



# Investigating compact objects at high time resolution in the optical band with AQUEYE+ and IQUEYE



**AQUEYE+**  
IQUEYE

**Michele Fiori, Luca Zampieri, Alessia Spolon**  
for the **AQUEYE+IQUEYE** team

*<http://web.oapd.inaf.it/zampieri/aqueye-iqeye/index.html>*

OAPd Days - June 28, 2024



# Fast Photon Counting Optical Astronomy: The FPC-OA project in Padova

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



## Scheda INAF FPC-OA

PI: L. Zampieri

### AQUEYE+IQUEYE Organization chart

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

OA Padova  
Univ. Padova

OA Roma  
OA Brera-Merate

OA Arcetri  
OA Catania  
Univ. Bologna

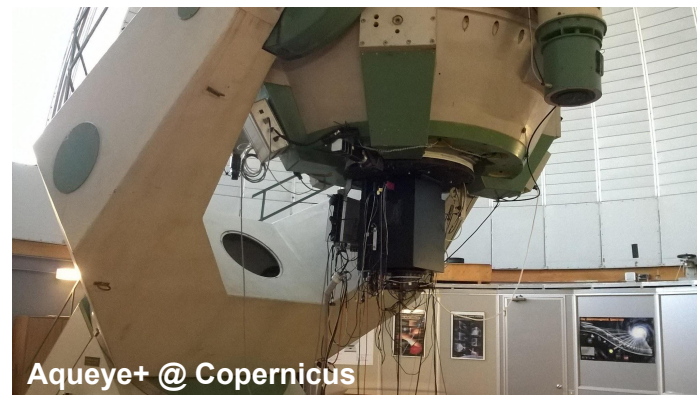
Funded by **INAF Large Grant 2022**  
(PI: A. Papitto)  
and **DFA-UniPD**

# Fast Photon Counting Optical Astronomy: Aqueye+ and Iqueye



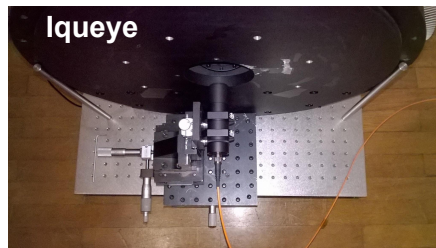
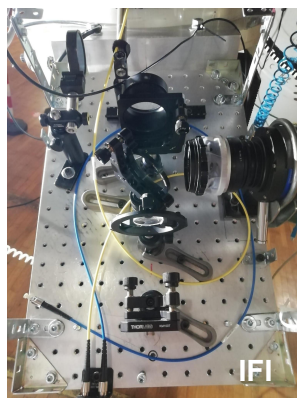
**Aqueye+ and Iqueye** are non-imaging instruments for very fast photon counting in the optical band (Barbieri et al. 2009; Naletto et al. 2009, 2013; Zampieri et al. 2015, 2019a)

- Field of view: few arcsec
- Optical design: **entrance pupil split in 4 parts** with a pyramidal mirror
- Detectors: **4 SPADs (by MPD) on-source + 1 SPAD on sky** (offset by 10 arcmin) with <50 ps time resolution
- Acquisition system: **sub-ns time tagging accuracy wrt UTC**



Aqueye+ @ Copernicus

**Aqueye+ mounted at Copernicus  
telescope in Asiago**



**Iqueye mounted at NTT, WHT, TNG,  
Galileo in Asiago (with the Iqueye  
Fiber Interface, IFI)**

# Fast Photon Counting Optical Astronomy: The FPC-OA project in Padova

Project page:  
<http://web.oapd.inaf.it/zampieri/aqueye-iqeye/index.html>



## FPC-OA - Technology

- Construction and development of FPC-OA instrumentation: **Aqueye+, Iqueye**
- Low-impact fiber-feeding of FPC-OA instrumentation: **IFI, EFI**
- **Infrared** Fast Photon Counting channel

## FPC-OA - Observing programs

**Two proposals approved (44+12 nights)** at the 1.8-m Copernicus telescope (cycles 22-24) and 2-3 nights/month granted at the 1.2-m Galileo tel. for:

- **Simultaneous multicolor observations of optical pulsars**
- **Searches for optical flashes from FRBs and magnetars**
- **Timing of optical transients and X-ray binaries**
- Monitoring the intra-night variability of Blazars
- Lunar and asteroidal occultations
- **Stellar Intensity Interferometry experiments**

**Simultaneous/coordinated MWL campaigns with:**

*SRT, NC, GMRT, TNG, NICER, HXMT, MAGIC*

Request of observations can be submitted at:  
[aqueye.iqeye@gmail.com](mailto:aqueye.iqeye@gmail.com)

Laboratory ASTRI-AQUEYE  
INAF-OA Padova (Cima Ekar)  
Oct 18, 2022



# Stellar Intensity Interferometry experiments: The Asiago Stellar Intensity Interferometer



Photon counting SII (with ns time resolution) successfully experimented on Vega with Aqueye+ and IFI+Iqueye in Asiago

**The Asiago stellar intensity interferometry experiment**

The two main observing facilities in Asiago (Italy), the 1.22 m Galileo telescope (T122) and the 1.82 m Copernicus telescope (T182), located in the resorts of Pennar and Cima Ekar, provide the infrastructure

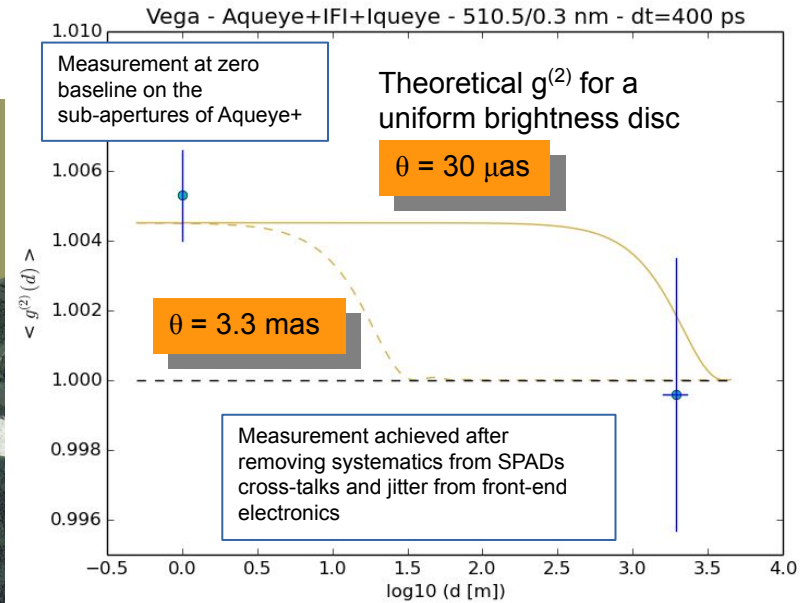
**IFI+Iqueye@Galileo**  
Fast optical photometer efficiently fiber-coupled to the telescope through a dedicated instrument (Iqueye Fiber Interface, with a FOV of 12.5")

Acquisition system of the two instruments provides sub-ns time tagging accuracy wrt UTC

**Goals of the experiment**  
Performing the first measurement of the correlation of the arrival times of photons from a star counting coincidences in post-processing  
Validating the feasibility of this type of measurements on a km baseline

**Aqueye+@Copernicus**  
Fast optical photometer with a FOV of 5", exploiting the original pupil-splitting optical design for measurements at zero baseline

The Aqueye+Iqueye Collaboration (2020)



Zampieri et al. (2021)

Crucial for future implementations of SII in photon counting on arrays of Cherenkov telescopes (like the INAF ASTRI Mini-Array; Zampieri et al. 2022)

Measurements consistent with the expected degree of coherence for a source with the 3.3 mas diameter of Vega

Constraint on the size of any potential very bright feature on the surface: angular size  $\theta > 30 \mu\text{as}$  ( $3.0 \times 10^9 \text{ cm}$ ) to be consistent with the absence of correlation on  $\sim 2 \text{ km}$



# Stellar Intensity Interferometry experiments: ASTRI Stellar Intensity Interferometry Instrument (SI<sup>3</sup>)

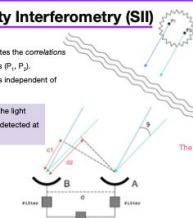
## Fast Photon Counting Stellar Intensity Interferometry: Prospects for the ASTRI Mini-Array

A. Spolon<sup>1</sup>, M. Fiori<sup>1</sup>, L. Zampieri<sup>1</sup>, L. Lessio<sup>1</sup>, L. Paoletti<sup>1</sup>, C. Pernechele<sup>1</sup>  
and the ASTRI Project  
<sup>1</sup>INAF - Astronomical Observatory of Padova, Italia

ASTRI Mini-Array  
ICSC  
Funded by the European Union

### Stellar Intensity Interferometry (SII)


**How it works?**  
Intensity interferometry evaluates the correlations between pairs of point sources (P<sub>1</sub>, P<sub>2</sub>). Each point radiates light and is independent of each other.  
SII is based on correlation of the light intensity fluctuations of a star detected at two or more telescopes.



Working principle of an intensity interferometer. From [1].

**What can we measure?**  
Radius and surface structures of bright and hot stars (D/B → F/G type).


SII was pioneered by **Brown & Twiss** in Narrabri, Australia [2]. They made the first direct astronomical measure of stellar radii via SII.



The two Narrabri SII telescopes.

Operating simultaneously ARRAY of large area telescopes  
+ connecting them electronically → renewed interest for SII  
→ Tool for imaging obs. in optical band  
(-long-baseline radio interferometric array).

### ASTRI Mini-Array



ASTRI Mini-Array  
El Teide, Tenerife,  
Spain

9 Imaging Atmospheric Cherenkov Telescopes [3] to:  
- study gamma-ray sources at very high energy (TeV)  
- perform optical SII observations → ASTRI SII Instrument (SI<sup>3</sup>)


**Goal:** using the long multiple baselines [4] of all 9 telescopes to do image reconstruction with resolution of ~100 μas [4]  
SI<sup>3</sup> ↔ optical window (1-3 nm filter; centered at 430-500 nm).

### Methods

Photon-Counting Intensity Interferometry  
Counting coincidences in photon arrival times measured at 2 telescopes and exploit the quantum properties of the light emitted from a star.  
**2<sup>nd</sup> order (discrete) degree of coherence of a star [5]**  
Measures the degree of correlation of its lights.  
Depends on telescopes separations  $d$  and the relative delay  $\tau$  between them.

$$g^{(2)}(\tau, d) = \frac{N_{XY} N}{N_X N_Y}$$

**The Aqueye/Iqueye team!**  
 $N_X, N_Y$  = # photons detected at telescopes X and Y in time  $\tau$   
 $N_{XY}$  = # simultaneous detection in bin of  $\tau$   
 $N$  = # intervals (from)

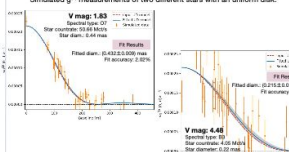


**ASIAGO SII experiment**  
1.22m Galleo (F/I-Iqueye) + 1.82m Copernico (Aqueye-) Telescopes @Asiago (Italy)

- First measurements of the correlation of the arrival times of photons from a star counting coincidences in post-processing.
- Validating the feasibility of this type of measurements on a km baseline

### ASTRI SII Simulations

Simulated  $g^{(2)}$  measurements of two different stars with a uniform disk.

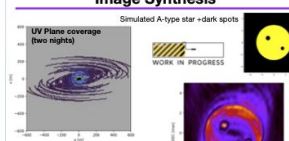


**V mag 4.83**  
Measured size of Star diameter: 0.6 mas  
Star diam.: 0.4 mas  
Fitted diam.: 0.62 ± 0.005 mas  
Fit accuracy: 0.00%

**V mag 4.46**  
Measured size of Star diameter: 0.32 mas  
Star diameter: 0.22 mas  
Fitted diam.: 0.31 ± 0.010 mas  
Fit accuracy: 0.4%

### Image Synthesis

Simulated A-type star + dark spots



UV Plane coverage (two nights)  
WORK IN PROGRESS

### References

1. Fowlie C., 2009, A&A, 507, 1719
2. Brown, R. H. & Twiss, R. Q. 1957, Proc. R. Soc. London Ser. A, 242, 300
3. Scudler et al. 2022, JHEAp, 16, 52
4. Zampieri L. et al., 2022, SPIE Conference Series, Vol. 12183
5. Zampieri L. et al., 2021, MNRAS, 506, 1585

Check out Alessia Spolon's poster!

# Optical Pulsars

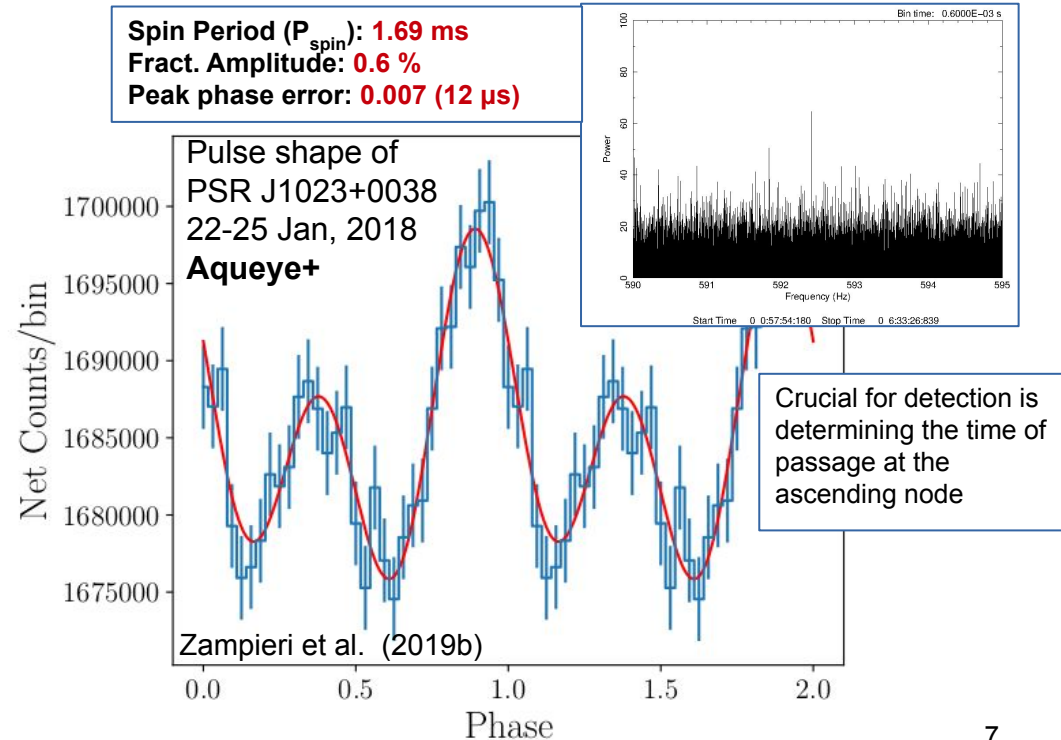
## PSR J1023+0038: The first ms optical and UV pulsar



- Rapidly rotating, weakly magnetized ( $1.e8-1.e9$  G) neutron star in a binary system, with a low mass ( $< 1M_{\text{sun}}$ ) companion
- 'Recycled' and spun up by deposition of angular momentum from the companion in an accreting Low Mass X-ray Binary phase (Wijnands & van der Klis 1998)
- *Swinging between a rotation-powered ms pulsar and an accretion (subluminous) phase* (Papitto & de Martino 2022); last transition in 2013
- Three such systems known, called **transitional Millisecond Pulsars** (tMPs):
  - PSR J1023+0038 (Archibald et al. 2009)
  - XSS J1227-4853 (de Martino et al. 2010)
  - IGR J1824-2452 (Papitto et al. 2013)
- Instrumental to understanding the formation of ms pulsars and the accretion physics in low magnetic field neutron stars

### Discovery of millisecond optical/UV pulsations

(Ambrosino et al. 2017, Zampieri et al. 2019b, Karpov et al. 2019; Burtovoi et al. 2020, Jaodand et al. 2021, Miraval Zanon et al. 2022)

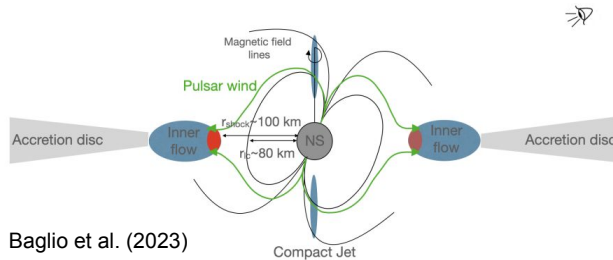


# Optical Pulsars

## PSR J1023+0038: Optical vs X-ray pulse

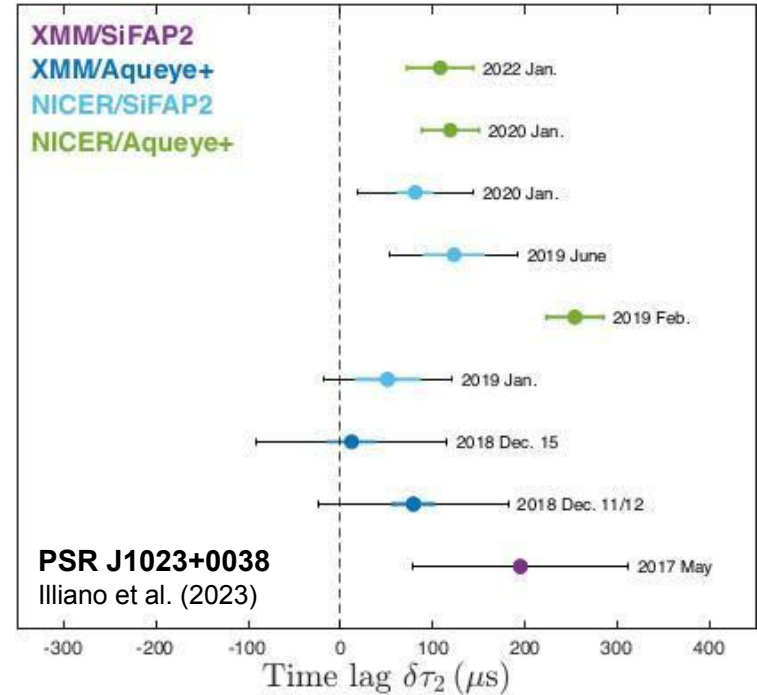


- Extensively monitored with Aqueye+ (2017-2023): Nearly simultaneous observations in the optical band (**Aqueye+** and **SiFAP2@TNG**) and in the X-ray band (**XMM-Newton** and **NICER**)
- **NICER and Aqueye+** provide the best absolute temporal uncertainty
- *The optical pulse lags that in the X-rays by  $\sim 150 \mu\text{s}$ . Both pulsations come from the same region, confirming a common emission mechanism*



'Mini pulsar wind nebula' in which the pulsar wind shocks on the inner flow (Papitto et al. 2019). Consistent also with the spin-down rate measured from Aqueye+ data, only  $\sim 5\%$  faster than that during the radio pulsar phase (Burtovoi et al. 2020).

Optical - X-ray delay of the second harmonic of the pulse profile

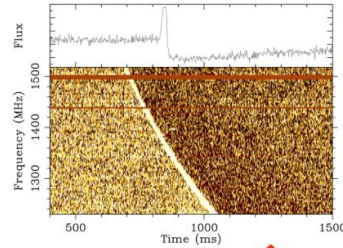




# Fast Radio Bursts



The first was discovered by Lorimer and Narkevic in 2007, looking through archival pulsar survey data (Lorimer et al. 2007)



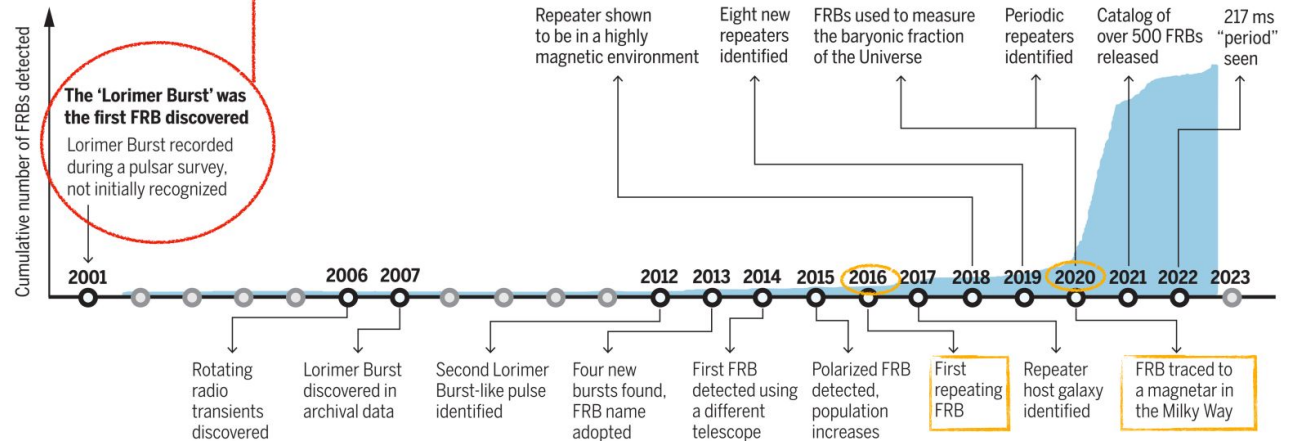
**Fast Radio Bursts (FRBs)** are *transient radio pulses lasting from a millisecond to a few seconds, with  $L=1.0e38-1.0e46$  erg/s, large dispersion measure and isotropic sky distribution*



Many FRBs have since been recorded (>500), including several that have been detected to repeat (~4%; e.g. Petroff et al. 2022)

Radio emission is likely coherent from relativistic particles (150 MHz-8 GHz)

The origin is still not understood, but several FRBs are associated to normal galaxies (at  $z < 0.5$ )



Several models 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 provide critical information on the nature of the progenitor and would greatly enhance our understanding of the FRB phenomenon**

# Fast Radio Bursts

## Magnetars: SGR J1935+2154



**Magnetar** with  $P = 3.25$  s and  $\dot{P} = 1.43 \times 10^{-11}$  s/s, *characteristic age 3.6 kyr and dipole magnetic field of  $2.2 \times 10^{14}$  G* (Israel et al. 2016), discovered through a short burst with Swift in 2014 (Stamatikos et al. 2014), sporadically going through hard X-ray burst/flaring activity (e.g., Borghese et al. 2020; Lin et al. 2020a; Younes et al. 2017, 2021)

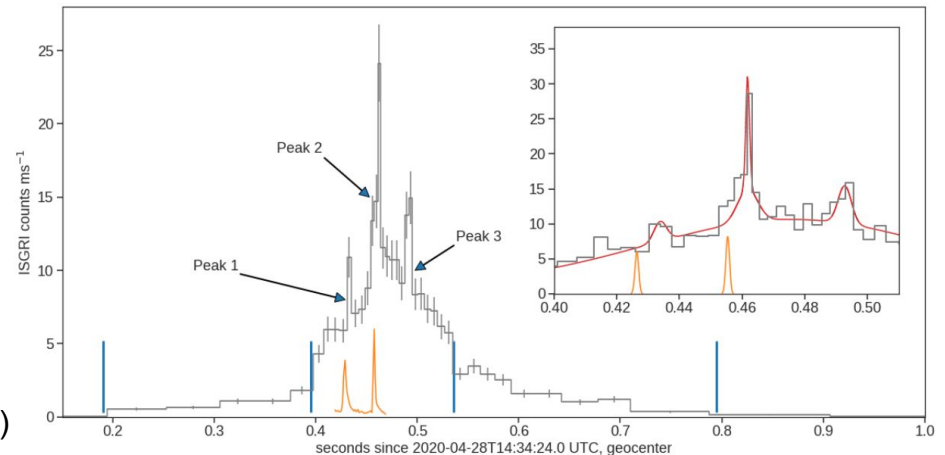
**Outburst episode observed in 2020** with tens of bursts in a few days

**On 2020 April 28 an extremely bright millisecond-duration radio burst (FRB 200428) was emitted** and detected with CHIME (CHIME/FRB Collaboration et al. 2020) and STARE2 (Bochenek et al. 2020)

**Coincident with a bright, hard X-ray burst** detected with INTEGRAL (Mereghetti et al. 2020), Konus-Wind (Ridnaia et al. 2021), Insight HXMT (Lin et al. 2020b) and AGILE (Tavani et al. 2021)

**No optical counterpart** in a simultaneous observation with BOOTES (Lin et al. 2020b; extinction-corrected fluence  $< 4.4$  Jy s)

Near-IR campaign with the Palomar-Gattini-IR places an **upper limit (J band)** on the second-timescale extinction-corrected fluence ( $< 0.125$  Jy s; De et al. 2020)



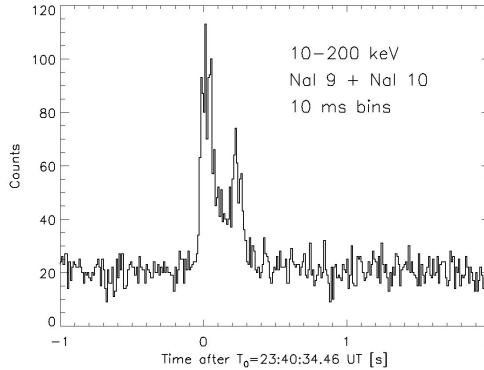
# Fast Radio Bursts

## Magnetars: Searching for prompt/delayed optical flashes in SGR J1935+2154



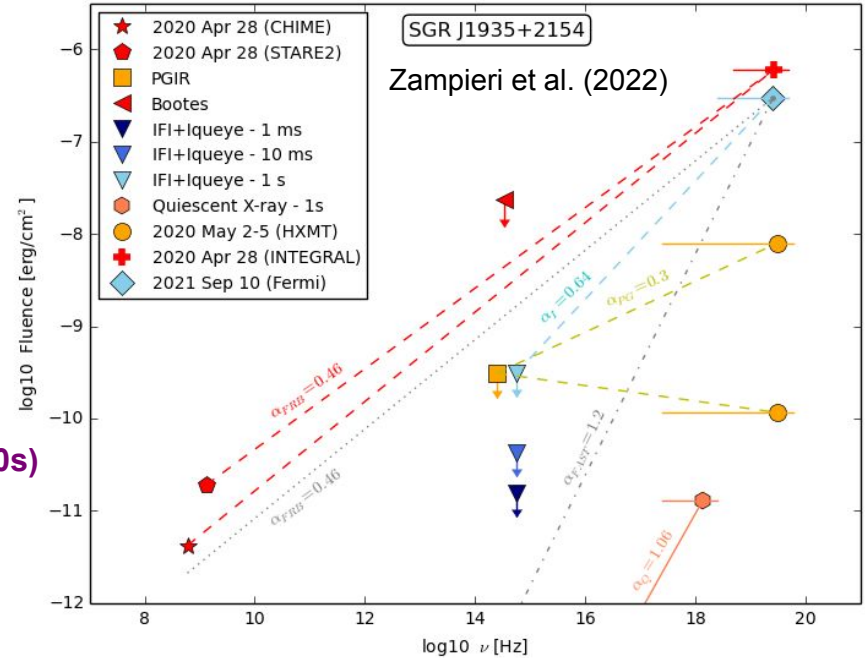
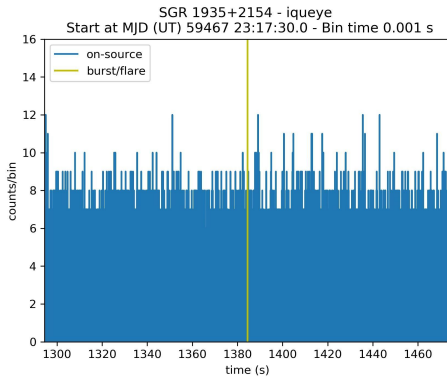
On Sep 10, 2021 a **hard X-ray burst** was detected with the Fermi GBM from **SGR J1935+2154**

**No optical peak around T0** in a simultaneous IFI+Iqueye observation



**Iqueye upper limit around T0**  
(sampling time 1 s, interval +/-90s)

$V_{min} = 10.1$  mag per sec (extinction corrected)  
 $F_{max} = 3.1 \times 10^{-10}$  erg/cm<sup>2</sup> (0.35 Jy s)  
 $L_{max} = 7.3 \times 10^{35}$  erg/s (at 4.4 kpc)



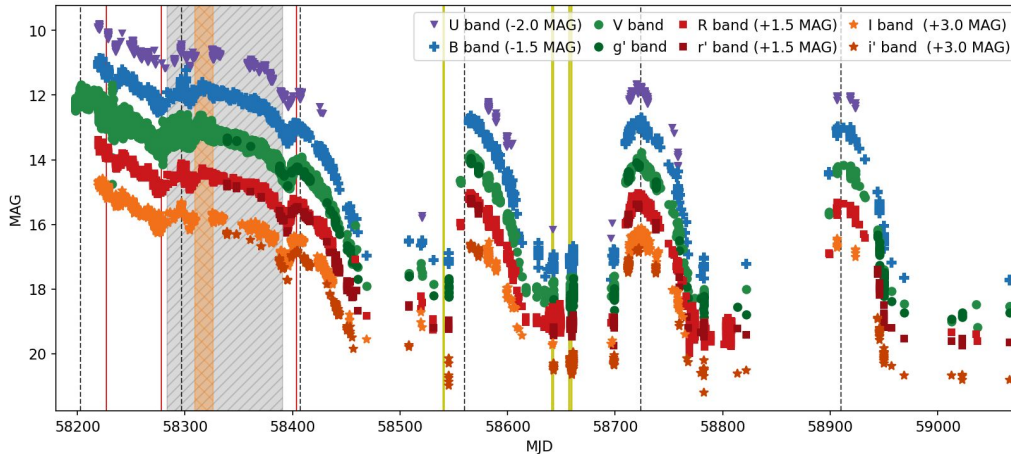
Bursts with radio counterpart ("2020 Apr 28"-type bursts), characterized by a much flatter radio-through-hard-X-ray slope, are, in principle, detectable in the optical band with a simultaneous observation with < 1s time resolution

# Optical transients

## MAXI J1820+070: Broadband multi-timescale variability of an outburst of a BH transient



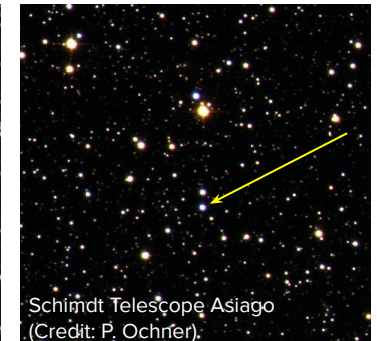
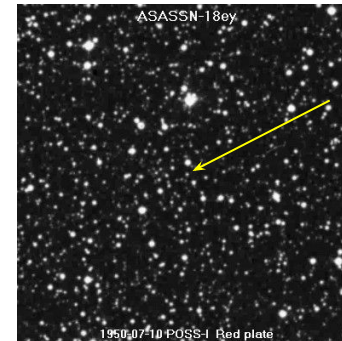
**Outbursts in Black Hole X-ray binaries (BHXRBs)** allow us to study the unique physical processes occurring in the accretion flow close to black holes. The **variability in the accretion flow** is usually **studied** in the **X-rays**, but can also propagate along the jet and be observed at **longer wavelengths**.



**MAXI J1820+070** is a bright BHXRB discovered on Mar 11, 2018 and soon after associated to the optical transient ASSASN-18ey (ATel #11399, #11400).

The source went through all the **typical states and transitions** of a **BH accreting X-ray binary** (e.g. Shidatsu et al. 2019)

- **4 subsequent re-brightenings** are detected after the main burst.
- During the first outburst a significant **optical super orbital modulation (16.9 hrs)** was detected
- After the transition to the Intermediate state a similar modulation seems to be present also in the X-rays (orange shaded area).
- During the Low-Hard state **LF QPOs** are detected in the **optical PDS**.



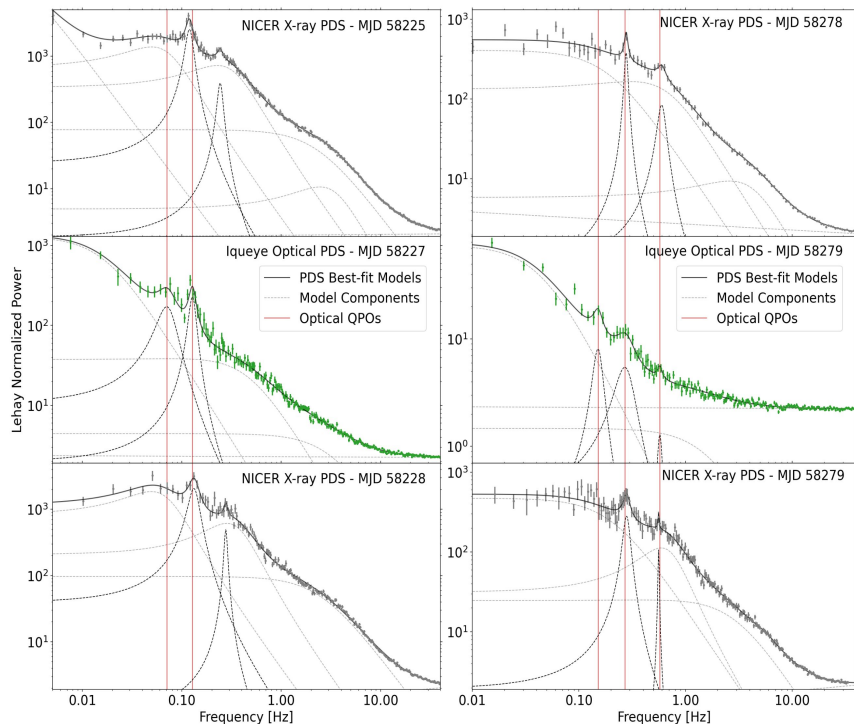
# Optical transients

## MAXI J1820+070: Optical (and X-ray) LF QPOs



**High Timing Resolution Optical Photometry:** 8 observing runs (Apr-Oct 2018) with IFI+lqueye and Aqueye+.

**X-ray observations:** NICER data from beginning of the outburst. Almost one observation per day between Mar 12 and Nov 21, 2018 (210 observations in 254 days, ObsID 1200120101-1200120278).



**Optical QPOs were detected with IFI+lqueye in 3 runs: Apr 2018, Jun 2018, Oct 2018.** A comparison of QPO2 with the closest X-ray observations always shows that it has a similar frequency (synchronous QPOs; Thomas et al. 22).

**April 2018**

**June 2018**

**1st X-ray observation [MJD 58225]**

**QPO2:  $\nu=119\pm 1$  mHz; FWHM= $23\pm 4$  mHz**

**QPO3:  $\nu=243\pm 4$  mHz; FWHM= $33\pm 16$  mHz**

**1st X-ray observation [MJD 58278]**

**QPO2:  $\nu=278\pm 5$  mHz; FWHM= $23\pm 11$  mHz**

**QPO3:  $\nu=598\pm 17$  mHz; FWHM= $117\pm 62$  mHz**

**Optical observation [MJD 58227]**

**QPO1:  $\nu=71\pm 4$  mHz; FWHM= $36\pm 16$  mHz**

**QPO2:  $\nu=128\pm 2$  Hz; FWHM= $24\pm 5$  mHz**

**Optical observation [MJD 58279]**

**QPO1:  $\nu=151\pm 6$  mHz; FWHM= $33\pm 16$  mHz**

**QPO2:  $\nu=268\pm 12$  mHz; FWHM= $150\pm 39$  mHz**

**QPO3:  $\nu=574\pm 13$  mHz; FWHM= $67\pm 51$  mHz**

**2nd X-ray observation [MJD 58228]**

**QPO2:  $\nu=132\pm 3$  mHz; FWHM= $36\pm 11$  mHz**

**QPO3:  $\nu=277\pm 5$  mHz; FWHM= $21\pm 16$  mHz**

**2nd X-ray observation [MJD 58279]**

**QPO2:  $\nu=280\pm 5$  mHz; FWHM= $47\pm 18$  mHz**

**QPO3:  $\nu=559\pm 9$  mHz; FWHM= $16\pm 21$  mHz**

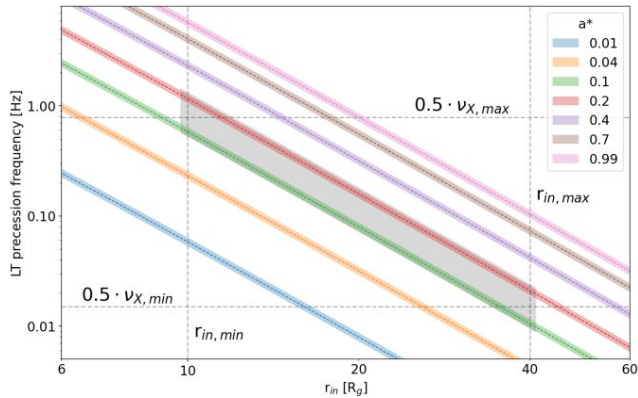
**QPO1 to QPO2 ratio  $\approx 1:2$**

**QPO1 to QPO2 ratio  $\sim 1:2$**





- **Synchronous LF QPOs** extend across several orders of magnitude (5) in energy. X-ray and optical variability emitting regions are very close during the hard state
- **Lense-Thirring (LT) precession** triggered by perturbations at  $r_{in}$  around a rotating BH (Stella & Vietri 98) could produce X-ray+optical LF QPOs with these properties.
- A **variable QPO frequency** implies a **variable characteristic radius**. If the frequency is small ( $< 1$  Hz), the radius can be relatively large ( $> R_{isco}$ )
- If the lowest modulation frequency is that observed in the optical PDS, the precession frequency is:  $\nu_{pr} = \nu_{opt} = \nu_x/2$



LT precession frequency

$$\nu_{LT} = \nu_{\phi} \left[ 1 - \sqrt{1 - \frac{4a^*}{r^{3/2}} + \frac{3a^*}{r^2}} \right]$$

### Fundamental LF QPOs: Optical

$$\nu_{pr} = \nu_{opt} = \nu_x/2$$

Varying  $r_{in}$ , LT precession interval consistent with observed LF QPO interval for a slowly spinning BH with  $a^* \sim 0.1-0.2$

### Fundamental LF QPOs: X-ray

$$\nu_{pr} = 2\nu_{opt} = \nu_x$$

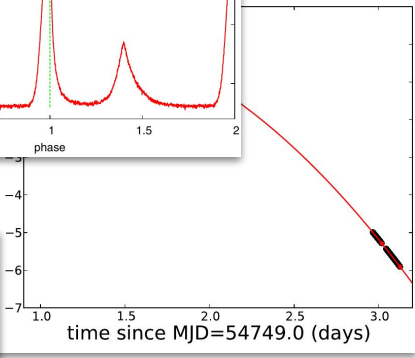
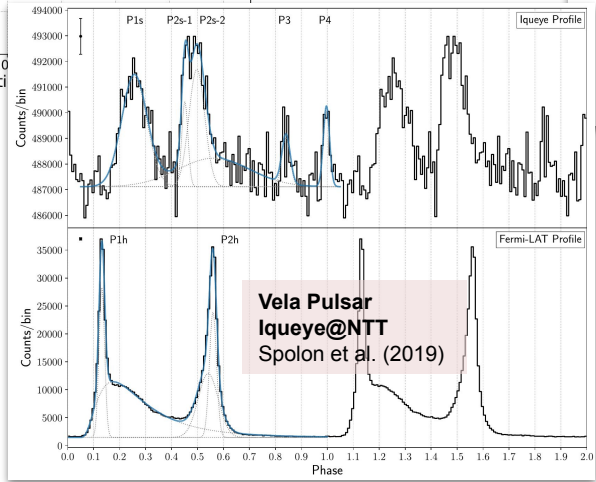
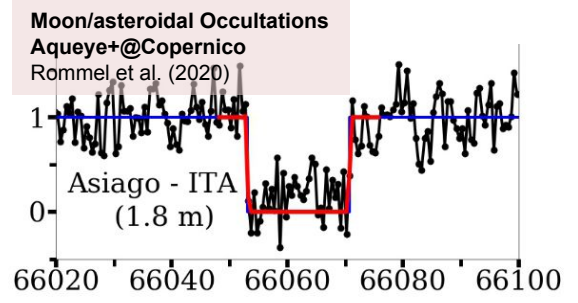
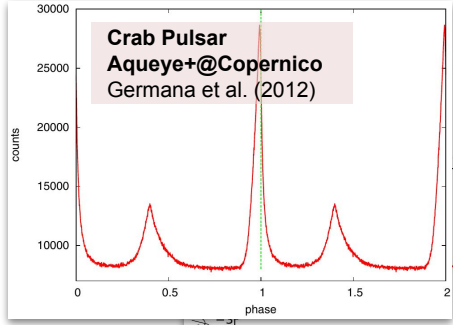
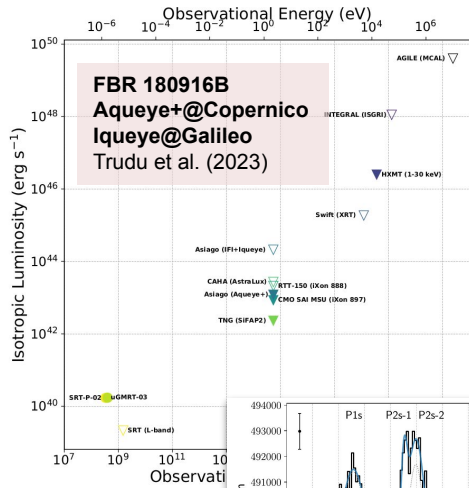
Varying  $r_{in}$ , LT precession interval consistent with observed LF QPO interval for a moderately spinning BH with  $a^* \sim 0.2-0.3$

**When  $r_{in} \sim 10r_g$ , standard disc extends inwards and self-irradiates the outer disc, possibly triggering a large scale super-orbital warp (observed in the optical).**

# But there is much more!



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



**INTERNATIONAL GEMINI OBSERVATORY**

**IQUEYE MOVING TO GEMINI SOUTH!**  
 8-meter class telescope  
 Cerro Pachón, Chile

**VISITING INSTRUMENT PROGRAM**



**Thank you for your attention!**

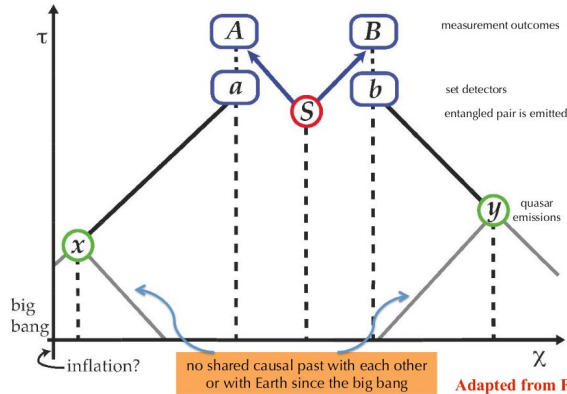
# Quantum Experiment on Bell Inequalities

## Preparatory work in Asiago in 2015-2016

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### COSMIC BELL CONFORMAL DIAGRAM



$x, y$  need  $z > 3.65$  (at  $180^\circ$ ) for no shared causal past with each other, source, detectors since end of inflation 13.8 Gyr ago

Preparatory observations made by A. Zeilinger's group for the *cosmic Bell experiment with polarization-entangled photons*, using random measurement settings from high-redshift quasars, later on carried out in La Palma (Scheidt et al. 2010; Gallicchio, Friedman & Kaiser 2013, 2014; Rauch et al. 2018)

Anton Zeilinger won the **2022 Nobel Prize in Physics** "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

