Searches for optical counterparts of Fast Radio Bursts: instrumentation and strategies

Luca Zampieri
INAF-Astronomical Observatory of Padova

M. Fiori, A. Spolon and the **Aqueye+Iqueye Team**

FRB-Italy 2025 – Bologna – May 8, 2025

Outline

- Fast Radio Bursts (FRBs) and optical observations
- Searches for Fast Optical Bursts (FOBs): instrumentation and techniques
- FRBs and FOBs: recent observing campaigns
- FOB search strategies: present and future

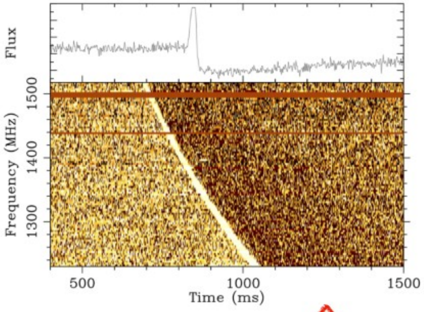
Fast Radio Bursts

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

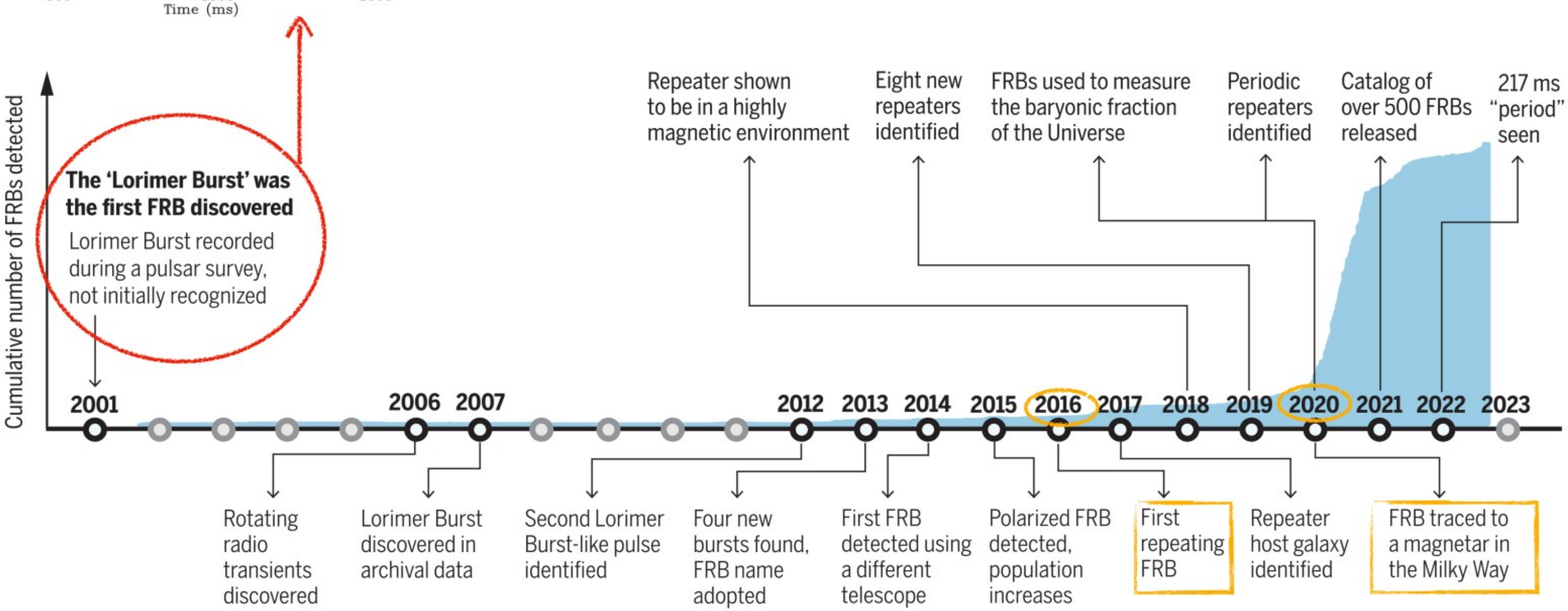
Many FRBs have since been recorded (>800), including several that have been detected to repeat (~7%; e.g. Petroff et al. 2022)

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*



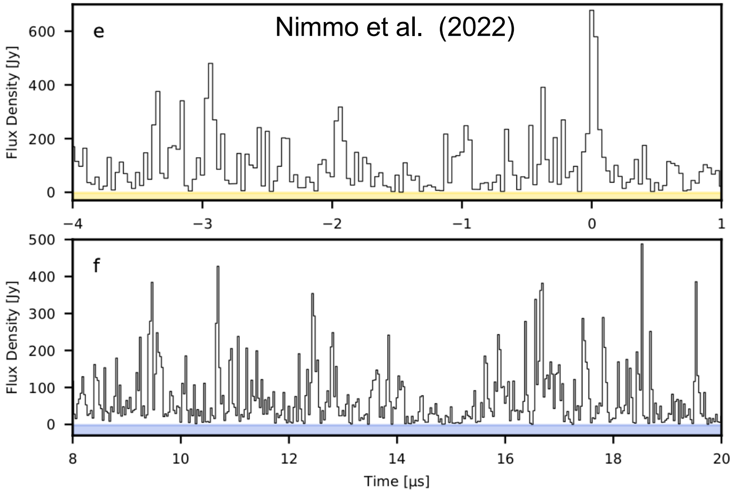
Fast Radio Bursts

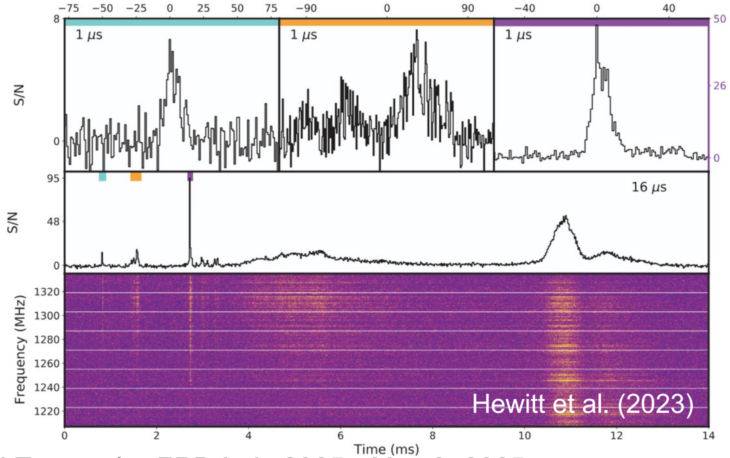
FRB 20200120E: isolated shots as short as **~60 ns**, with brightness temperatures up to 3×10^{41} K, comparable to 'nano-shots' from the Crab pulsar, while polarimetric properties consistent with those of repeaters (Nimmo et al. 2022)

FRB 20220912A: bursts with luminous, broad-band, **short-duration structures (~16 μs, 'microshots'**; Hewitt et al. 2023)

FRB 20121102A: isolated **~10 μs-duration bursts (ultra-fast)**, with polarimetric properties resembling those of longer-lasting bursts (Snelders et al. 2023)

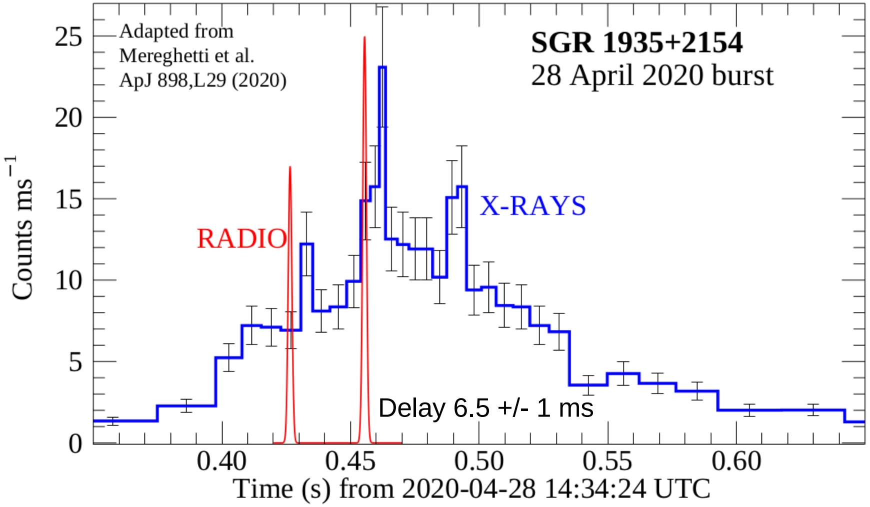
FRB 20191221A: strict **periodicity between sub-bursts of 216.8 ms** (CHIME/FRB Collaboration et al. 2022)





Fast Radio Bursts
MWL/Optical observations

Bright FRB-like burst from the Galactic magnetar SGR 1935+2154 provided first direct link between FRBs and magnetars (Mereghetti et al. 2020; Lin et al. 2020; Ridnaia et al. 2021; Tavani et al. 2021)



X-ray observation of two glitches within ~9 hrs bracketing an FRB on 14 October 2022 (Hu et al. 2024)

FRB 20180916B: no evidence for prompt or persistent optical or high-energy X-ray or gamma-ray emission (Scholz et al. 2020; Pilia et al. 2020; Andreoni et al. 2020; Kilpatrick et al. 2021; Ridnaia et al. 2023; Trudu et al. 2023)

FRB 20200120E: associated to a nearby globular cluster in M81 (3.6 Mpc, Bhardwaj et al. 2021) providing the best opportunity for multiwavelength (MWL) detections, but no such emission has yet been found (Kirsten et al. 2021; Mereghetti et al. 2021)

FRB 121102 and FRB 20220912A: limits on simultaneous and delayed optical emission 0.046 Jy ms and vLv ~ 10^{42} erg/s with 15-400 s exposures (Hardy et al. 2017; Hiramatsu et al. 2023)

FRBs preferentially select massive star-forming host galaxies (Sharma et al. 2024), with notable exceptions (FRB 20200120E in a globular cluster and FRB 20240209A in a quiescent galaxy; Bhardwaj et al. 2021, Shah et al. 2025)

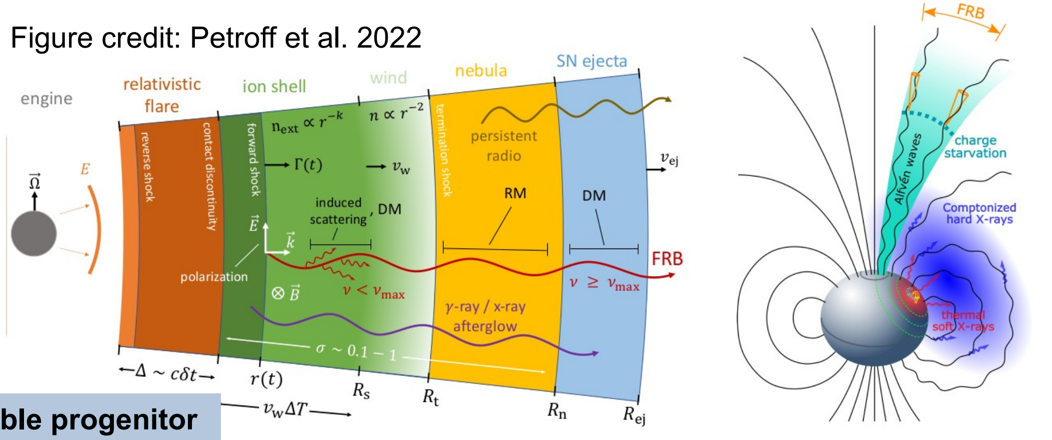
FRB 20220610A: localized to a morphologically complex host galaxy system at redshift z = 1.016 ± 0.002 (Ryder et al. 2023)

Fast Radio Bursts
A glimpse on models

While FRB emission is widely accepted to be generated in a **coherent process**, the exact radiation mechanism is the subject of debate (Petroff et al. 2022)

Most models center around an **energetic neutron star or magnetar progenitor** but place the **location of emission at different radial distances** from the surface of the star

Figure credit: Petroff et al. 2022



(a) Shock models (b) Magnetospheric models

models of FRB emission. (a) Shock model from Metzger et al. (2019) produced at large (10^{10} cm) radii from the compact central engine (e.g., k hole). (b) Magnetospheric model from Lu et al. (2020) where the FRB neutron star magnetosphere.

Possible progenitor systems

Neutron stars (isolated and in binaries), winds in ULXs, compact object mergers

The debate on the actual location/mechanism

Microstructures within FRB pulses on timescales ~< 10 μs may rule out locations such large radii (e.g. Nimmo et al. 2022; Hewitt et al. 2023; Snelders et al. 2023)

Also scintillation scales (from material in the Milky Way and host galaxy) in the frequency spectrum of FRB 20221022A constrain the emission to < 3×10^4 km, inconsistent with large radii (Nimmo et al. 2025)

Along with a shock into the environment at > 10^{12} cm (producing a coherent radio burst through synchrotron maser), magnetar Giant Flares (GFs) can drive a shock into the crust leading to ejection of baryonic material (Cehula et al. 2024)

GF ejecta have an ion-rich composition that can explain the high rotation measures inferred for active FRB sources (e.g. Michilli et al. 2018; Niu et al. 2022)

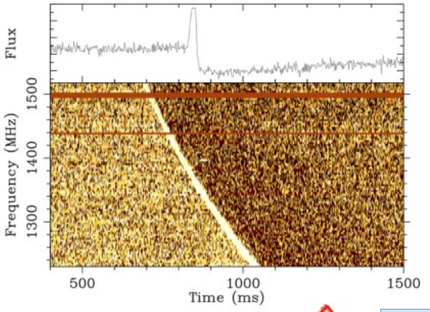
Fast Radio Bursts

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

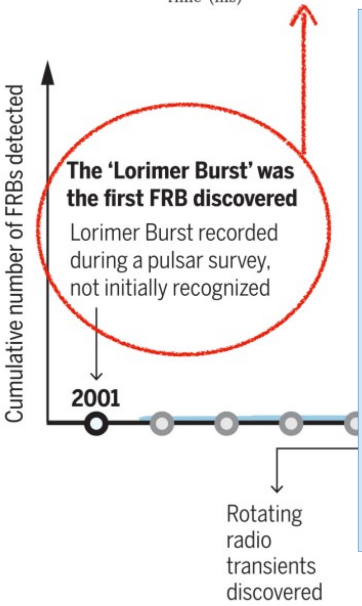
Many FRBs have since been recorded (>500), including several that have been detected to repeat (~4%; e.g. Petroff et al. 2022)

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)

For example, for flares associated with magnetospheric reconfigurations in neutrons stars/magnetars, contemporaneous bursts at other wavelengths, and/or an afterglow may be detectable (Lyutikov and Lorimer 2016)

A short GRB-like burst, **a ms-duration optical flash**, and/or a high-energy afterglow are the most promising scenarios

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

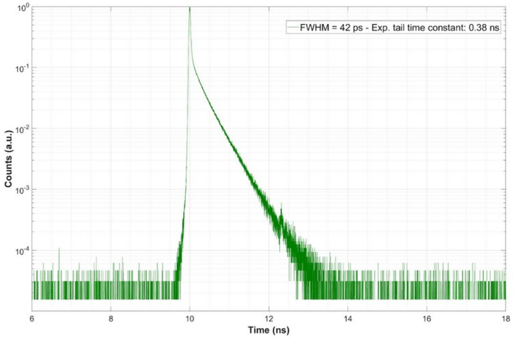
Searches for Fast Optical Bursts
Instrumentation and techniques

For FRBs with arc-second localization, rapid photometry at the source position is possible

Given the fast transient nature of FRBs, all the instruments capable of acquiring **frames at a rate 10-1000 Hz or higher** are to be considered ideal for FRB searches

Fast optical photometers with Si-avalanche-detectors technology clearly represent the perfect tool **(μs to ns time resolution)**

- **Aqueye+** (Barbieri et al. 2009, Naletto et al. 2013, Zampieri et al. 2015) at the 1.82-m Copernicus telescope in Asiago
- **Iqueye** (Naletto et al. 2009, Zampieri et al. 2019), till recently at the 1.2-m Galileo telescope in Asiago
- **SiFAP2** (Meddi et al. 2012, Ambrosino et al. 2016) at 3.58-m Telescopio Nazionale Galileo (TNG) in La Palma



Ultrafast timing resolution

Typical 35 ps FWHM

- **OPTIMA, GASP, BVIT, ARCONS**

No longer available or not frequently mounted at present

Also **high-speed optical cameras** based on CCDs with windowing and fast readout, electron-multiplying (EM) CCDs, or complementary metal-oxide-semiconductor (CMOS) technology are suitable (**~ms time resolution**)

- **HiPERCAM** (based on ULTRACAM; Dhillon et al. 2007, 2016) at GTC
- **ULTRASPEC** (Dhillon et al. 2014) at TNT
- **AstraLux** (Hormuth et al. 2008) at Calar Alto
- **PlanetCam** (Mendikoa et al. 2016) at Calar Alto
- **LuckyCam** (Law et al. 2006) at NOT
- **Wide FastCam** (Velasco et al. 2016) at Carlos Sánchez
- **SALTICAM** (O'Donoghue et al. 2006) at SALT
- **OPTICAM** (Castro et al. 2019) at San Pédro Mártir

Searches for Fast Optical Bursts
Instrumentation and techniques

Instantaneous FOB magnitude **(Lyutikov et al. 2016, Yang et al. 2019, Nicastro et al. 2021)**

$$V_{ins} = 16.4 - 2.5 \log(\tau_{ms} F_{mJy} / T_{ms})$$

With a sampling time T_{ms} = 1-10 ms and for a burst flux, duration F_{mJy} = 10 mJy, τ_{ms} = 1 ms: **V_{ins} = 13.9-16.4 in 1-10 ms**

Expected FOB magnitude decreases with decreasing readout time --> **Best observing strategy is sampling the light curve with a time bin comparable to the burst duration** (~1 ms)

Bin time limited by the time accuracy of the instrument (for Aqueye+ and Iqueye it can be as low as 1 ns)

FOBs detected when counting statistics per bin is in excess of the sky background Poissonian level, with **significance thresholds set taking into account the number of trials (bins)** of the considered time interval (e.g. Zampieri et al. 2022)

Spurious events (e.g., cosmic rays, artificial satellites, meteors) may contaminate the observations → **Simultaneous observations with more than one instrument** and/or at two sites are needed

Fast optical photometers

Photon counting instruments can reach the **highest sensitivity to short duration events** but have a narrow FoV

High-speed optical cameras

More limited sensitivity to < 1-10 ms duration events, but **larger FoV makes them suitable for monitoring campaigns of less well localized sources**

Approach similar to that adopted in conventional photometry, but with some caveats (e.g. Hardy et al. 2017):

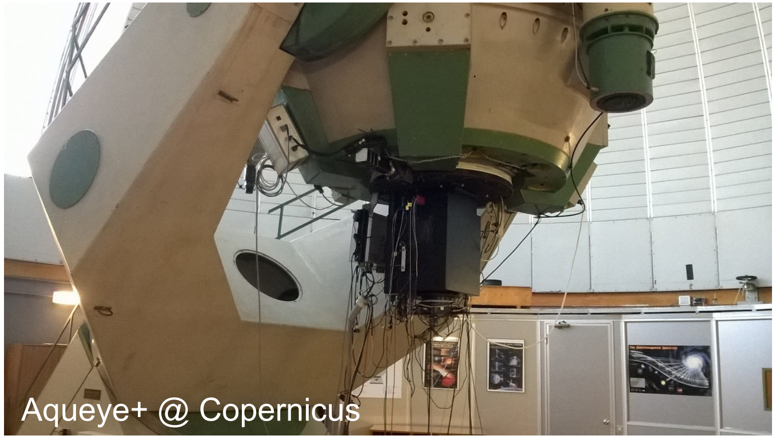
- aperture photometry with a fixed-sized aperture preferable over PSF photometry (extracting photons from a region that contains no source)
- aperture sufficiently large to accommodate the positional uncertainty and the average seeing

Searches for Fast Optical Bursts
Instrumentation: fast optical photon counters

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)*

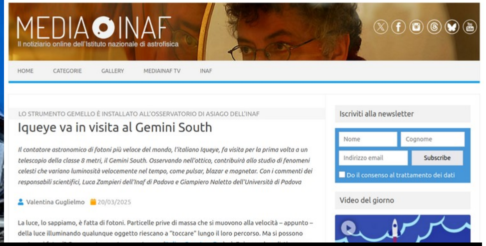
AQUEYE+ IQUEYE

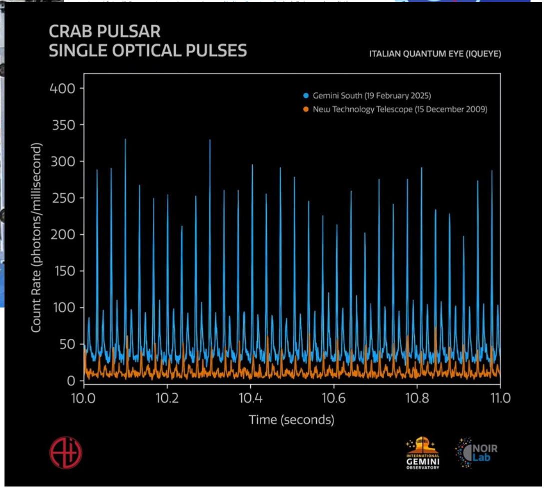
http://web.oapd.inaf.it/zampieri/aqueye-iqueye/index.html



- *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), and now...





Iqueye@Gemini South!

Visiting instrument
Next run in 2026

FRBs and FOBs: recent observing campaigns
FRB 20180916B

Simultaneous multi-instrument/MWL campaigns carried out during 2020-2021 (ATel #13446, #13462, Pilia et al. 2020, Trudu et al. 2023)

FRB 20180916B

Repeating burst activity (The CHIME/FRB Collaboration 2019)

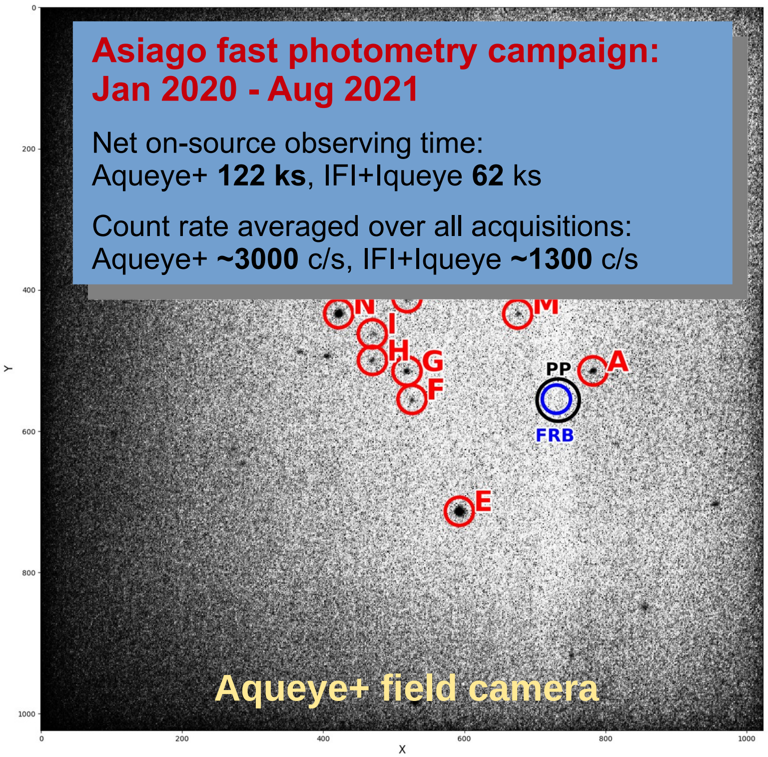
Localized with high accuracy and associated to a star-forming region in a nearby spiral galaxy (Marcote et al. 2020)

16.33 periodicity (activity window +/- 2.6 days) in the arrival times of FRBs (The CHIME/FRB Collaboration 2020; Pleunis et al. 2021)

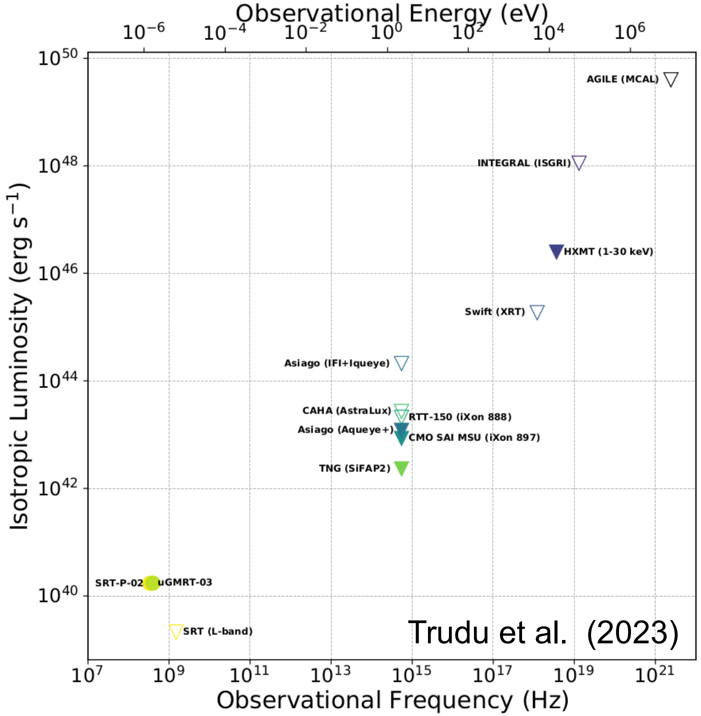
Asiago fast photometry campaign: Jan 2020 - Aug 2021

Net on-source observing time:
Aqueye+ **122 ks**, IFI+Iqueye **62** ks

Count rate averaged over all acquisitions:
Aqueye+ **~3000** c/s, IFI+Iqueye **~1300** c/s



9 bursts detected with SRT in Nov 2020 and **5 bursts** detected with GMRT in Feb and Aug 2021 fall inside Aqueye+ and/or IFI+Iqueye observing windows



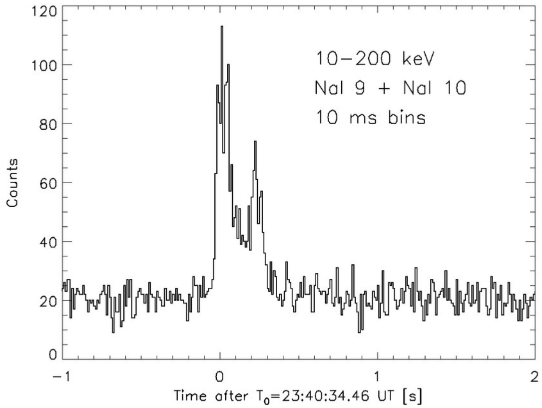
Aqueye+/SiFAP2 upper limits at tburst (sampling time 1 ms, interval +/-100ms)

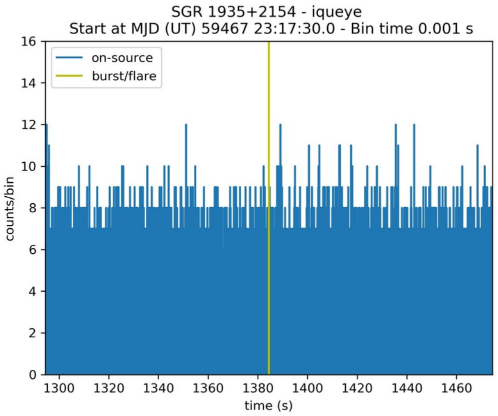
Vmin = **14.64/16.42** mag per ms
Fmax = **(4.6/0.9) x 10^{-15}** erg/cm2 (5.0/1.02 mJy ms)
Lmax = **(12/2.4) x 10^{42}** erg/s (at 150 Mpc)

Magnetars and FOBs: recent observing campaigns
SGR J1935+2154

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

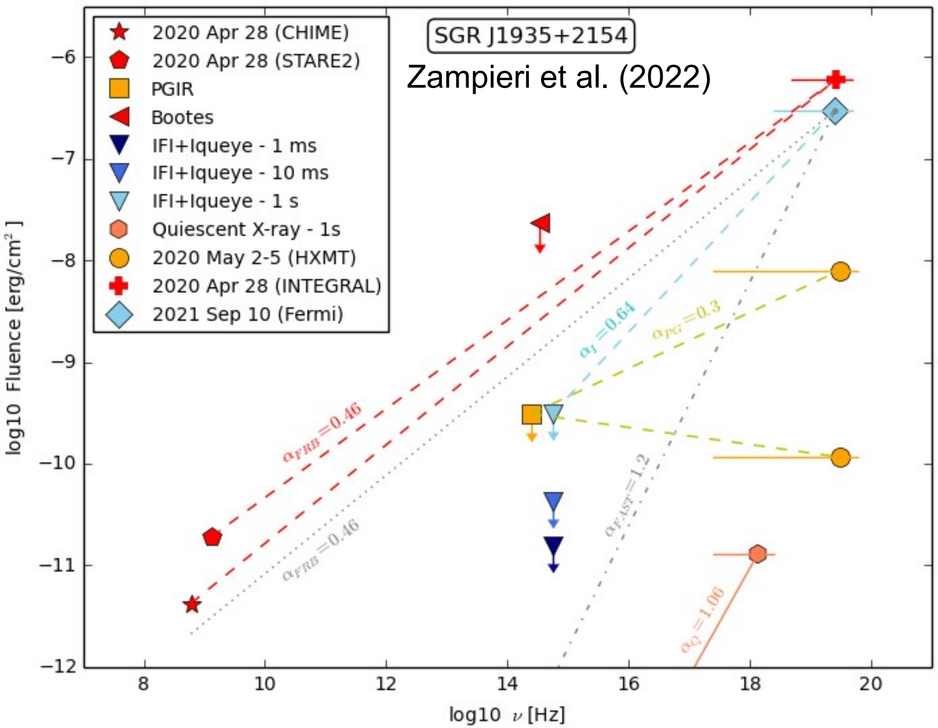
No optical peak around T0 in a simultaneous IFI+Iqueye observation





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)



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

FRBs and FOBs: recent observing campaigns
FRB 20180916B

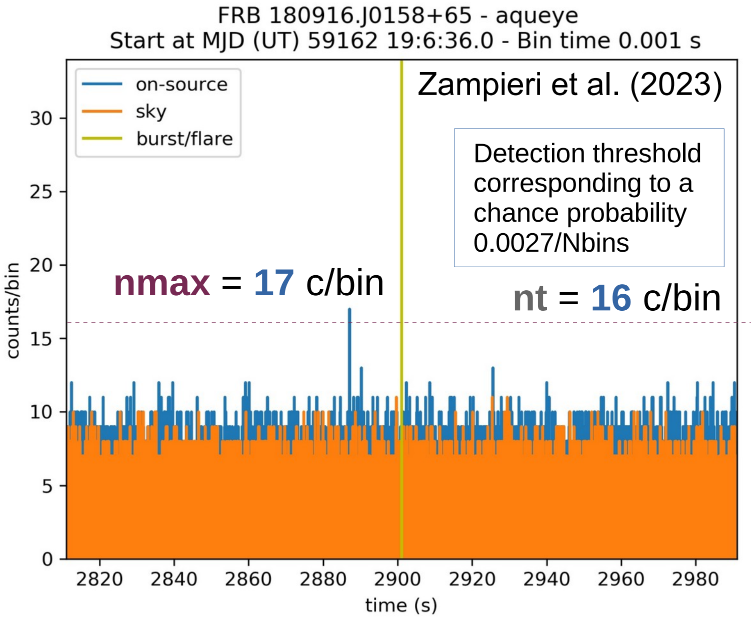
Simultaneous multi-instrument/MWL campaigns carried out during 2020-2021 (ATel #13446, #13462, Pilia et al. 2020, Trudu et al. 2023)

FRB 20180916B

Repeating burst activity (The CHIME/FRB Collaboration 2019)

Localized with high accuracy and associated to a star-forming region in a nearby spiral galaxy (Marcote et al. 2020)

16.33 periodicity (activity window +/- 2.6 days) in the arrival times of FRBs (The CHIME/FRB Collaboration 2020; Pleunis et al. 2021)



Aqueye+@Copernicus 1 ms binned light curve

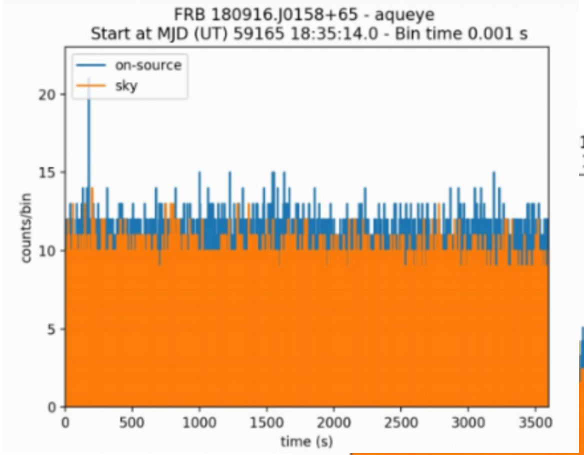
Detection of a Fast Optical Burst with 14.4 mag per ms and a specific fluence of 7 mJy ms (L = 1.6 x 10^{43} erg/s at 150 Mpc)

Difficult to tag this event as the counterpart of the burst

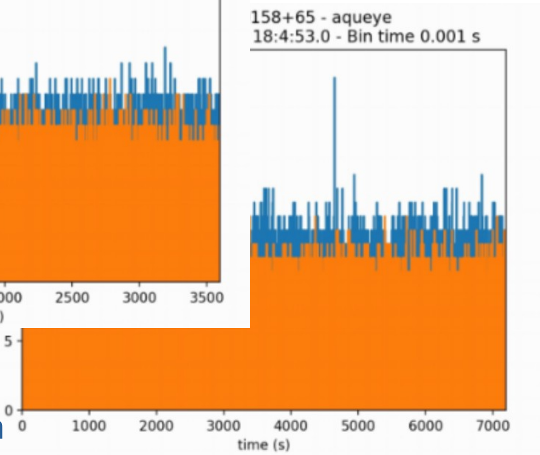
Low significance when considering similar intervals around all bursts inside Aqueye+ windows

Leading the FRB inconsistent with a large number of theoretical models (if originating from a magnetar)

Other events detected far from tburst: ~0.1 ev/hr



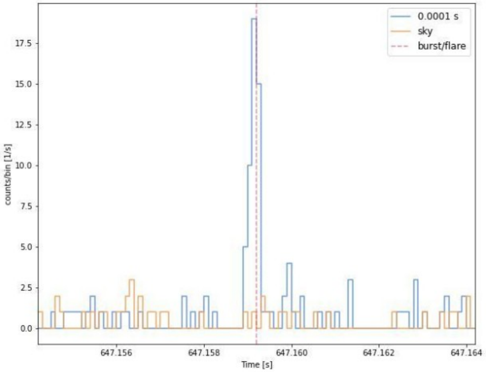
What are they?



Mostly meteors? See presentation by Alessia Spolon

FRBs and FOBs: recent observing campaigns
FRB 20220912A (vs field of PSR J1023+0038)

FRB 20220912A



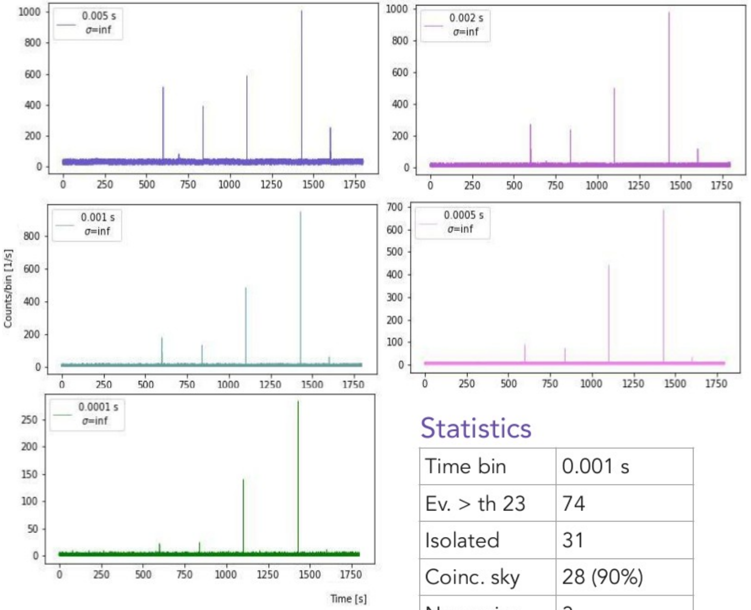
n ID	Time bin [s]	Time of peak [s from start]	Time of peak [UT]	on-source SPAD counts/bin	on-source SPAD σ	on-source SPAD FWHM [s]	sky-SPAD counts/bin	sky-SPAD σ	sky-SPAD FWHM [s]
33434	0.0001	647.1592	22:45:23.1591	19	>10	0.0002	-	-	-

ogna - 8 May 2025 6

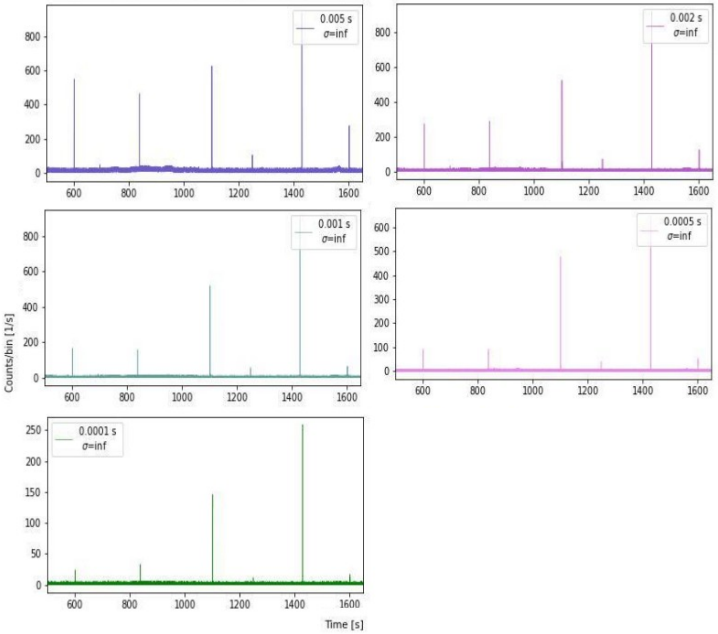
Observations and Data Analysis - PSR J1023+0038

13 Dec. 2018 [Aqueye+]

ON-source



SKY



Statistics

Time bin	0.001 s
Ev. > th 23	74
Isolated	31
Coinc. sky	28 (90%)
Non coinc.	3

A. Spolon, FRB-Italy 2025 - Bologna - 8 May 2025 9

FOB search strategies: present and future (non-exhaustive list)

FRBs with arc-second localization

Rapid photometry at the source position is possible (in addition to studies of the potential host galaxy), with fast optical photometers representing the perfect tool

Active and/or periodic repeaters are primary targets

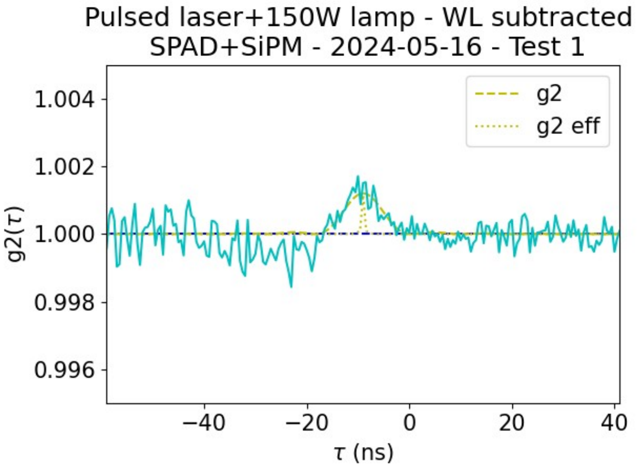
Since the mechanism(s) of the emission is not yet identified, burst times may not be synchronous on millisecond timescales

- Pointed optical observations shadowing radio observations
  Similar to strategy for MWL campaigns carried out so far
- Radio observations shadowing deep pointed optical observations
  * **With photometers installed at 10m-class telescopes**, e.g. Iqueye@Gemini South
  * Reversal of scheduling priority
- Coordinated optical-optical monitoring campaigns
  * Monitoring with pointed observations for several nights with telescopes having comparable FOV and size (sensitivity)
  * If multiple telescopes detect a source simultaneously, then even a low significance measurement can become relevant

FOB search strategies: present and future (non-exhaustive list)

- Coordinated X-ray-optical campaigns on Galactic magnetars during flares

- Optical campaigns of on-off source fields with single instruments
  * Statistics/morphology of events, looking for excesses/anomalies wrt expected background-foreground levels (**see talks by Alessia Spolon, Filippo Ambrosino and Carlo Campa**)
  * Search for rapid variability with 2nd order correlation function (Dravins et al. 2005; Lacki 2025)? More powerful than detection of single events if they are **marginally undetectable individually**, **but not too rare**



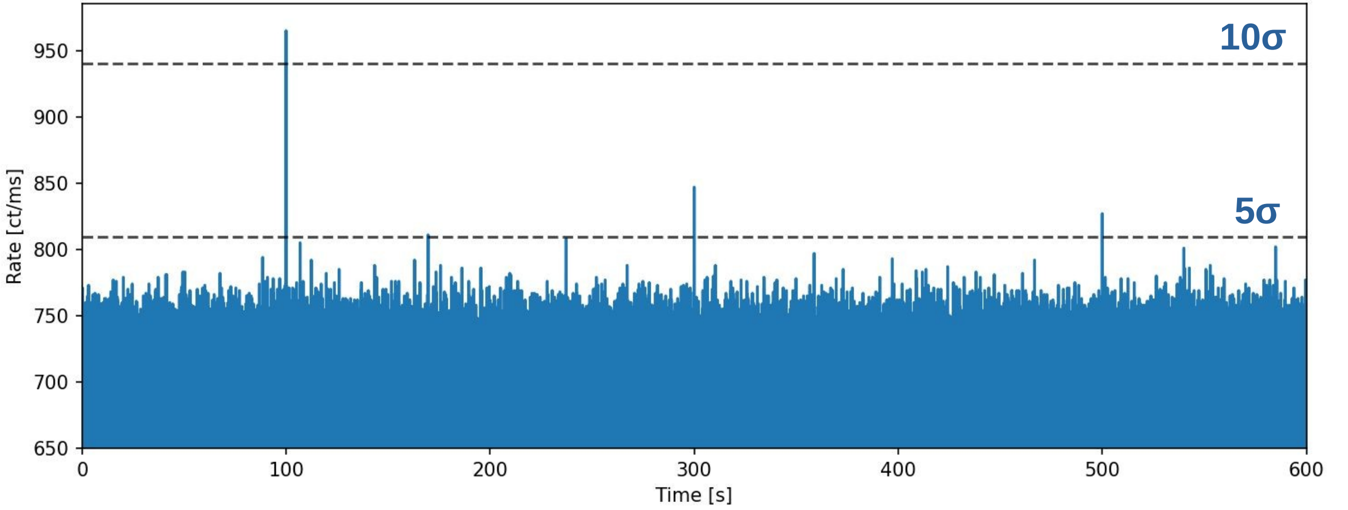
FOB search strategies: present and future (non-exhaustive list)

FRBs with arc-minute localization

- Surveys of large areas with < 1 ms sampling times for non-well localized repeaters or one-off events

  * Dedicated large area, low dark counts fast photometers based on SPAD matrices/arrays ("BURSTY: a SPAD array optical instrument for the search of fast radio bursts", S. Farina)

  * Cherenkov telescopes equipped with fast optical photon counters (e.g. ASTRI-SI3, Zampieri et al. 2024)



Simulated ASTRI-SI3 light curve (550/50 nm, 10 minutes with low moon background) + 3 1 ms FOB signals

Vlim = 8.5 in 1 ms
FOV = 6 arcmin
9 telescopes

Conclusions

- Searches for FOBs: instrumentation and techniques
- FRBs and FOBs: recent observing campaigns
- FOB search strategies: present and future

  * Pointed optical observations shadowing radio observations

  * Radio observations shadowing deep pointed optical observations with photometers installed at 10m-class telescopes, e.g. Iqueye@Gemini South

  * Coordinated optical-optical monitoring campaigns

  * Coordinated X-ray-optical campaigns on Galactic magnetars during/off flares

  * Optical campaigns of on-off source fields with single instruments: statistics/morphology of events, search for rapid variability with 2nd order correlation function?

  * Surveys of large areas with < 1 ms sampling times for non-well localized repeaters or one-off events

Acknowledgments

AQUEYE+

IQUEYE

AQUEYE+ IQUEYE

Based on observations collected at the Copernicus telescope (Asiago, Italy) of the INAF-Osservatorio Astronomico di Padova and at the Galileo telescope (Asiago, Italy) of the University of Padova

Presently funded by INAF (Research Grants “Uncovering the optical beat of the fastest magnetised neutron stars (FANS)” and “Coordinated multiwavelength exploration of Fast Radio Bursts” (COMEFAR)) and the University of Padova (DOR grant)