Fast Photon Counting Optical Astronomy: Rapid Variability in Astrophysical Sources and Beyond

Luca Zampieri

for the **AQUEYE+IQUEYE team**
http://web.oapd.inaf.it/zampieri/aqueye-iqueye/index.html

Audizioni INAF RSN4 - May 10, 2022
Scheda FPC-OA (RSN4 e 5)

AQUEYE+

IQUEYE

Outline

- Team and goals
- Scientific and technological results/activity
- Program, leadership, funds, critical aspects

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Scheda FPC-OA

AQUEYE+IQUEYE Organization chart

Project page:
http://web.oapd.inaf.it/zampieri/aqueye-iqueye/index.html

Instrument design, Technological development	Optics and Opto-mechanics	Acquisition electronics and instrum. software	Technical support and operations at telescopes	Daily/weekly photometric and spectrosc. coverage	Observations	Science data processing and analysis	Interpretation and paper writing	Coordination
C. Barbieri	L. Lessio	G. Naletto	L. Lessio	U. Munari	A. Burtovoi	A. Burtovoi	C. Barbieri	G. Naletto
G. Naletto	G. Naletto	L. Zampieri	P. Ochner	P. Ochner	M. Fiori	M. Fiori	T. Belloni	L. Zampieri
L. Zampieri	G. Umbriaco		G. Umbriaco		G. Naletto	A. Miraval-Zanon	A. Burtovoi	
	L. Zampieri				L. Zampieri	A. Spolon	P. Casella	Teaching, training and outreach
						L. Zampieri	M. Fiori	
							G. Naletto	G. Naletto
							A. Miraval-Zanon	P. Ochner
							A. Papitto	L. Zampieri
							A. Spolon	
							U. Munari	
							L. Zampieri	

OA Padova
Univ. Padova

OA Roma
OA Brera-Merate

OA Arcetri

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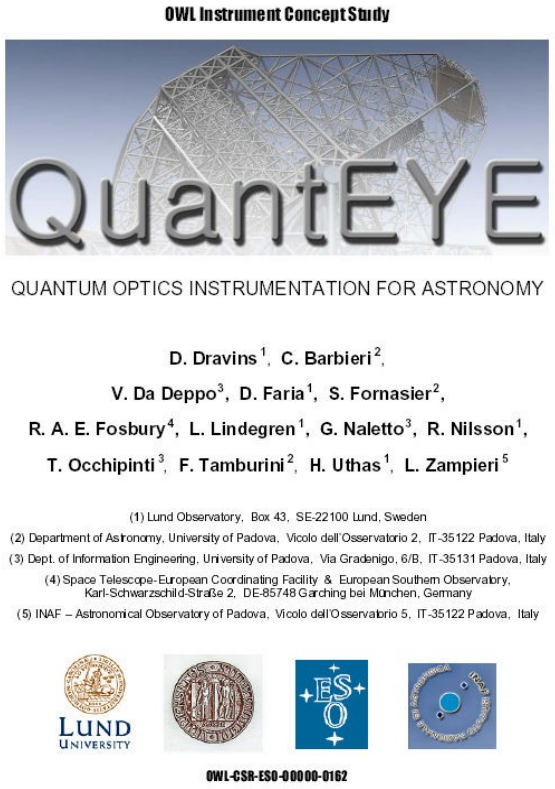
OWL Instrument Concept Study

QuantEYE

QUANTUM OPTICS INSTRUMENTATION FOR ASTRONOMY

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, Box 43, SE-22100 Lund, Sweden
(2) Department of Astronomy, University of Padova, Vicolo dell'Osservatorio 2, IT-35122 Padova, Italy
(3) Dept. of Information Engineering, University of Padova, Via Gradenigo, 6/B, IT-35131 Padova, Italy
(4) Space Telescope-European Coordinating Facility & European Southern Observatory, Karl-Schwarzschild-Straße 2, DE-85748 Garching bei München, Germany
(5) INAF – Astronomical Observatory of Padova, Vicolo dell'Osservatorio 5, IT-35122 Padova, Italy

LUND UNIVERSITY

OWL-CSR-ESO-00000-0162

Starting from the seminal design study **QuantEYE** (the ESO Quantum Eye; Dravins et al. 2005) for new instrumentation for the Overwhelmingly Large telescope

Main scientific objectives:

- **study phenomena with a temporal resolution up to and below 1 ms in the optical band**
- **measure the entropy of light through the statistics of photon arrival times**

To achieve these goals, we built two ultra-fast photon counters, Aqueye+ (Asiago Quantum Eye; Barbieri et al. 2009) and Iqueye (Italian Quantum Eye; Naletto et al. 2009)

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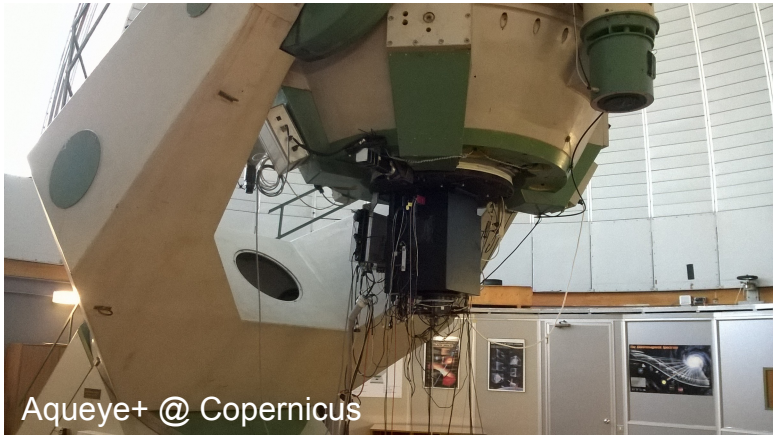
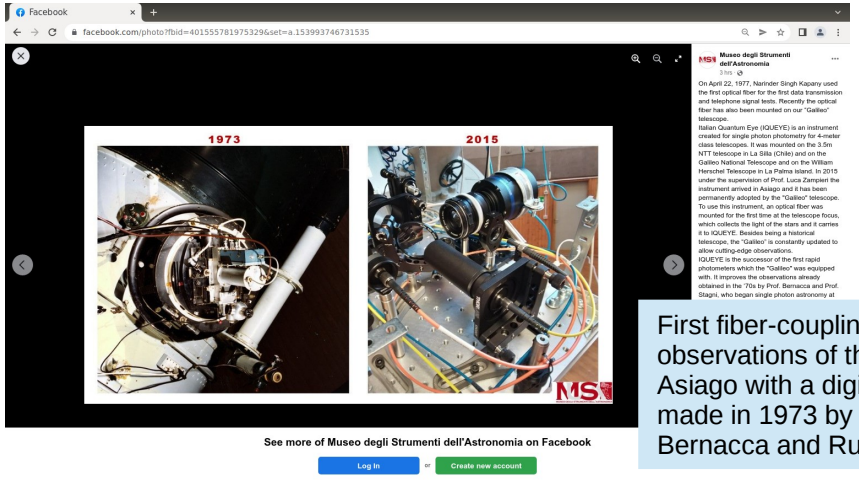
Aqueye+ and Iqueye *are non-imaging instruments for very fast photon counting in the optical band (Barbieri et al. 2009; Naletto et al. 2009, 2013; Zampieri et al. 2015, 2019a)*

- Field of view: few arcsec
- Optical design: entrance pupil split with a pyramidal mirror
- Detectors: SPADs with **<50 ps time resolution**
- Acquisition system: **sub-ns time tagging accuracy wrt UTC**
- Fiber coupling of Iqueye performed through the **Iqueye Fiber Interface (IFI)**





First fiber-coupling in 2015, but first observations of the Crab pulsar in Asiago with a digital photometer made in 1973 by Pier Luigi Bernacca and Ruggero Stagni

Iqueye mounted at NTT, WHT, TNG, Galileo in Asiago (with IFI)

http://web.oapd.inaf.it/zampieri/aqueye-iqueye/index.html

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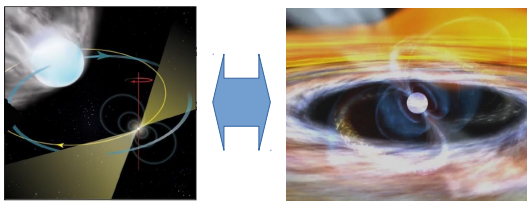
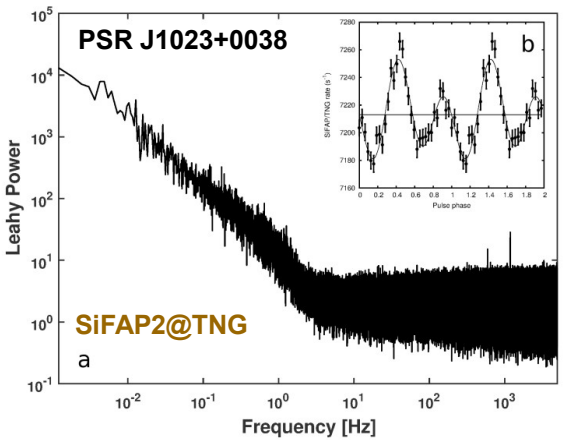
Fast sub-second variability is a characteristic property of sources with compact objects of stellar origin and is essential for understanding the properties of matter and particle acceleration/emission in strong gravity and/or magnetic fields, *with the optical band providing unique info in some cases*

Transitional Millisecond Pulsars

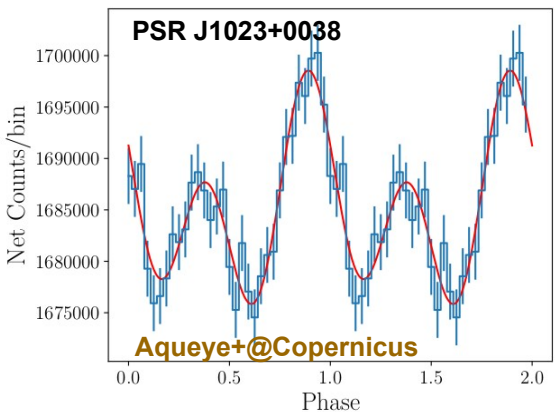
(link scheda **MSP**; A. Papitto)



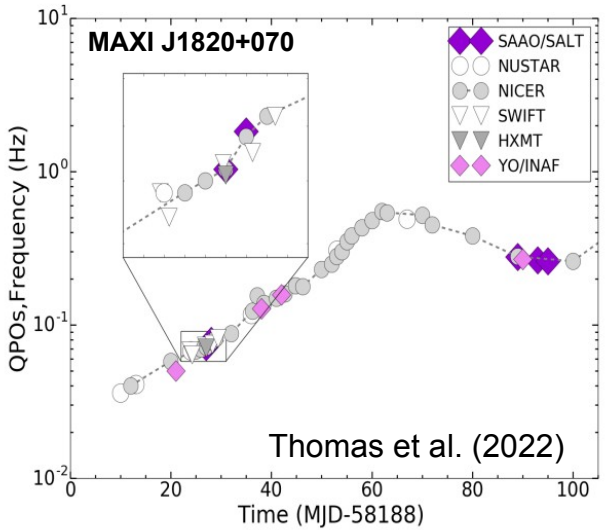
Ambrosino et al. (2017)



Zampieri et al. (2019b)



X-ray Binaries



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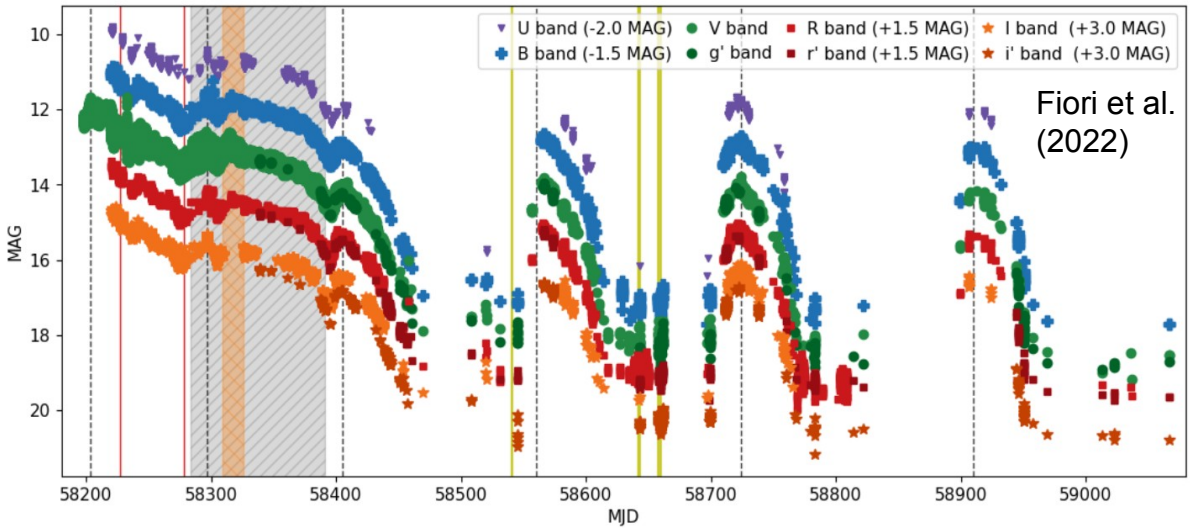
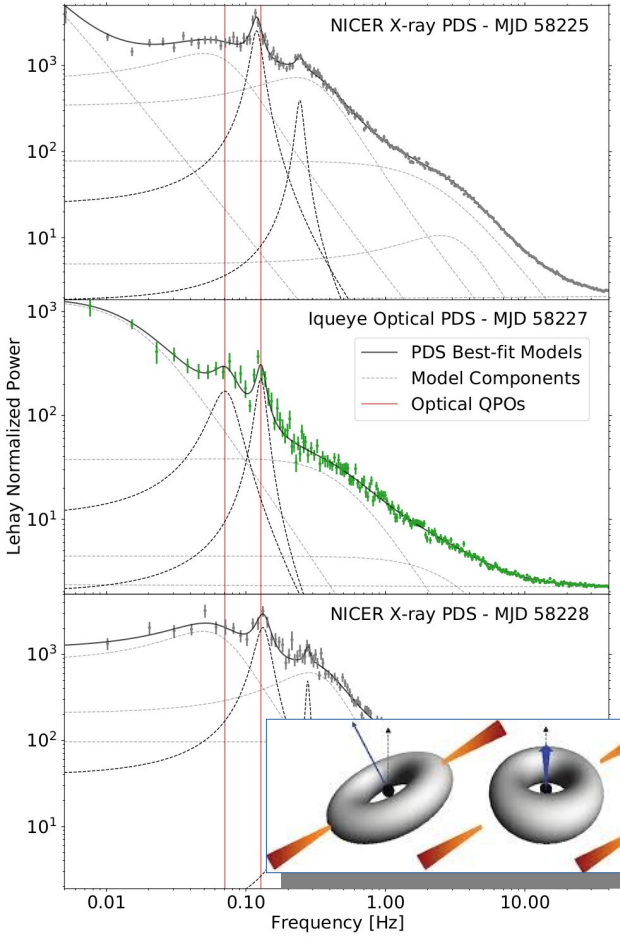


Fast photometric monitoring campaign with IFI+Iqueye and Aqueye+ (ATel #11723, #11824, #11936)

Joint photometric and spectroscopic campaign with the Asiago and ANS Collaboration telesc. (ATel #11899, #12157)



MAXI J1820+070

Lowest modulation frequency related to the inner disc+jet precession frequency

Optical QPO appears to mark the characteristic precession frequency

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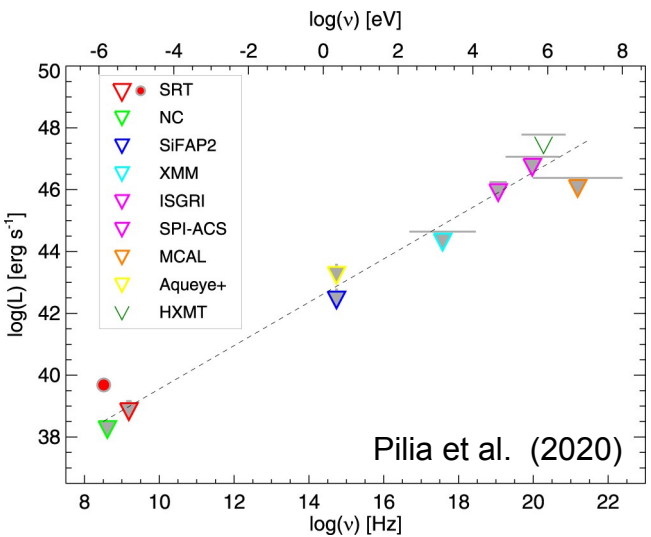
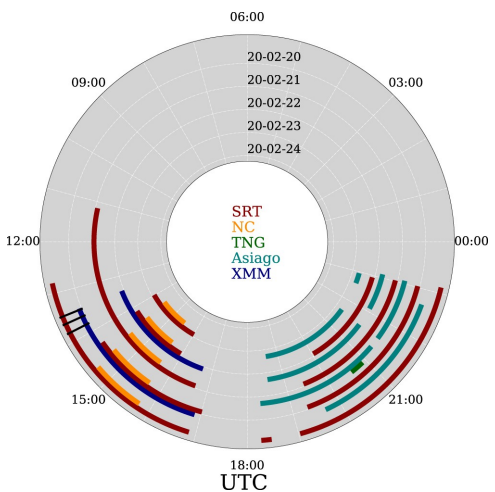
… and Beyond: Searches for prompt/delayed optical flashes from FRBs and magnetars

Several models of Fast Radio Bursts (FRBs) and magnetars predict the existence of multiwavelength counterparts in the form of an afterglow or an impulsive event (e.g. Nicastro et al. 2021)

A MWL and/or optical detection would have the potential to reveal the engine and the nature of the progenitor and would greatly enhance our understanding of the FRB phenomenon

Ongoing multiwavelength campaigns on **FRB 180916.J0158+65** (ATel #13492, #13493; Pilia et al. 2020; Trudu et al. 2022), that shows repeating burst activity, is localized with high accuracy, and has a 16.35 +/- 0.18 day periodicity





+ AGILE, INTEGRAL and HXMT

FRBs (link scheda **FRB_Italy**; A. Possenti)

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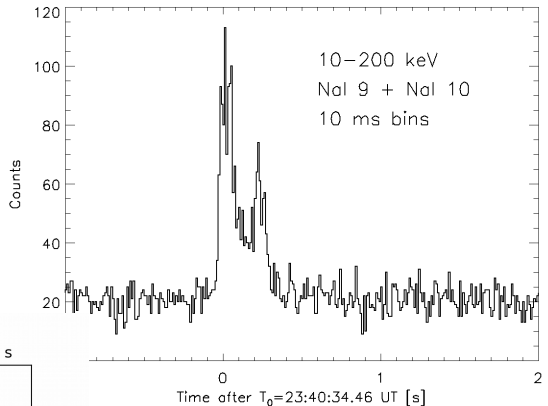
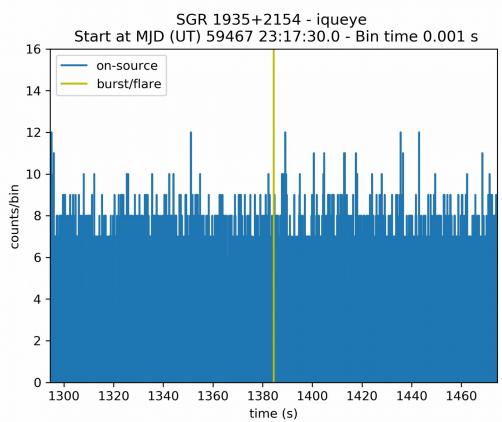
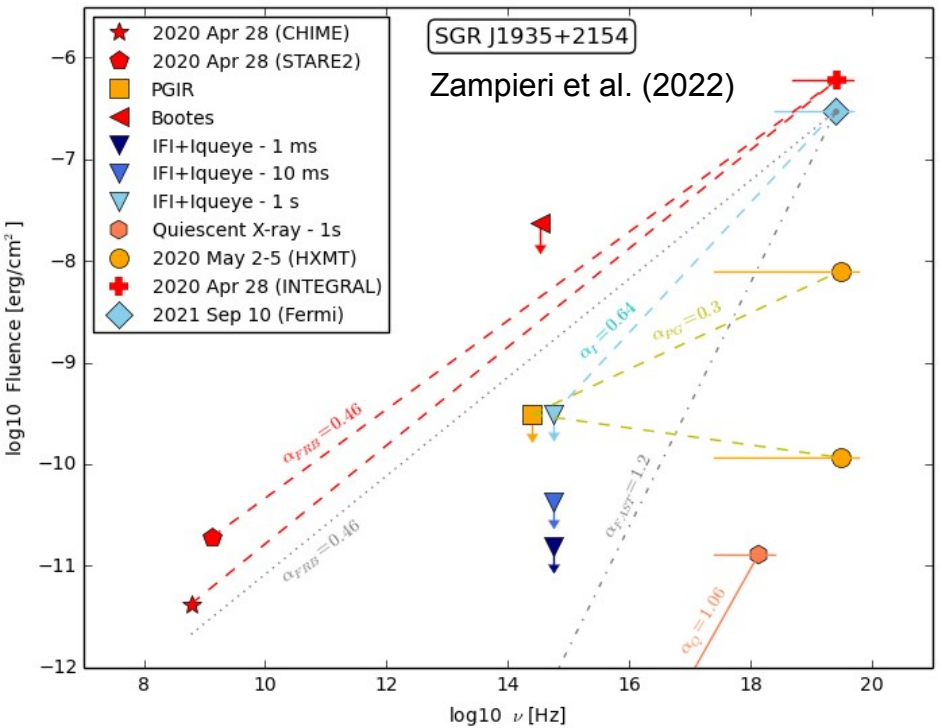
… and Beyond: Searches for prompt/delayed optical flashes from FRBs and magnetars

On Sep 10, 2021 a **hard X-ray burst** was detected with the Fermi GBM from **SGR J1935+2154**





No significant optical peak is detected around T0 during a simultaneous IFI+Iqueye observation



Bursts with radio counterpart, characterized by a much flatter radio-through-hard-X-ray slope, are, in principle, detectable in the optical band with a simultaneous observation with < 1s time resolution

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… and Beyond: The beauty of speed!

Photon counting SII (**with ns time resolution**) successfully experimented with Aqueye+@Copernicus and IFI+Iqueye@Galileo in Asiago

Crucial for future implementations of SII in photon counting on arrays of Cherenkov telescopes (scheda **ASTRI-SII**)

The pilot Aqueye+Iqueye experiment of Stellar Intensity Interferometry (SII)

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **00,** 1 (2021) https://doi.org/10.1093/mnras/stab1387

Stellar intensity interferometry of Vega in photon counting mode

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Accepted 2021 May 10. Received 2021 May 10; in original form 2021 January 29

ABSTRACT

Stellar intensity interferometry is a technique based on the measurement of the second-order spatial correlation of the light emitted from a star. The physical information provided by these measurements is the angular size and structure of the emitting source. A worldwide effort is presently underway to implement stellar intensity interferometry on telescopes separated by long baselines and on future arrays of Cherenkov telescopes. We describe an experiment of this type, realized at the Asiago Observatory (Italy), in which we performed for the first time measurements of the correlation counting photon coincidences in post-processing by means of a single photon software correlator and exploiting entirely the quantum properties of the light emitted from a star. We successfully detected the temporal correlation of Vega at zero baseline and performed a measurement of the correlation on a projected baseline of ∼2 km. The average discrete degree of coherence at zero baseline for Vega is $< g^{(2)} > = 1.0034 \pm 0.0008$, providing a detection with a signal-to-noise ratio $S/N \gtrsim 4$. No correlation is detected over the km baseline. The measurements are consistent with the expected degree of spatial coherence for a source with the 3.3 mas angular diameter of Vega. The experience gained with the Asiago experiment will serve for future implementations of stellar intensity interferometry on long-baseline arrays of Cherenkov telescopes.

Key words: instrumentation: interferometers – techniques: interferometric – stars: individual: α Lyr (Vega).

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... and Beyond: low-impact fiber-feeding

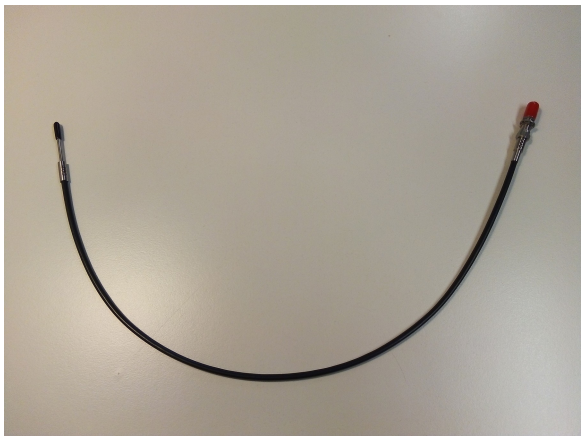
Injecting light directly in an **optical fiber positioned at the focal plane**

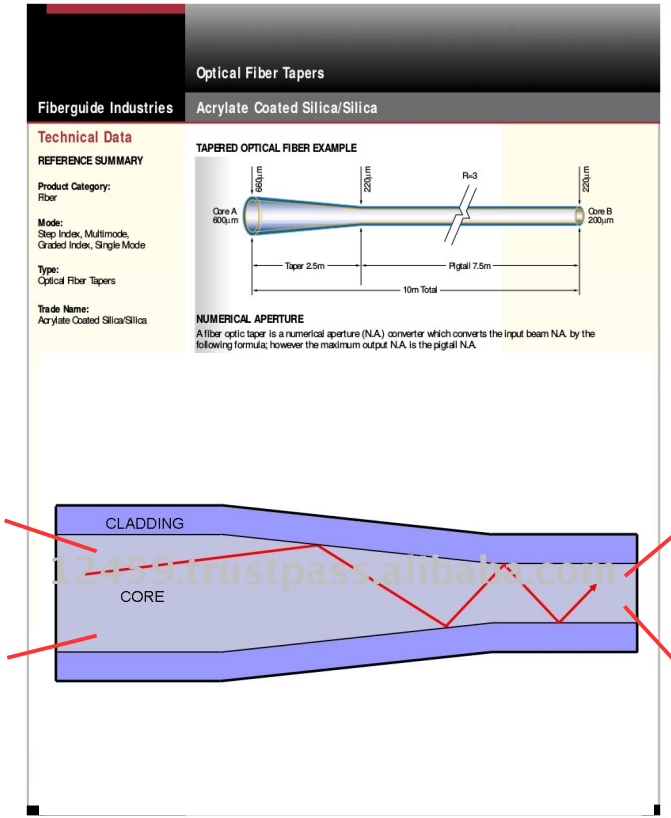
The key technical problem is to couple the relatively large FOV at the focal plane with the small detector area of the instrument

Solution is adopting a **tapered optical fiber with low numerical aperture**

Currently being implemented for Aqueye+

Fiber-fed solution considered also for **temporarily installing a refurbished version of Iqueye at the 1.5 m Cassini telescope at Loiano**, to increase the observing time for searching FRB counterparts





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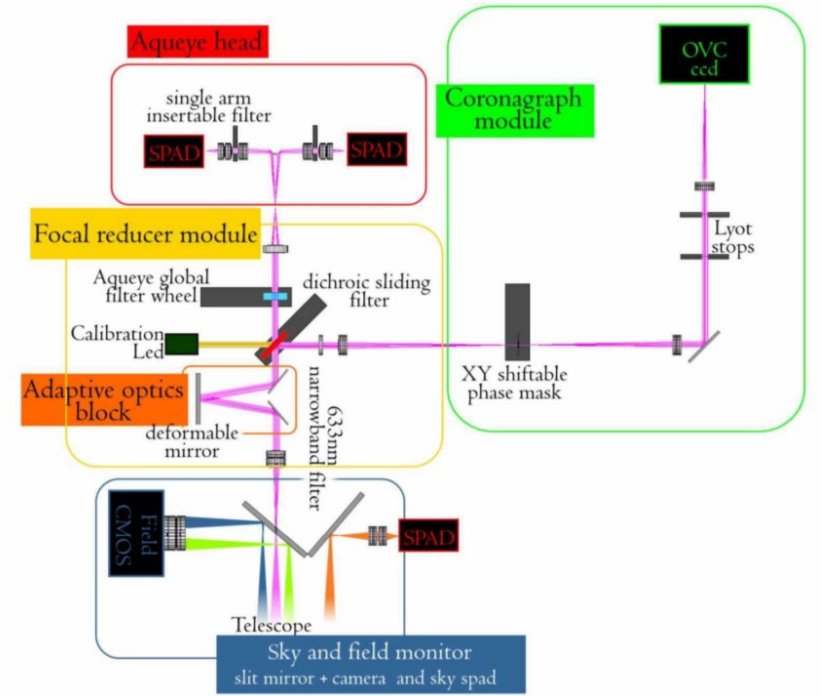
... and Beyond: upgrading Aqueye+ and IFI

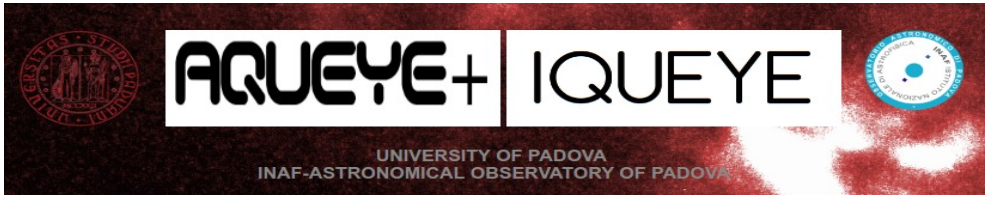
Extending the spectral coverage of Aqueye+, with an infrared channel (**Aqueye+NIRC**, Aqueye+ with a Near InfraRed Channel)

It will make it possible to perform simultaneous **optical+infrared fast photometric observations**, greatly enhancing the scientific utilization of the instrument

Adding a new near **infrared SPAD detector** illuminated through a dichroic filter (dedicated INAF Minigrant 'Augmented Aqueye+' submitted to the last INAF call)

Designing an **upgraded version of IFI** with on-board fiber-fed SPAD detectors, to make IFI an additional light-weight independent instrument





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Programs and leadership

Two proposals approved (**44+12 nights)** at Copernicus telescope (cycle 2022-2024) and 2-3 additional nights per month granted at Galileo telescope for:

- Simultaneous multicolor observations of optical pulsars
- Timing of optical transients and X-ray binaries
- Searches for optical flashes from FRBs and magnetars
- Monitoring the intranight variability of Blazars
- Lunar and asteroidal occultations

Technological activities:

- Low-impact fiber-feeding
- Upgrade of Aqueye+ (NIRC) and IFI
- Refurbishment of Iqueye for re-installation

Simultaneous/coordinated MWL campaigns (in which we lead the optical timing observations) with:
SRT, NC, GMRT, TNG, NICER, HXMT, MAGIC

Programs linked to schede:

SiFAP2, F. Ambrosino
MSP, A. Papitto

JetVar, P. Casella
SCOX-0, T. Belloni

FRB_Italy, A. Possenti
UnIAM, S. Mereghetti

Asiago-Ekar, L. Tommasella
ASTRI-SII, L. Zampieri

With the exquisite temporal resolution of our instrumentation (that led to the most accurate measurements on optical pulsars to date and to pave the way to photon counting SII), **we (as INAF) are certainly at the forefront in this area worldwide**

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Funds and critical aspects

Tabella fondi:

#	Provenienza	Certi 2022 (k€)	Certi 23 (k€)	Certi 24 (k€)	Presun. 2022 (k€)	Presun. 23 (k€)	Presun. 24 (k€)	Totale Certi (k€)	Totale Presunti (k€)
1	Università di Padova	4	0	0	2	2	2	4	6
2	Accordo attuativo ASI/INAF n. 2017-14-H.0	13	0	0	0	0	0	13	0
3	Large Grants INAF 2022	0	0	0	20	40	20	0	80
4	"Fondo italiano per la Scienza" starting grant 2021 (PI: D. Michilli)	0	0	0	0	62	63	0	125

Recently the resources are drawn from some residual funds of the University of Padova (DOR) and of the ASI/INAF contract n. 2017-14-H.0

The degree of scientific maturity that the project has reached in recent years is unfortunately countered by the lack of adequate economic resources for its future development

As regards human resources, the constant availability of **at least 0.6/0.7 FTE of dedicated contract staff** would be necessary to enhance the observations in service mode and the science data processing and analysis activities, and would allow a significant boost in the scientific productivity of the project

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Back up slides

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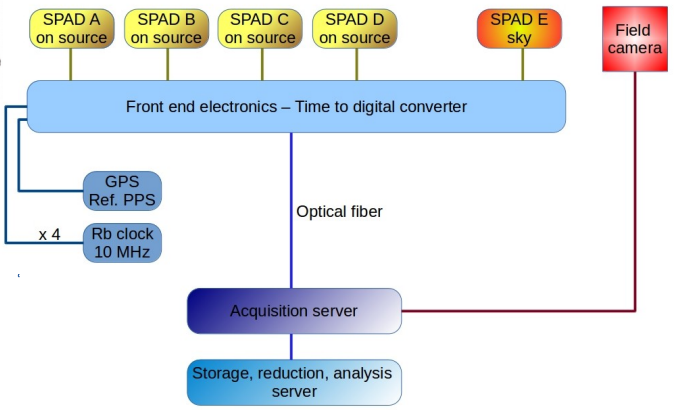
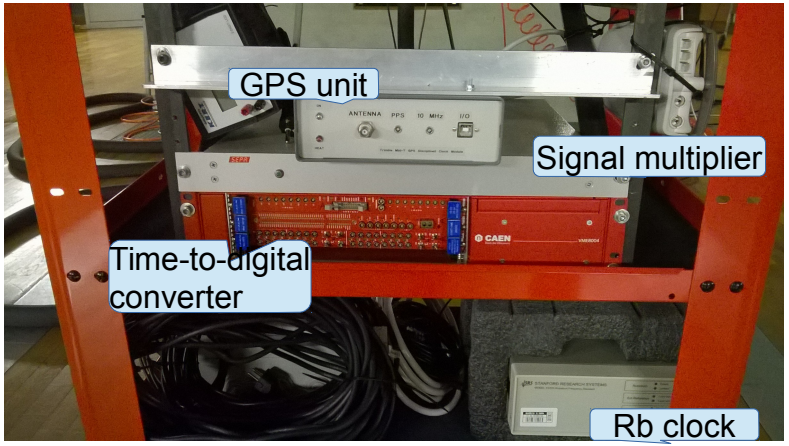
Aqueye+Iqueye: A very accurate acquisition and timing system

*SPADs have <**50 ps time resolution**,* ~100 cts/s dark count rate, 6-8 MHz maximum count rate, quantum efficiency up to 60%





Our instruments time tag and store the arrival time of each detected photon with a <100 ps relative time accuracy and <500 ps absolute time accuracy (wrt UTC)

All times are stored in event lists that can be analyzed in post-processing

At present the maximum data rate is of the order of few MHz (in the linear regime)

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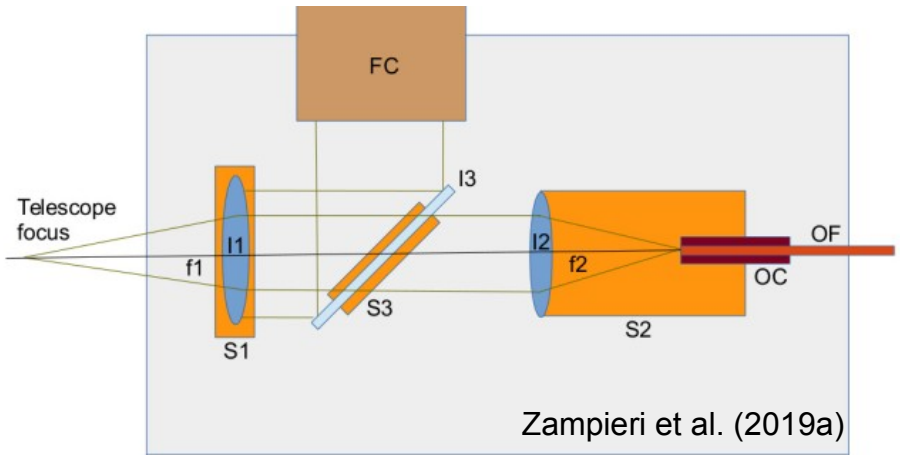
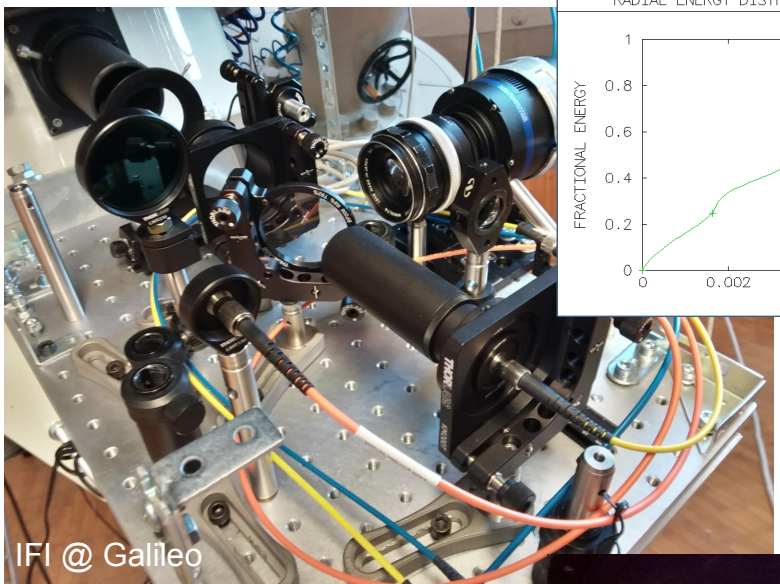
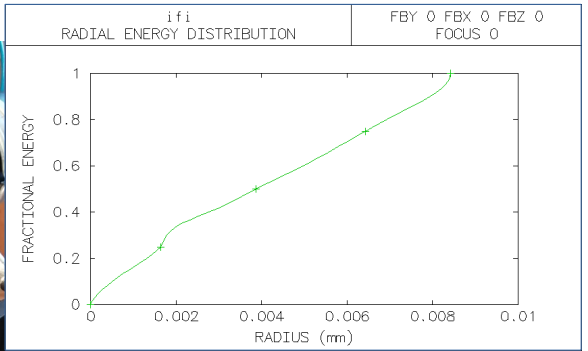
Iqueye Fiber Interface (IFI)







Gaiani (2021)

Overall efficiency of IFI tested in the lab **~80%**

Specifications of optical fiber are carefully chosen so as to reproduce the original spot size and telescope aperture