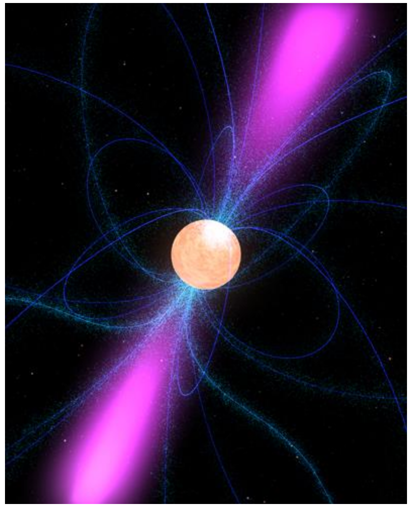
MSP - Pulsar al millisecondo in sistemi binari compatti

Alessandro Papitto
INAF Osservatorio Astronomico di Roma

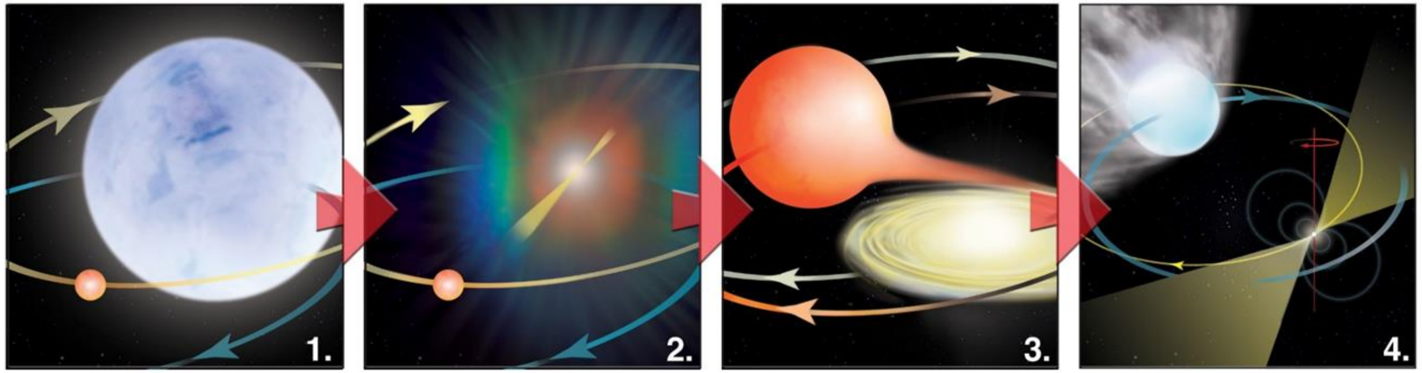
2021 May 26, INAF RSN4 Audit

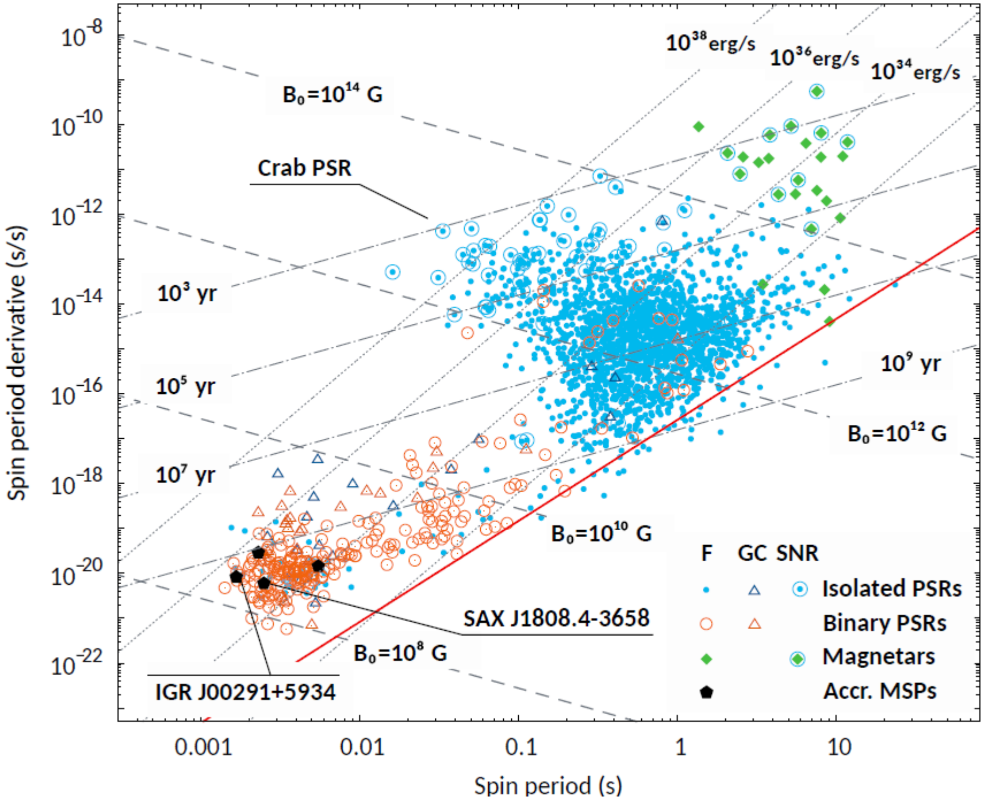
Millisecond Pulsars



Most compact (M≈1.4-2 Msun, R≈10 km)
& quickest spinning (10-15% of the speed of light at the equator)

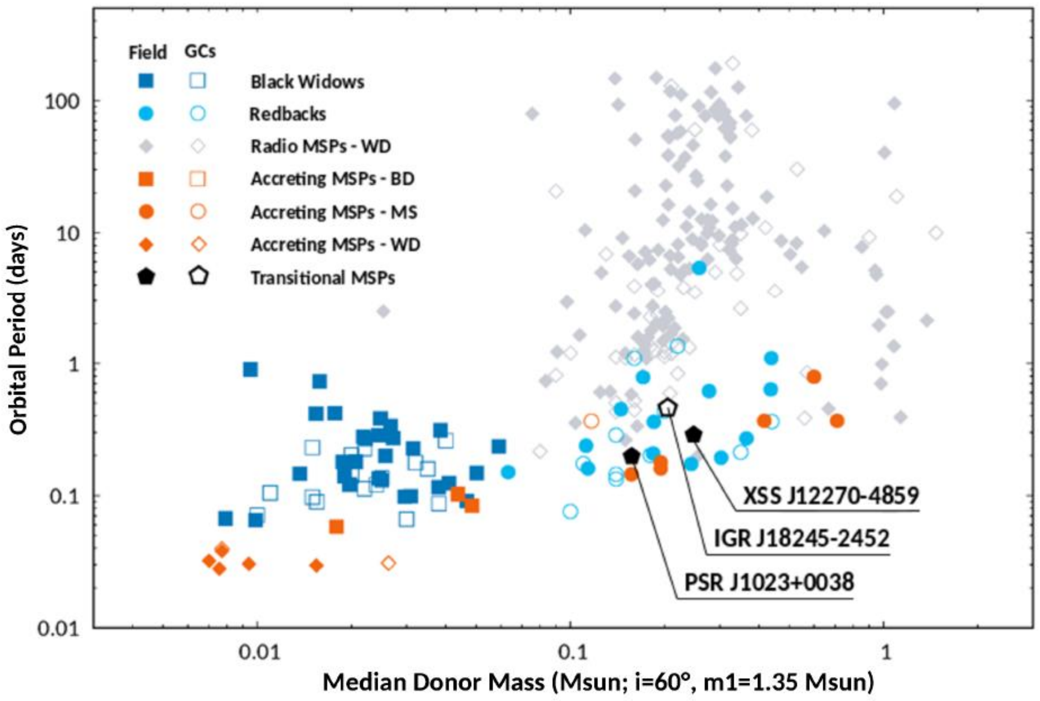
- → Test GR in double neutron star binaries
- → Probe the neutron star equation of state
- → Look for steady GW emission
- → Outcome of a complex evolutionary history of mass accretion in a low mass X-ray binary





Millisecond Pulsars in compact (Porb<day) binaries

Can we observe the progenitors of radio MSPs?
Yes, accreting millisecond pulsars



How do the pulsar wind and the accretion flow balance to produce either spin-powered radio MSPs or accreting X-ray MSPs?

Can we observe state transitions?
Yes (at last) -> Transitional millisecond pulsars

How does the pulsar wind of an MSP interact with the matter issued from the companion star to accelerate particles and eject matter from the binary?

Can spin and accretion powered emission mechanisms coexist? -> Optical millisecond pulsars

The MSP team

Leaders in high-time resolution observations of compact binary

Discovery of new classes of systems

Redbacks, transitional millisecond pulsars

Innovative interpretative frameworks

Pulsar/plasma interaction, High energy emission, Spin and orbital evolution

Opening of new avenues to study MSPs

Fast optical photometry, X-ray polarimetry, SKA precursors

The MSP team

INAF 14 staff (6 since 2016) + 5 postdocs (60/40 gender bal.) **2.1 FTE/year**
Univ. 3 staff + 3 postdocs **0.6 FTE/year**
Intl. collaborations (Barcelona, Geneva, Cape Town, IAC, TNG)

OA Roma
Luigi Stella
Piergiorgio Casella
Alessandro Papitto (coord.)
Filippo Ambrosino
Arianna Miraval Zanon
Alessandro Di Marco (IAPS)
Simone Dall'Osso (GSSI)

OA Capodimonte
Domitilla de Martino
Elena Mason (OATs)

OA Brera
Sergio Campana
Paolo D'Avanzo
Sara Motta

OA Cagliari
Marta Burgay
Andrea Possenti
Maura Pilia
Alessandro Ridolfi
Alessandro Corongiu
Delphine Perrodin

OA Padova
Luca Zampieri
Aleksandr Burtovoi

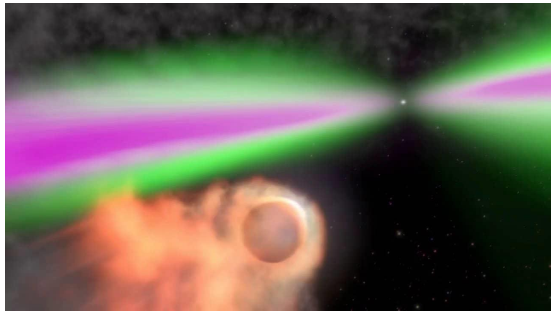
Univ. Cagliari/Palermo
Luciano Burderi
Tiziana Di Salvo
Alessandro Riggio
Andrea Sanna
Fabio Pintore (IASF PA)

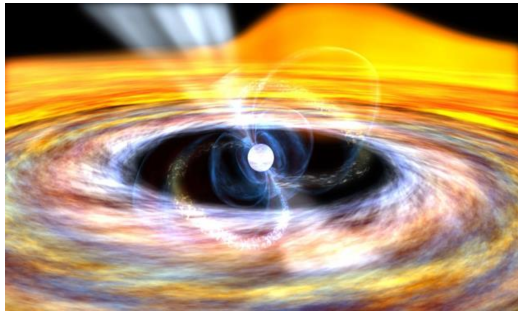
The MSP team

Spin-powered radio MSPs

OA Cagliari

M. Burgay, A. Possenti,
M. PIlia, A. Ridolfi,
A. Corongiu, D. Perrodin

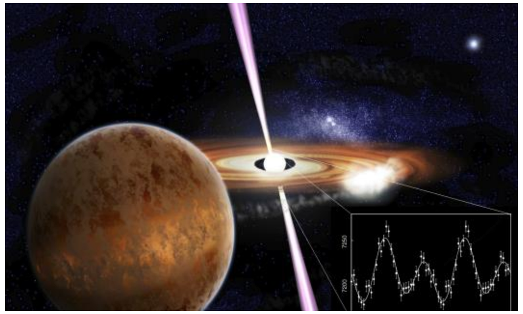




Accreting X-ray MSPs

Uni PA/CA, OAR, OAC, IAPS, IASF

L. Burderi, T. Di Salvo, A. Riggo,
A. Sanna, F. Pintore, A. Papitto,
M. Pilia, A. Di Marco



Optical MSPs

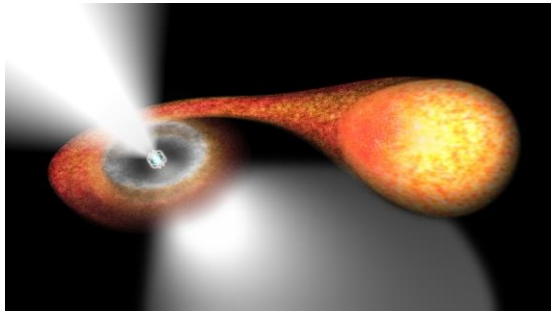
OAR, OAPd

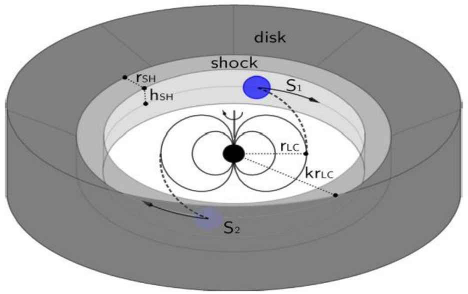
A. Papitto, F. Ambrosino, A.
Miraval, L. Zampieri, A. Burtovoi

Transitional radio/X-ray MSPs

OAR, OAB, OANa, OAC, OATs

A. Papitto, S. Campana, D. de Martino,
L. Stella, P. Casella, M. Burgay,
A. Possenti, P. D'Avanzo, F. Ambrosino,
A. Miraval, A. Di Marco, S. Dall'Osso,
E. Mason, S. Motta, A. Ridolfi





Interpretation

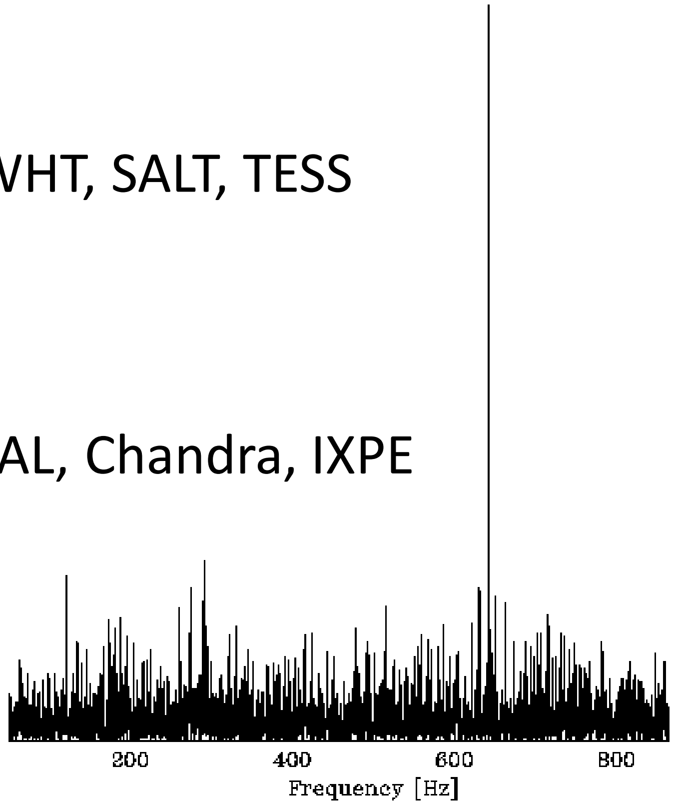
OAR, OAB, OANa, Uni PA/CA

L. Stella, S. Campana, L. Burderi,
T. Di Salvo, D. de Martino, A. Papitto,
S. Dall'Osso

Research facilities

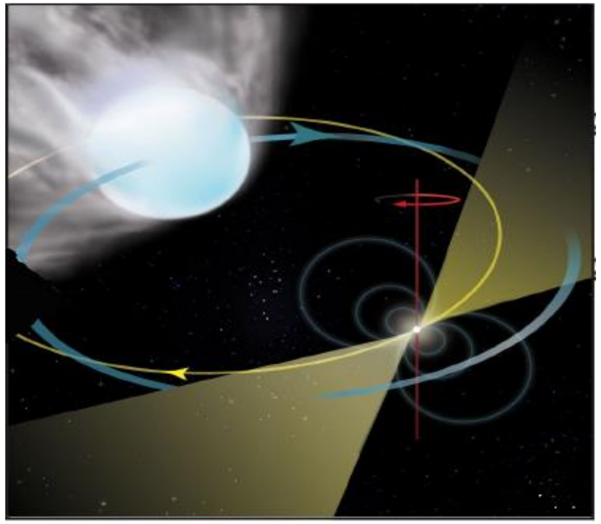
Fast Time Domain Astronomy at all wavelengths

Radio	**Sardinia Radio Telescope**, Parkes, ATCA, LOFAR, MeerKAT, SKA, VLA, FAST
near-infrared	**REM**, GTC
Optical	**TNG/SiFAP2**, **Copernicus/Aqueye**, VLT, NTT, WHT, SALT, TESS
UV	Hubble Space Telescope
X-rays	XMM Newton, Swift, NuSTAR, NICER, INTEGRAL, Chandra, IXPE
gamma-rays	Fermi



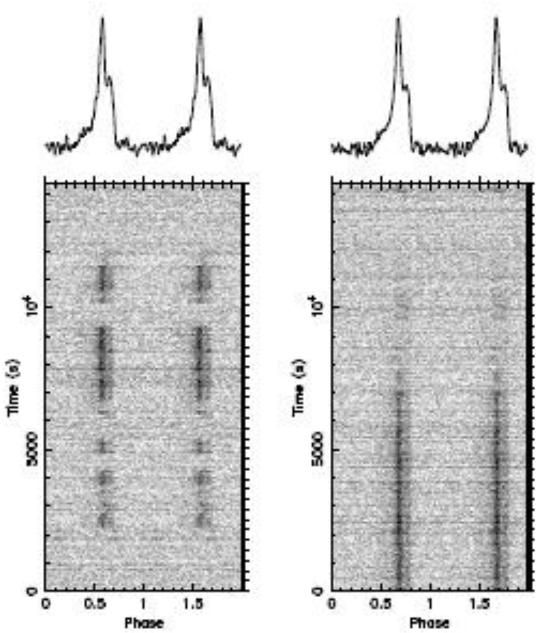
Spin-powered Radio MSPs

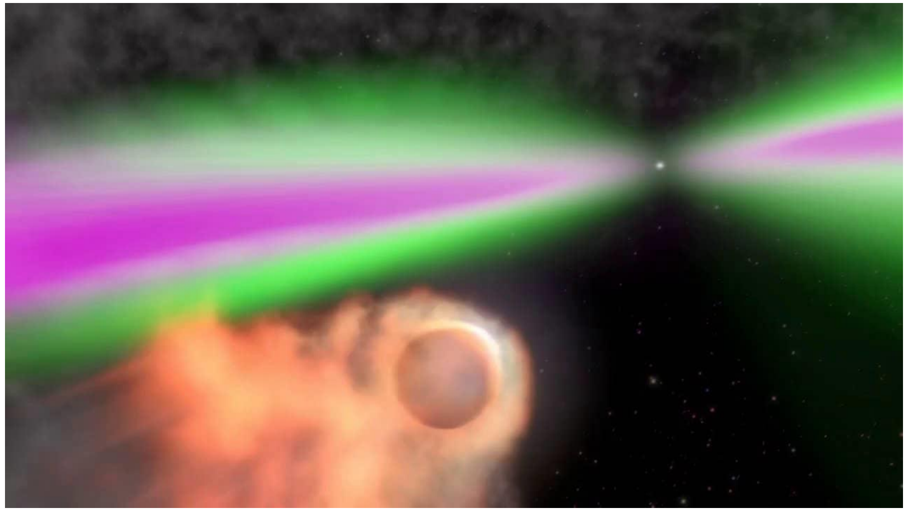
Discovery of first interacting radio pulsar with a MS companion [D'Amico+ 2001]



Interaction of the pulsar wind with the mass-losing companion forms a shock emitting up to gamma-rays & ablates the companion star [Bailes+ 2011]

Eclipses & delays of the radio pulsations allow a tomography of the shock region

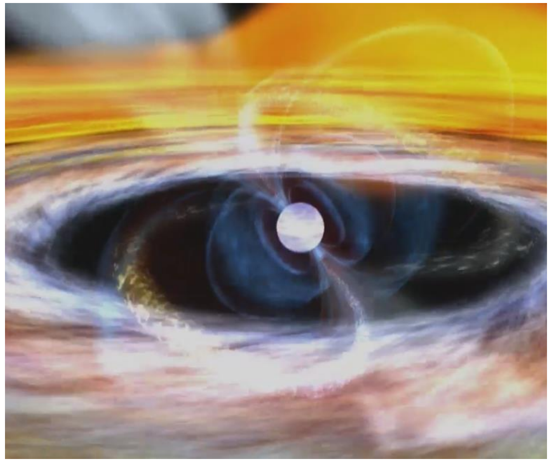




<u>Present & Future:</u>
Surveys for MSPs in the Galactic field & globular clusters with SKA precursors
(e.g. Ridolfi+ 2021)

See **SKA-Science-Prandoni** & **SPUFS Corongiu**

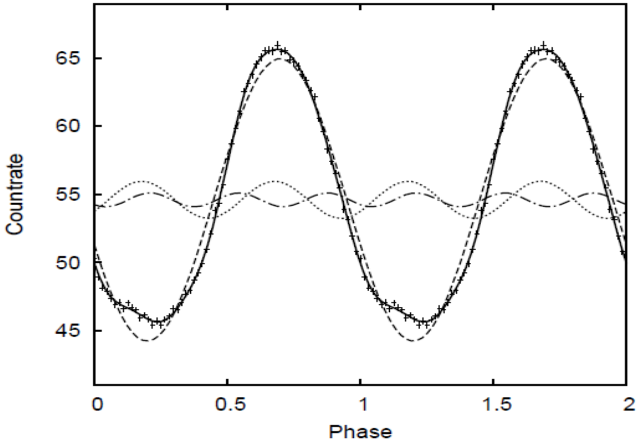
Accreting X-ray MSPs



Discovery of 40% of the two dozens accreting MSPs known in X-ray transients
[see reviews by Campana & Di Salvo 2018; Di Salvo & Sanna 2020]

X-ray & optical emission in quiescence: suggestions of a radio pulsar
[Burderi+ 2003, Campana+ 2002, 2004]

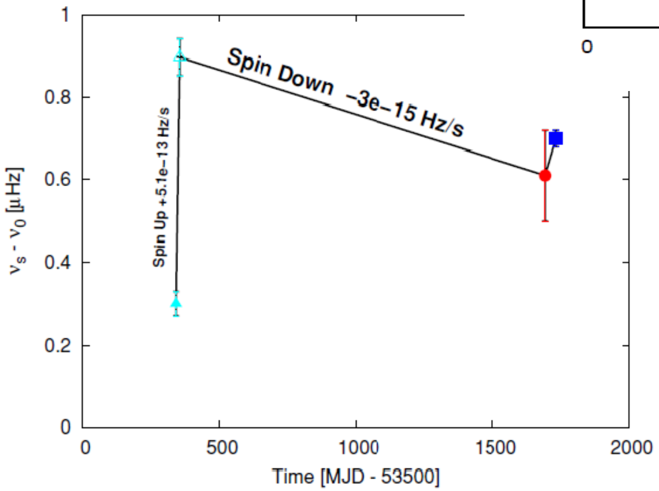
Modelling of the spin & orbital evolution
[e.g. Burderi+ 2006, Di Salvo+ 2008, Burderi+ 2009]

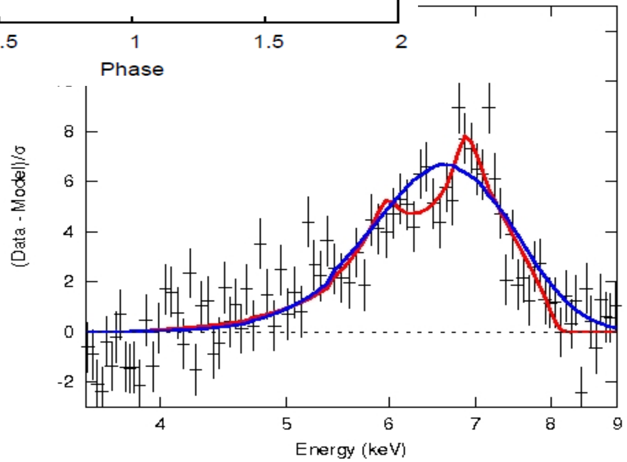


Probing the inner disk plasma motions with X-ray spectroscopy
[e.g. Papitto+ 2009]

<u>Present & Future:</u>
What is the fastest spin a neutron star can attain by accreting matter?

Measure the NS equation of state with IXPE X-ray polarimetry and pulse waveform modelling





Transitional (radio/X-ray) MSPs

LETTER

doi:10.1038/nature12470

Swings between rotation and accretion power in a binary millisecond pulsar

A. Papitto[1], C. Ferrigno[2], E. Bozzo[2], N. Rea[1], L. Pavan[2], L. Burderi[3], M. Burgay[4], S. Campana[5], T. Di Salvo[6], M. Falanga[7], M. D. Filipović[8], P. C. C. Freire[9], J. W. T. Hessels[10,11], A. Possenti[4], S. M. Ransom[12], A. Riggio[3], P. Romano[13], J. M. Sarkissian[14], I. H. Stairs[15], L. Stella[16], D. F. Torres[1,17], M. H. Wieringa[18] & G. F. Wong[8,14]

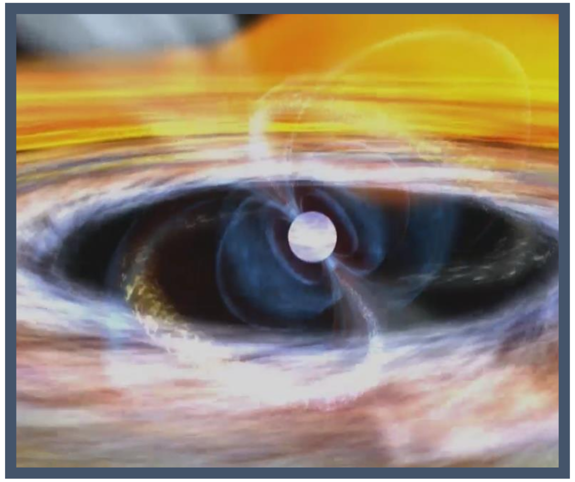
Discovery of two (out of three) transitional MSPs & two strong candidates [de Martino+ 2010, 2013; Papitto+ 2013; Coti Zelati+ 2019]

Intermittent X-ray pulsations [Papitto+ 2015]

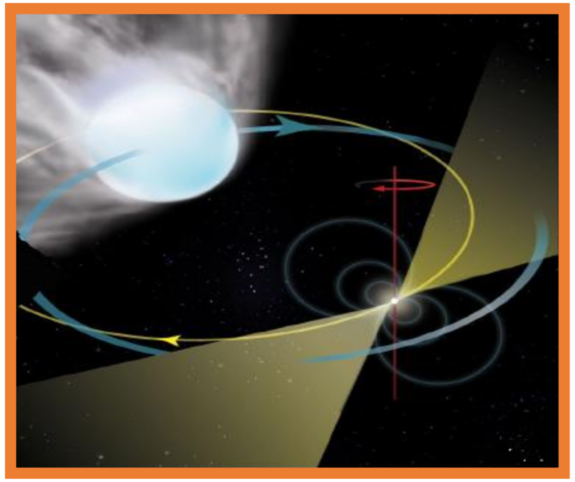
Broadband variability characterization [CZ+2018, Papitto+ 2019] (e.g. campaign involving XMM, NuSTAR, Swift, HST, VLT/FORS2, NTT/SOFI, SALT, REM, ALMA, VLA, FAST on June 3, 2021; PI: Campana)

Interpretative framework [e.g. Papitto 2014, 2015, 2019; Campana+ 2016]

Accretion-powered (X-ray) PSR



Mass in-flow rate



Spin-powered (radio) PSR

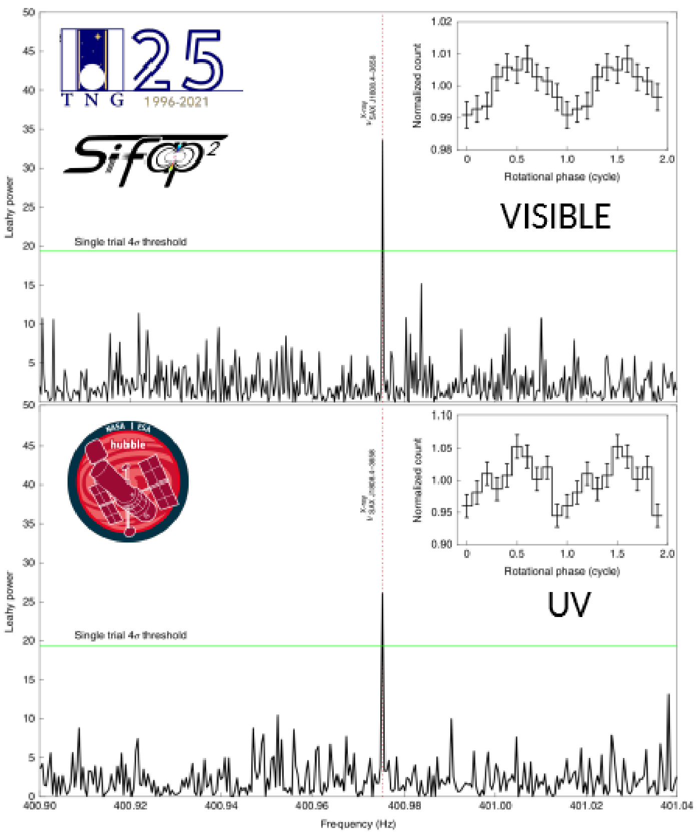
nature astronomy
LETTERS
DOI: 10.1038/s41550-017-0266-2

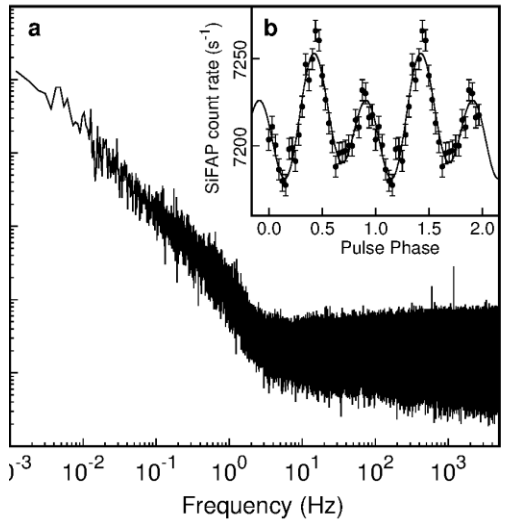
Optical pulsations from a transitional millisecond pulsar

F. Ambrosino[1,2], A. Papitto[3]*, L. Stella[3], F. Meddi[1], P. Cretaro[4], L. Burderi[5], T. Di Salvo[6], G. L. Israel[3], A. Ghedina[7], L. Di Fabrizio[7] and L. Riverol[7]

Optical and ultraviolet pulsed emission from an accreting millisecond pulsar

F. Ambrosino[1,2,3,22] ✉, A. Miraval Zanon[4,5,22] ✉, A. Papitto[1], F. Coti Zelati[5,6,7], S. Campana[5], P. D'Avanzo[5], L. Stella[1], T. Di Salvo[8], L. Burderi[9], P. Casella[1], A. Sanna[9], D. de Martino[10],



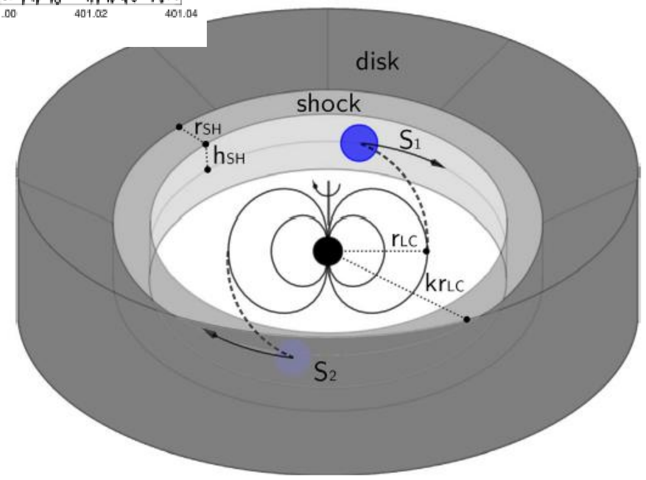


How many optical MSPs are out there?

[Ambrosino, Papitto+ 2017, Ambrosino, Miraval Zanon+ 2021]

A new avenue for pulsar timing [Zampieri+ 2019, Burtovoi+2020]

Do spin & accretion powered mechanisms coexist? [Papitto+ 2019]



Leadership: Observing time (as P.I.) breakdown

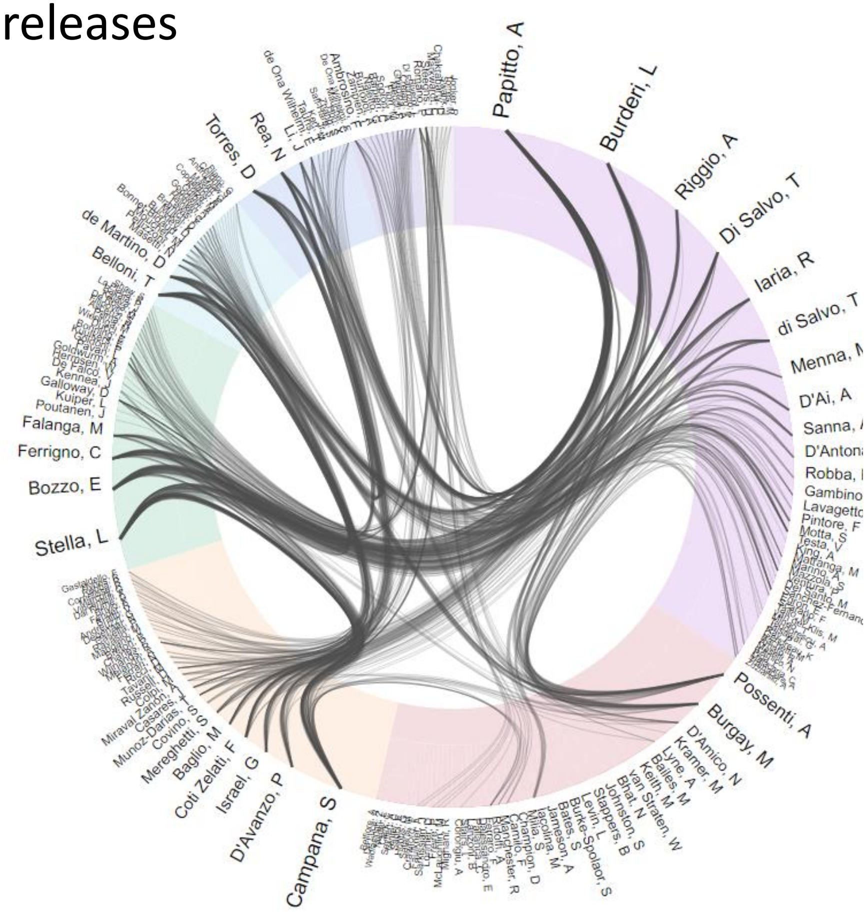
X-rays	GO	Time (ks)	ToO/DDT	Time (ks)
XMM-Newton	29	1630	14	630
NICER	-	-	15	200
NuSTAR	4	400	10	450
Chandra	2	150	2	50
INTEGRAL	1	500	-	-
TOTAL	36	2680	41	1330

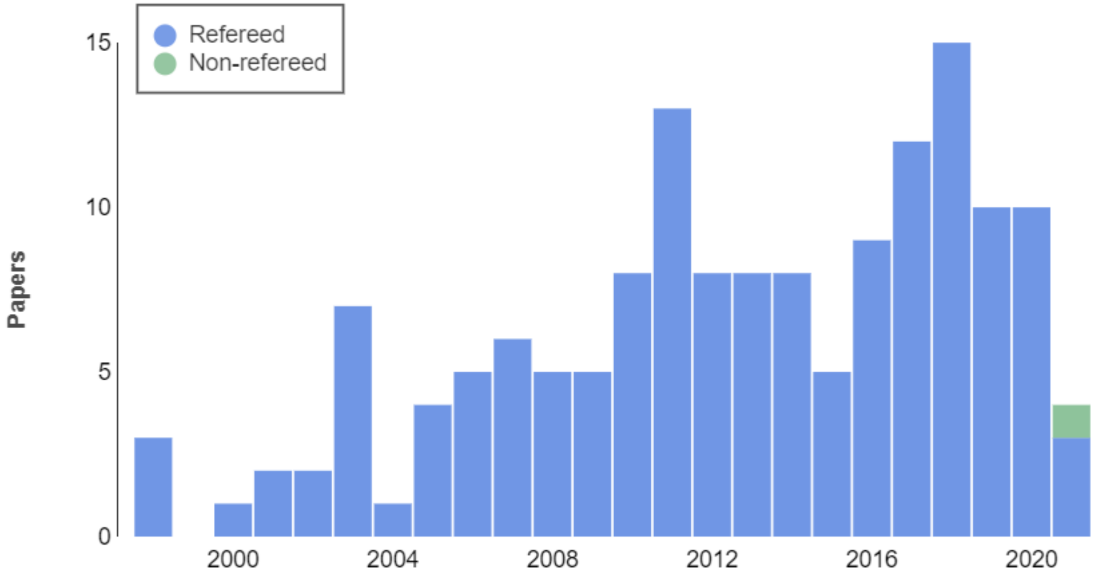
UV/Optical/nIR	GO	Time (hours)	ToO/DDT	Time (hours)
INAF TNG	7	70	4	15
HST	1	6	1	6
ESO (NTT/VLT)	12	120	-	-
INAF REM	7	190	-	-
LOIANO	3	48	-	-
TOTAL	22	436	5	21

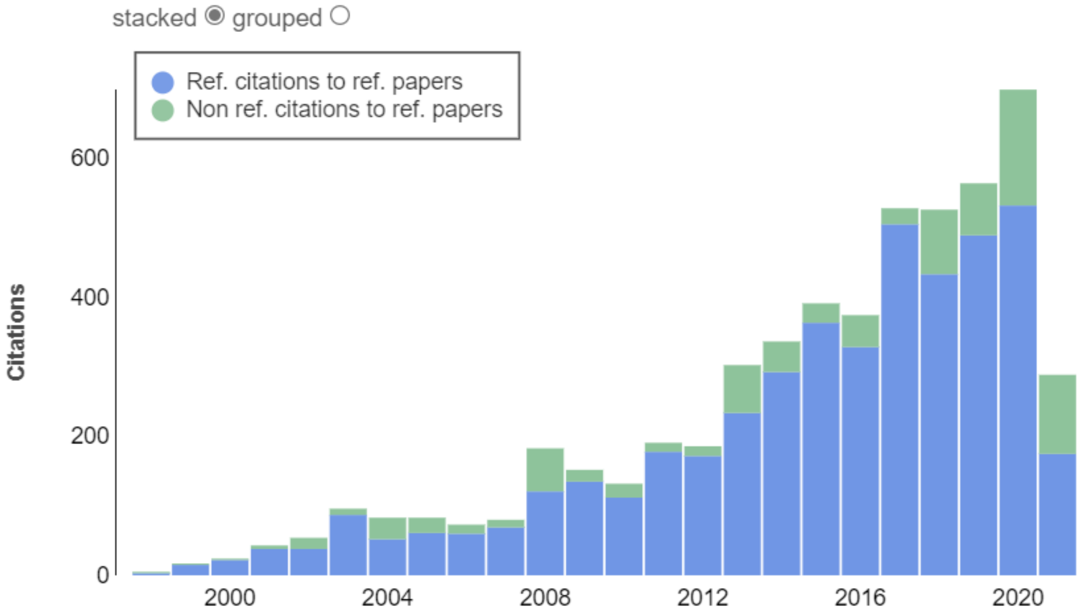
Radio	GO	Time (h)		
ATNF Parkes	11	860		
ATNF ATCA	2	24		
INAF SRT	13	230		
LOFAR	1	7		
TOTAL	27	1120	3	49

Leadership: publications

150 refereed articles
5300 citations (35 per paper); h-index 43
1 Nature (cited 300+ times), 2 Nature Astronomy,
1 A&ARv, 1 Science
Several press releases







Leadership: new observing windows

Fast optical photometry

SiFAP2 @ Galileo Telescope (see scheda **SiFAP2 – Ambrosino**)

Silicon photomultipliers (CTA, ASTRI, etc)

Extension to nearIR & polarimetry

Aqueye+/Iqueye @ Copernicus Asiago (see scheda **FPC-OA – Zampieri**)

Single Photon Avalanche Diodes (SPAD)

X-ray polarimetry

IXPE (accreting MSP observation subWG leader)

SKA precursors (e.g. MeerKAT)

Definition of the science cases of future facilities

SOXS@NTT, eXTP, THESEUS, Athena, LSST and CTA

Workflow (a typical basic research tale…)

- writing of scientific proposals for Earth and Space-based facilities
- observations; setup of observation parameters and in a few cases (e.g. SiFAP2@TNG, Aqueye+) actual fulfilment of the observation
- Temporal and spectral analysis of the data obtained and interpretation of the results
- Writing of scientific papers
- Preparation of the science cases of future facilities (e.g. IXPE, SOXS, SKA, CTA)
- Grant proposal writing

Criticalities: funding sources

EU H2020 (Marie Sklodowska Curie framework), PHAROS COST Action ≈ 200 k€
INAF/ASI grants for NuSTAR observations (PI: Papitto, de Martino) ≈ 50 k€
INAF/ASI grants for High Energy observations (PI: **Belloni, see scheda SCOX-0**; De Rosa), ≈ 150 k€
SKA/CTA grant (PI: Possenti, Giroletti), ≈ 25 k€
PRIN (PI: D'Amico), ≈ 200 k€
Certainly available for 2021-23 = 40k€
proposed (PRIN PI: Astone, INFN, 100 k€); EU ERC funding scheme

Funds obtained mostly as part of larger collaborations

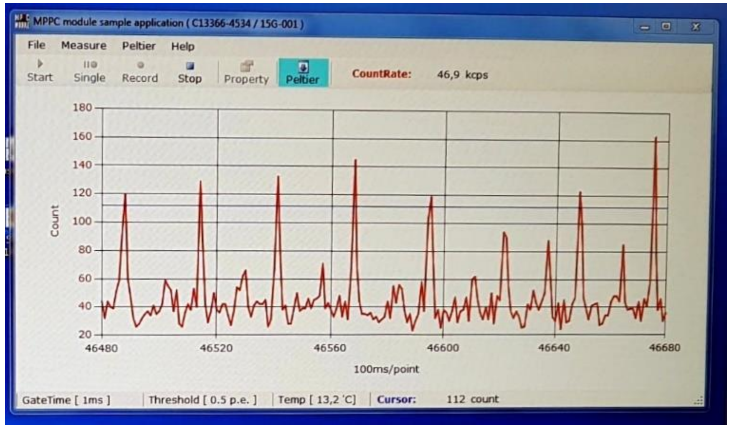
Access to INAF/ASI funds for data analysis uncertain

Funds dedicated to HW (e.g. SiFAP2 extension to nIR, 100-500k€) required to fully exploit **the INAF leadership in fast optical photometry**

Uncertain prospects to train postdoc & students and form new generation of scientists who will exploit the facilities of time-domain astronomy of the next decades (LSST, CTA, SKA, eXTP)

So far, optical astronomy has lagged behind radio, X-ray and gamma-ray astronomy

SiFAP2 at the **Telescopio Nazionale Galileo** has joined the endeavor to fill the gap.



SiFAP2 in a nutshell

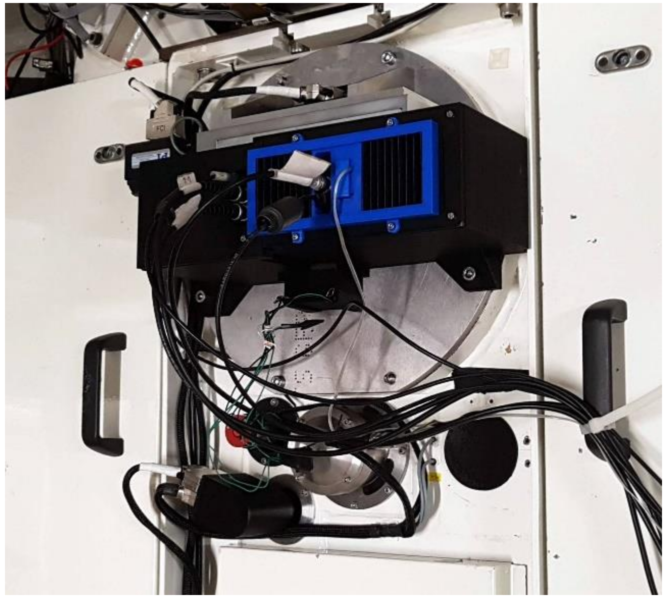
Mounted at the F/11 direct focus of the Nasymith interface

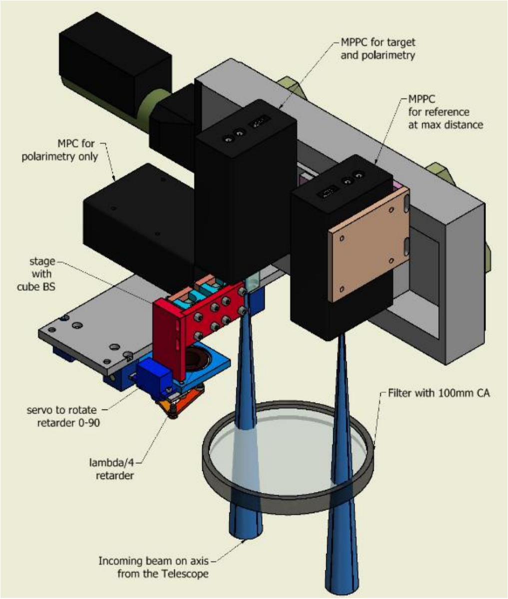
Commercial Hamamatsu Silicon multipixel photon counters (SiPM)

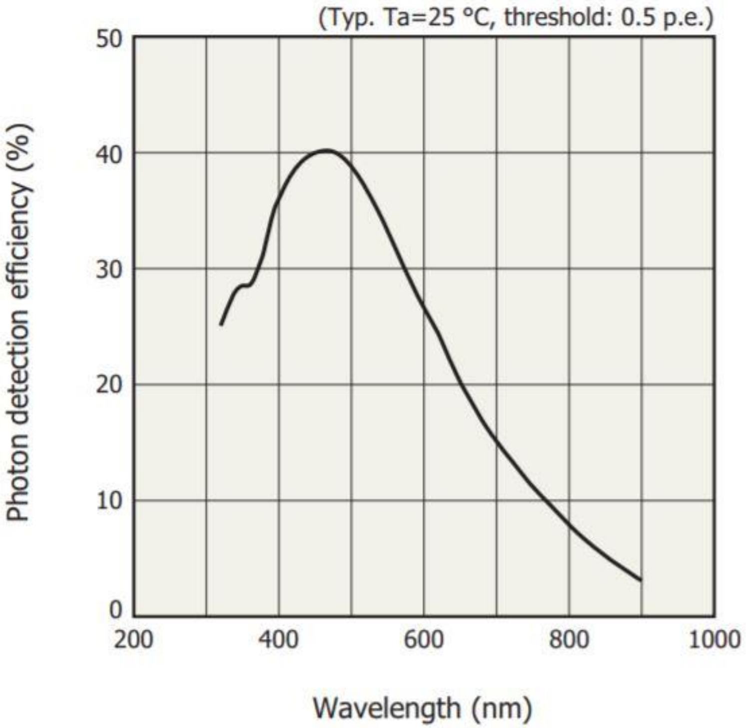
→ **8 ns resolution** (60 µs absolute accuracy)
→ linear up to **V ≈ 10 mag**
→ 320-900 nm, efficiency peaks at 475 nm (**g band**)
→ **Polarimetric** capabilities (linear and circular)

http://www.tng.iac.es/instruments/sifap2/

Ambrosino+ 2014,2018; Ghedina+ 2018







The path to extended SiFAP

Use same detectors & fibers
accurate differential photometry
to detect impulsive flares

Readout electronics and absolute/relative time accuracy (**MWL pulsars & XRBinaries**)

Polarimetry (analysis of Crab pulsar observations ongoing)

Extension to the **near infrared**
- search for pulsars and bursters in absorbed environments
- MWL variability of X-ray binaries (e.g. disk-jet connection)

Explore the **connections with CTA & ASTRI**
for Intensity interferometry