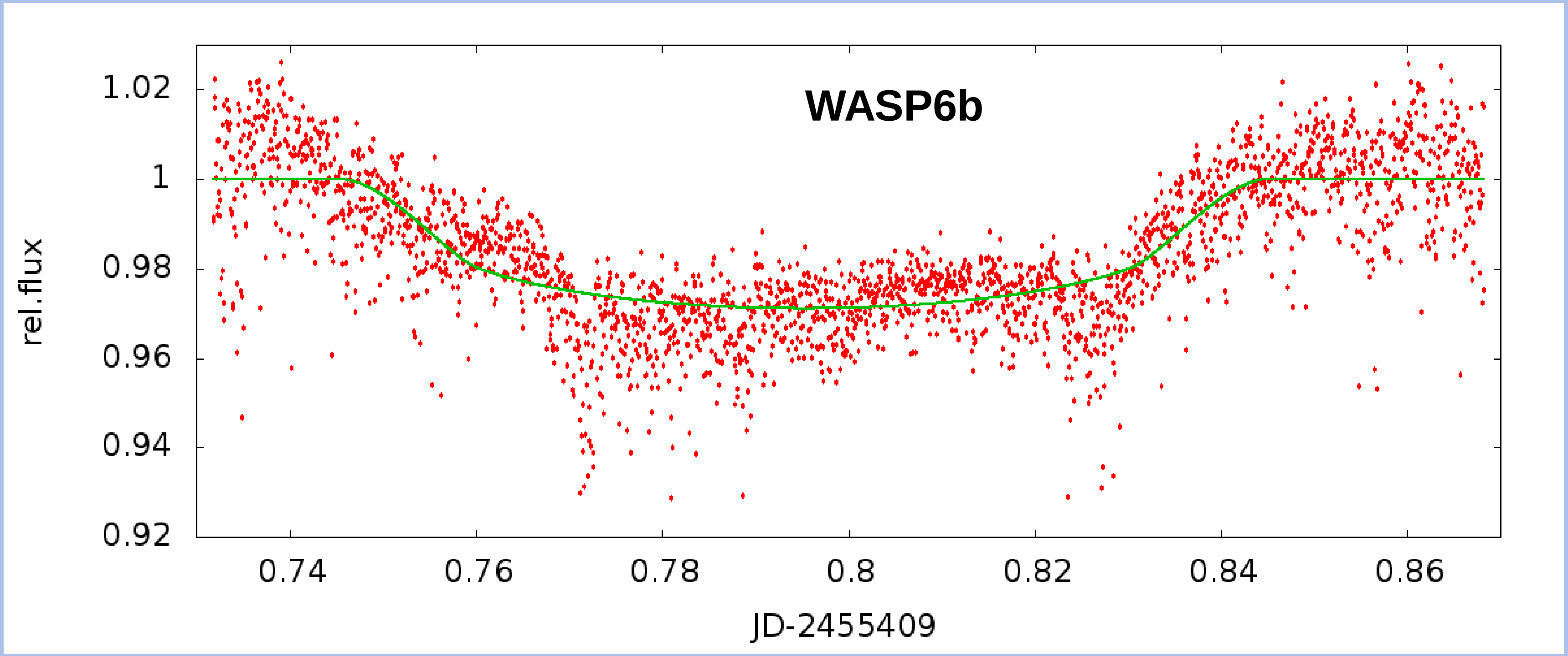
Applications to Extrasolar Planets

Transits are slow phenomena, however very high time resolution has several virtues:

- The presence of a second planet can produce short term periodic variations on the transiting planet. Precise temporal measurements of the mid-transit time can reveal the presence of the perturbing body, like a super-Earth planet or a massive satellite. The nodal precession induced by the second planet can cause *Transit Time Variations (TTV)*.

- The detection of the perturbing body requires that mid-transit times are measured with great precision, while the current best precision of mid-transit measurements from ground is around 15 s for most of the transiting planets. These precisions are a limiting factor for the detection of *TTV* and, in fact, a better precision would represent a major advantage.

With its high temporal resolution and high optical throughput, Aqueye and IQuEye are well suited for studying TTV.



Light curve of WASP 6b in white light acquired on 31 Jul 2010.
M_{pl} =0.5 M_J, R_{pl} = 1.2 R_J, P=3.36 d.
Data binned in 1s bin (for clarity only the 20% of the points are shown).
The air-mass trend is removed with a low order polynomial.
The light-curve rms is 0.004 per minute.
The mid transit time is T_c = 2455409.795296 +/- 5 sec, namely 2 times better than the value quoted in the discovery paper (Gillon et a., 2009).

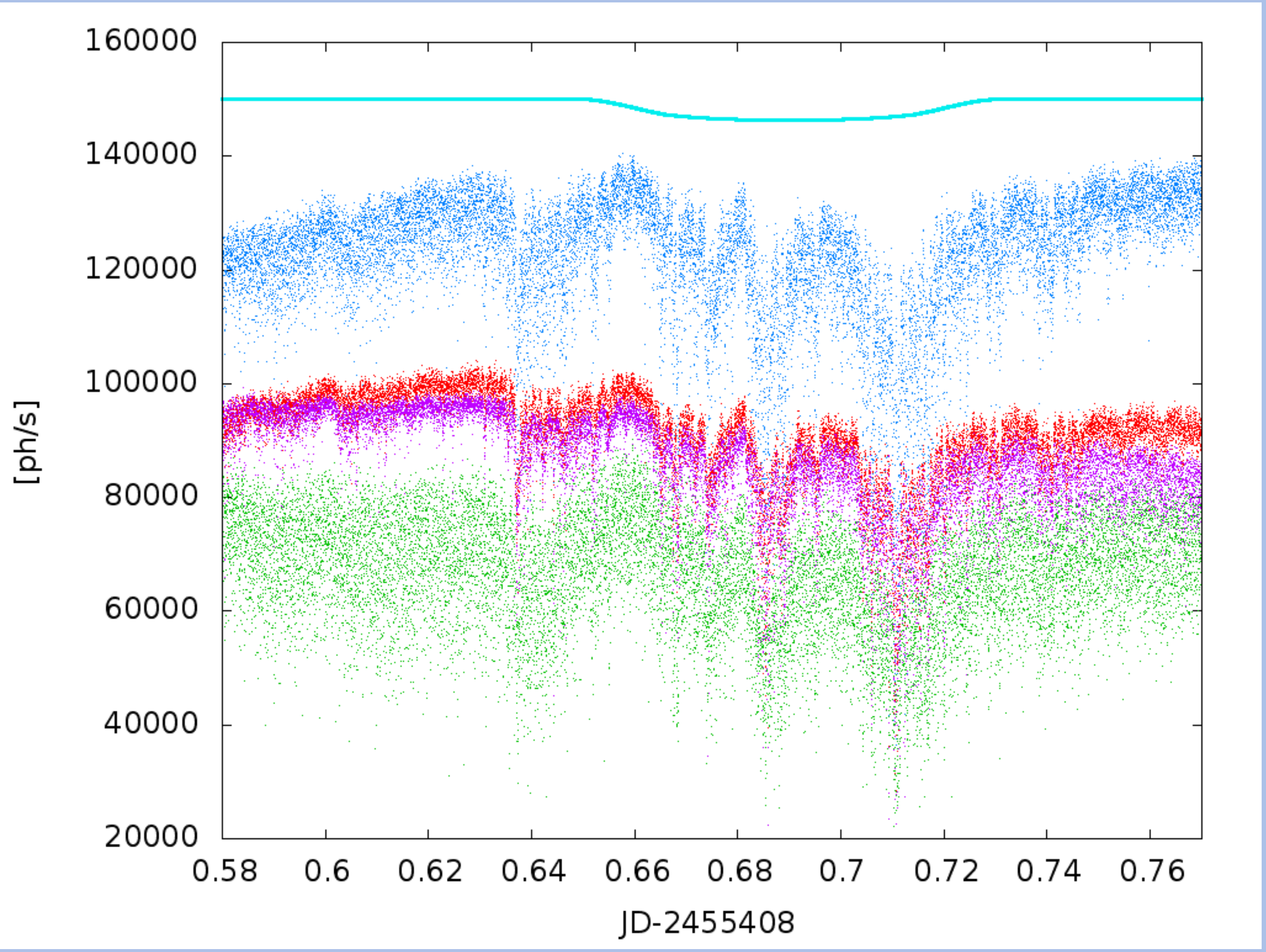
We are improving these preliminary results, using:
- **correct limb darkening parameters for our system response**
- **improving the removal of the air-mass trend, and of other systematic effects using the data collected with the field camera.**

Atmospheres of Extrasolar Planets

The capability of Aqueye and Iqueye to make simultaneous observations in 4 bandpasses helps to reduce the photometric ‘red’ noise and allows the determination of stellar limb darkening coefficients.

- It offers, at the same time, the opportunity of studying the atmospheres of the extrasolar transiting planets. During the transit, the height at which the planetary atmosphere becomes opaque to the grazing star light varies with wavelength. The depth of the transit at various wavelenghts, which is related to the planetary radius, allows one to recover the *transmission spectrum* of the planetary atmosphere along its limb.

- Using appropriate narrow band filters, it can help to detect early ingresses or late egresses caused by the presence of *clouds of materials orbiting around the star*. These clouds are originated by the evaporating atmosphere of the planet that escape from the planet’ Roche lobe, and orbit the star, following or preceding the planet.



Planet HD189733b, R=1.15 R_J, M=1.15 M_J, P=2.22 d.

Star K2V, T_{eff} = 5000K,

depth of transit approximately 2.5%

Lightcurves of HD 189733 observed on 30 July 2010, with intermediate filters 546nm (red), 580nm (green), 610nm (blue) e 694nm (violet), in cyan the theoretical lightcurve in R band. Photon arrival times are binned in 1s bins. Notice the presence of spikes at the 2^{nd} and 3^{th} contacts.

Final considerations on **Time - 1**

The comparison between the Aqueye/Iqueye optical data and the Jodrell Bank data required a careful consideration of the ***definition of the second***.

Actually two definitions are in usage in different software packages:

the Barycentric Coordinate Time (***TCB***, e.g. in *Tempo2*), the Barycentric Dynamical Time (***TDB***, e.g. in *Tempo/tempo1 used by JB*). TCB is a coordinate time referred to the barycenter of the Solar System, synchronized with the proper time of a distant observer comoving with it. TDB is measured in units that differ subtly from the conventional SI second (Hobbs et al. 2006).

It is as if the time dilation effects were not correctly accounted for using TDB units, so that, for example, ***rotational periods in the TCB system are systematically longer than the TDB ones, by approximately 0.5 ns.***

Final considerations on **Time - 2**

The ratio of the two time units derived from the comparison Aqueye/Iqueye vs. JB data is:

$$K \sim 1 + 1.53 \times 10^{-8} \pm 1.3 \times 10^{-10}$$

fully consistent with the values reported by Irwin & Fukushima (1999) and Hobbs et al. (2006). The constant ***K*** sums up a contribution from the linear term of the Einstein delay, ***LC***, and another term from the gravitational plus spin potential of the Earth, ***LG***.

Thanks to their timing capability and performances, Aqueye and Iqueye can detect the need of the corrections ***LC*** and ***LG*** and measure their values in only two days of data taking on the Crab pulsar.

Time definition and determination should became again a major duty of Astronomy, as it was in the past. If at all possible, the E-ELT should contain a primary time laboratory, of the same quality at NIST or USNO.

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