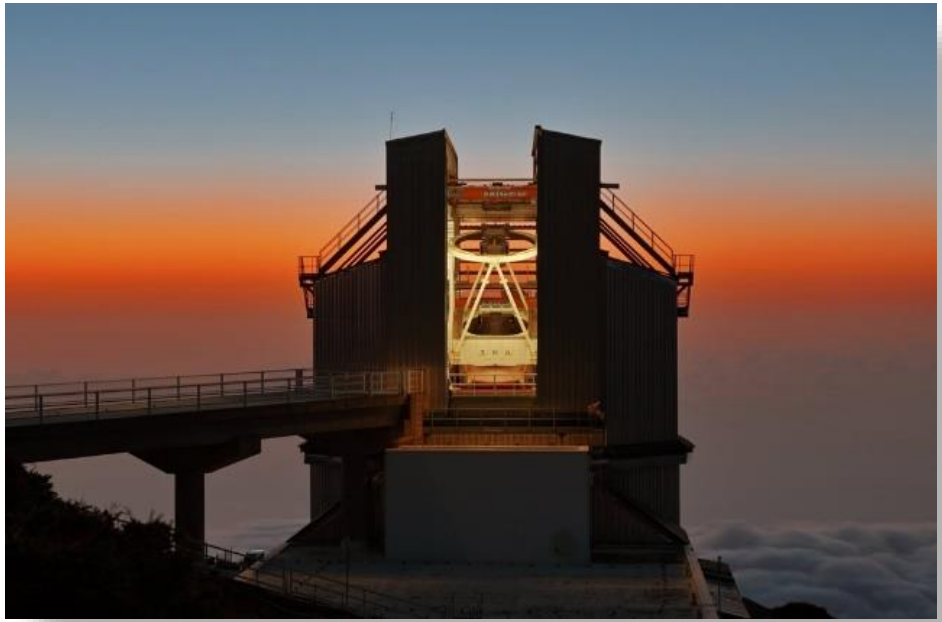
SiFAP @ italian telescopes:

Observational results of optical high speed photometry of isolated pulsars and pulsars in binary systems



Dr. Filippo Ambrosino **on behalf of SiFAP team**

(filippo.ambrosino@roma1.infn.it)

Outline:

1. SiFAP: High Speed Photometry of variable sources
2. Data Analysis Methods for the search of pulsations: FFT and EFS
3. SiFAP @ TNG: Crab pulsar
4. SiFAP @ Cassini Telescope: binary system Hz Her/Her X-1
5. Conclusions and future perspectives

1. SiFAP: High Speed Photometry of variable sources

SiFAP: Silicon Fast Astronomical Photometer

APDs

➔ **Binary behaviour** (on/off)

Segmentation in pixels

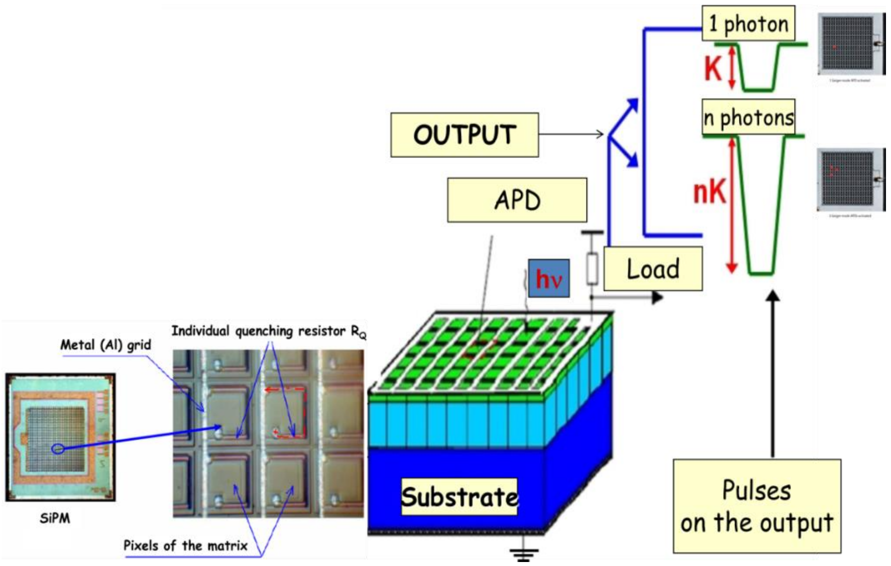
➔ **Recovery of the analog information**

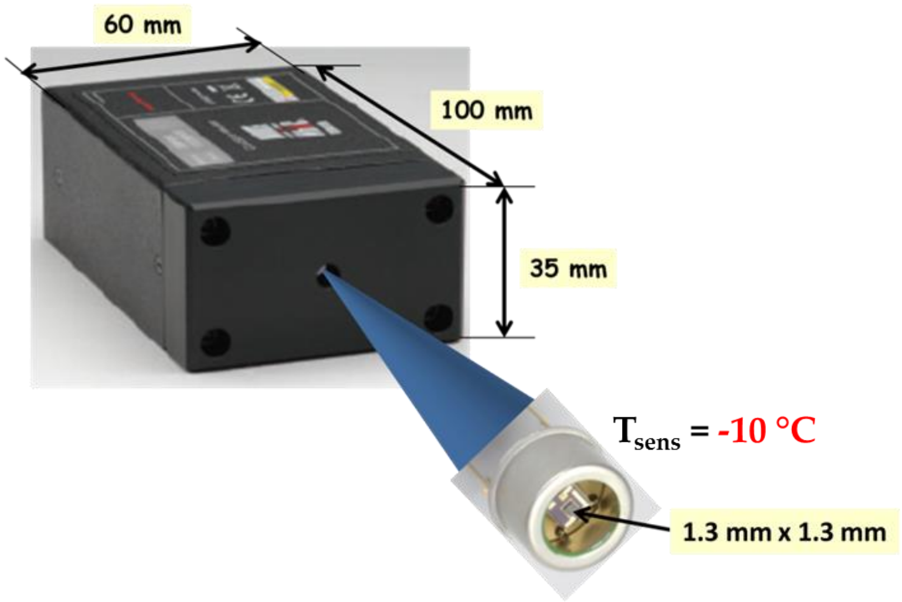
Silicon Photo Multiplier — Multi-Pixel Photon Counter

SiPM = MPPC

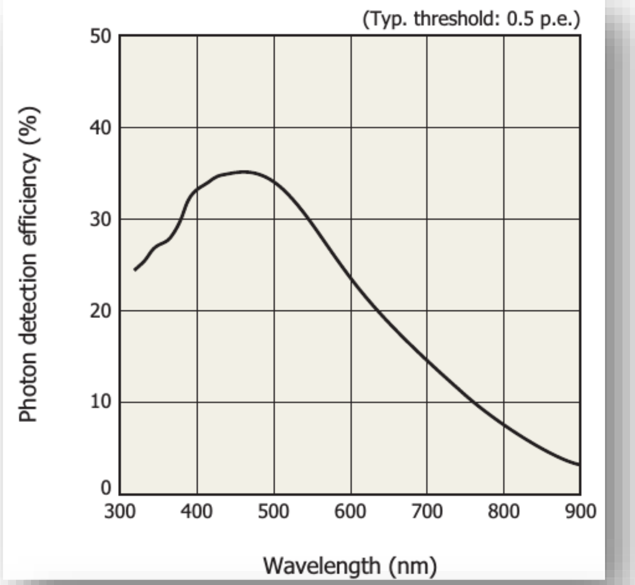
HAMAMATSU

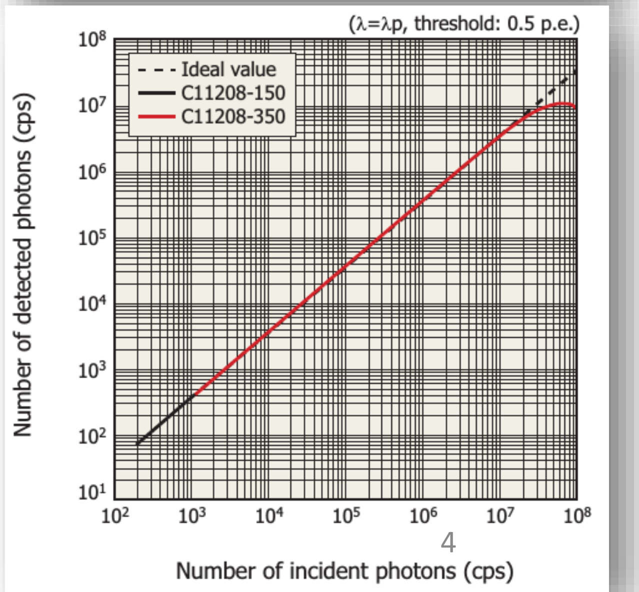
HAMAMATSU PHOTONICS K.K., Solid State Division
1126-1, Ichino-cho, Higashi-ku, Hamamatsu City, 435-8558, Japan
Telephone: (81)53-434-3311, Fax: (81)53-434-5184
www.hamamatsu.com





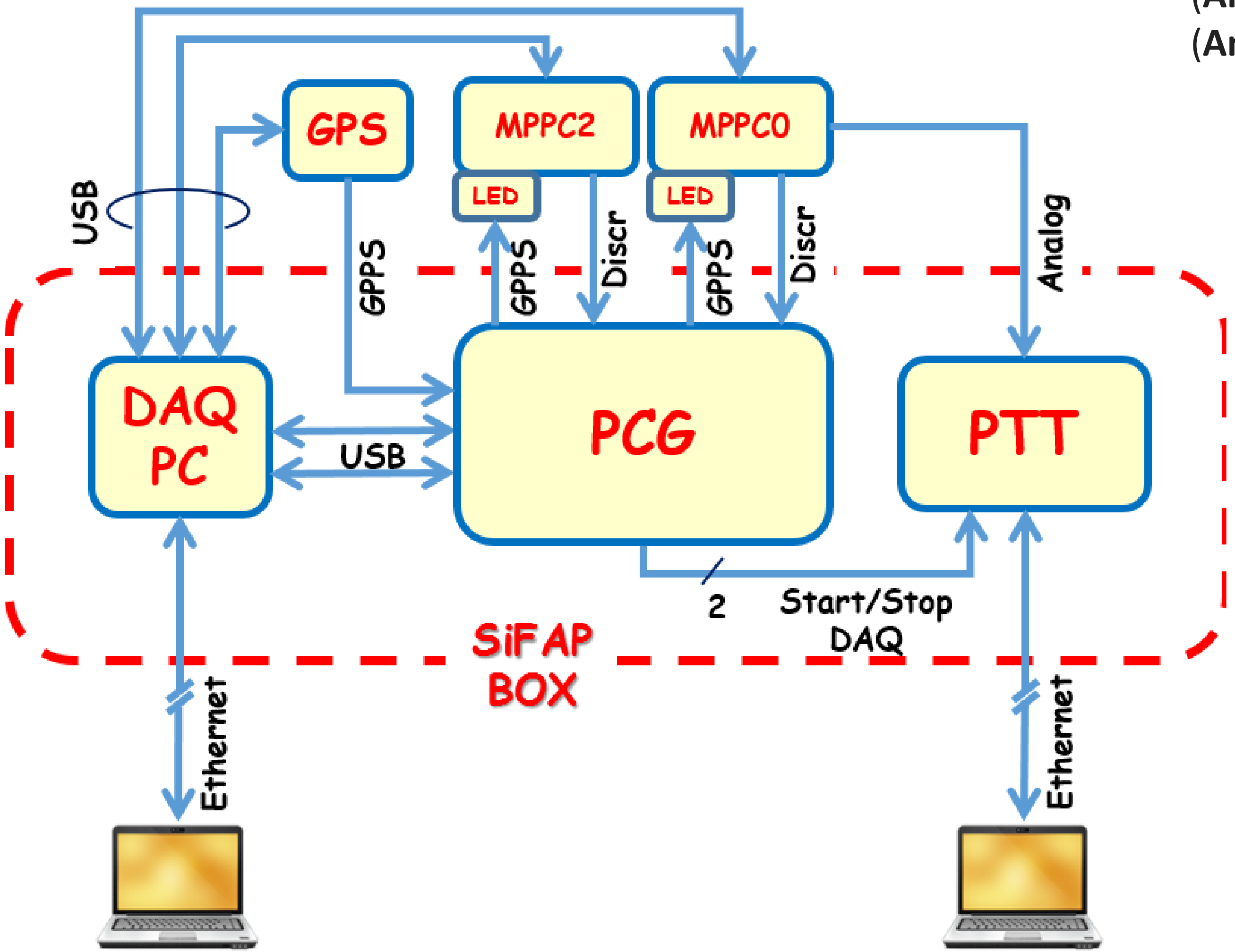
T_{sens} = -10 °C

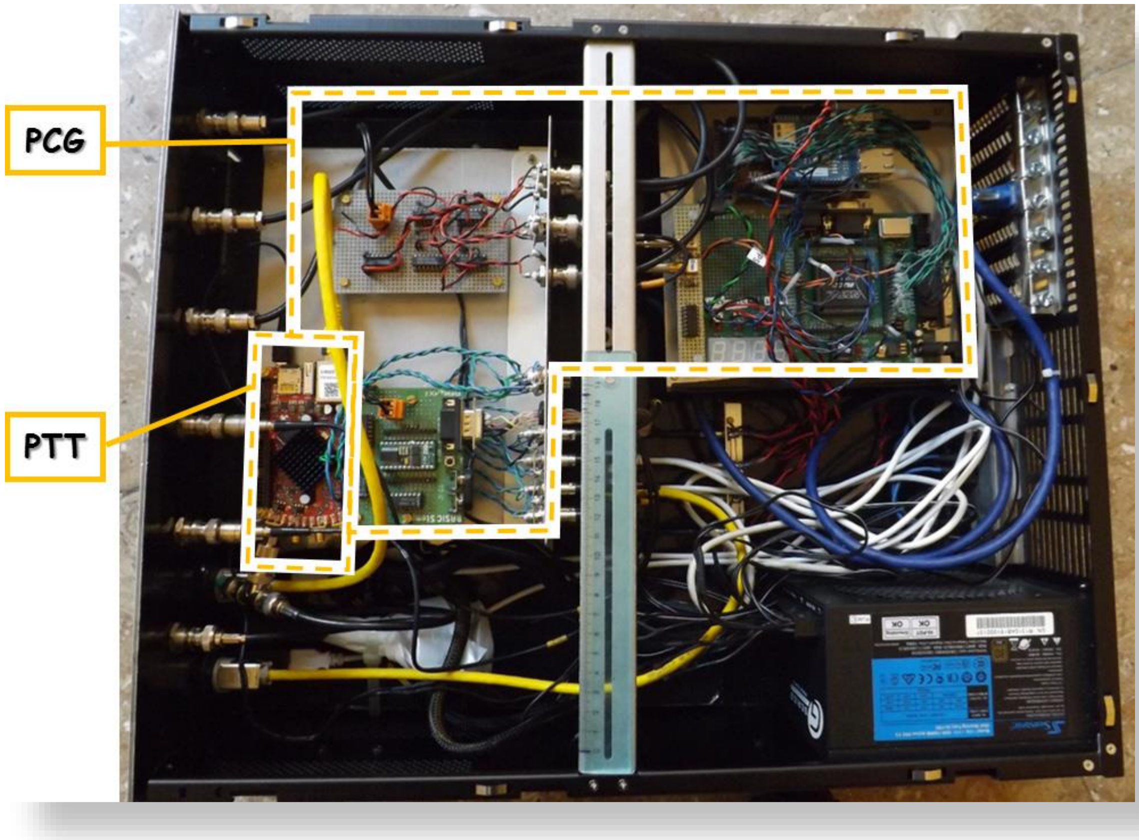




SiFAP: Electronic chains

(Meddi, F., **Ambrosino, F.** et al., PASP, 2012)
(**Ambrosino, F.** et al., JAI, 2013)
(**Ambrosino, F.** et al., Proc. SPIE, 2014)
(**Ambrosino, F.** et al., JAI, 2016)





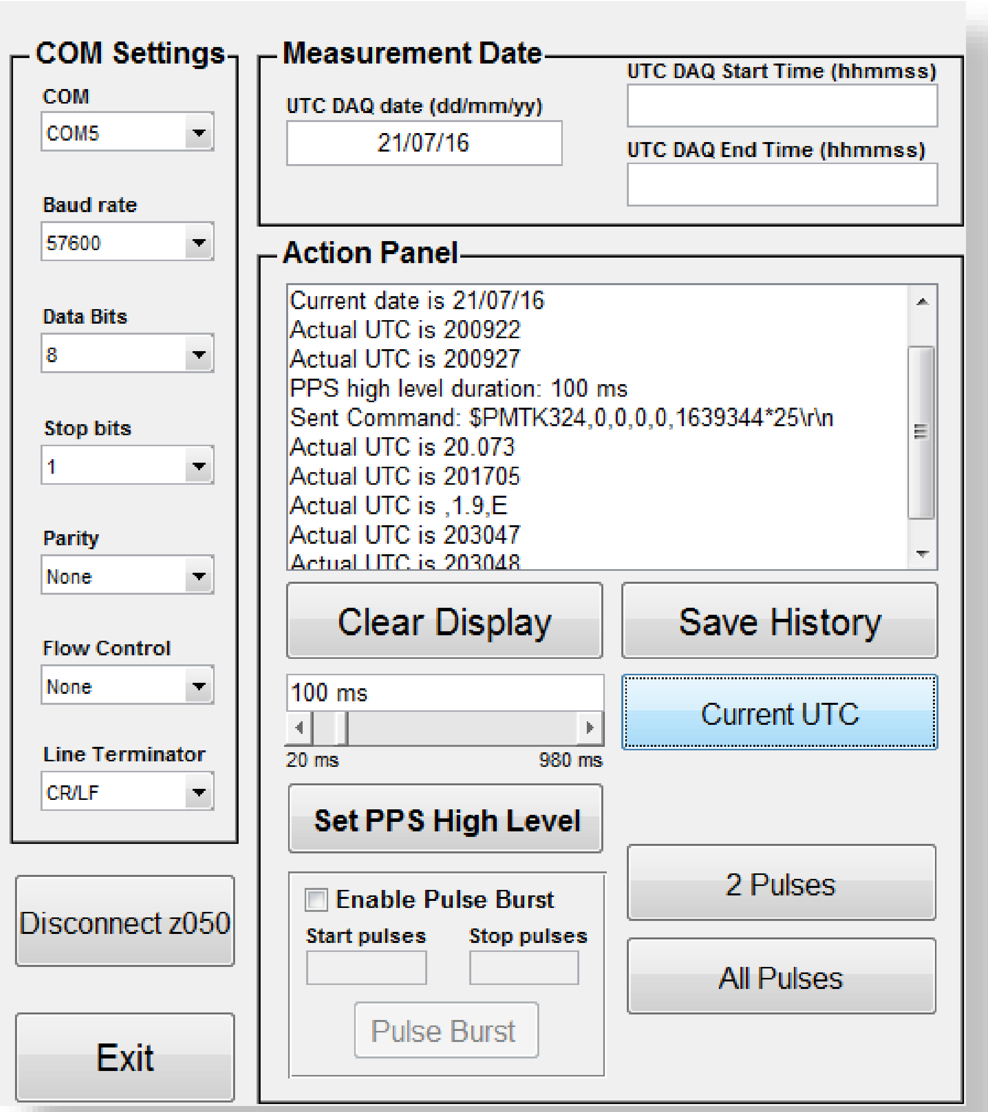
SiFAP: GPS unit

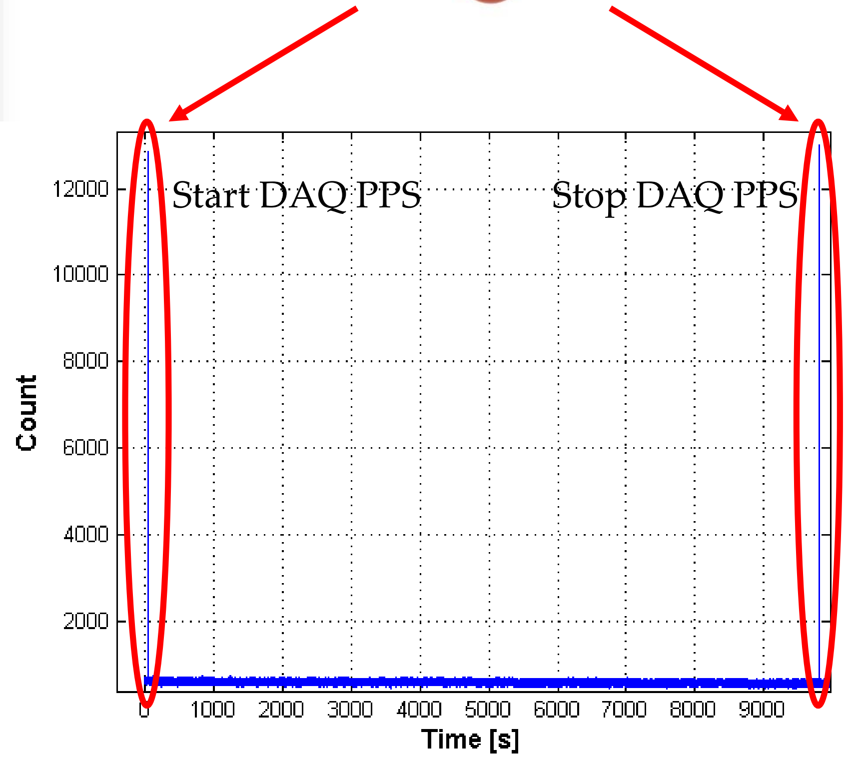
ZTI – Model Z050

Custom Hardware

Parameter	Value
Update Rate	1 Hz (default), up to 5 Hz
Number of channels	22
Accuracy	
Position (autonomous)	<2.5 m 50%, <5 m 90%
Position (SBAS)	<2 m 50%, <4 m 90%
Altitude (autonomous)	<5 m 50%, <8 m 90%
PPS	< ±25 ns @ 50%
Acquisition time	
Re-Acquisition	2 s 50%
Hot Start	2 s 50%
Warm Start	35 s 50%
Cold Start	38 s 50%
Sensitivity	
Tracking	–160 dBm
Acquisition	–146 dBm
Dynamics (Acceleration)	2 g
Operational Limits	Altitude <18,000m (60,000 ft) or velocity <515m/s (1,151 mph). Either limit may be exceeded but not both (COCOM limit)

Custom Matlab GUI





2. Data Analysis Methods for the search of pulsations: FFT and EFS

Pulsar timing corrections

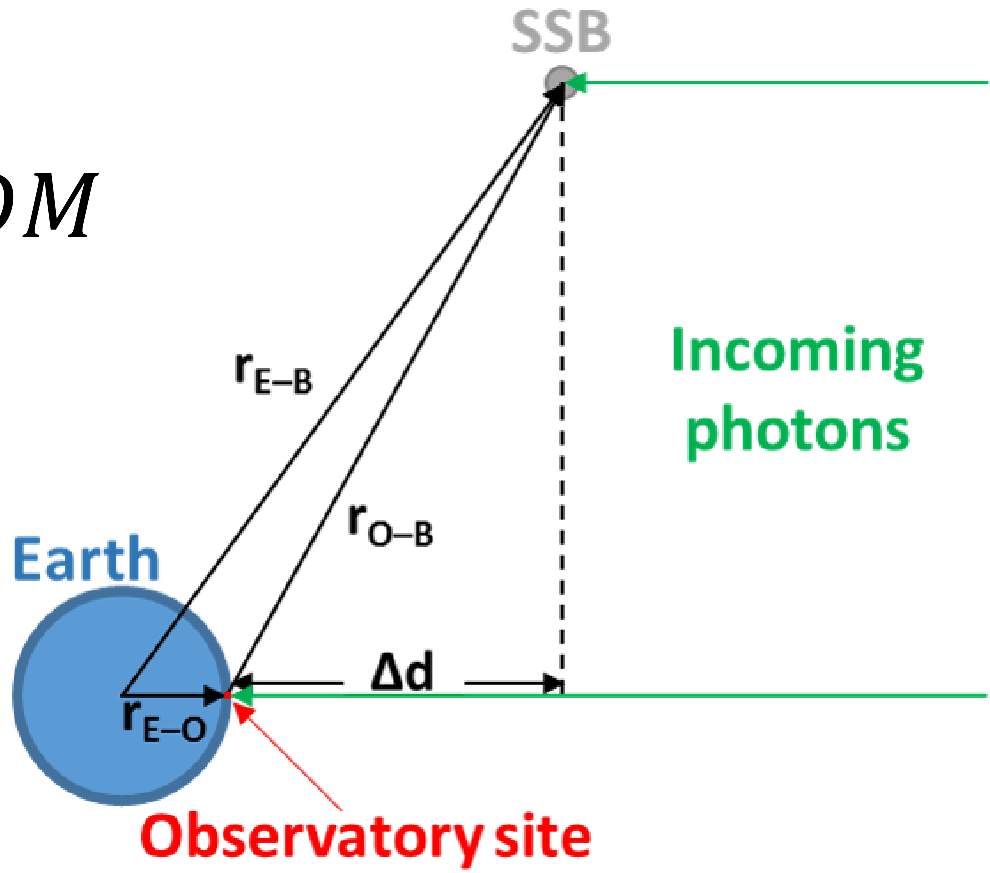
Isolated Pulsar

Earth reference frame system ➔ **NOT inertial!!**

➔ **SSB** (**S**olar **S**ystem **B**arycenter)

$$t_{BDT} = t_{obs} + t_{clk} + \Delta_R + \Delta_E - \Delta_S - DM$$

t_{BDT} = Barycentic photon ToA (Time of Arrival)
t_{obs} = ToA of observed photons
t_{clk} = corrections converting local clock time (UTC) to BDT (Barycentric Dynamical Time)
Δ_R = Rømer delay (geometric)
Δ_E = Einstein delay (relativistic)
Δ_S = Shapiro delay (relativistic)
DM = Dispersion Measure



Pulsar timing corrections

Pulsar in a binary system

$$t_{em} = t_{arr} + \cancel{\frac{d}{c}} - \frac{a \sin i}{c} sin\left[\frac{2\pi}{P_{orb}}(t_{arr} - T_{asc})\right]$$

t_{em} = time of true emission

t_{arr} = photon ToA (in a given reference time system)

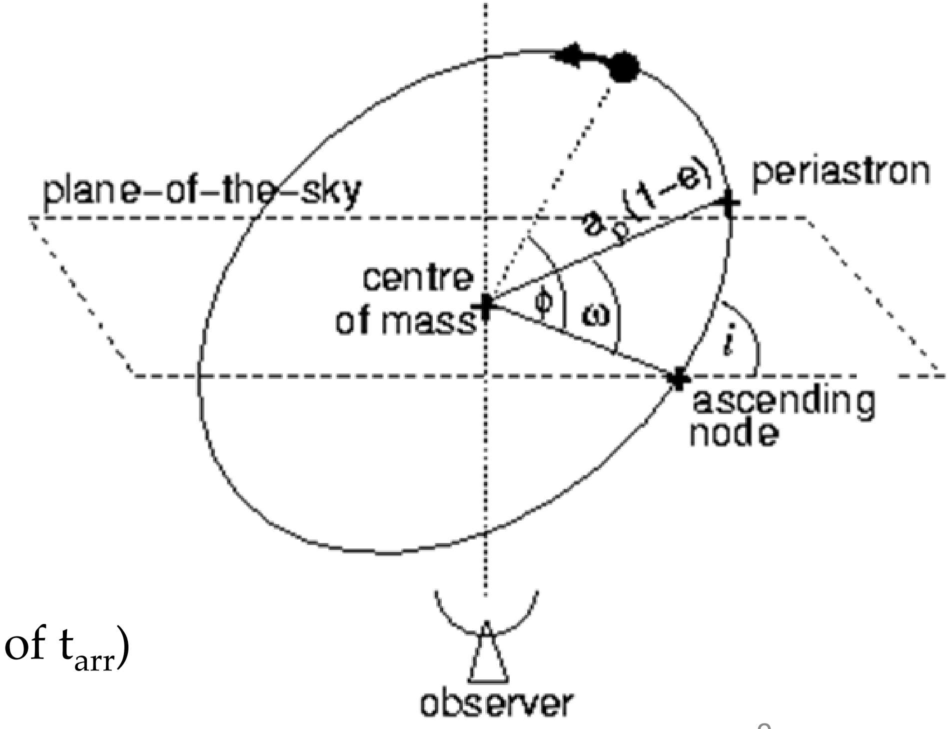
d = distance to the system

a = semi-major axis of orbit

i = inclination angle of the orbital plane (w.r.t. observer's plane)

P_{orb} = orbital period of the system

T_{asc} = epoch of ascending node (in the same reference time system of t_{arr})



Searching for pulsar spin period

1st approach: Fourier Analysis (FFT)

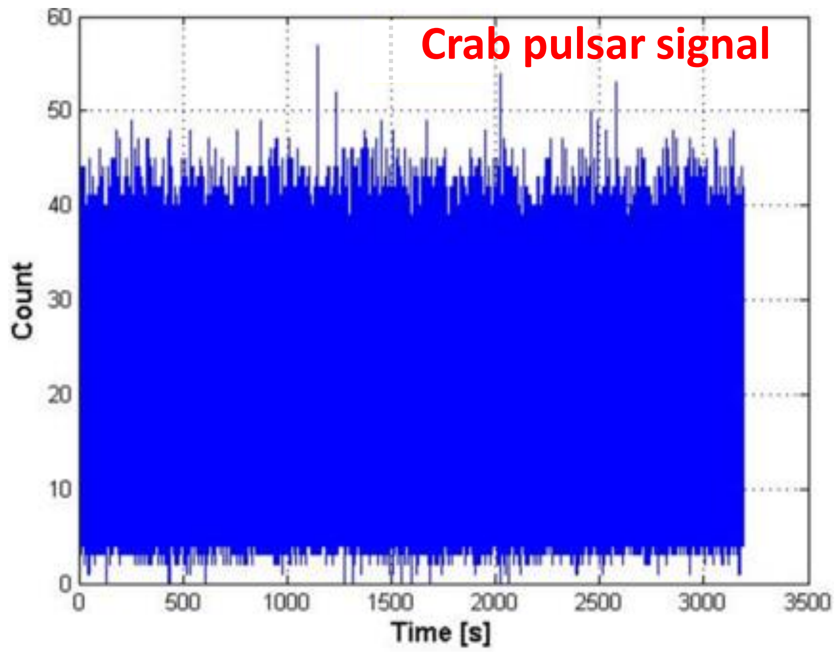
Searching for **periodic signals**…

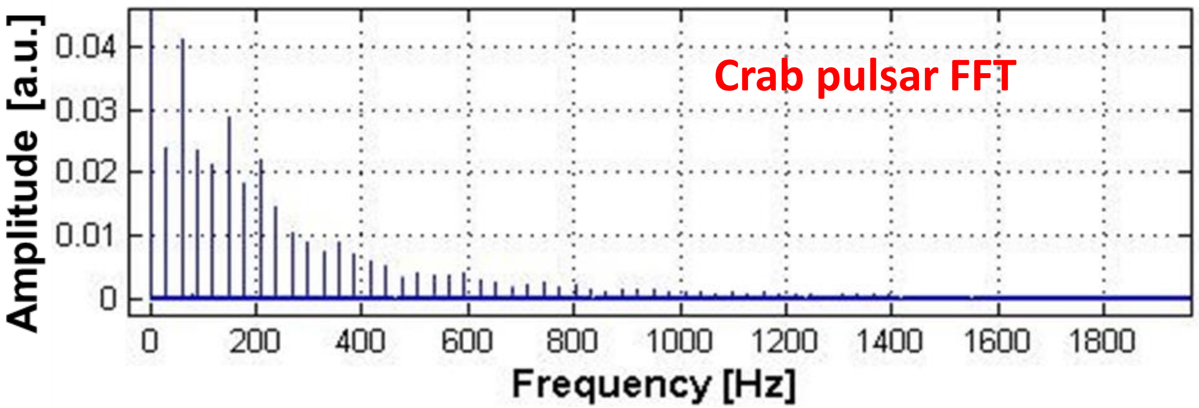
$$H(f) = \int_{-\infty}^{\infty} h(t) e^{2\pi i f t} dt \quad \text{(continuous)}$$

$$H(f_n) = \int_{-\infty}^{\infty} h(t) e^{2\pi i f_n t} dt \rightarrow \Delta t \sum_{k=0}^{N-1} h_k e^{2\pi i n k / N}$$

$$f_n = \frac{n}{N\Delta t}, \quad n = -\frac{N}{2}, \ldots, \frac{N}{2} \quad \text{(discrete} \rightarrow \text{time series)}$$

$$\textit{Nyquist critical frequency } f_c = \frac{1}{2\Delta t}$$





Searching for pulsar spin period
2nd approach: Epoch Folding Search (EFS)

Absence of pulsations (or any secular trend)
➔ counts in each bin of the folded curve at any given trial period are **Poisson distributed**

Since the number of events in each time/phase bin is usually rather large (> 1000)
➔ counts x_i in the bins are **Gaussian distributed** with their mean equal to their variance

$$S = \sum_{i=1}^{n} \frac{(x_i - \mu_{exp})^2}{\mu_{exp}} = \sum_{i=1}^{n} \frac{(R_i T_i - R T_i)^2}{R T_i} = \sum_{i=1}^{n} \frac{(R_i - R)^2}{\sigma_i^2}$$

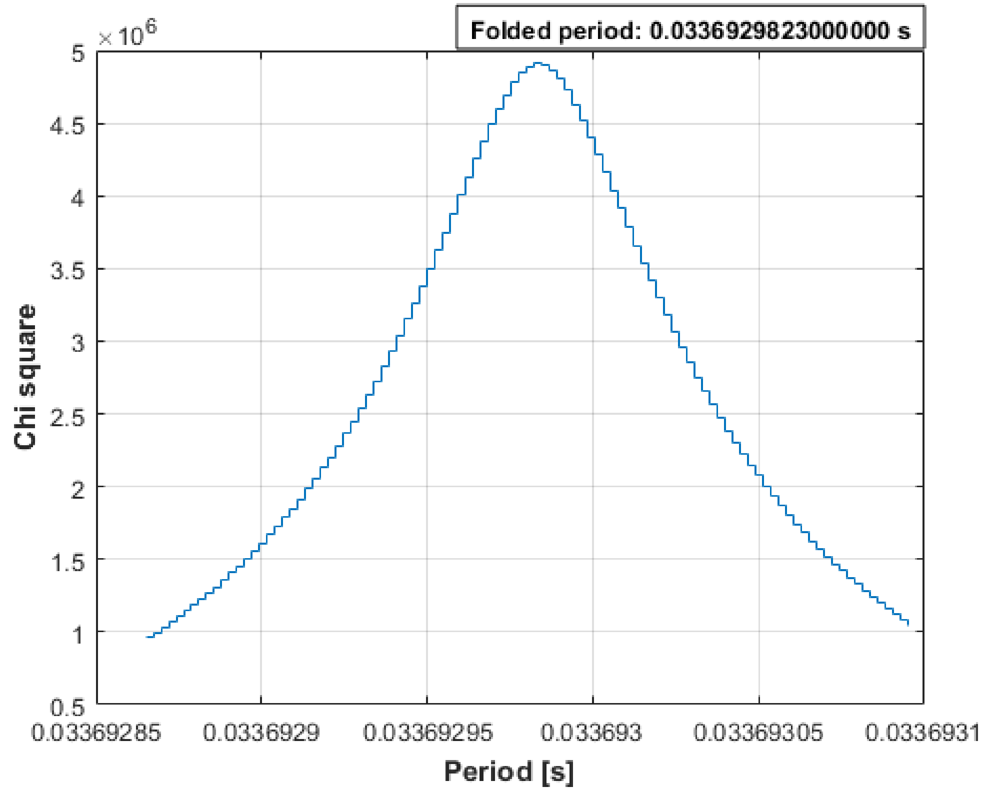
$S \approx n - 1$ **(= d.o.f.)**
(expected with noise only)

$\mu_{exp} = \mu_{exp,i} = RT_i$ ➔ expected counting rate (varying as T_i varies)

$R_i = x_i / T_i$ ➔ counting rate at the *i*-th bin

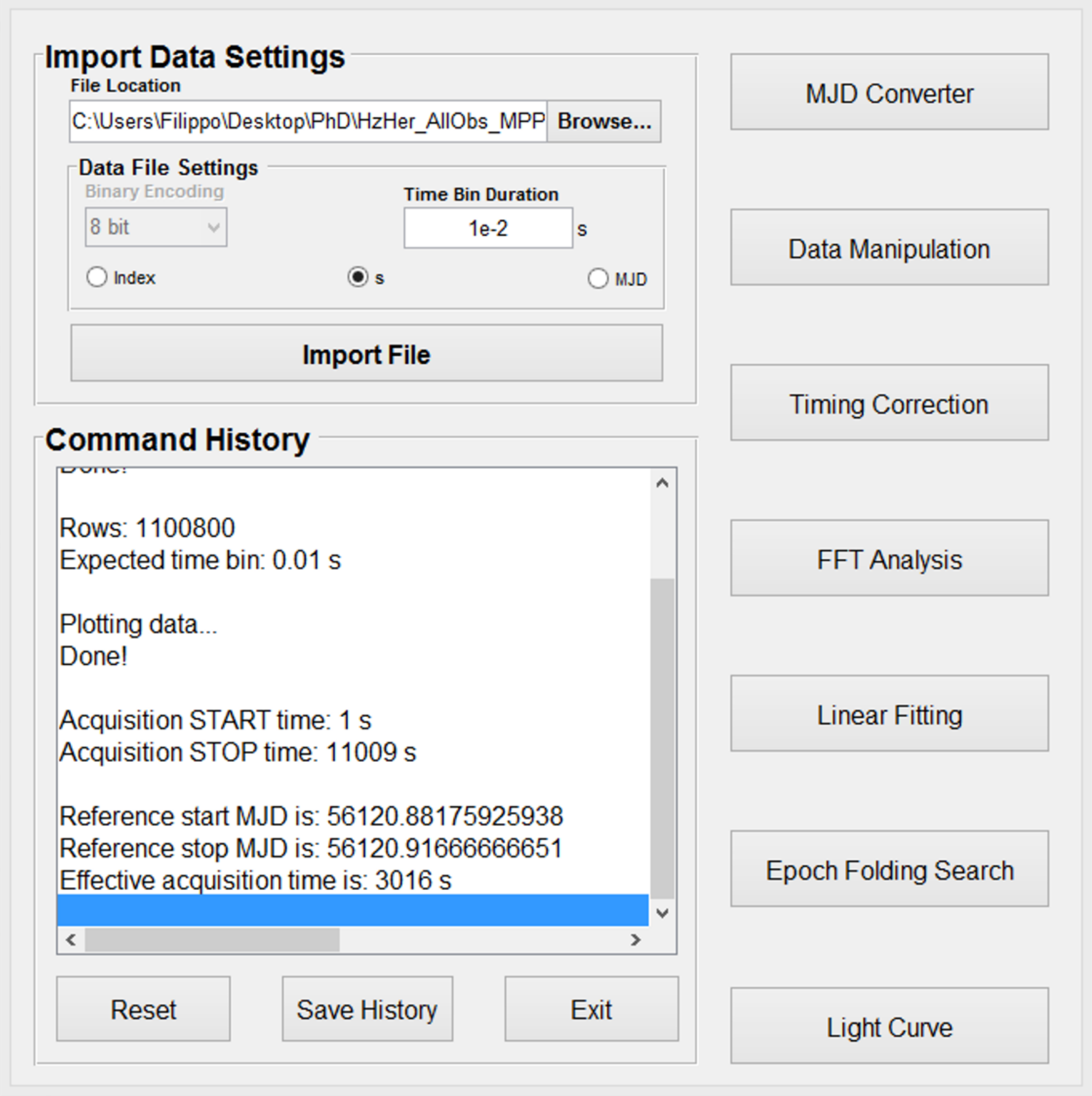
$R = x_{tot} / T$ ➔ total counting rate

$\sigma_i^2 = \frac{R}{T_i}$ ➔ variance of the *i*-th bin

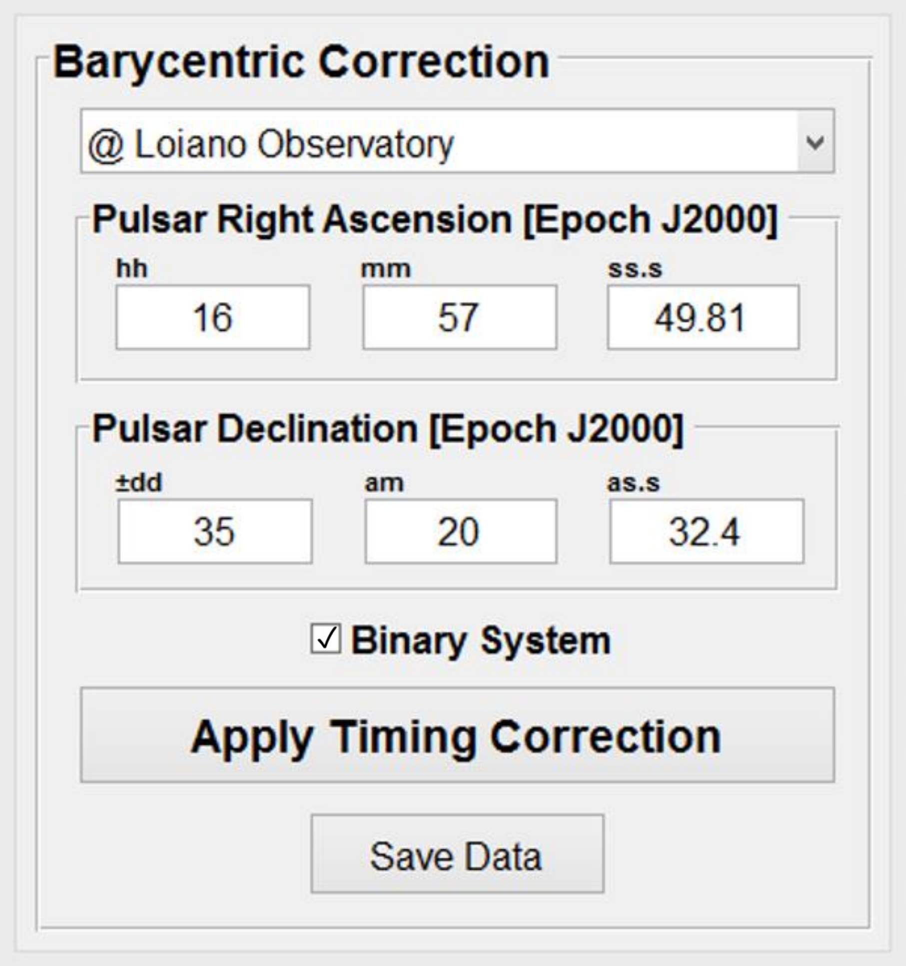


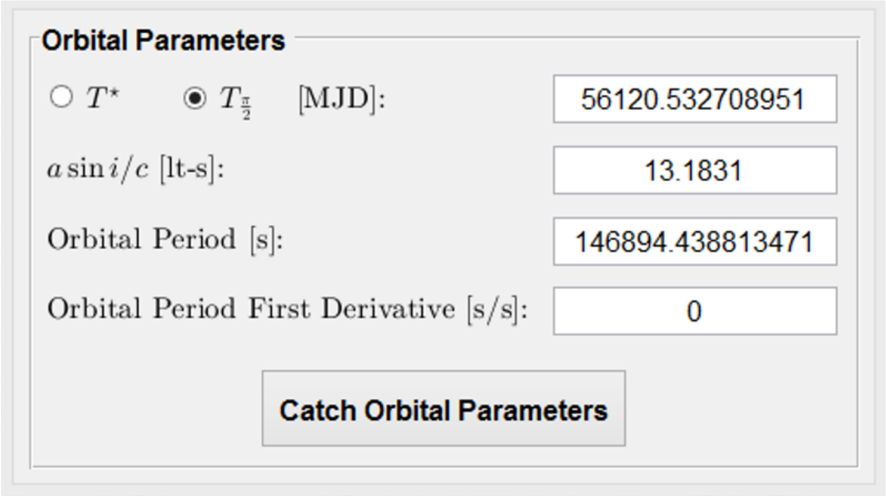
GUIDA 2: main panel

(**Ambrosino, F.**, submitted to PASP, 2017)

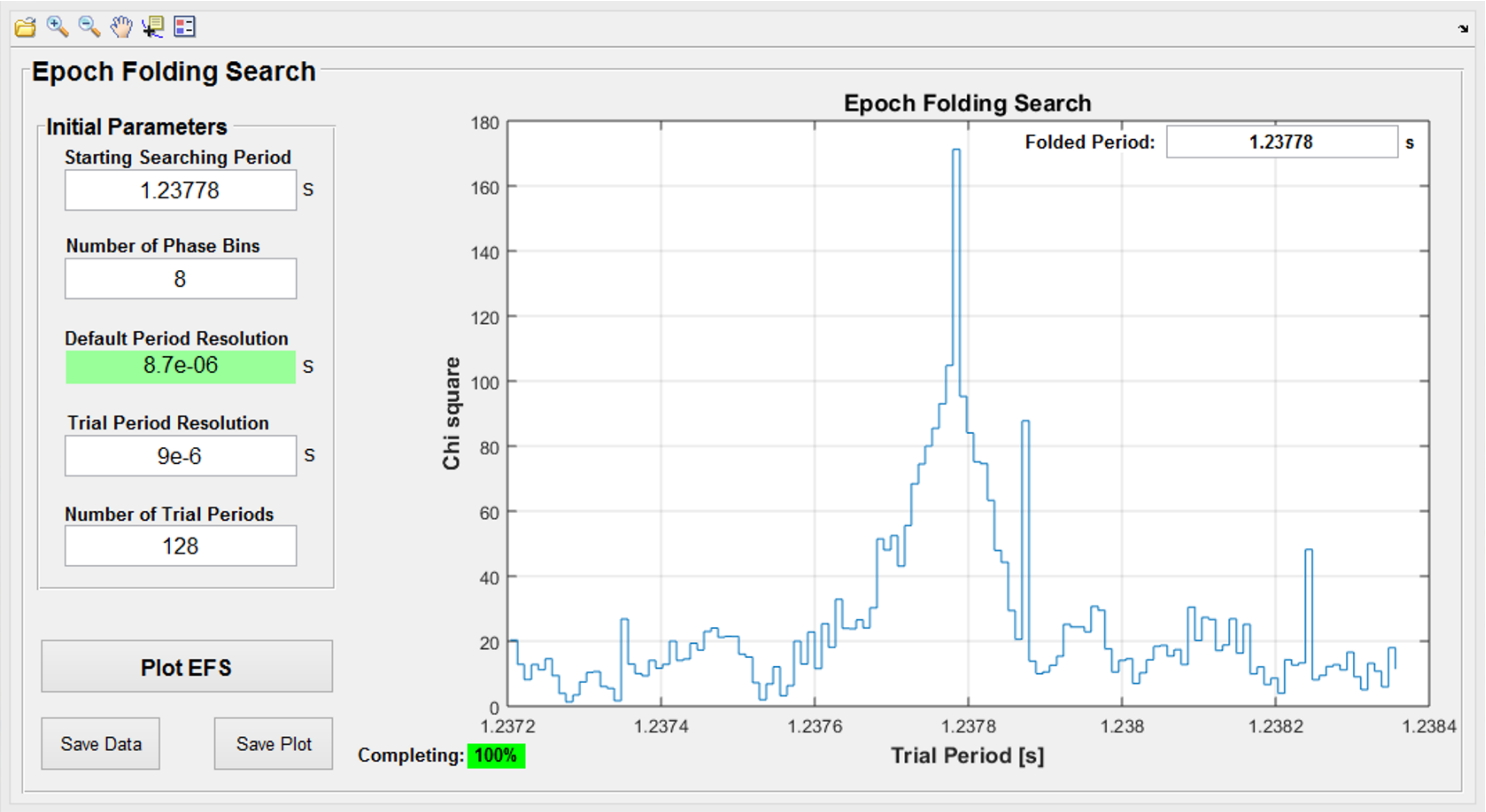


GUIDA 2: Timing Correction task panels



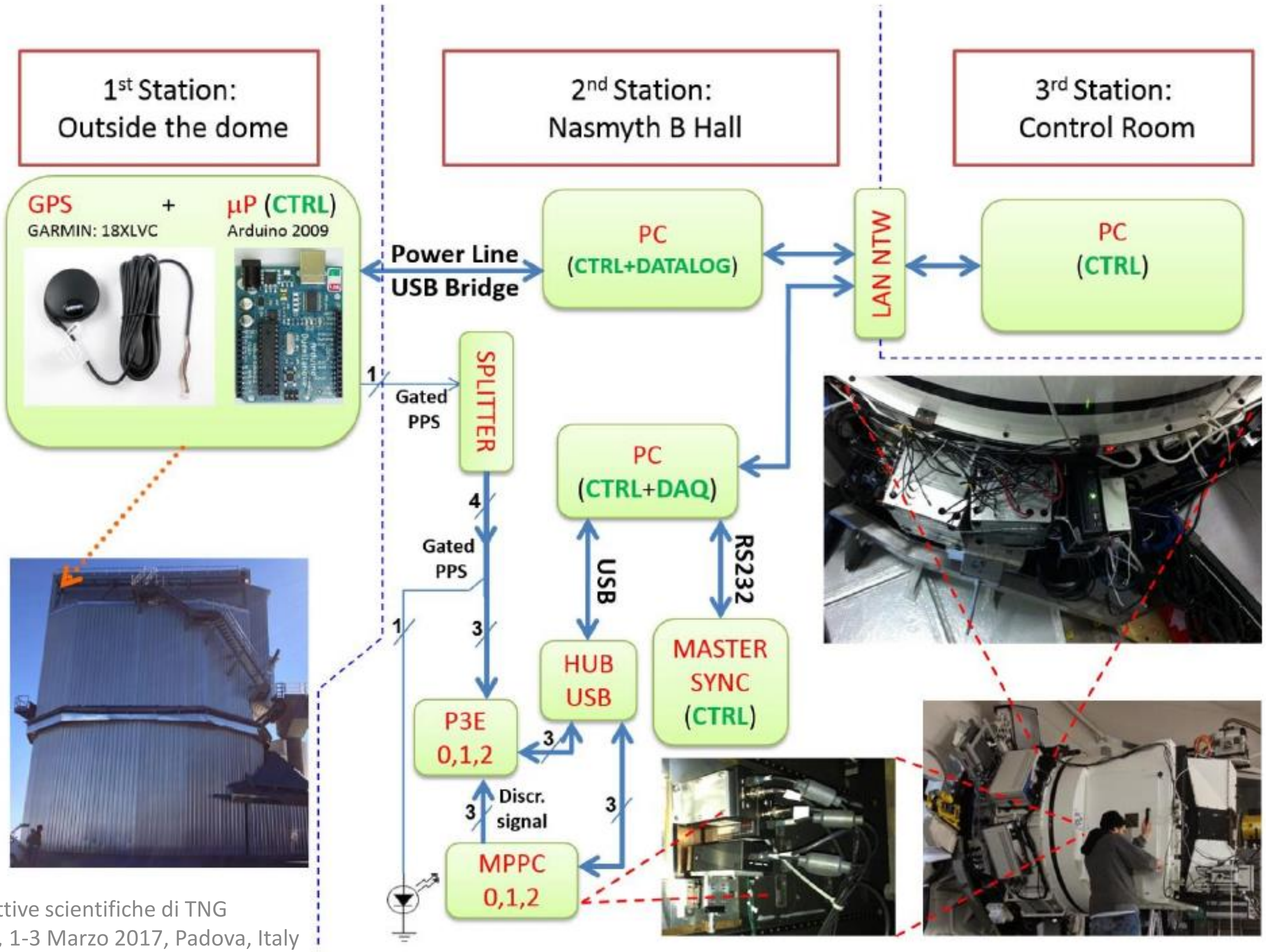


GUIDA 2: EFS task panel

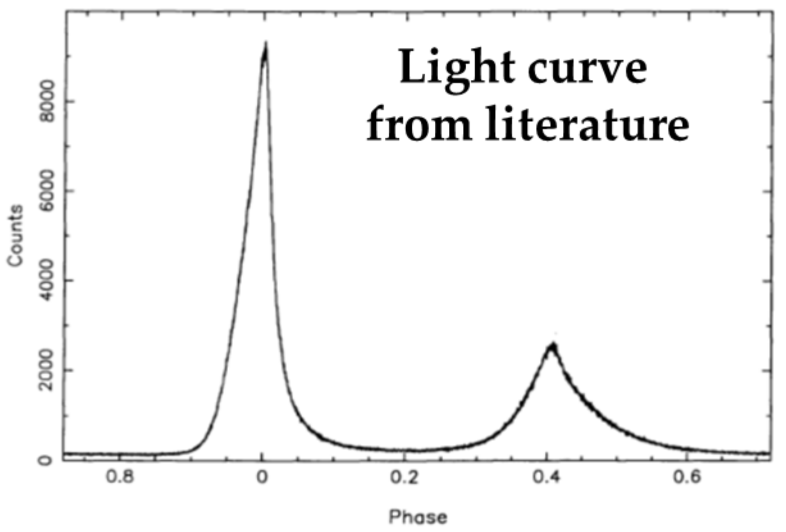


3. SiFAP @ TNG: Crab pulsar

SiFAP @ TNG


1st Station:
Outside the dome
2nd Station:
Nasmyth B Hall
3rd Station:
Control Room
GPS
+
µP (CTRL)
GARMIN: 18XLVC
Arduino 2009
Power Line
USB Bridge
PC
(CTRL+DATALOG)
LAN NTW
PC
(CTRL)
1
Gated
PPS
SPLITTER
PC
(CTRL+DAQ)
4
Gated
PPS
USB
RS232
1
3
HUB
USB
MASTER
SYNC
(CTRL)
P3E
0,1,2
3
Discr.
signal
3
3
MPPC
0,1,2

SiFAP @ TNG: Crab pulsar



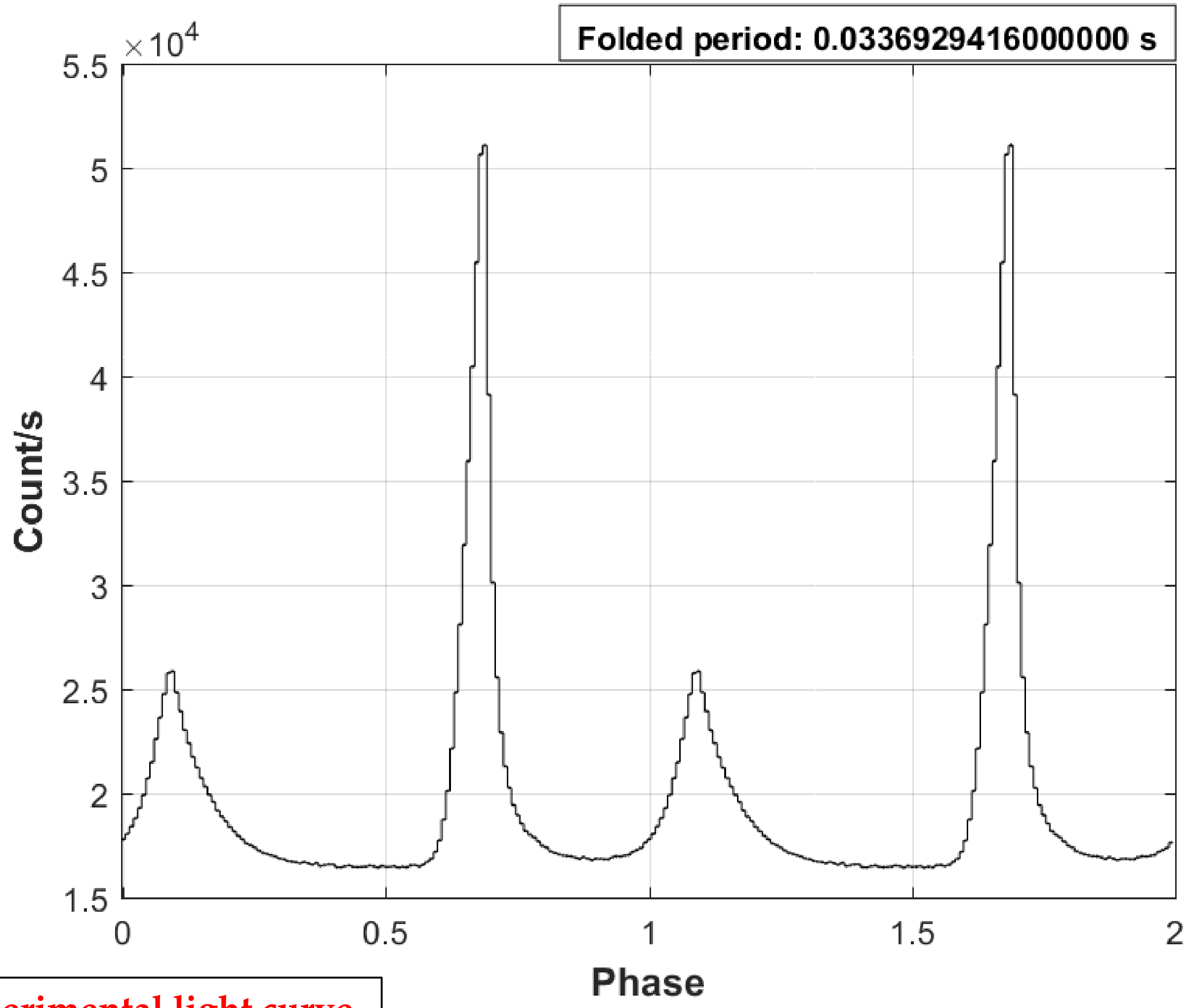
Experimental folded period (FFT): 0.033692942(3) s

$\Rightarrow \; |P_{Exp} - P_{JBO}| \approx 3\ \text{ns}$

Refined analysis using EFS

➔ folded period: 0.0336929416(3) s

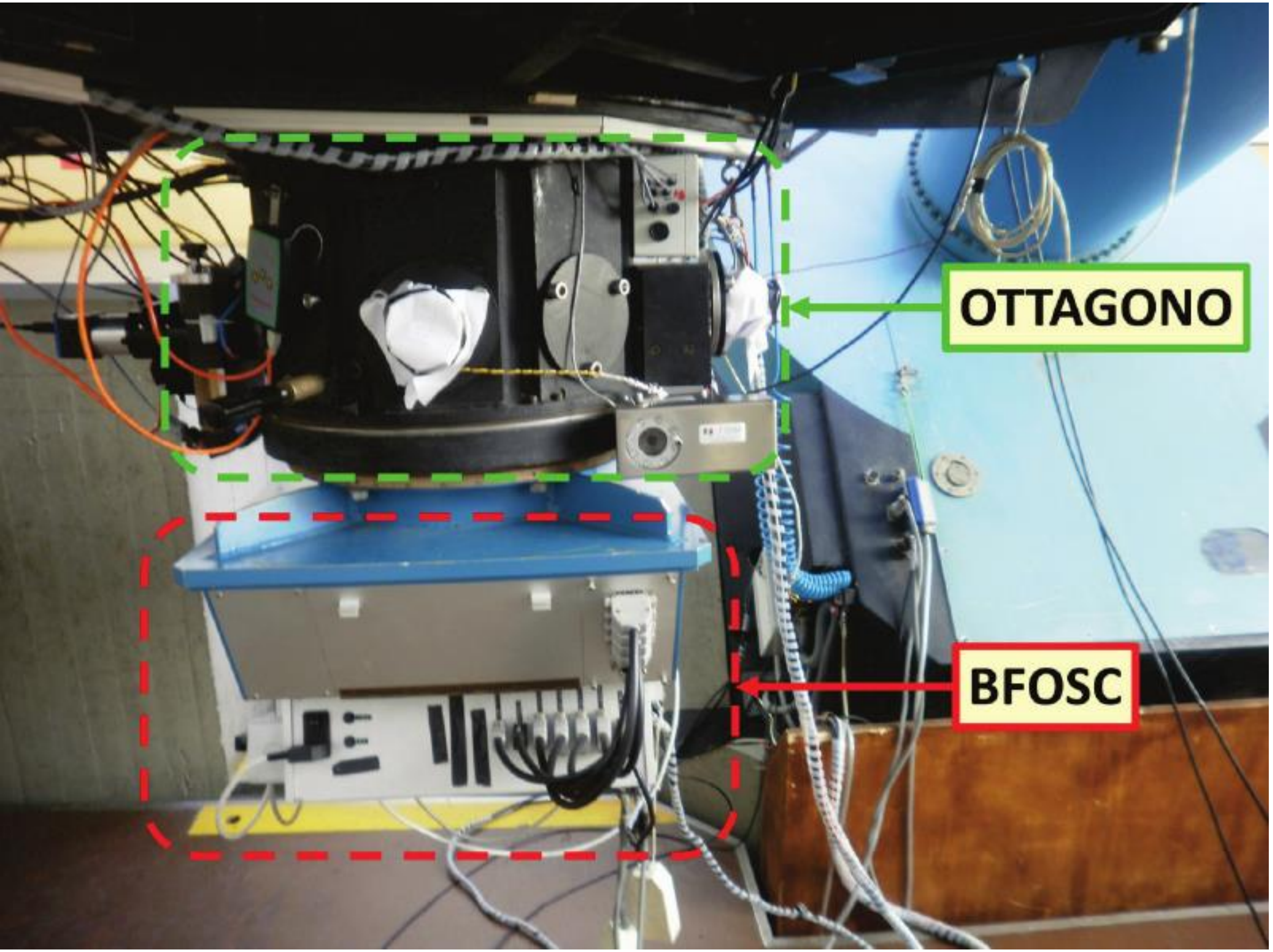
$\Rightarrow \; |P_{Exp} - P_{JBO}| \approx 3\ \text{ns}$

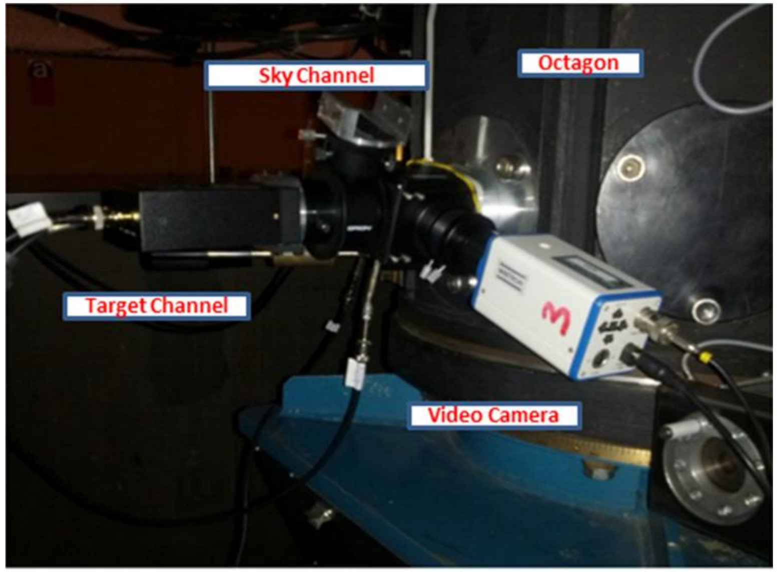


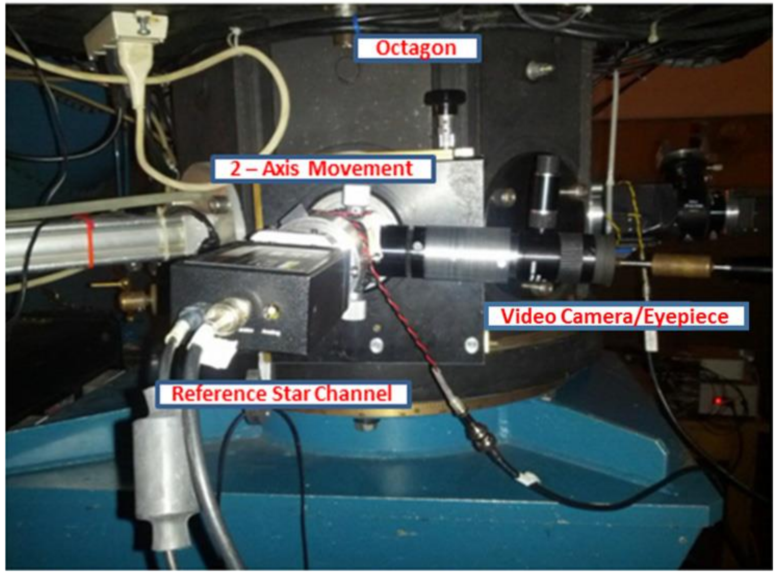
Experimental light curve
February 26, 2014

4. SiFAP @ Cassini Telescope: binary system Hz Her/Her X-1

SiFAP @ Cassini Telescope



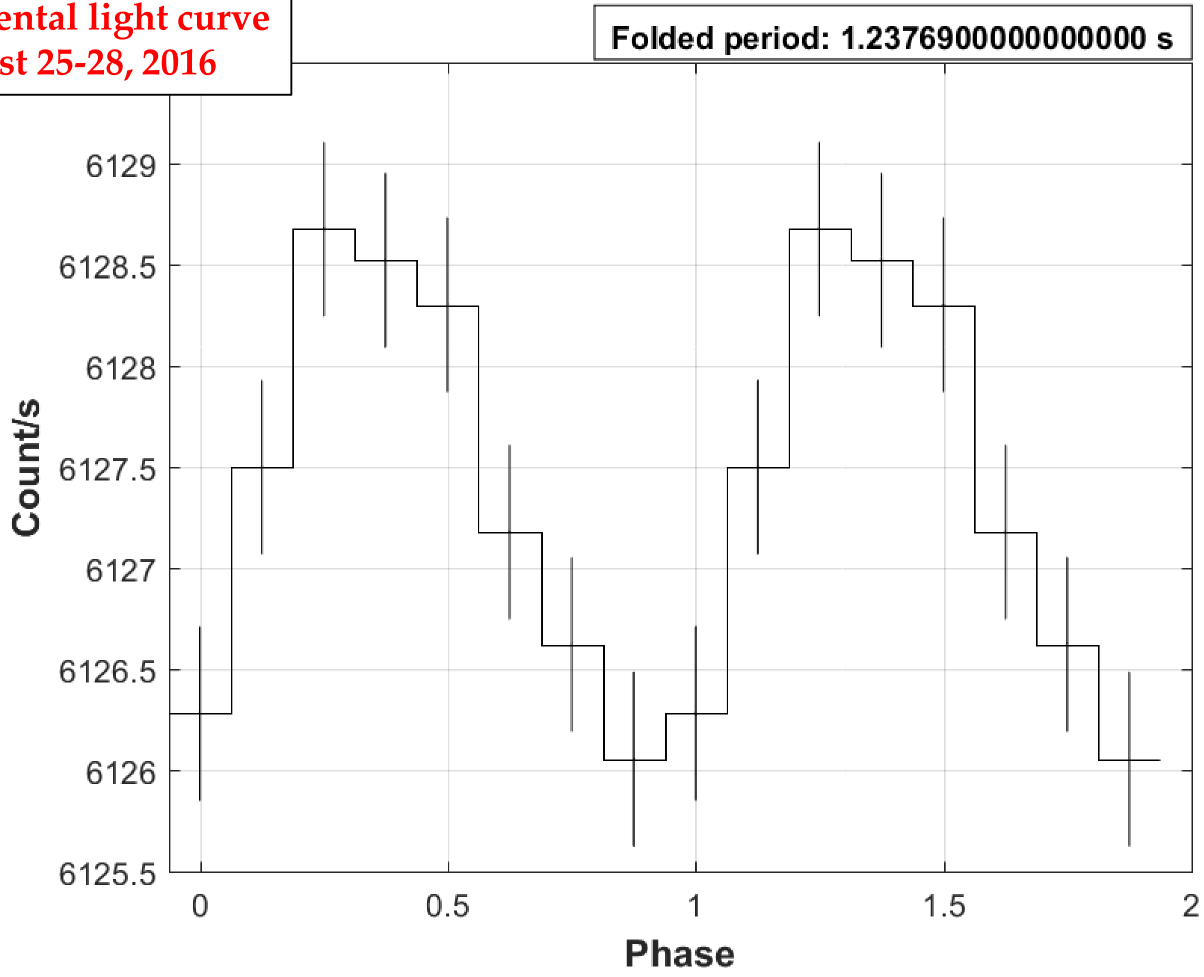


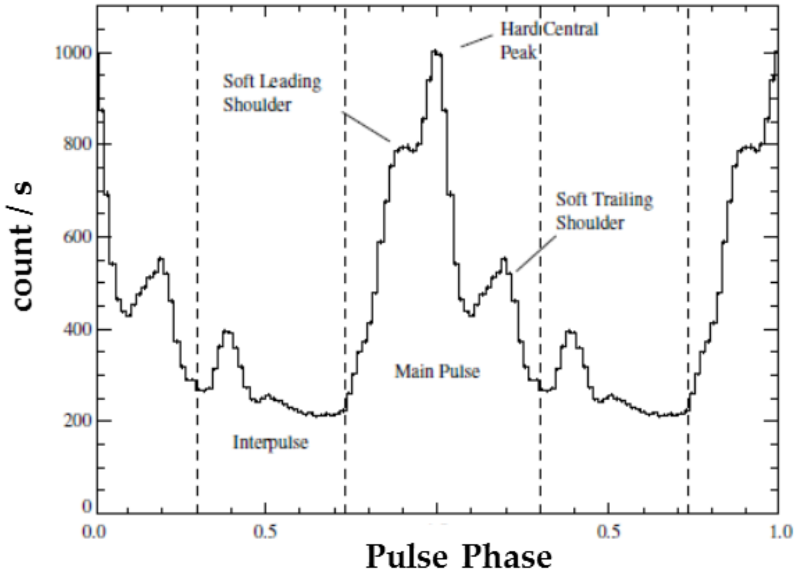


SiFAP @ Cassini Telescope:

Binary system Hz Her/Her X-1 (IMXRB)

Experimental light curve
August 25-28, 2016



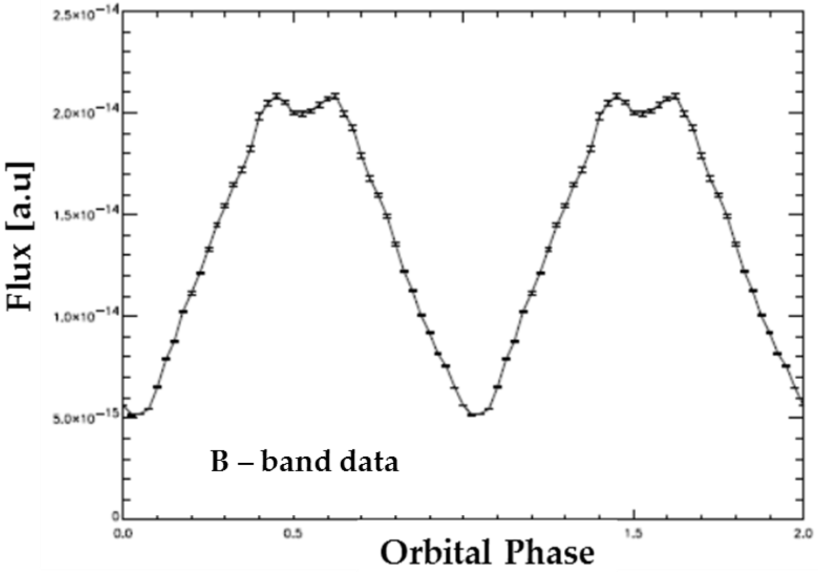


Light curve from literature
(Kuster, M., 2004 and reference therein)

Experimental folded period: 1.23769(1) s

$$\Rightarrow |P_{Exp} - P_{Eph}| \approx 400\ \text{ns}$$

SiFAP @ Cassini Telescope:
Binary system Hz Her/Her X-1 (IMXRB)



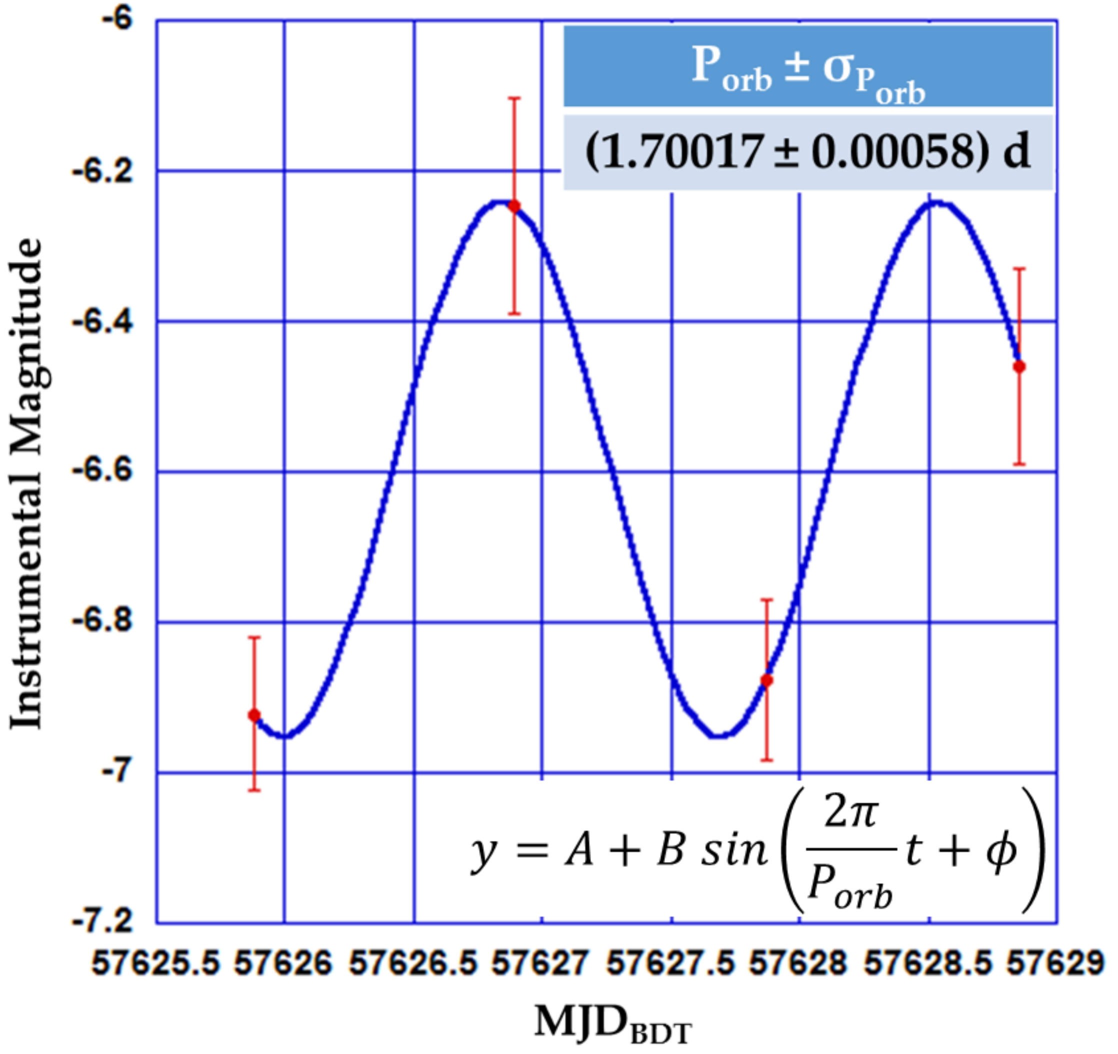
Experimental fitted Orbital Period: 1.70017(58) d

➔ $|P_{Exp} - P_{clas\ phot}| \approx 3.6 \cdot 10^{-6}$ d

Can not directly compare measurements

➔ need for more points (observations)

➔ need for observing in B/V/R bands

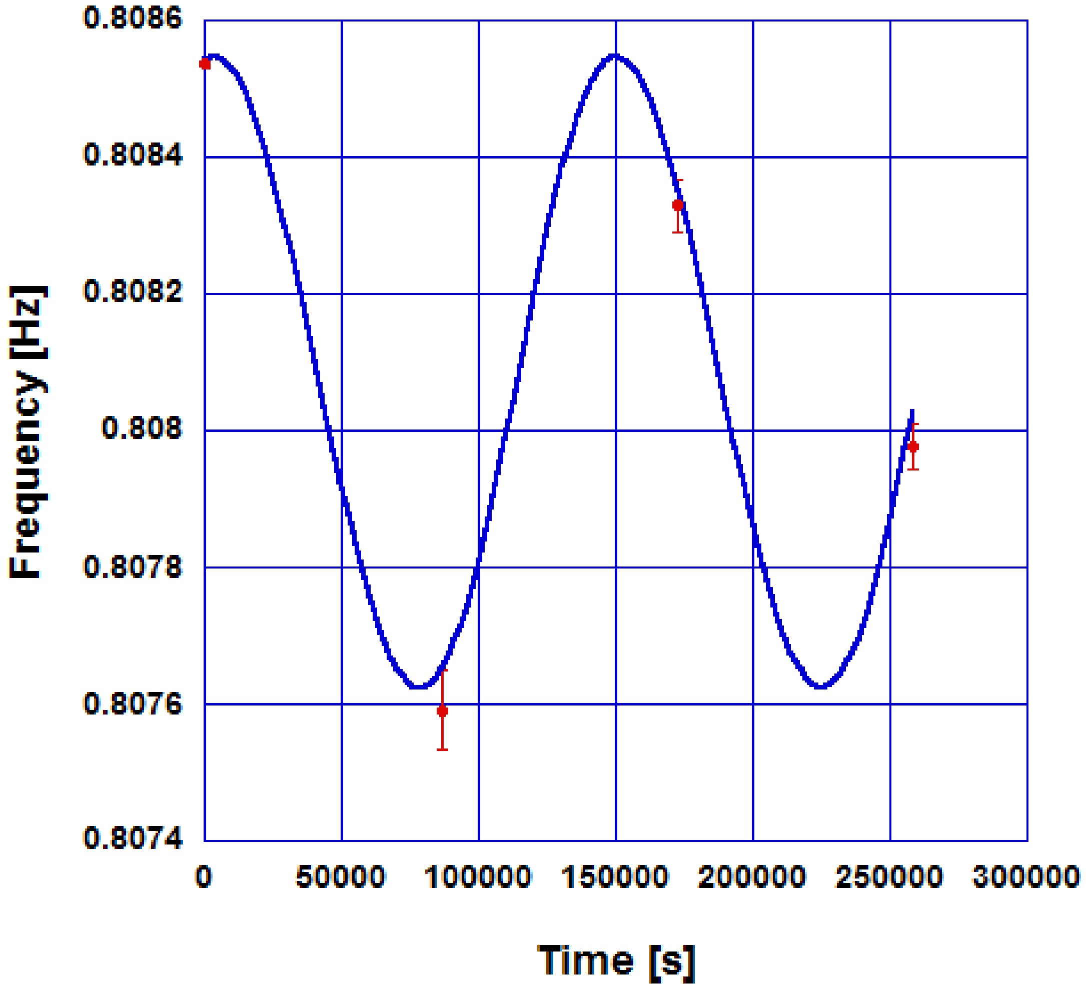


SiFAP @ Cassini Telescope:

Binary system Hz Her/Her X-1 (IMXRB)

Orbital Parameter	Value
Longitude of periastron	$\omega = (1.613 \pm 0.047)$ rad
True emission frequency	$\nu_{em} = (0.8080855 \pm 0.0000063)$ Hz
Orbital period	$P_{orb} = (146595 \pm 17)$ s
Semi-major axis projection	$a \cdot \sin(i)/c = (13.31 \pm 0.19)$ lt-s
Epoch of ascending node	$T_{asc} = (57625 \pm 13)$ d
Eccentricity	$e = (0.019 \pm 0.032)$

$$\nu = a\frac{\sin i}{c}\frac{2\pi\nu_{em}}{P_{orb}}\left[-\cos\left(\frac{2\pi}{P_{orb}}(t-T_{asc})+\omega\right)-\mathrm{e}\cos\left(\frac{4\pi}{P_{orb}}(t-T_{asc})+\omega\right)\right]+\nu_{em}$$



5. Conclusions and future perspectives

Conclusions

✓SiFAP @ TNG (Crab pulsar)

➔ Discrepancy of **3 ns** between the experimaental spin period and that expected from JBO radio ephemeris
➔ **Reconstruction** of the **light curve** of Crab Pulsar (shape very similar to that expected from literature)

✓ SiFAP @ Cassini (Hz Her/Her X-1)

➔ Discrepancy of about **400 ns** between the experimental spin period and that expected from X-ray ephemeris
➔ **Reconstruction** of the **light curve** of Hz Her/Her X-1 binary system
(shape quite similar to that expected from literature)
➔ Discrepancy of about **$3.6 \cdot 10^{-6}$ d** between the orbital period computed with a sinusoidal fit and that expected from BVR photometry
➔ Shape of the orbital light curve **not directly comparable** to that obtained from BVR photometry
(too **few data points** from observations, need for **BVR photometry with SiFAP**)
➔ Estimate of orbital parameters

Future perspectives

SiFAP @ TNG

➔ Observation of **fainter targets** (up to V=22 expected from computation)

➔ **Lower** sky **background** signal & **larger** telescope **area**

➔ Extend observations to targets down to about **-20° dec**

➔ not possible with Cassini telescope

➔ Detection of a **possible optical counterpart** of **extragalactic** X-ray pulsars

➔ 3XMM J004301.4+413017 in M31 and ULX in NGC 5907