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

Michele Fiori, Luca Zampieri, Alessia Spolon
for the **AQUEYE+IQUEYE team**
http://web.oapd.inaf.it/zampieri/aqueye-iqueye/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 †	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	
			T. Forte			L. Zampieri	S. Conforti	
			M. Mosele				M. Fiori	
							G. Naletto	
							A. Papitto	
							A. Spolon	
							U. Munari	
							L. Zampieri	

Teaching, training and outreach

G. Naletto
P. Ochner
L. Zampieri

OA Padova
Univ. Padova

OA Roma
OA Brera-Merate

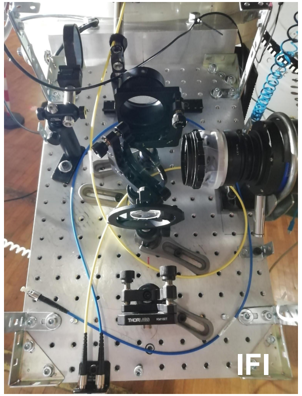
OA Arcetri
OA Catania
Univ. Bologna

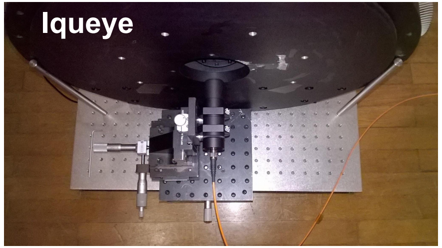
Funded by **INAF Large Grant 2022** (PI: A. Papitto) and **DFA-UniPD**

Fast Photon Counting Optical Astronomy:
Aqueye+ and Iqueye

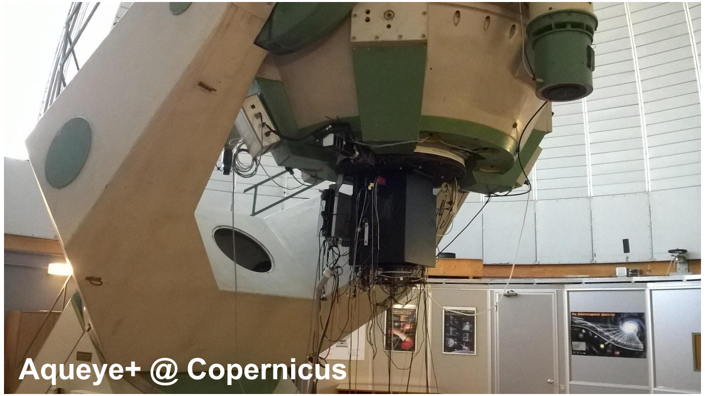
Aqueye+ and Iqueye *are non-imaging instruments for very fast photon counting in the optical band (Barbieri et al. 2009; Naletto et al. 2009, 2013; Zampieri et al. 2015, 2019a)*

- 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**





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



Aqueye+ mounted at Copernicus telescope in Asiago

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

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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

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

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**

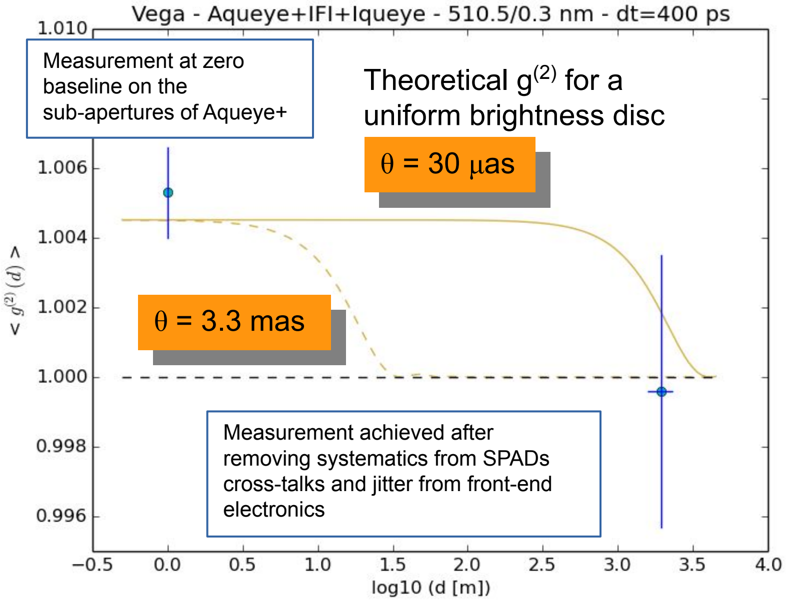
Simultaneous/coordinated MWL campaigns with:

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

Request of observations can be submitted at:
aqueye.iqueye@gmail.com

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



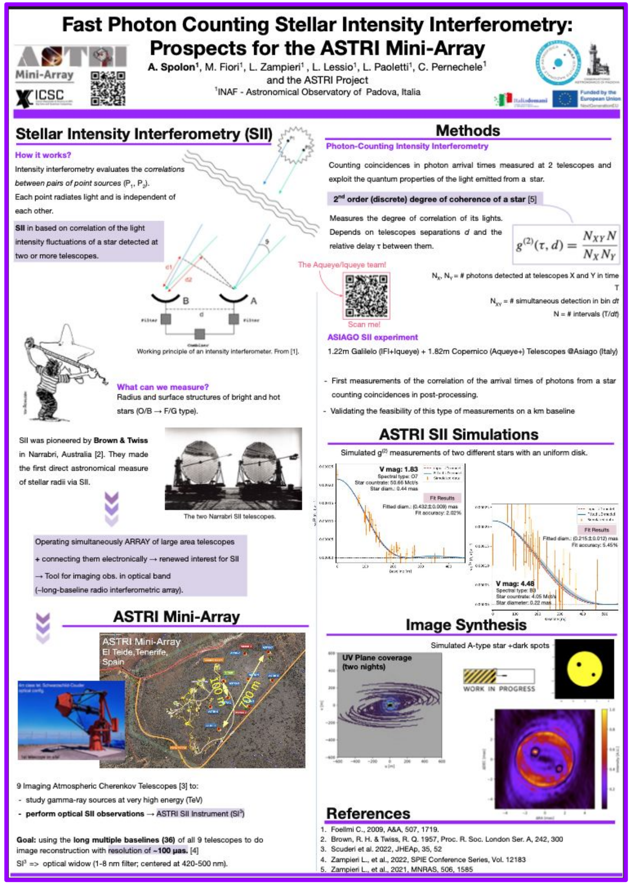
Zampieri et al. (2021)

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 θ > 30 μas (3.0e9 cm) to be consistent with the absence of correlation on ~2 km

Stellar Intensity Interferometry experiments:
ASTRI Stellar Intensity Interferometry Instrument (SI^3)



Check out Alessia Spolon's poster!

Optical Pulsars

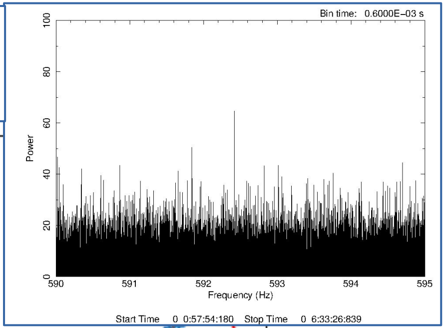
PSR J1023+0038: The first ms optical and UV pulsar

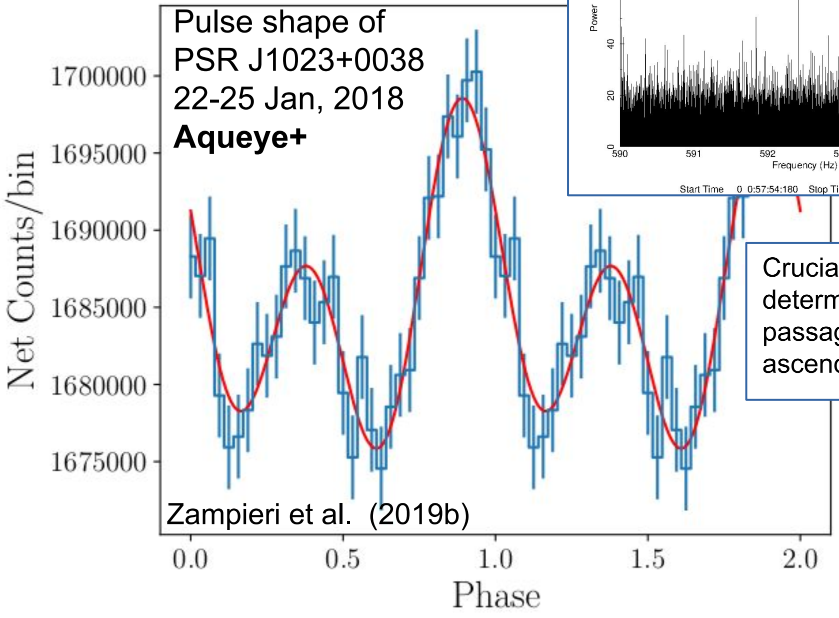
- Rapidly rotating, weakly magnetized (1.e8-1.e9 G) neutron star in a binary system, with a low mass (< 1Msun) companion
- 'Recycled' and spun up by deposition of angular momentum from the companion in an accreting Low Mass X-ray Binary phase (Wijnands & van der Klis 1998)
- *Swinging between a rotation-powered 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)

Spin Period (P_{spin}): 1.69 ms
Fract. Amplitude: 0.6 %
Peak phase error: 0.007 (12 μs)





Crucial for detection is determining the time of passage at the ascending node

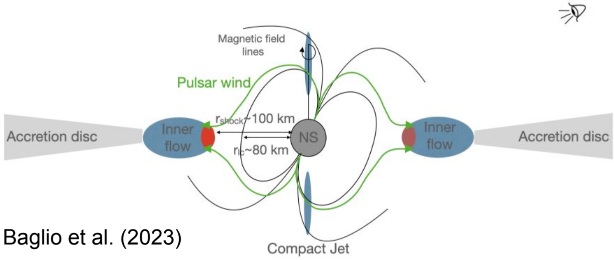
Optical Pulsars

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

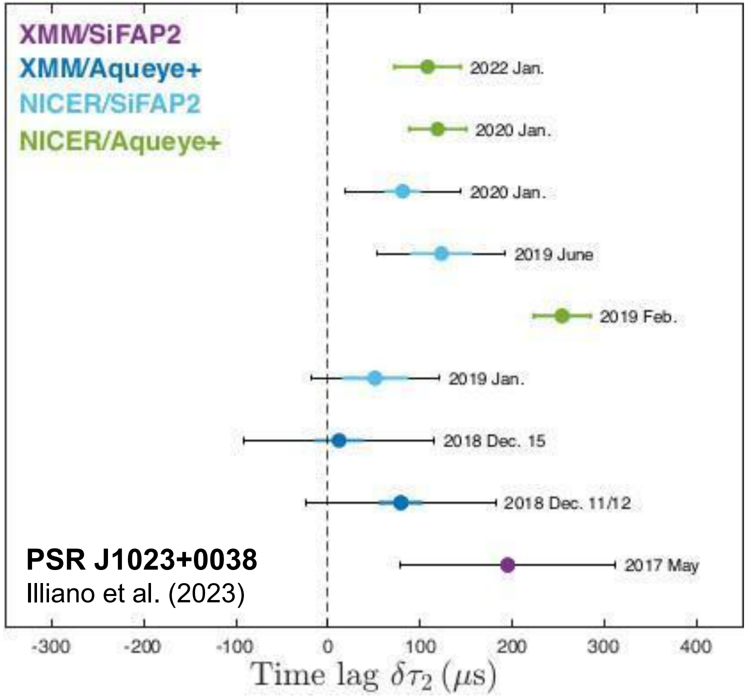
- *The optical pulse lags that in the X-rays by ~150 μs. Both pulsations come from the same region, confirming a common emission mechanism*



Baglio et al. (2023)

'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 ~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



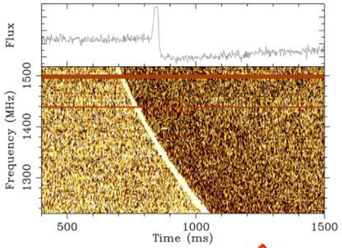
Fast Radio Bursts

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

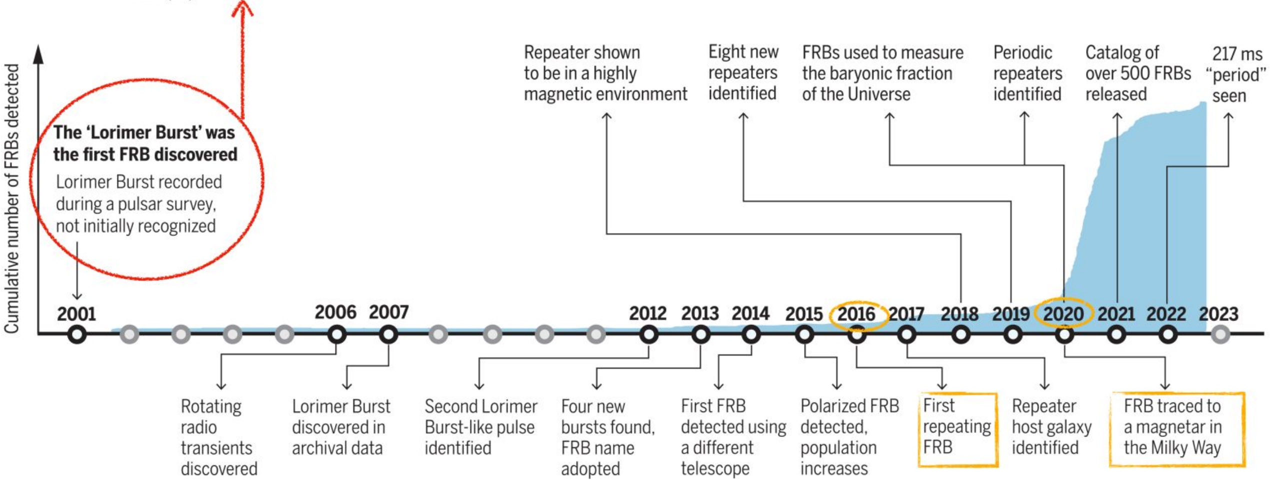
Many FRBs have since been recorded (>500), including several that have been detected to repeat (~4%; e.g. Petroff et al. 2022)

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)



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*



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 Pdot = 1.43e-11 s/s, *characteristic age 3.6 kyr and dipole magnetic field of 2.2x10^{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)

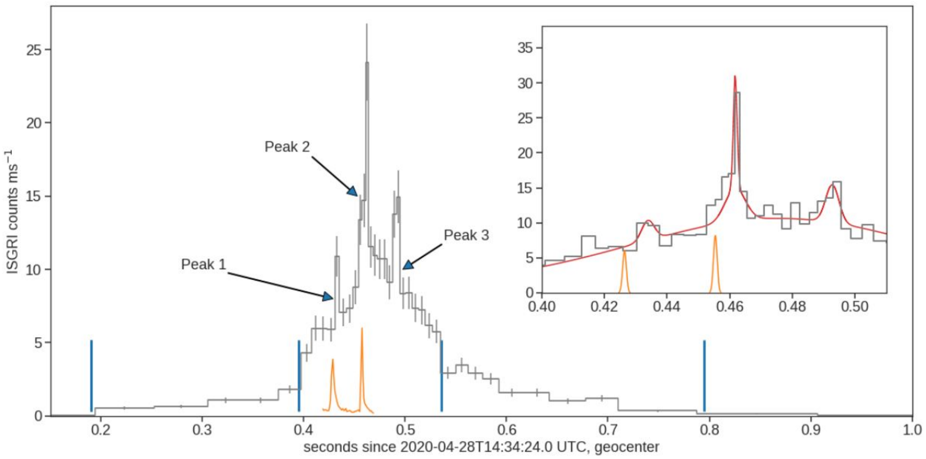
Outburst episode observed in 2020 with tens of bursts in a few days

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)

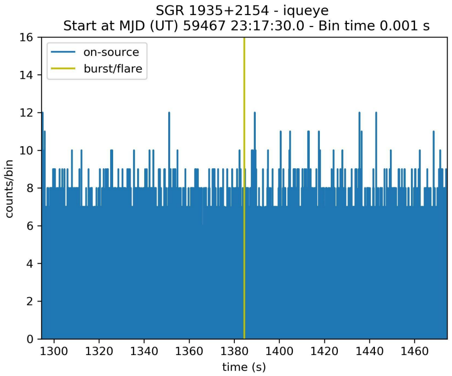


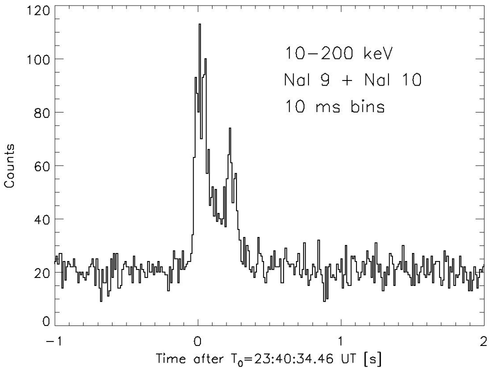
Fast Radio Bursts

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**

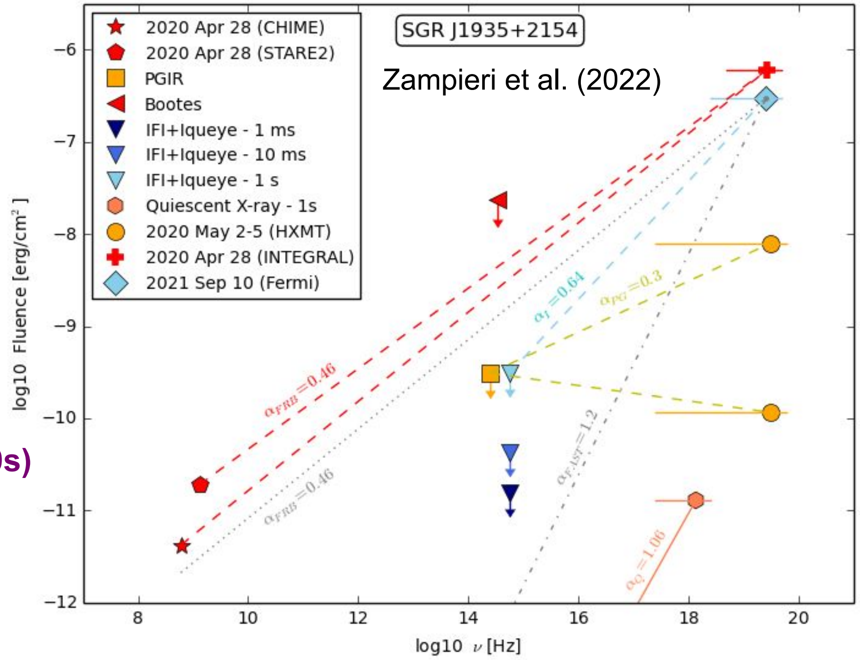
No optical peak around T0 in a simultaneous IFI+Iqueye observation





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

Vmin = **10.1** mag per sec (extinction corrected)
Fmax = **3.1 x 10^{-10}** erg/cm2 (0.35 Jy s)
Lmax = **7.3 x 10^{35}** erg/s (at 4.4 kpc)



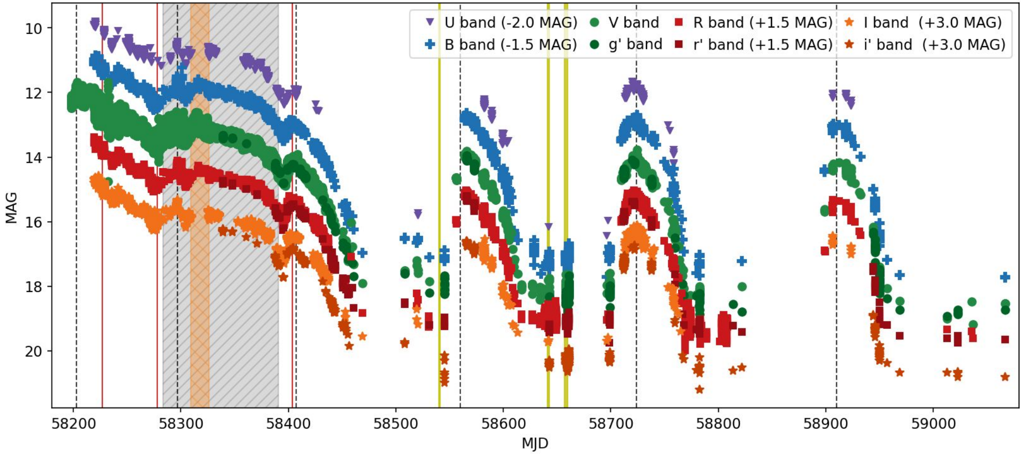
Zampieri et al. (2022)

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

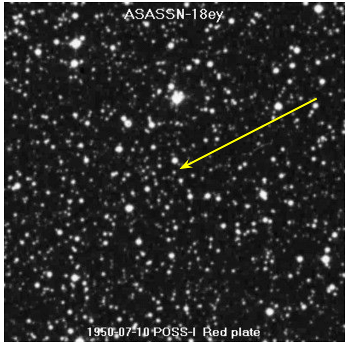
Outbursts in **Black Hole X-ray binaries (BHXRBs)** allow us to study the unique physical processes occurring in the accretion flow close to black holes. The **variability in the accretion flow** is usually **studied** in the **X-rays**, but can also propagate along the jet and be observed at **longer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

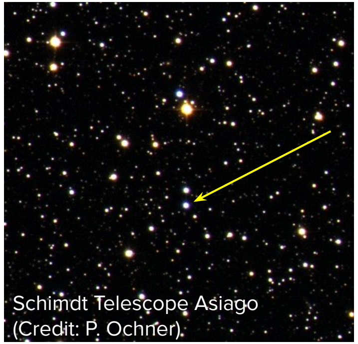


- **4 subsequent re-brightenings** are detected after the main burst.
- During the first outburst a significant **optical super orbital modulation (16.9 hrs)** was detected
- After the transition to the Intermediate state a similar modulation seems to be present also in the X-rays (orange shaded area).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

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)



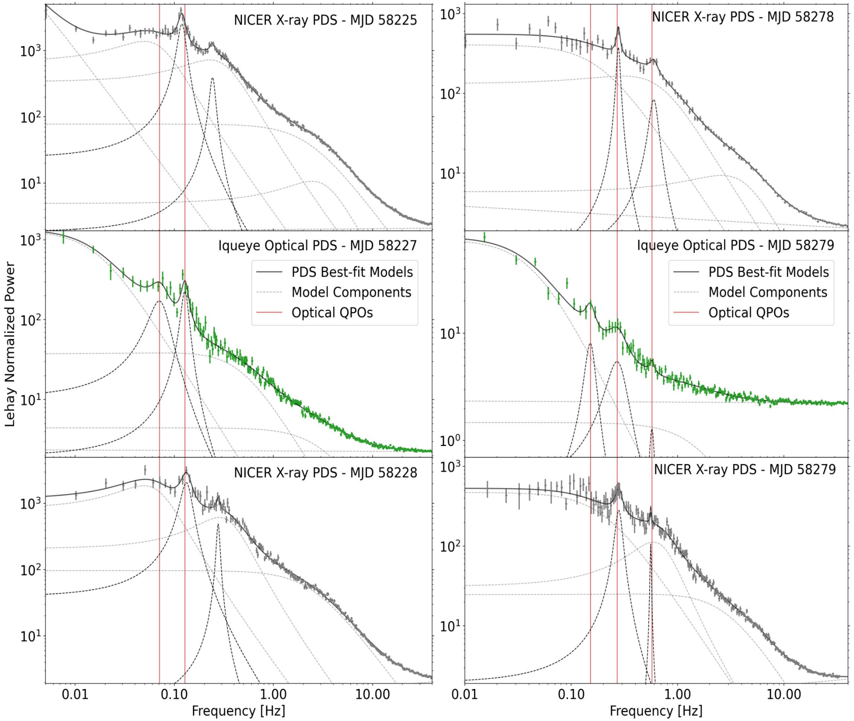


Schimdt Telescope Asiago
(Credit: P. Ochner).

Optical transients

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

High Timing Resolution Optical Photometry: 8 observing runs (Apr-Oct 2018) with IFI+Iqueye 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).



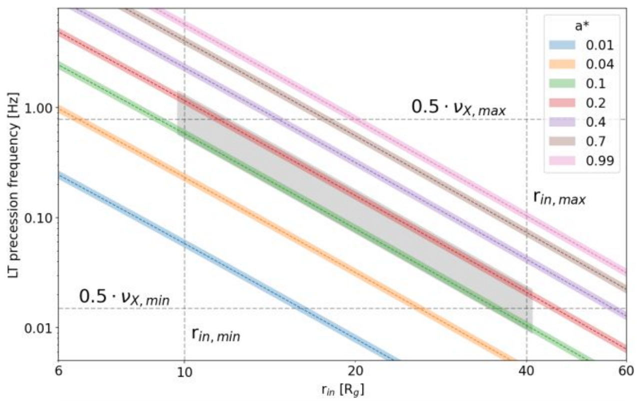
Optical QPOs were **detected** with **IFI+Iqueye** in 3 runs: **Apr 2018, Jun 2018**, Oct 2018. A comparison of QPO2 with the closest X-ray observations always shows that it has a similar frequency (synchronous QPOs; Thomas et al. 22).

April 2018	June 2018
1st X-ray observation [MJD 58225]	**1st X-ray observation [MJD 58278]**
QPO2: v=119±1 mHz; FWHM=23±4 mHz	**QPO2: v=278±5 mHz; FWHM=23±11 mHz**
QPO3: v=243±4 mHz; FWHM=33±16 mHz	**QPO3: v=598±17 mHz; FWHM=117±62 mHz**
Optical observation [MJD 58227]	**Optical observation [MJD 58279]**
QPO1: v=71±4 mHz; FWHM=36±16 mHz	**QPO1: v=151±6 mHz; FWHM=33±16 mHz**
QPO2: v=128±2 Hz; FWHM=24±5 mHz	**QPO2: v=268±12 mHz; FWHM=150±39 mHz**
	QPO3: v=574±13 mHz; FWHM=67±51 mHz
2nd X-ray observation [MJD 58228]	**2nd X-ray observation [MJD 58279]**
QPO2: v=132±3 mHz; FWHM=36±11 mHz	**QPO2: v=280±5 mHz; FWHM=47±18 mHz**
QPO3: v=277±5 mHz; FWHM=21±16 mHz	**QPO3: v=559±9 mHz; FWHM=16±21 mHz**
QPO1 to QPO2 ratio ∽1:2	**QPO1 to QPO2 ratio ~1:2**

Optical transients

MAXI J1820+070: LF QPO induced by Lense-Thirring precession?

- **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: $\mathbf{nu_{pr} = nu_{opt} = nu_x/2}$



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

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

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

Fundamental LF QPOs: X-ray

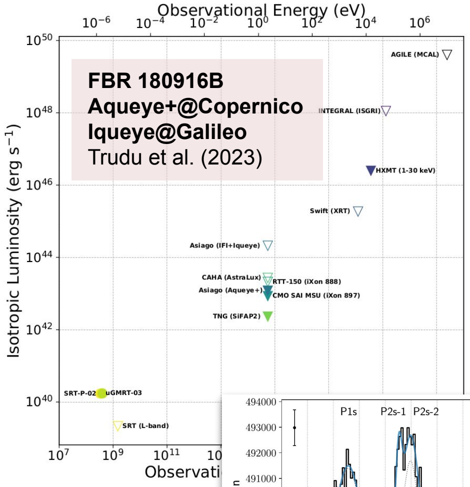
$\mathbf{nu_{pr} = 2nu_{opt} = nu_x}$

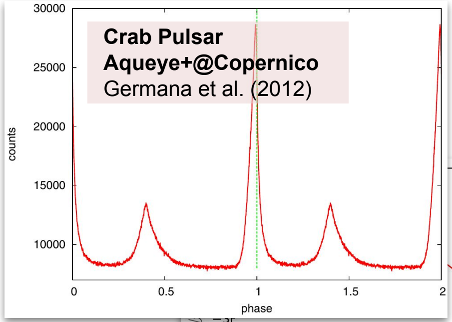
Varying rin, LT precession interval consistent with observed LF QPO interval for a moderately spinning BH with **a* ~ 0.2-0.3**

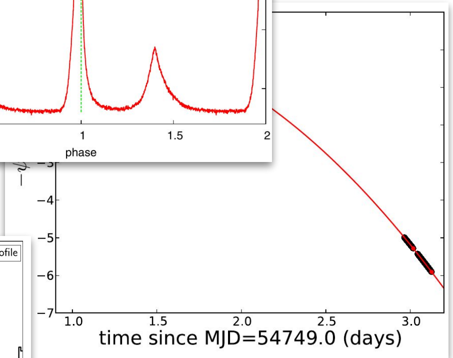
When r_{in} ~ $10r_g$, standard disc extends inwards and self-irradiates the outer disc, possibly triggering a large scale super-orbital warp (observed in the optical).

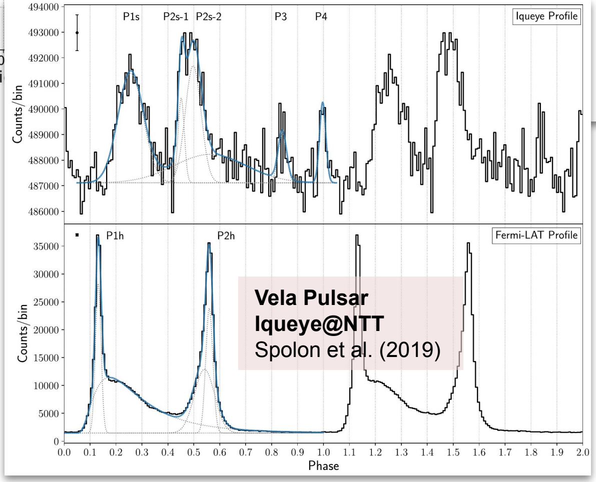
But there is much more!

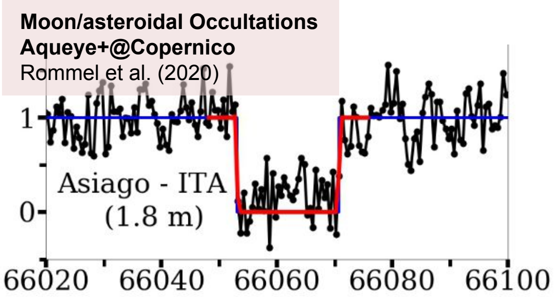
Project page:
http://web.oapd.inaf.it/zampieri/aqueye-iqueye/index.html











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

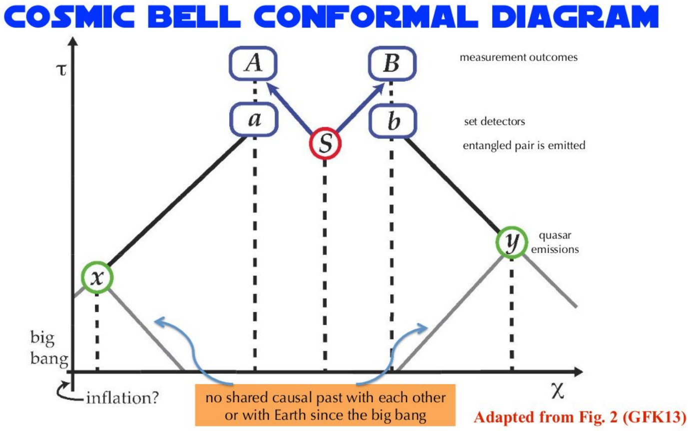
VISITING INSTRUMENT PROGRAM

Thank you for your attention!

Quantum Experiment on Bell Inequalities

Preparatory work in Asiago in 2015-2016

Backup Slide



x, y need z >3.65 (at 180°) 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 (Scheidl 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"