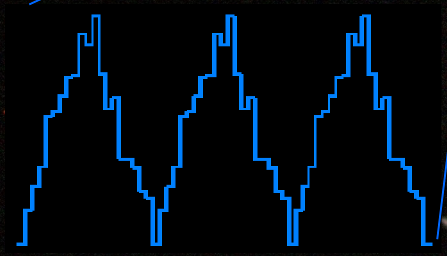
The Extragalactic population of NS and the ULX paradigm revolution

GianLuca Israel (AO Roma)

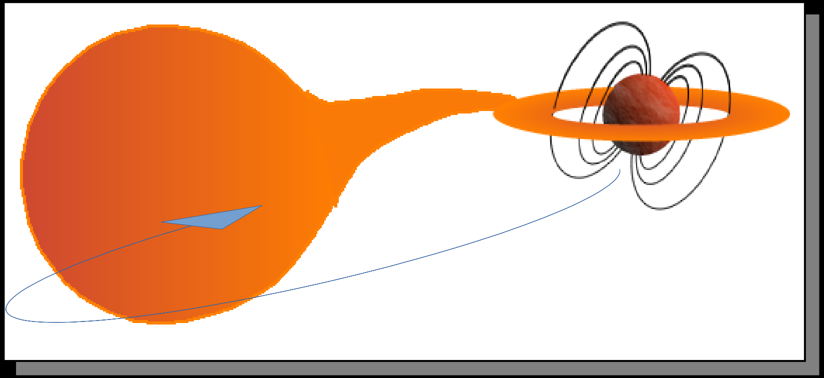


Outline

- Data mining & periodicity search
- The CATS@BAR and EXTraS projects
- The sample of new pulsators: the magnetic gating scenario
- The extragalactic pulsars (M31 and beyond)
- Pulsating ULXs
- Beaming vs super-Eddington accretion
- The UNSEEN project and the next steps

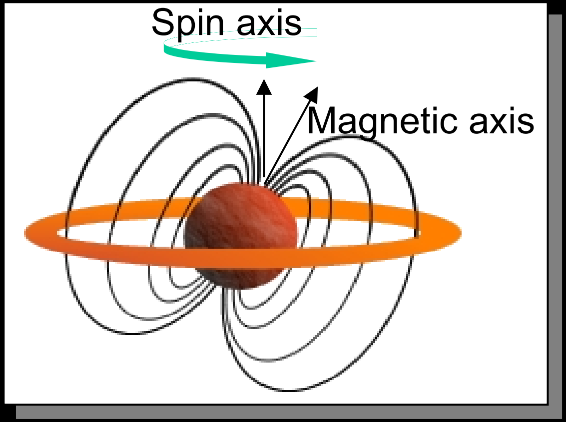
What can X-ray Signals Tell Us?

- Timing => characteristic timescales = PHYSICS !



- Binary orbits (NSs, WDs, BHCs)
  - [super-]orbital period (hr-months)
  - HM vs LMXBs
  - sizes of emission regions and occulting objects, masses, etc.
  - orbital evolution (Mdot/GWs)

- Rotation of stellar bodies (NSs, WDs)
  - spin periods (ms-hours)
  - stability of rotation (NS vs WD)
  - torques acting on system, Lx, etc.



Why

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For about 98% of detected sources no timing info are available

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1) Search for new classes of X-ray pulsators or in rare eolutionaty paths
[large number of sources and photons]

EXOSAT: 4U0142+614, prototype of the magnetar class (I+94);
ROSAT PSPC: HD497985, a massive WD in a post common envelope phase (I+96, Mereghetti+09)
ROSAT HRI: HM Cnc, a 2-WD binary; 5.4min (!!) orbital period (I+99, I+02, Esposito+14)

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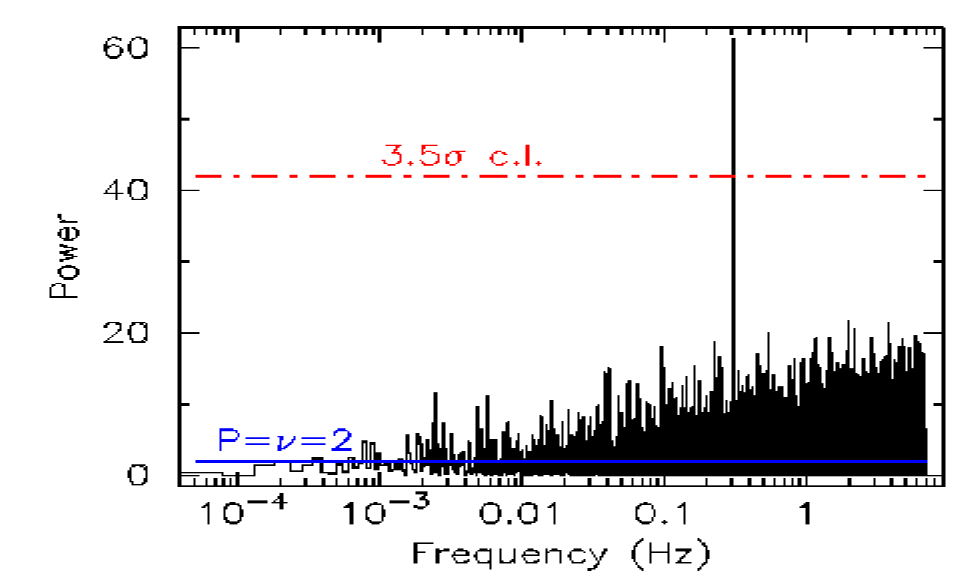
2) Extending the luminosity interval over which the physics of the (accretion) emission mechanism can be investigated and/or pushing the search to nearby galaxies
[large throughput and narrow psf]

Implication: cut-off in the number of detectable NS for low Lx and/or only detection of long-period low-flux pulsators

How

FFT algorithm + ad hoc algorithm for signal detection (local threshold)

- Well known technique;
- Independent from the search period;
- Works in presence of non-Poissonian noise components;
- Optimized for uninterrupted obs. and sinusoidal signals;
- Limits on low statistics and/or highly non sinusoidal signals



THE DETECTION PROCESS IN A PSD

The process of detecting something in a power spectrum against the background of noise has several steps:

- knowledge of the probability distribution of the noise powers
- The detection level: Number of trials (frequencies and/or sample)
- knowledge of the interaction between the noise and the signal powers (determination of the signal upper limit)
- Specific issues related to the intrinsic source variability (non Poissonian noise)
- Specific issues related to a given instrument/satellite (spurious signals – spacecraft orbit, wobble motion, large data gaps, etc.)

COMPUTING USEFUL POWER SPECTRA

• The "Leahy" normalization is useful for computing significances (DETECTION). In the following we will refer to it as the default

$$P_j \equiv \frac{2}{N_{ph}} |a_j|^2 \qquad j = 0, \ldots, \frac{N}{2}$$

• N_{ph} is the total number of photons
• With this normalization, the Poisson noise level (**for a constant source**) is distributed like a χ^2 with $\nu = 2N_{PSD}$ degrees of freedom (in units of counts; N_{PSD} is the number of averaged PSD)
- $E[\chi^2|\nu] = \nu$ → 2 for N_{PSD}=1
- $\sigma[\chi^2|\nu]$ = sqrt(2ν) → 2 for N_{PSD}=1 → noisy

NOISE PROBABILITY DISTRIBUTION

For a wide range of type of noise (including that of counting photon detectors used in X-ray astronomy), the noise powers $P_{j,noise}$ follow a χ^2 distribution with $\nu=2N_{PSD}$ degrees of freedom.

$$Q(\chi^2|\nu) \equiv \left[2^{\nu/2}\Gamma\left(\frac{\nu}{2}\right)\right]^{-1} \int_P^{+\infty} P^{\frac{\nu}{2}-1} e^{\frac{P}{2}} dP$$

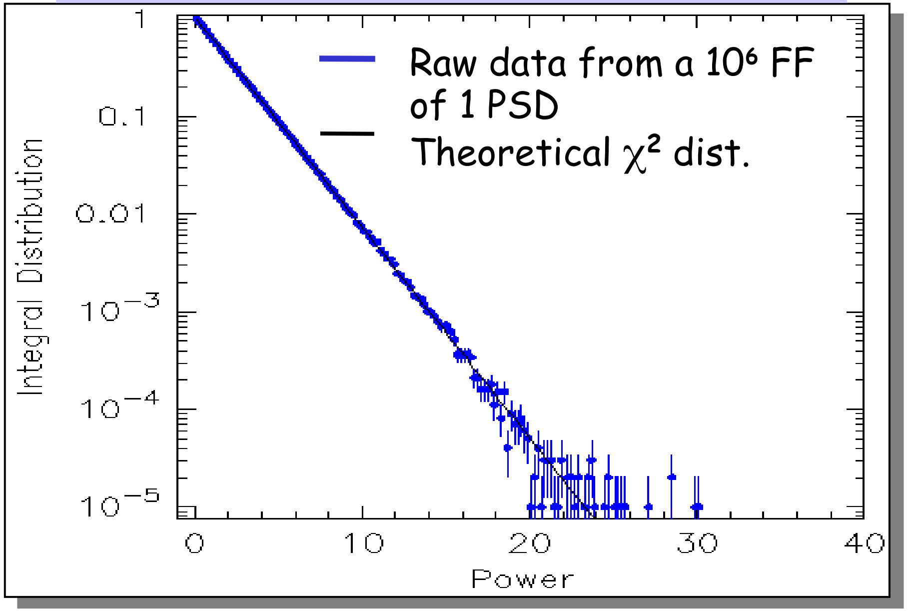
However, for $\nu=2$ it reduces to

$$Q(\chi^2|2) = e^{-\frac{P}{2}}$$

Correspondingly, the signal detection process results in defining a P_{thre}, such that the probability of having $P_{j,noise}$ > P_{thres} is small enough (according to the χ^2 probability distribution)

$$\text{Prob}(P_{j,noise} > P_{thres}) = e^{-\frac{P_{thres}}{2}}$$

Ex: a power of 44 (in a white noise PSD) has a probability of $e^{-44/2}=3\times10^{-10}$ of being noise.



THE SEARCH THRESHOLD AND N_{TRIALS}

- We define *a priori* a confidence level (1-ε) of the search (typically 3.5σ), corresponding to a power $P=P_{thres}$ which has a small probability ε to be exceeded by a noise power

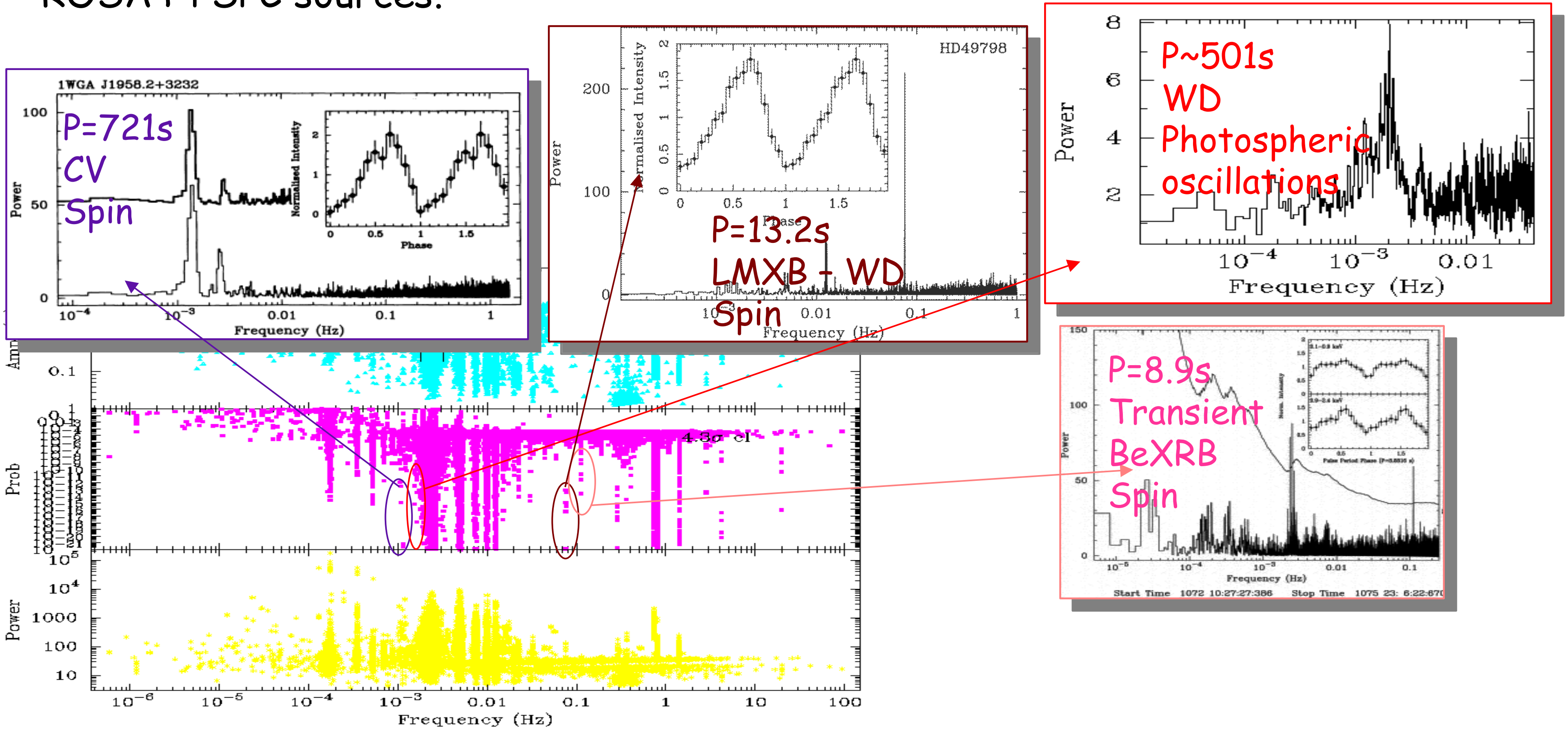
- A crucial consideration, occasionally overlooked, is the number of trial powers N_{trial} over which the search has been carried out
  - o N_{trial} = to the powers in the PSD if all the Fourier frequency are considered;
  - o N_{trial} < than the powers in the PSD if a smaller range of frequencies has been considered;
  - o N_{trial} moltiplied by the number of PSD considered in the project

$$\frac{\varepsilon}{N_{trial} N_{PSD}} = Q(P_{thres}|2) = e^{-\frac{P_{thres}}{2}}$$

Ex: the previous probability of $3x10^{-10}$ has to be multiplied by 1.048.000 trial frequencies and 1 PSD
$Prob*N_{trial}= 3x10^{-10}*1.048.000$
$=3x10^{-4}$
Still significant!!

LARGE DATASETS

FFT application to large databses of light curves is routinely used. Below is the case of ~30000 light curves of serendipitous ROSAT PSPC sources.



LARGE DATASETS: N_{TRIAL} !!

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$Prob*N_{trial}= 3x10^{-10}*1.048.000=3x10^{-4}$

Still significant!!

Ex: If you have searched on 10000 light curves you should consider the whole dataset.

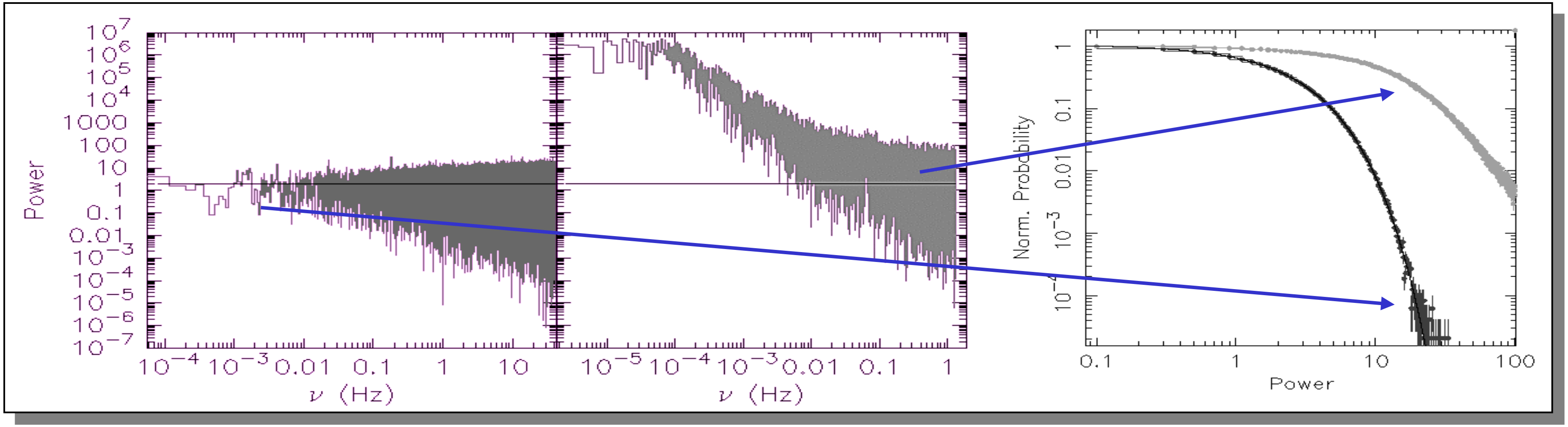
$N_{trial}=N_{freq}*N_{LCs}$

$Prob*N_{trial}= 3x10^{-10}*1.048.000*10000 = 3x10^{-2}$

Not significant!!!!

INTRINSIC NON-POISSONIAN NOISE

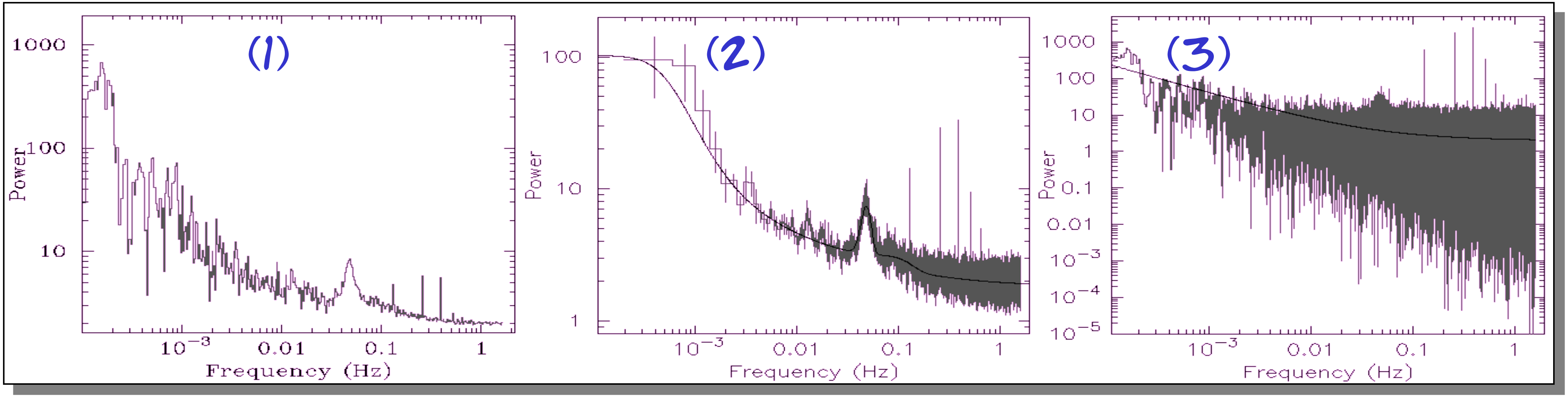
Many different classes of X—ray sources show aperiodic variability which translates into non-Poissonian noises (red-noise, blue-noise, low frequency noise, shot noise, etc.).



Implication: powers are not distributed anymore like a χ^2 with n d.o.f. → **no statistical tools to assess the significance of power peaks.**

INTRINSIC NON-POISSONIAN NOISE-2

Three different but similar approaches: (1) Rebin of the original PSD, (2) Average of more PSD by dividing the light curve into intervals, (3) Evaluation of the PSD continuum through smoothing. The common idea is to use the information of a sufficiently high number of powers such that it is possible to rely upon a known distribution of the new powers and/or continuum level (χ^2 or Gaussian or combination).



Note that the the processes above modify the PSD Fourier resolution (1/T), but leave unchanged the maximum sampled ν (1/2Δt)

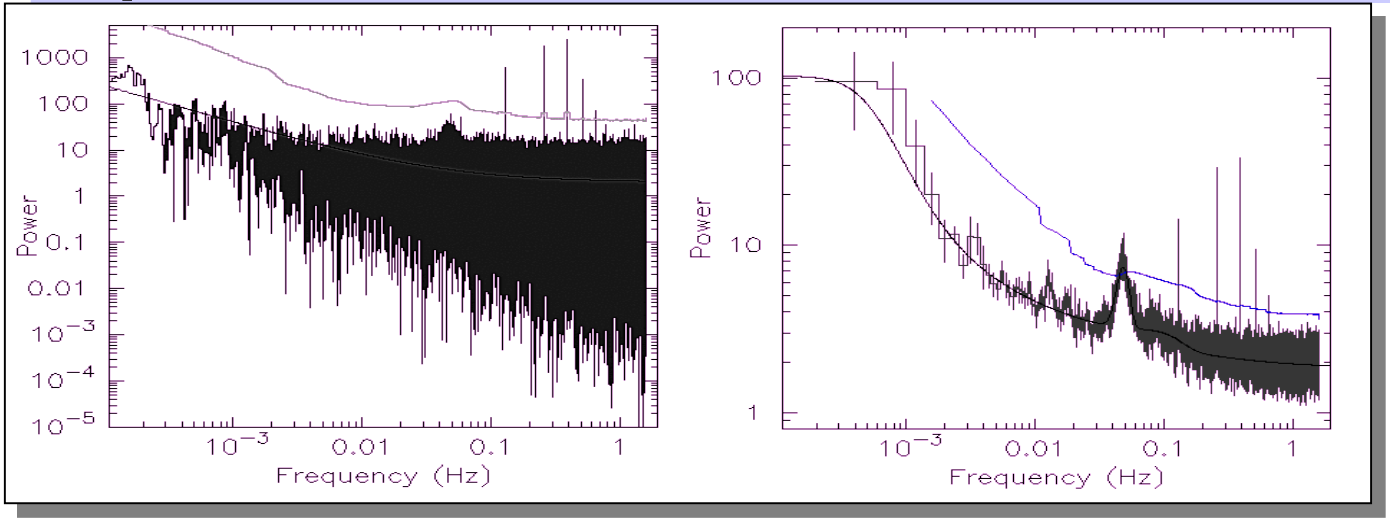
INTRINSIC NON-POISSONIAN NOISE-3

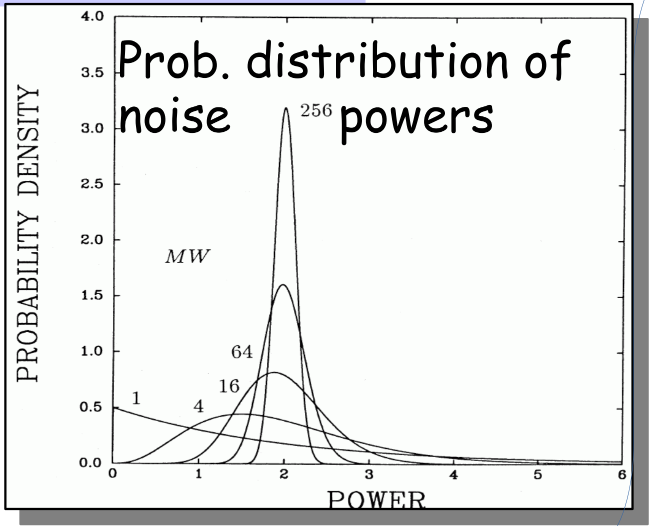
If M spectra are considered and/or W contiguous frequencies are averaged, the new variable (in cases 1 and 2) will be distributed like a rescaled χ^2/MW with 2MW d.o.f. In practice, everything is rescaled in order to have $E[\chi^2|2MW] = 2MW/MW = 2$.

Therefore $\sigma[\chi^2|2MW] = sqrt(2MW)/MW$ → less noisy !!

Note that for MW>30÷40 the χ^2 → Gaussian

Implications: the noise scatter is largely reduced and faint and





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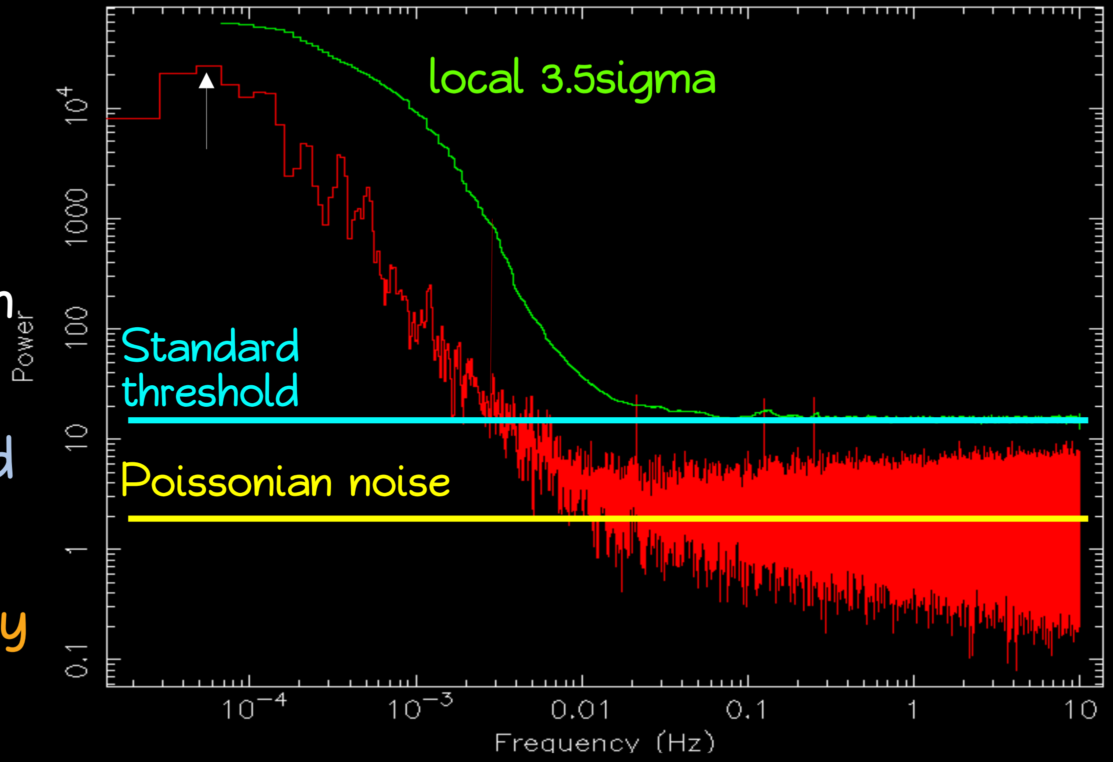


CATS@BAR

Chandra Acis Timing Survey @ Brera And Rome AOs:
an ad hoc pipeline (C-shell/Fortran/C++) developed and applied in an automatic fashion to the ACIS I/S archive (imaging obs. only).

First run in June 2012. Updated every few months. Living project

So far:
~14,000 archival pointings,
~100,000 timeseries (>150 photons) searched for signals (~550000 detections),
~260,000 peaks (in the majority spurious)

~260,000 → **~100**
after filtering for instrumental signals (DITHER_REGION ciao task)
and after removing real signals from known pulsators

The catalog:
50 new pulsators

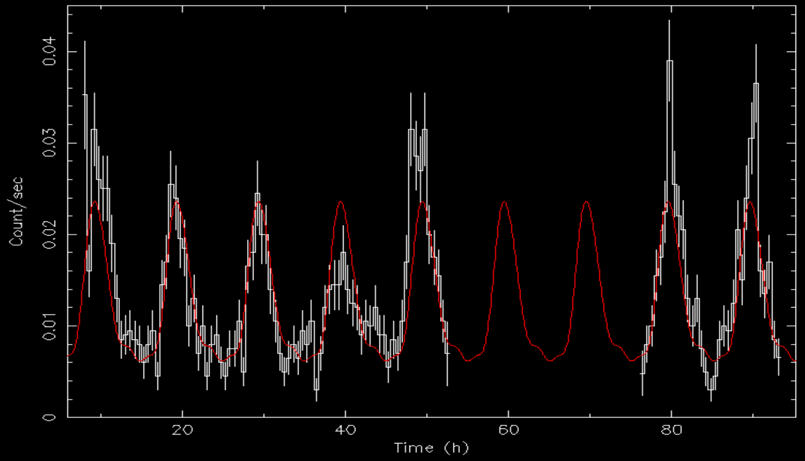
Zoology:

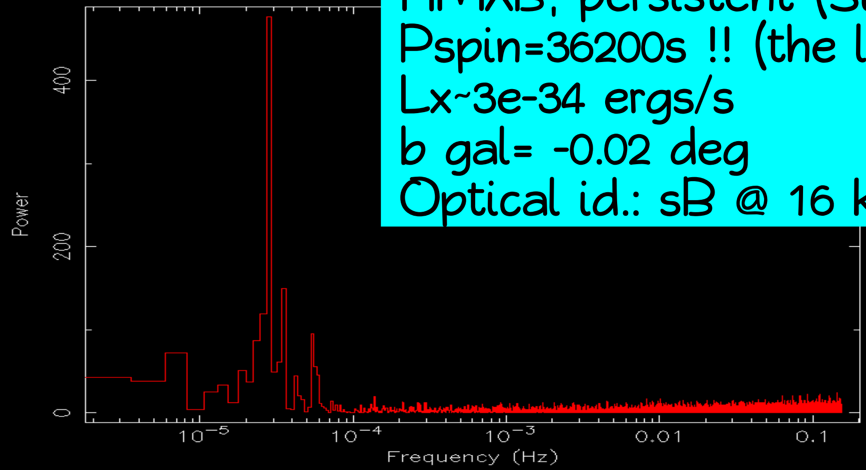
3 transient NSs in the SMC
3 persitent accreting NS (Galactic plane)
3 CVs in globular clusters (NGC6541, 47Tuc,NGC5946)
1 CV in an open cluster (NGC869)
4 in external Galaxies (Circinus, NGC300, NGC4490)
10 CVs (Polars and IPs)
> 35 pulsators of unknown nature

[~30 signals confirmed by means of XMM, Swift and Chandra data]

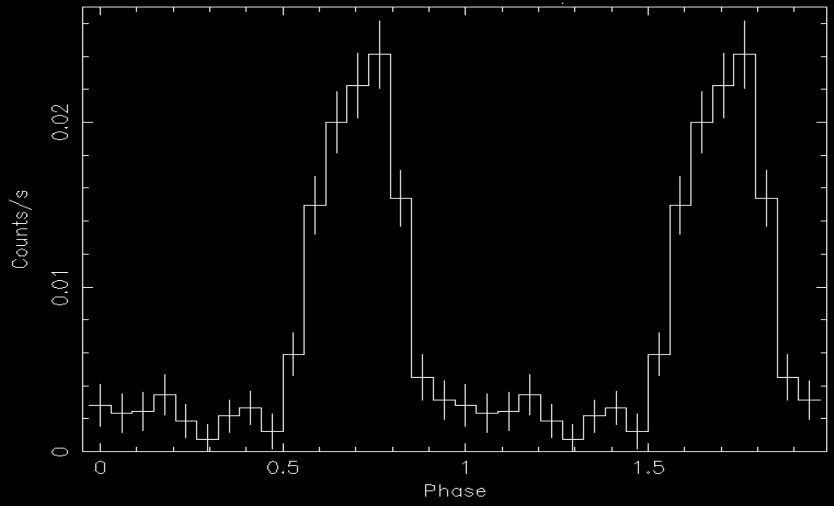
Name	R.A. (hh mm ss.s)	Dec. (° ′ ″)	b (°)	Period[a] (s)	Flag[b]	Flux[c] ($erg\ cm^{-2}\ s^{-1}$)	XMM/Chandra[d]
CXO J002415.9–720436	00 24 15.9	–72 04 36.4	–44.9	8 649(1)	***	0.5–0.8	C(16)
CXOU J004814.1–731003	00 48 14.1	–73 10 03.7	–44.0	50.669(1)	***	4–45	C(1)/X(2)
CXOU J005048.0–731817	00 50 48.0	–73 18 18.2	–43.8	292.784(5)	***	5–22	C(6)
CXOU J005440.5–374320	00 54 40.5	–37 43 20.2	–79.4	21 180(485)	*	0.9	C(1)
CXOU J005758.4–722229	00 57 58.4	–72 22 29.5	–44.7	7.918 07(5)	***	4–20	C(2)/X(1)
CXO J021950.4+570518	02 19 50.5	+57 05 18.2	–3.7	4 782(5)	***	0.3–0.6	C(4)/X(1)
CXOU J055930.5–523833	05 59 30.5	–52 38 33.5	–28.9	21 668(200)	*	0.2	C(3)
CXOU J063805.3–801854	06 38 05.3	–80 18 54.1	–27.3	13 151(330)	**	4	C(1)
CXOU J091539.0–495312	09 15 39.0	–49 53 12.9	–49.9	55.97(1)	*	1.2	C(1)
CXOU J111133.7–603723	11 11 33.7	–60 37 23.0	-60.6	9 766.8(5)	***	1.2	C(7)/X(1)
CXOU J112347.4–591834	11 23 47.4	–59 18 34.2	–59.3	1 525.92(6)	***	2.8–5.5	C(7)/X(2)
CXO J123030.3+413853	12 30 30.3	+41 38 53.1	+74.9	23 148(396)	***	0.2–1	C(5)/X(2)
CXOU J123823.4–682207	12 38 23.4	–68 22 07.0	–5.5	5 065(40)	*	2.1	C(1)
CXOU J141332.9–651756	14 13 32.9	–65 17 56.5	–3.8	6 377(4)	***	0.4–0.6	C(2)/X(1)
CXO J141430.1–651621	14 14 30.1	–65 16 23.3	–3.8	6 120(2)	***	1.1–1.4	C(4)/X(1)
				64 200(500)	**		
CXOU J153539.8–503501	15 35 39.8	–50 35 01.4	–4.2	12 334(567)	**	9	C(1)
CXO J161437.8–222723	16 14 37.9	–22 27 23.7	+20.2	5 671(137)	**	0.5	C(1)
CXOU J163855.1–470145	16 38 55.1	–47 01 45.8	–0.1	5 684(40)	***	0.9	C(2)/X(1)
CXO J170113.3+640757	17 01 13.3	+64 07 58.5	+36.2	5 674(1)	***	0.3	C(9)/X(1)
CXO J170214.7–295933	17 02 14.7	–29 59 33.6	+7.2	11 467(500)	***	0.2	C(6)
CXO J170227.3–484507	17 02 27.4	–48 45 07.1	–4.3	3 080(40)	***	0.7–1.4	C(2)/X(2)
CXO J171004.6–321205	17 10 04.6	–32 12 05.5	+4.5	4 990(15)	***	0.9–2.8	C(2)
CXOU J173037.7–212633	17 30 37.7	–21 26 33.0	+4.6	5 059.40(7)	***	0.3	C(9)
CXOU J173113.7–212552	17 31 13.7	–21 25 52.1	+6.7	15 532(64)	*	11	C(2)
CXO J173359.0–220614	17 33 59.1	–22 06 14.1	+5.8	4 745(23)	*	0.4	C(1)
CXOU J174042.3–534029	17 40 42.3	–53 40 28.9	–12.0	21 134(33)	***	5.7	C(5)
CXO J174245.1–293455	17 42 45.1	–29 34 55.4	+0.2	12 220(1164)	*	0.5	C(2)
CXO J174638.0–285325	17 46 38.0	–28 53 25.9	–0.2	21 887(538)	***	2.0	C(4)/X(2)
CXOU J174811.0–244930	17 48 10.1	–24 49 03.0	+1.6	5 017(19)	***	0.4	C(2)
CXOU J180839.8–274131	18 08 39.8	–27 41 31.6	–9.9	854(14)	*	27	C(1)
CXO J180900.0–435039	18 09 00.1	–43 50 40.0	–11.4	5 842(115)	*	1.6	C(1)
CXOU J181516.4–270851	18 15 16.4	–27 08 51.6	–4.8	472(1)	**	4.5	C(2)
CXOU J181924.1–170607	18 19 24.1	–17 06 07.2	–0.9	407.8(1)	***	8.5–46	C(1)/X(3)
CXO J184441.7–030549	18 44 41.7	–03 05 49.4	+0.1	6 366(236)	**	0.4-11	C(3)/X(3)
CXOU J185415.8–085641	18 54 15.8	–08 56 41.2	–4.7	5 790(208)	*	0.6	C(1)
CXOU J191043.7+091629	19 10 43.7	+09 16 29.2	–0.02	36 204(109)	**	4–24	C(2)/X(1)
CXO J193437.8+302524	19 34 37.8	+30 25 24.4	+5.0	5 906(200)	***	1.8	C(1)/X(1)
CXOU J204734.8+300105	20 47 34.8	+30 01 05.2	–8.4	6 097(82)	***	9–21	C(1)/X(1)
CXOU J215447.8+623155	21 54 47.8	+62 31 55.0	+6.3	9 933(10)	***	1.6	C(4)
CXOU J215544.5+380116	21 55 44.5	+38 01 16.3	–13.0	14 090(43)	**	0.3	C(2)
CXOU J225355.1+624336	22 53 55.1	+62 43 36.8	+2.9	46.673 66(4)	***	20–50	C(5)/X(1)

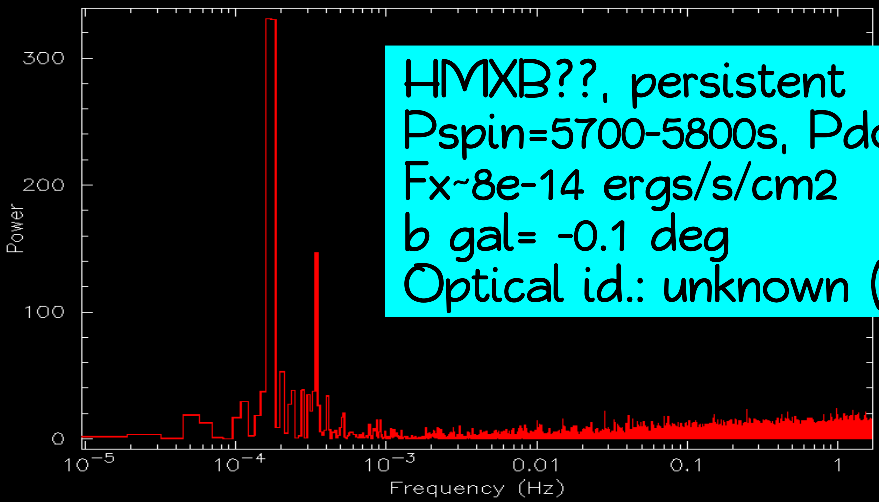
The NS sample





AX J1910.7+0917
HMXB, persistent (Sidoli+17)
Pspin=36200s !! (the longest ever)
Lx~3e-34 ergs/s
b gal= -0.02 deg
Optical id.: sB @ 16 kpc





HMXB??, persistent
Pspin=5700-5800s, Pdot=+25(8)s/yr
Fx~8e-14 ergs/s/cm2
b gal= -0.1 deg
Optical id.: unknown (IR bright obj.)

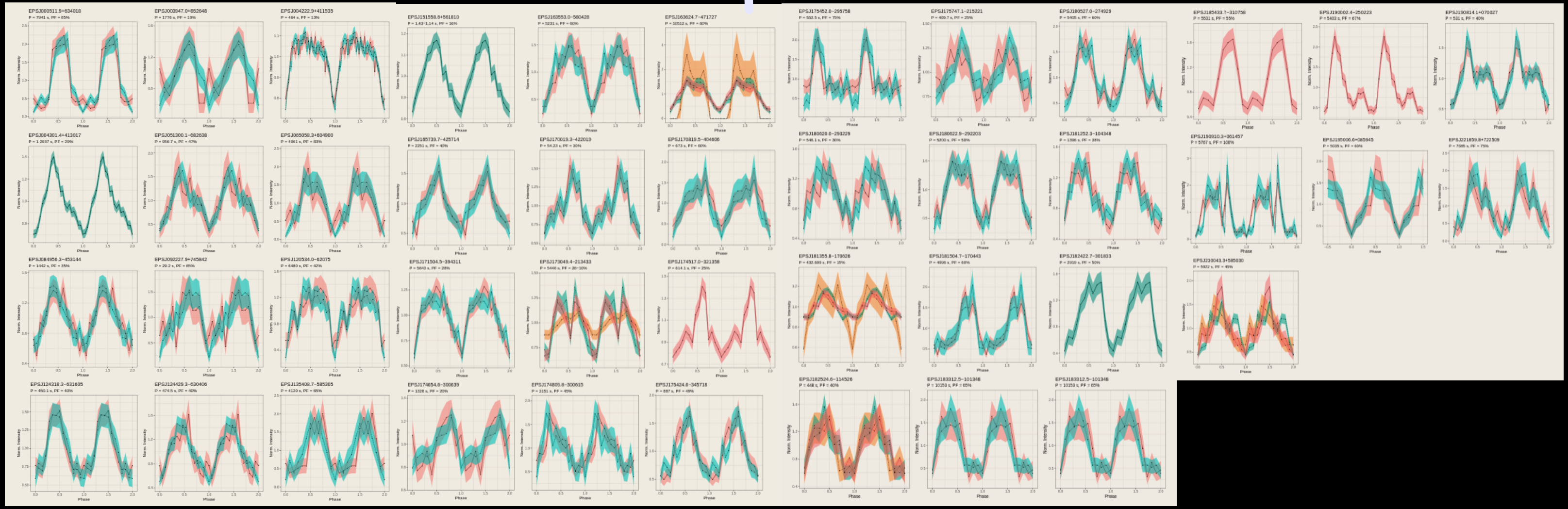
XMM blind search for pulsations

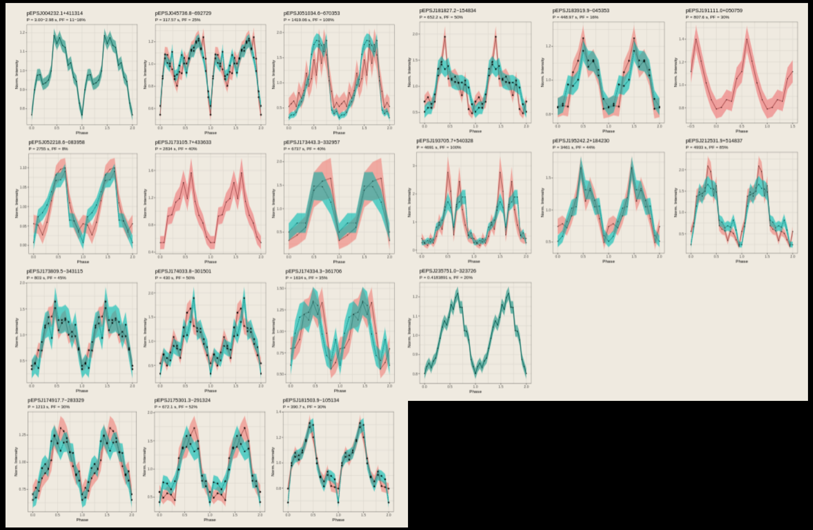
EXploring the Transient and variable x-ray Sky .
Focused on the time variability of sources in the EPIC 3XMM catalog (~500,000, ~1.5M detections).

EXTraS WP3 (periodicity search) in numbers:

- 15 years of public data
- >10,000 datasets
- >6,000,000 times series (TSs)
- ~300,000 TSs with >50 photons searched for signals
- >10 milions PSDs generated (different searching modes)
- ~150,000 peaks
- 60 new X-ray pulsators (still counting)

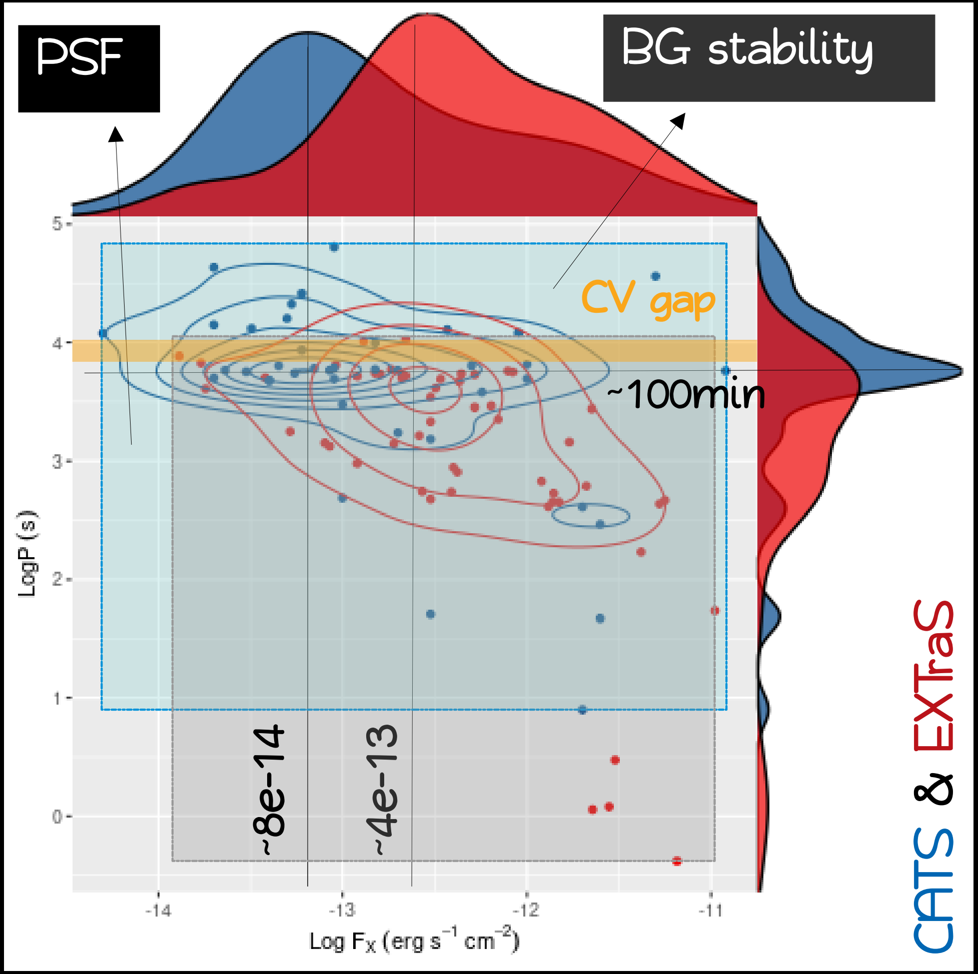
The EXTraS new pulsators





Post-EXTraS new pulsators (pEXTraS)
still counting
(latest update Dec 2020)

Chandra vs XMM = CATS@BAR vs EXTraS



Differences in peak flux and period intervals, but SAME peak period !!

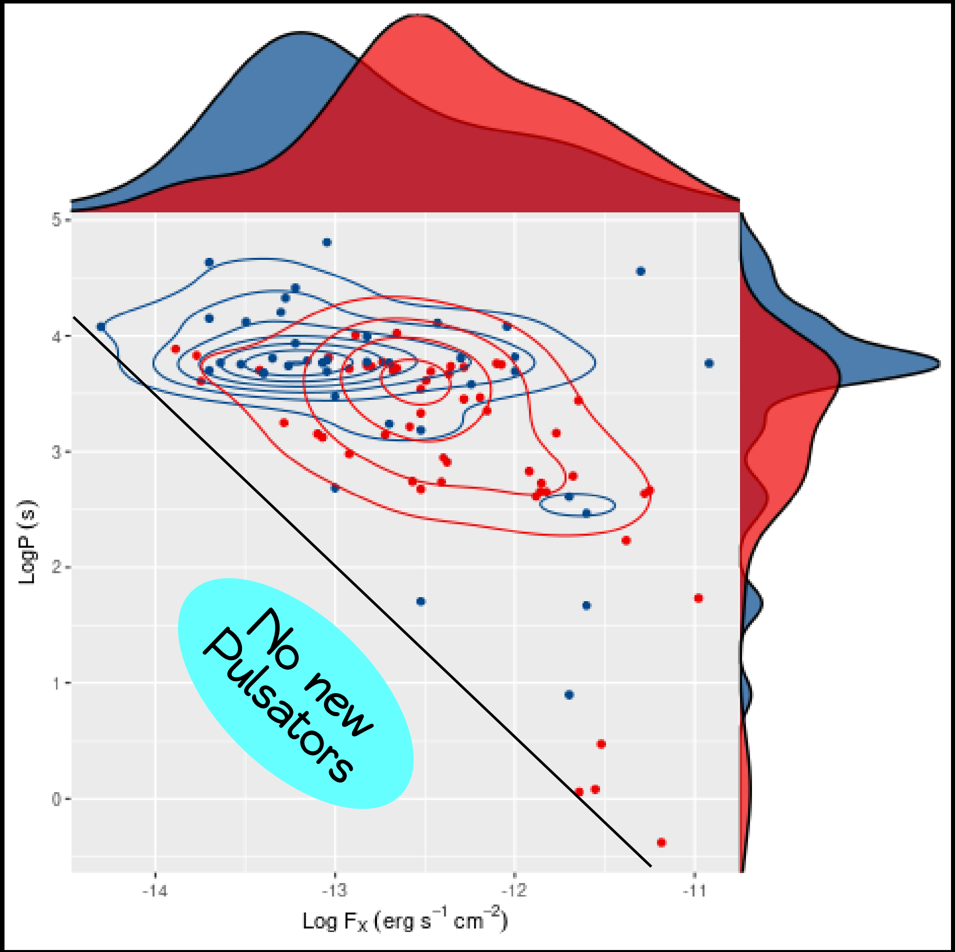
Sampled flux/period ranges dominated by different PSFs, background stability, sampling time, compact object population.

Missed pulsators?

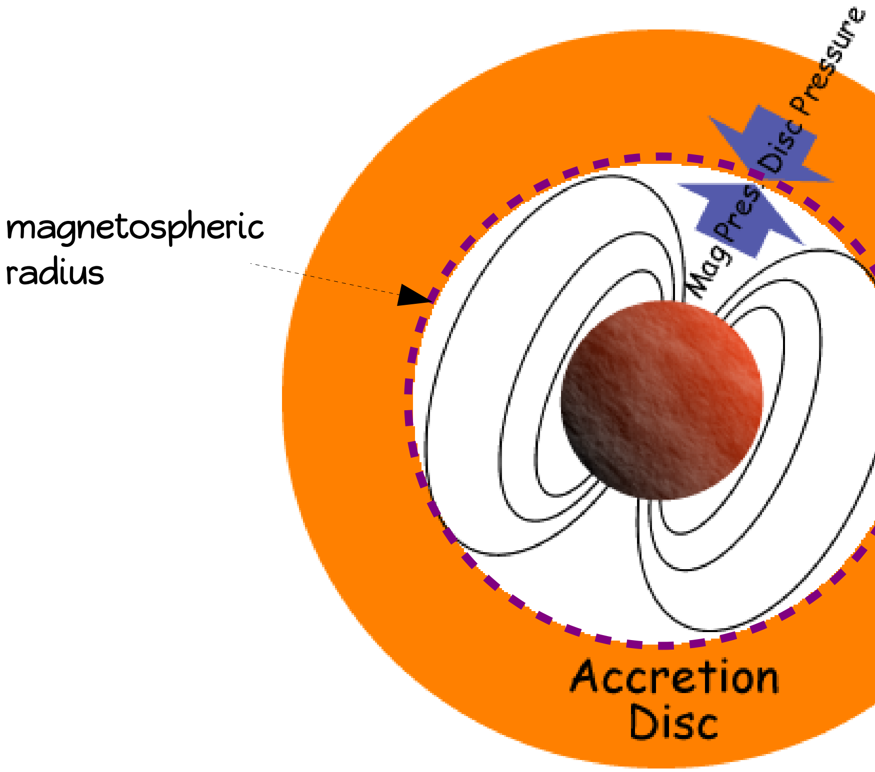
No low-flux short-period new pulsators !

Likely related to magnetic gating and propeller effect (magnetic NSs) => high Mdot needed to have accretion ($r_m < r_{co}$) for short P

Warnings:
1) No known distances (Lx)
2) overabundance of CVs wrt NSs



Disc - Magnetic Field Interaction



Magnetospheric radius r_m: distance where the magnetic field rules the dynamical properties of the infalling matter. $r_m \propto B^{4/7} \dot{M}^{-2/7}$

Corotation radius r_{co}: distance where the Keplerian velocity of matter in the disc is equal to that of the star at the same distance. $r_{co} \propto P^{2/3}$

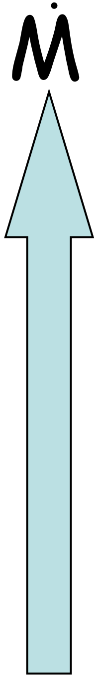
Light cylinder radius r_{LC}: distance where the the velocity of the star (magnetic field lines) exceeds c. $r_{LC} \propto P$

Disc Pressure proportional to $\dot{M}$

Magnetic Pressure Proportional to B^2

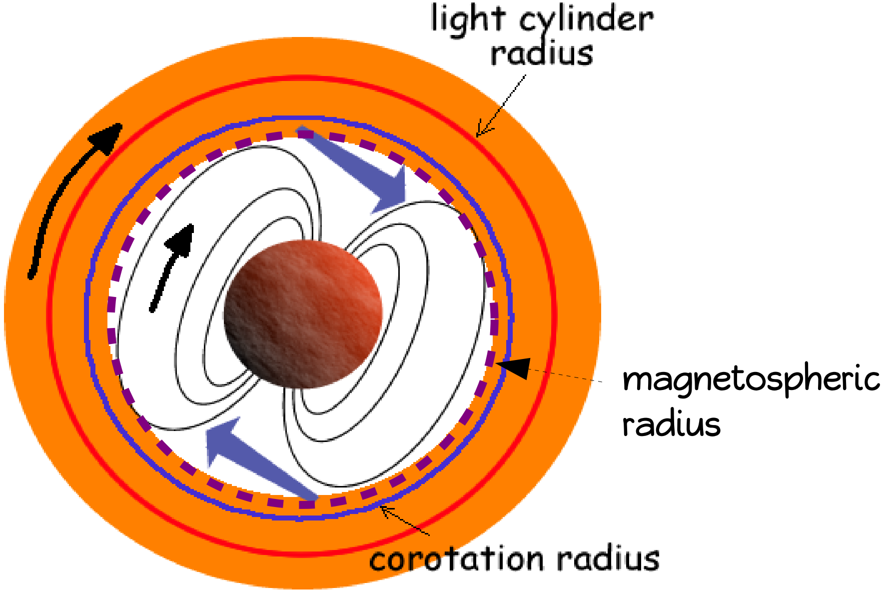
Accretion regimes: 1

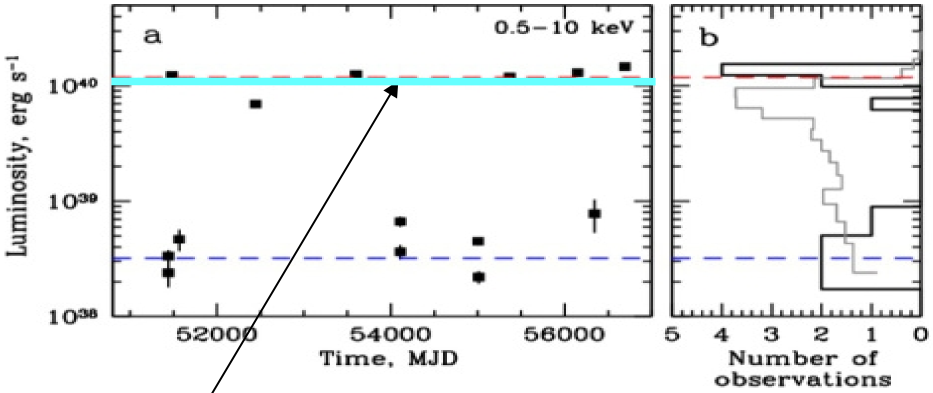
(Illarionov & Sunyaev 1975)



Accretion regime

R(m) < R(cor)



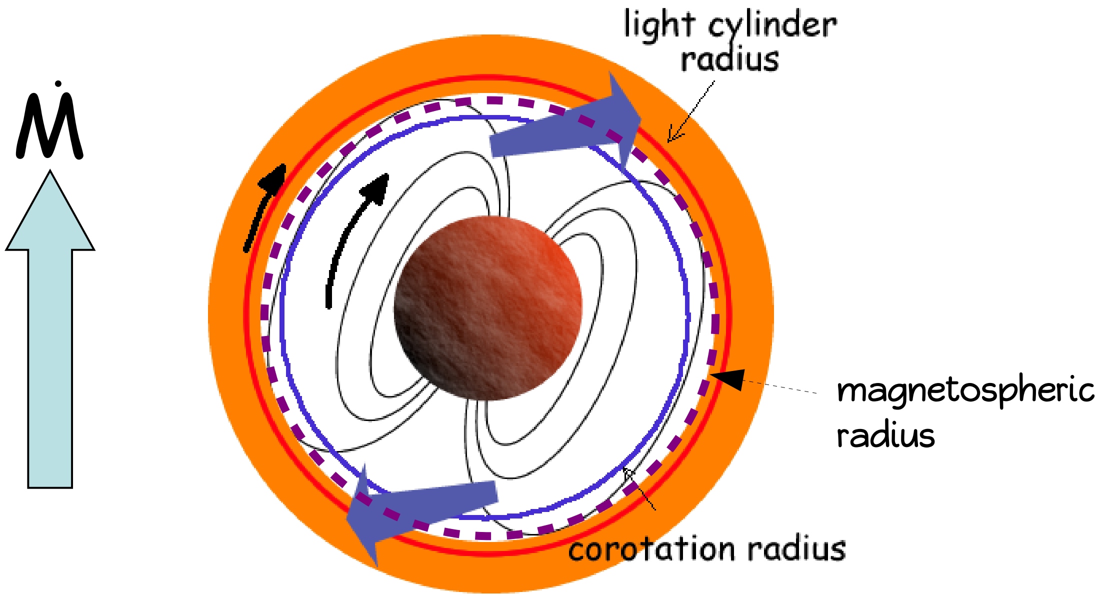


- accretion onto NS surface (magnetic poles)
- energy release L=G M Mdot/R*

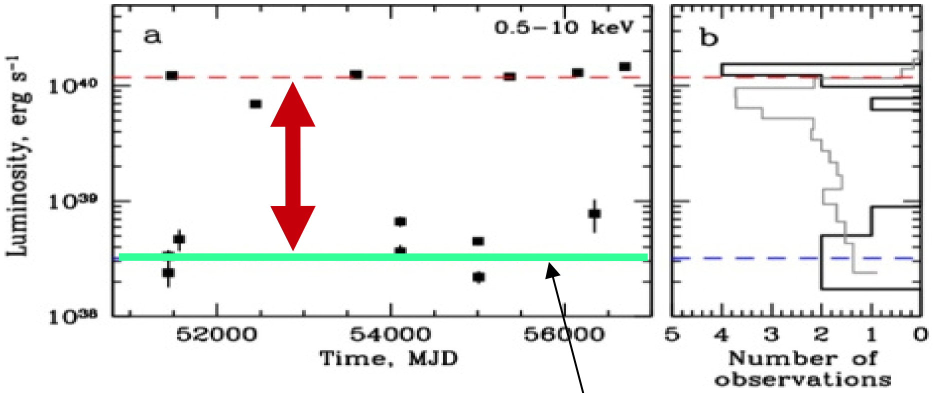
Accretion regimes: 2

<u>Propeller regime</u>

R(cor) < R(m) < R(lc)



Size of the gap depends on
L(NS*)/L(m) prop $P^{2/3}$
Long P → large jump
Propeller onset prop B^2 $P^{-7/2}$



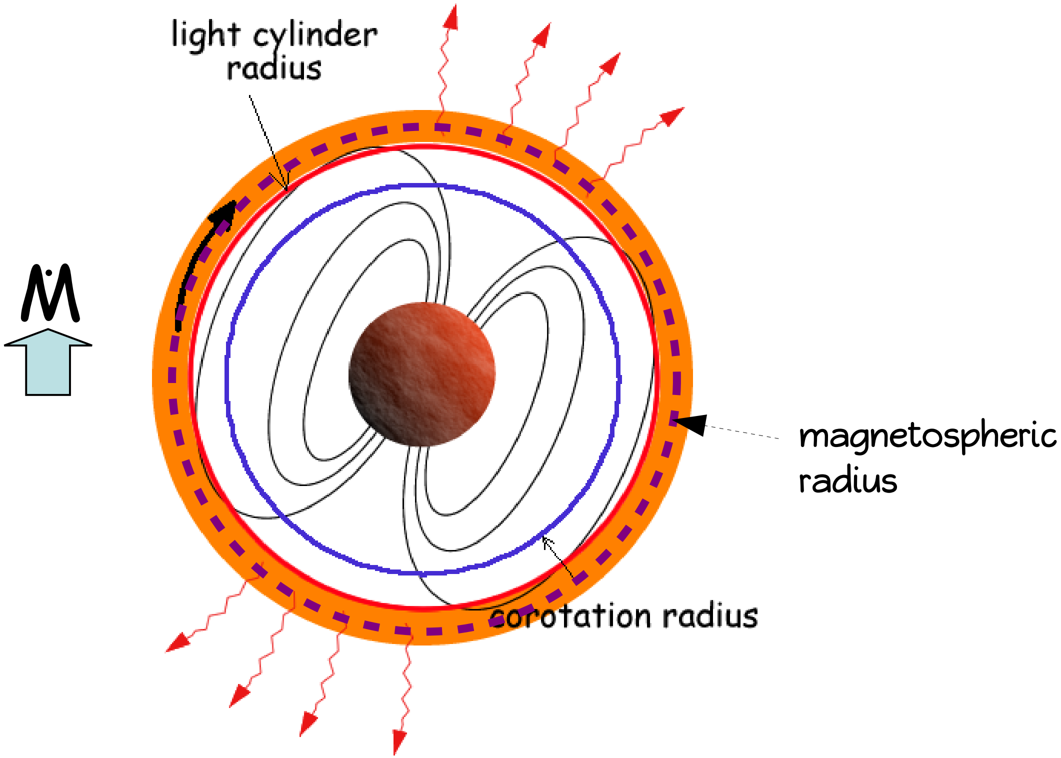
- centrifugal barrier closes (B-field drag stronger than gravity)
- matter accumulates or is ejected from R(m)

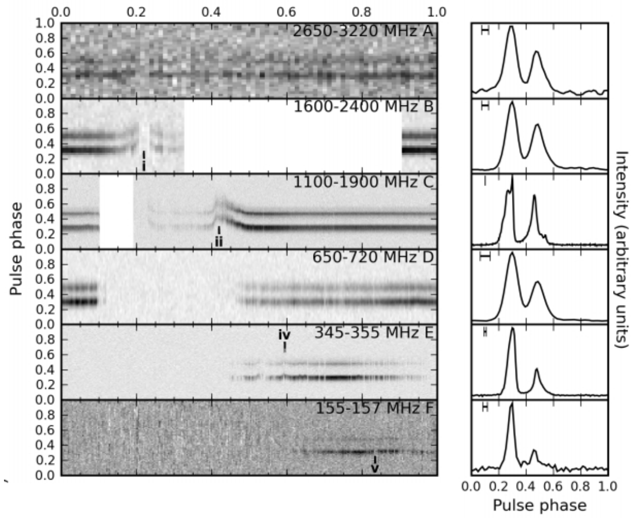
accretion onto R(m): L=G M Mdot/R(m)   R(m) > R*
lower gravitational energy released

Accretion regimes: 3

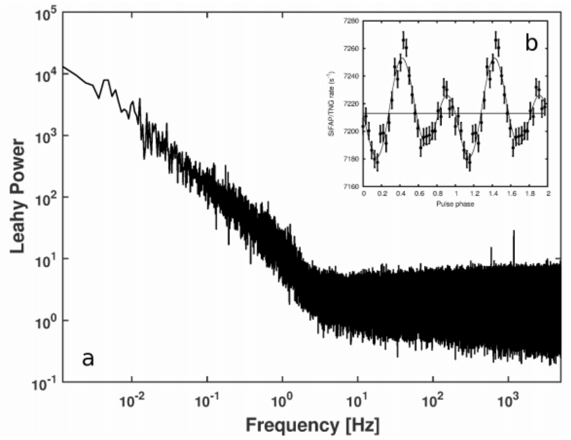
Transitional millisecond Pulsars

Radio Pulsar regime
$R(m) > R(lc)$





(Archibald+ 2010;



Papitto+ 2019)

- no accretion

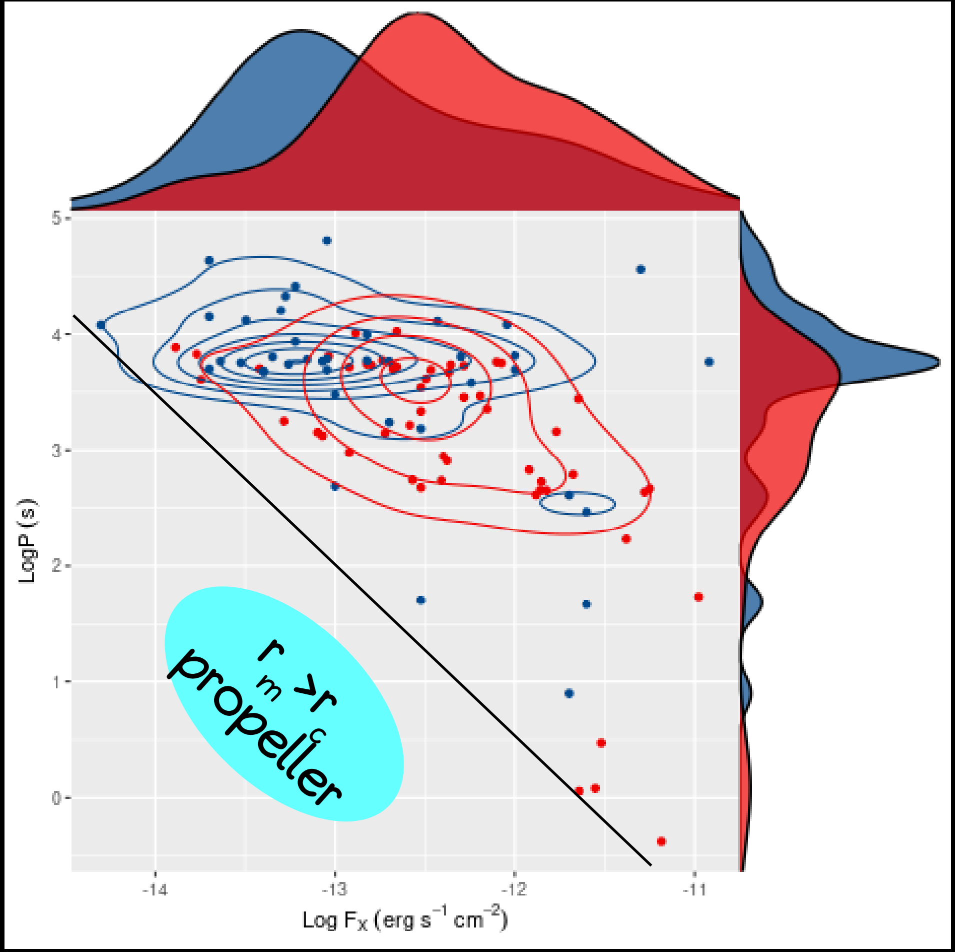
disk matter swept away by pulsar wind and pressure

Missed pulsators?

No low-flux short-period new pulsators !

Likely related to magnetic gating and propeller effect (magnetic NSs) => high Mdot needed to have accretion ($r_m < r_{co}$) for short P

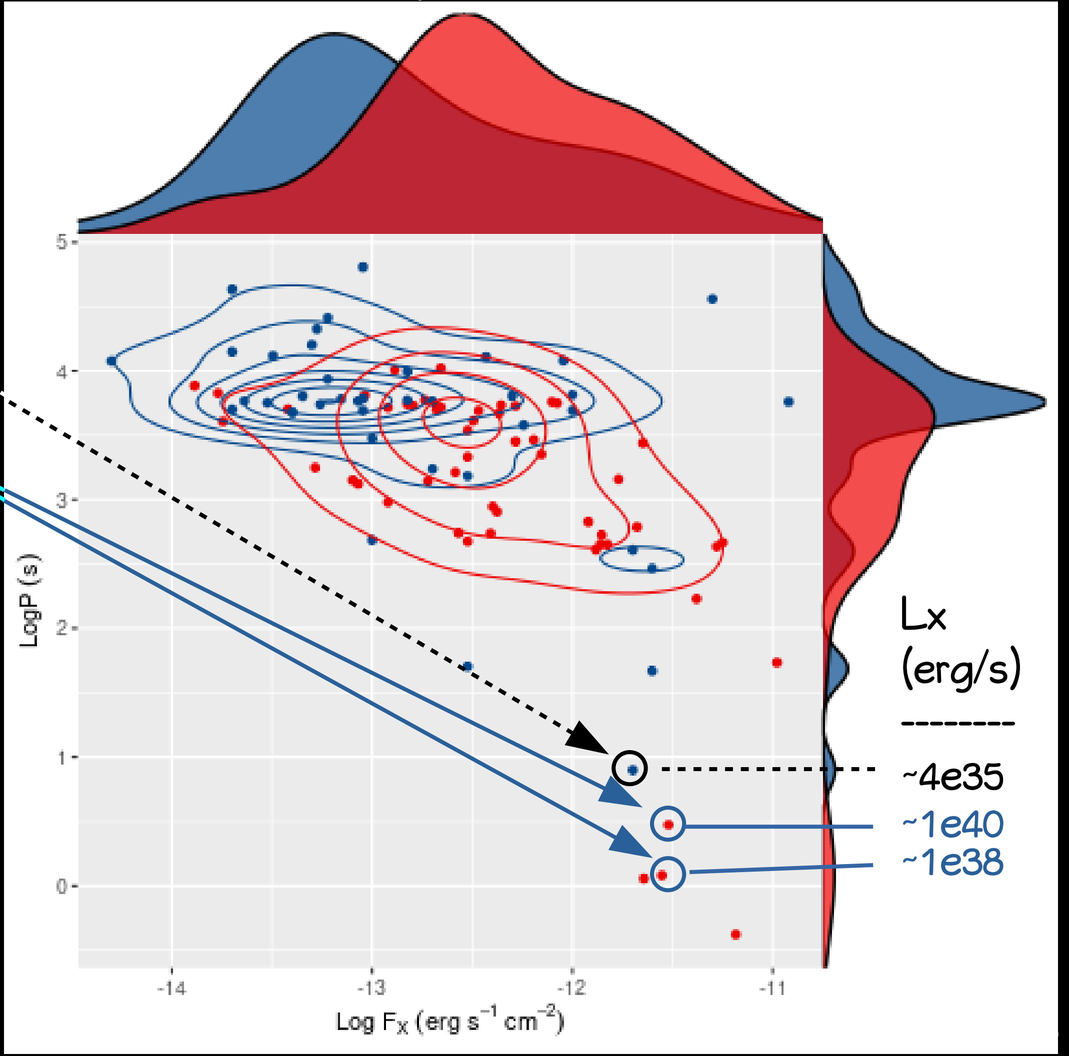
Magnetic gating/propeller ($r_m > r_c$)
Short P need high L to accrete onto NS
Low L systems need long P to accrete



The rise of a new population of pulsars

Below 10s period:

- 1 transient source in the SMC
- 2 pulsars in M31 (the first ever)



INAF ISTITUTO NAZIONALE DI ASTROFISICA

EXTraS: first NS discovered in M31

ESA SPACE SCIENCE

European Space Agency

Our Universe
- About Space Science
- ESA's 'Cosmic Vision'

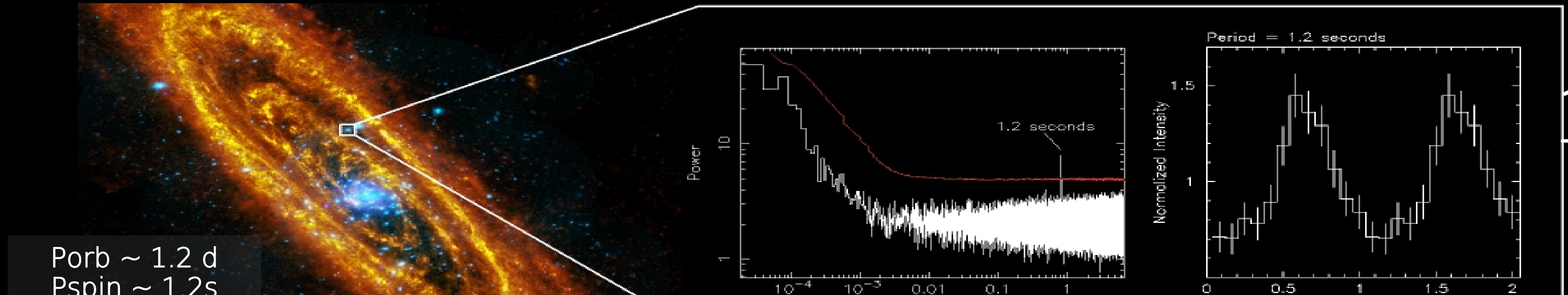
Science missions
- Mission navigator

Target groups

ESA > Our Activities > Space Science

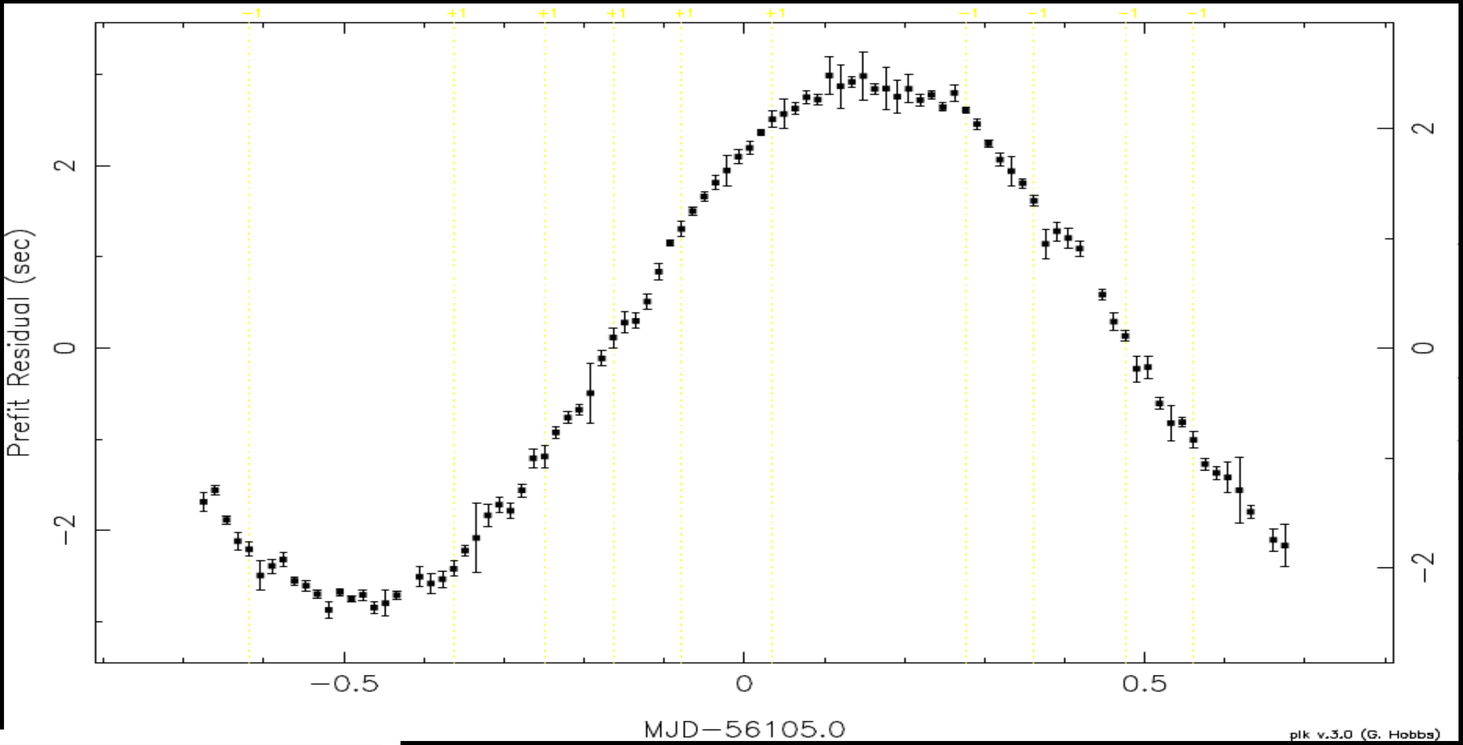
FOUND: ANDROMEDA'S FIRST SPINNING NEUTRON STAR

31 March 2016 Decades of searching in the Milky Way's nearby 'twin' galaxy Andromeda have finally paid off, with the discovery of an elusive breed of stellar corpse, a neutron star, by ESA's XMM-Newton space telescope.



(Esposito+16

… in a 1.2d binary system

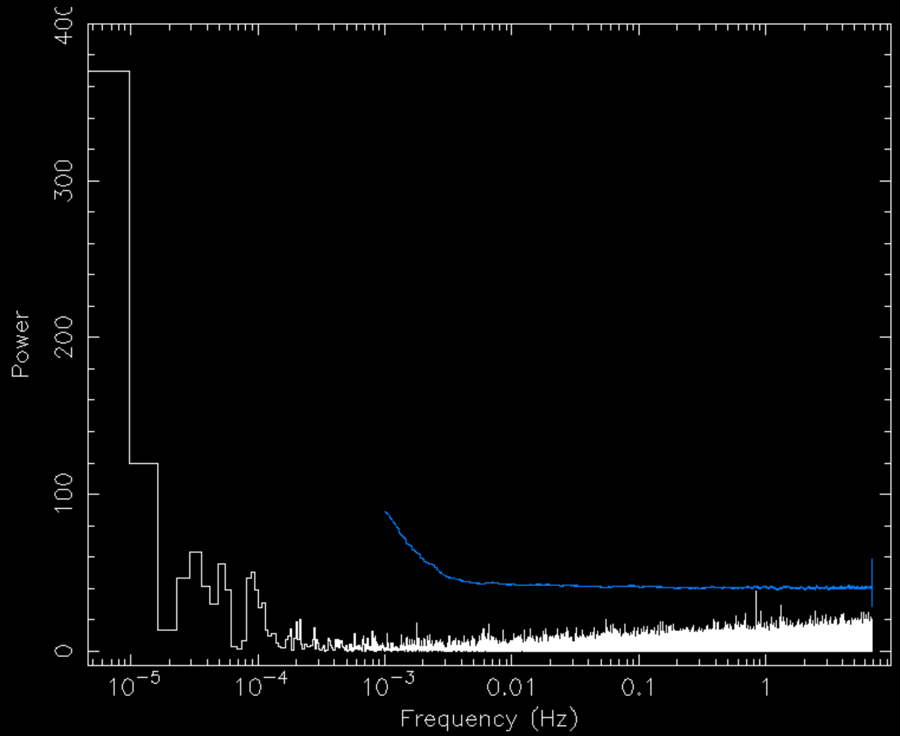


Parameter	Value
Orbital period, $P_{\rm b}$ (d)	$1.27397828 \pm 0.00000071$
Epoch of ascending node, $T_{\rm asc}$ (MJD)	56104.7912 ± 0.0011
Projected semi-axis, $A_{\rm X} \sin i$ (lt-s)	2.884 ± 0.017
Eccentricity, e	0.011 ± 0.009^{a}
Longitude of periastron, ω (°)	276 ± 41
Mass function ($M_{\odot}$)	0.0159 ± 0.0008
Minimum companion mass[b] ($M_{\odot}$)	0.36

[a] Upper limit at the 3σ confidence level: $e < 0.037$.
[b] Value computed for an orbit viewed edge-on, $i = 90°$.

(Esposito et al. 2016,)

Recovering a signal in an orbit

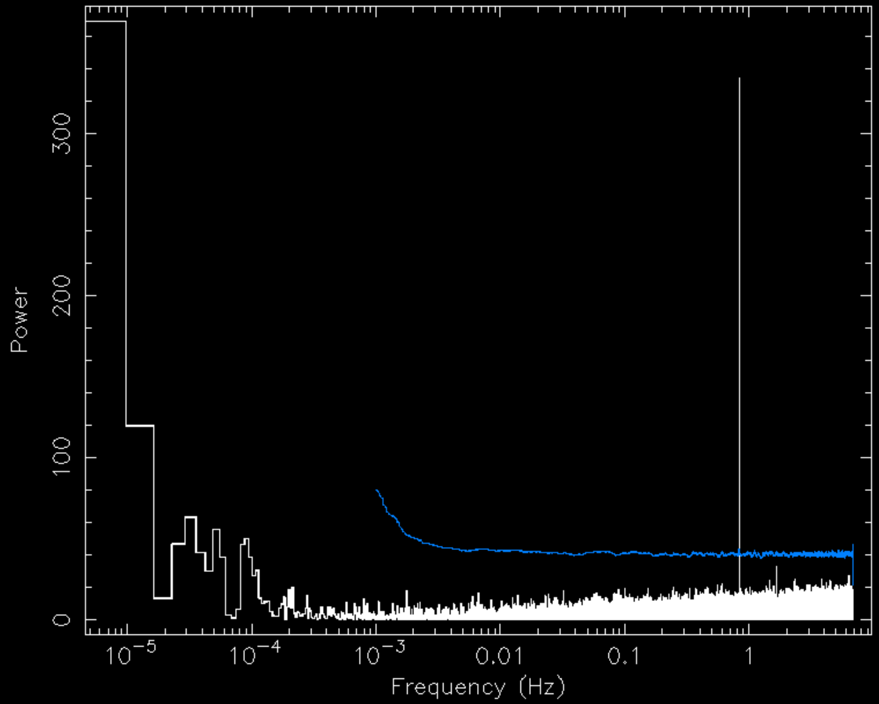


Uncorrected (raw data)

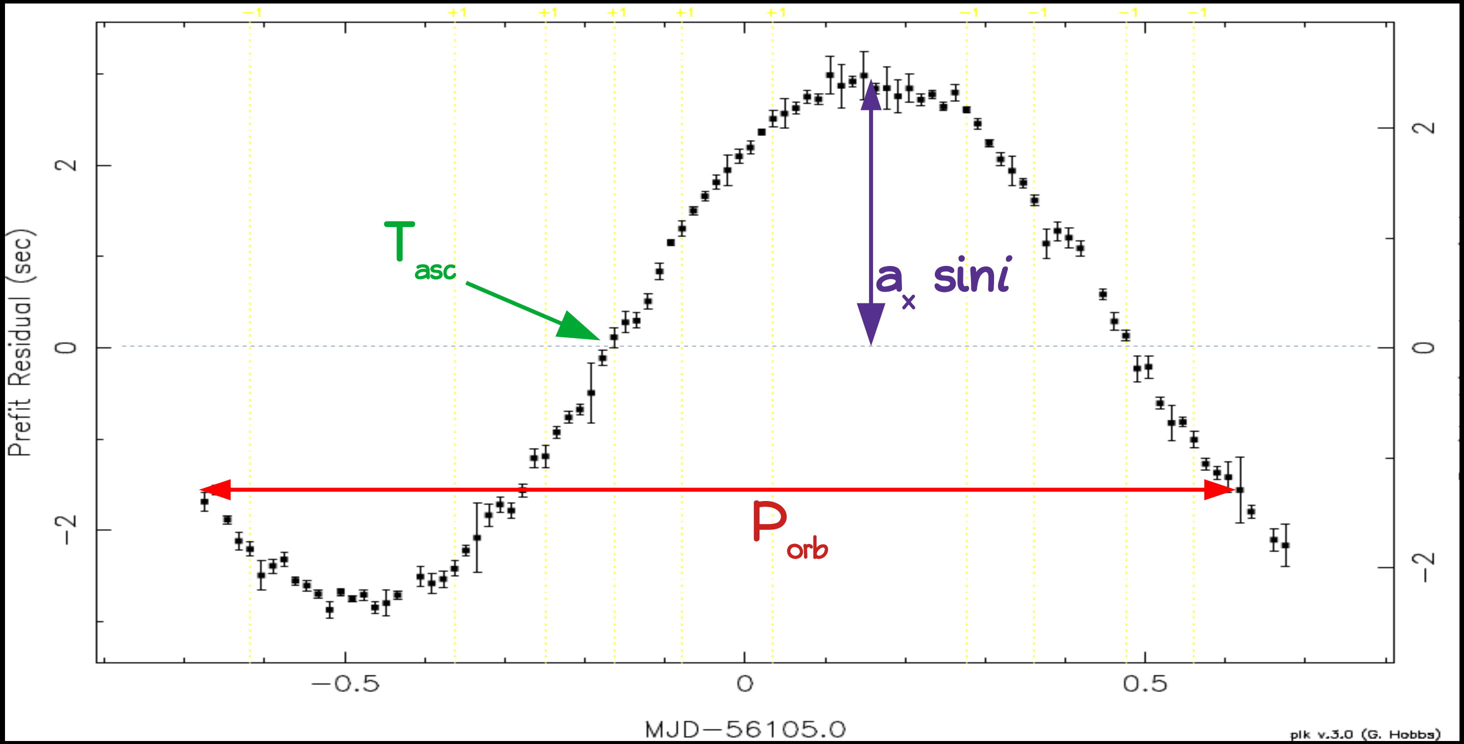
Precorrecting photon times:

$t' = t - a_x \sin i * \sin[(2\pi/P_{orb})*(t-T_{asc})]$

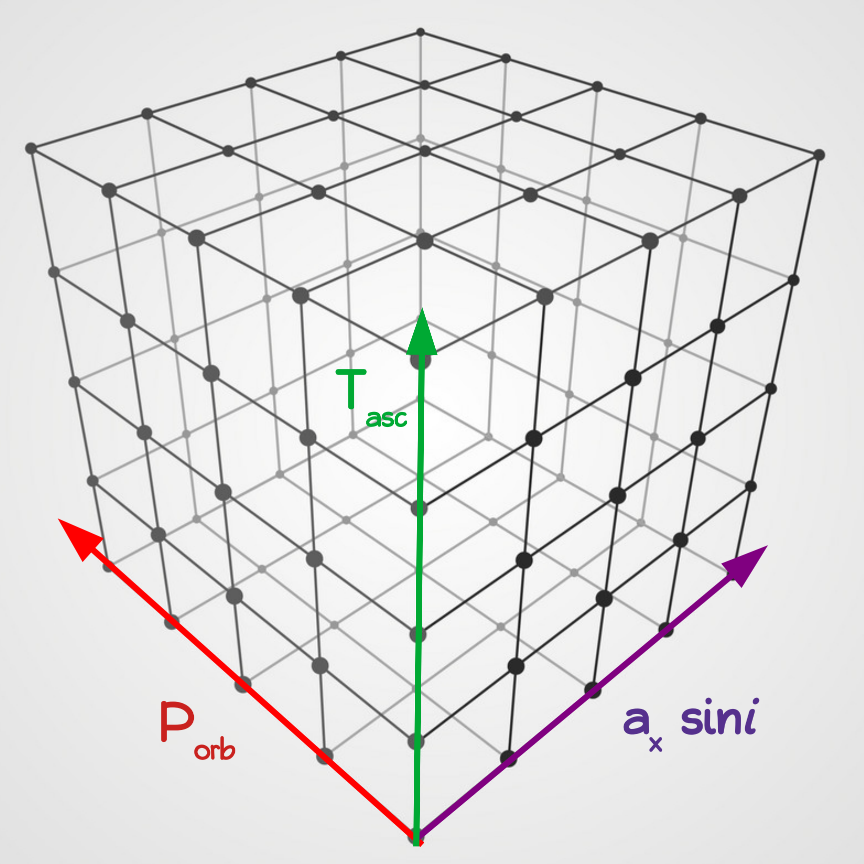
function of: $a_x \sin i$, P_{orb}, T_{asc}



Recovering a signal in an orbit



Recovering a signal in an unknown orbit



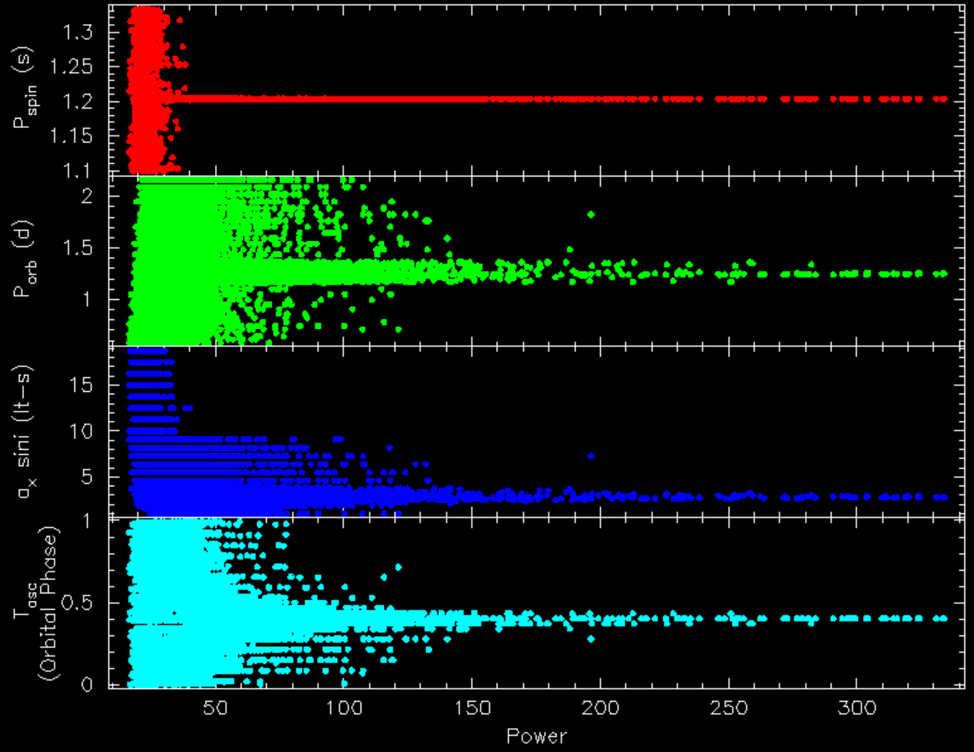
High resolution of the 3 parameters implies a higher chance of sampling the right values

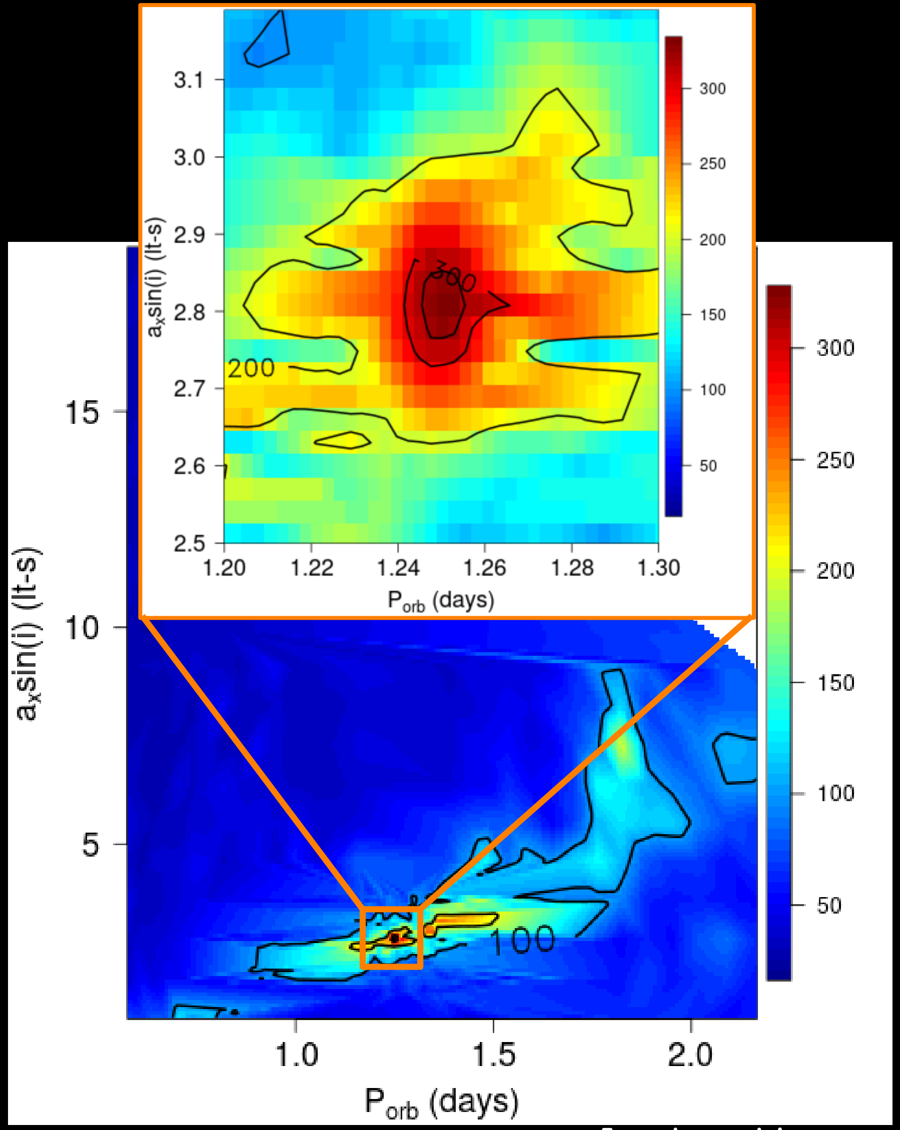
Problem: CPU-consuming

A 100x100x100 grid = 1 million FFTs (~30s)
Human time: 1years for 1 source !!!!!

Ways around:
1) More cores
2) working with RAM (factor of ~10)
3) working on GPU (factor of ~10)
4) HPC (up to a factor of 1000)

Recovering a signal in an unknown orbit





Not yet affordable for a large number (>10^3) of time series

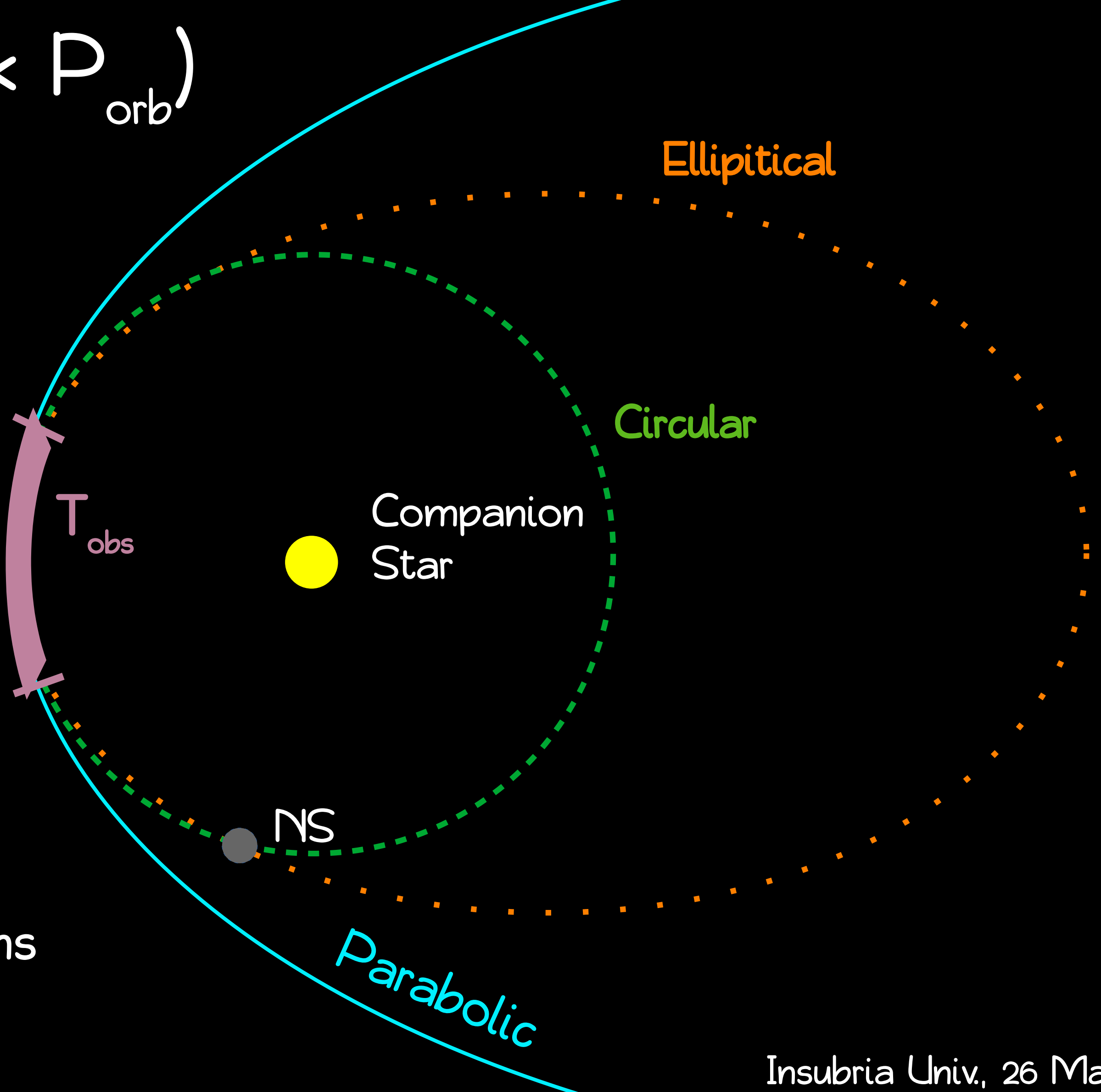
A way around ($T_{obs} << P_{orb}$)

Parabolic approximation of a circular or elliptical orbit

$$t' = t + \frac{1}{2}\frac{\dot{\nu}}{\nu}t^2 = t - \frac{1}{2}\frac{\dot{P}}{P}t^2$$

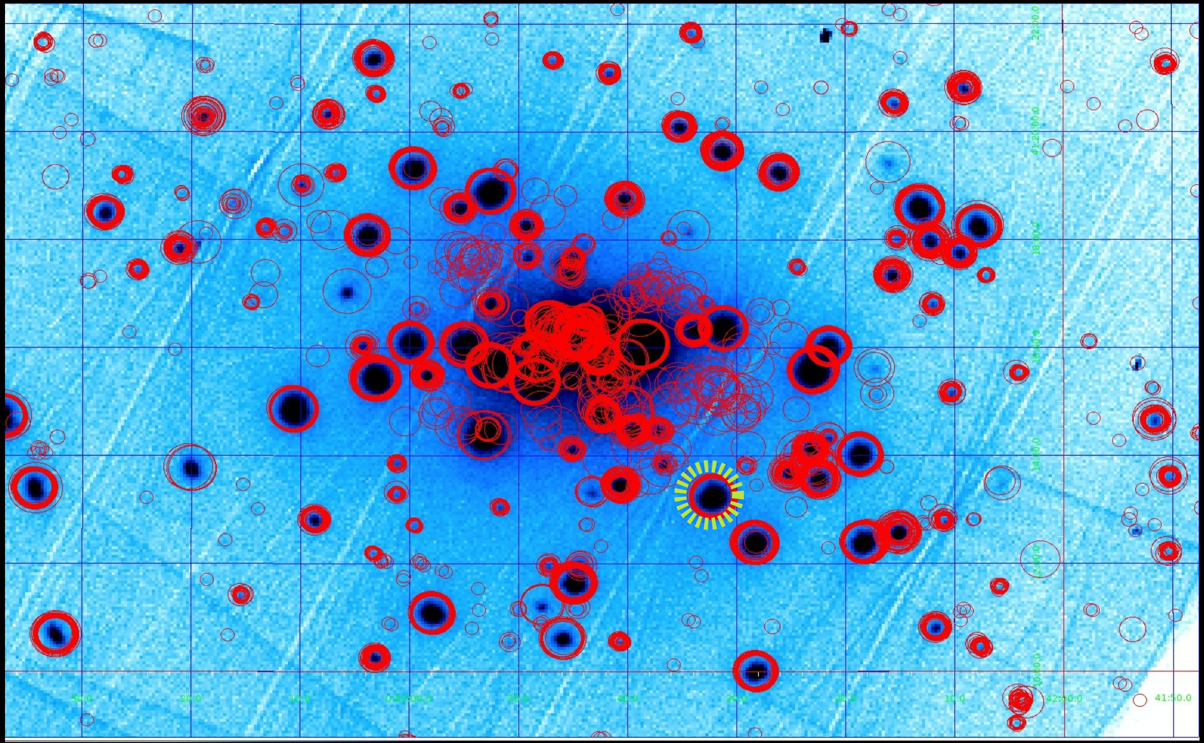
Only one free parameter: Pdot/P (we do not know the period a priori)

Fast wrt the orbital corrections



Cross-check on M31

Cross-check on M31

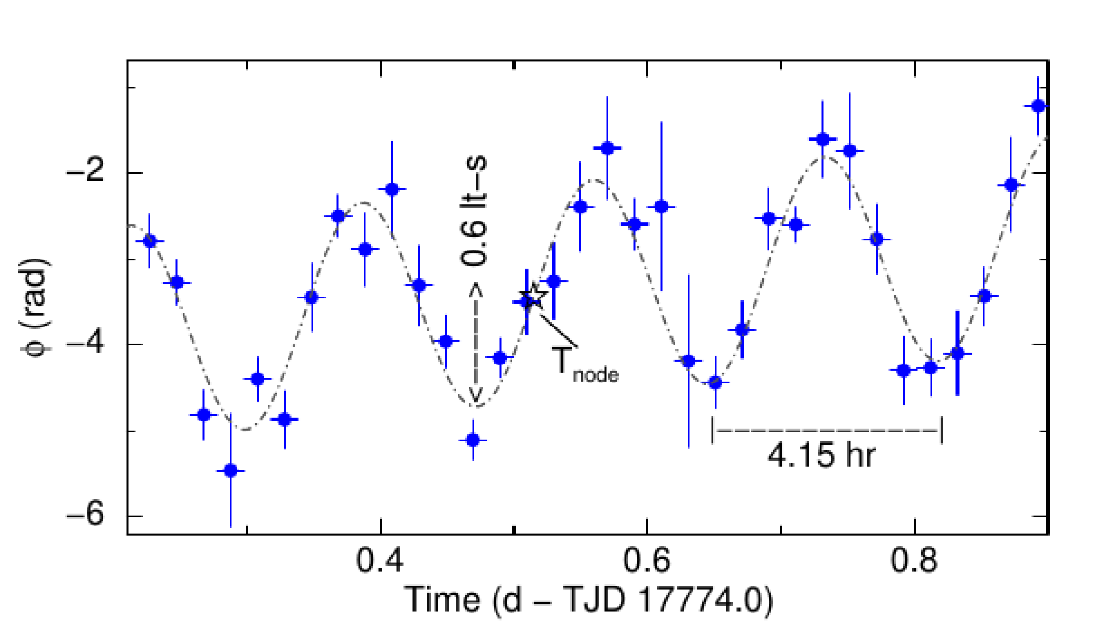


Overview

- 85 OBSID
- 9647 PPS detections
- 3842 unique sources
- Total T(exp)~1.9Ms

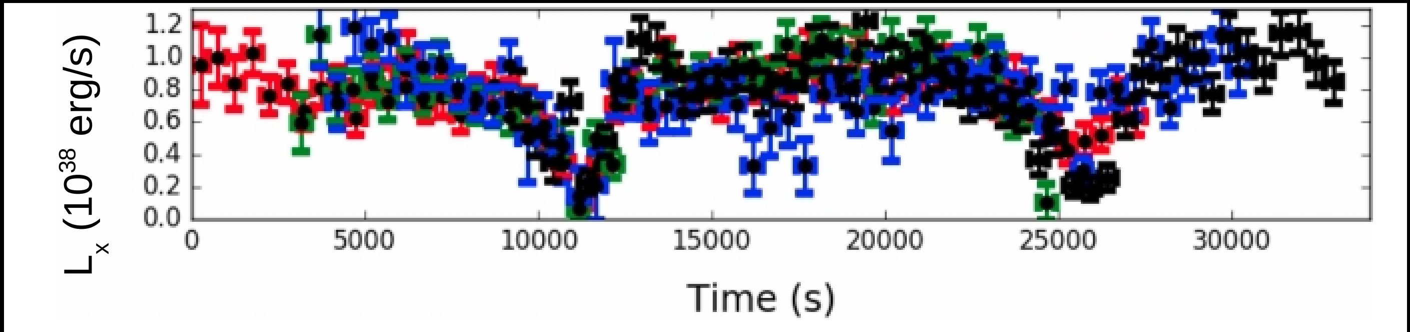
We found again the 1.2s pulsar but...
we also found a new X-ray pulsar !!

A 3s X-ray pulsar in a dipping LMXB

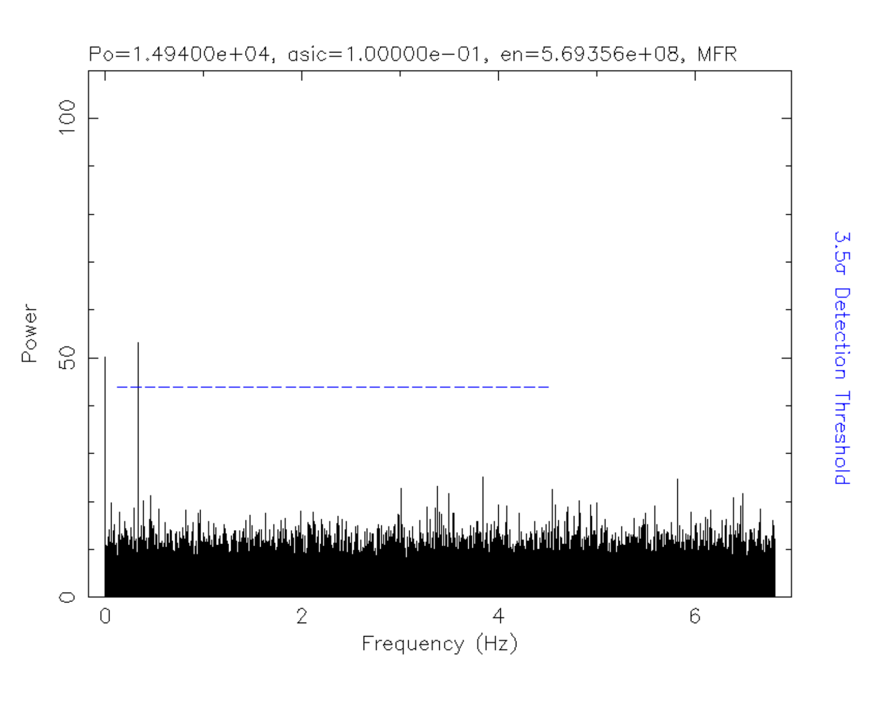


Parameter	Value
Orbital period, $P_{\rm orb}$ (h)	4.15(4)
Epoch of ascending node, $T_{\rm node}$ (TJD)	17774.525(3)
Projected semi-axis, $a_{\rm X} \sin i$ (lt-s)	0.59(4)
Mass function, $f(M)$ ($M_\odot$)	$7(2) \times 10^{-3}$
Companion mass[a] ($M_\odot$)	0.22–0.32

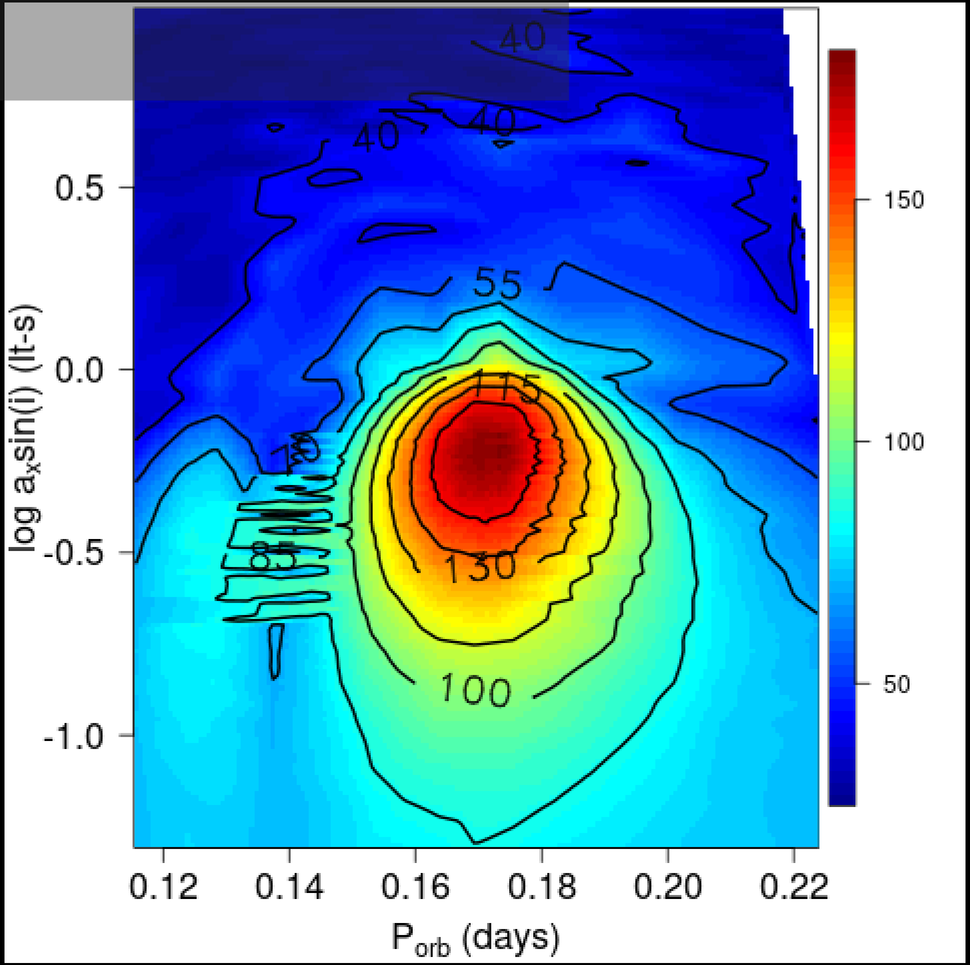
[a] For i between 60 and 80°, as estimated by Marelli et al. (2017), and a NS with mass of 1.5 $M_\odot$. The range widens to 0.19–0.46 $M_\odot$ for NS masses in the (1–2.8) $M_\odot$ interval.



Cross-check



Po=1.49400e+04, asic=1.00000e−01, en=5.69356e+08, MFR
Power
Frequency (Hz)
3.5σ Detection Threshold
0
50
100
0
2
4
6

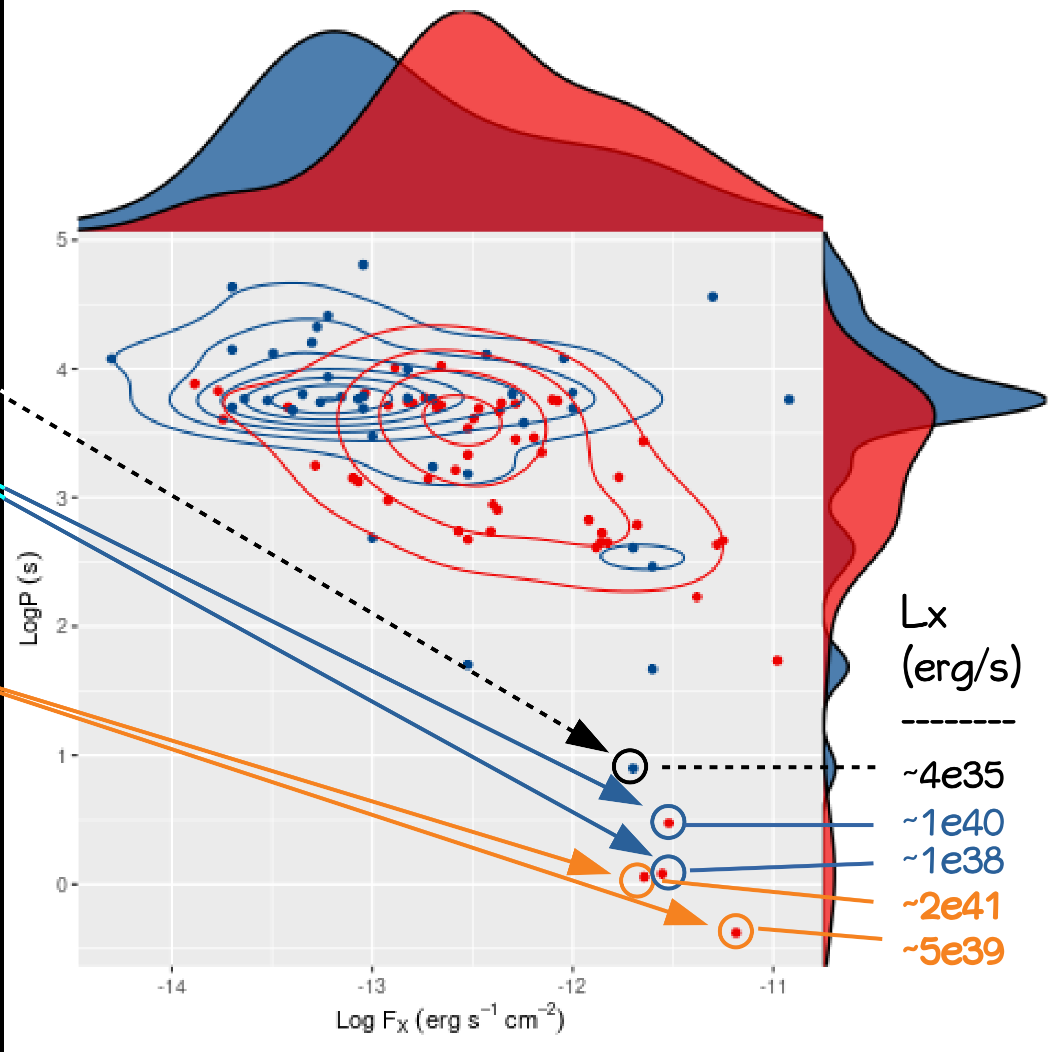


log $a_x$sin(i) (lt-s)
P_{orb} (days)
0.5
0.0
-0.5
-1.0
0.12
0.14
0.16
0.18
0.20
0.22
40
40
40
55
115
130
100
150
100
50

The rise of a new population of pulsars

Below 10s period:

- 1 transient source in the SMC
- 2 pulsars in M31 (the first ever)
- 2 pulsars in distant Galaxies (4Mpc < d < 17Mpc) classified as ULX



Maximum Lx for an accreting compact object

$$\frac{4\pi G m_p c}{\sigma_T} M \equiv L_{edd}.$$

- m_p proton mass
- σ_T Thomson scattering cross section
- M mass of the accreting object

NOTE: Idependent by R !!

$$L_{edd} = 1.2 \times 10^{38} \left(\frac{M}{M_\odot}\right) \quad \text{erg/sec},$$

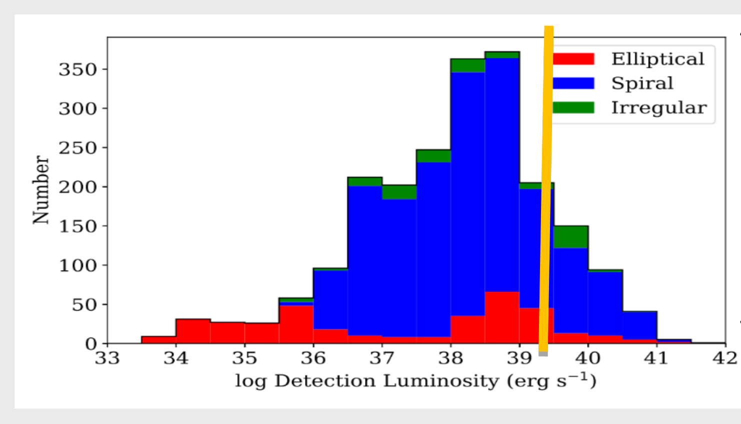
For a NS [~1.5-3M⊙] → L_{Edd} ~ 2-3.5 x 10^{38} erg/s

or

For a Lx of 1.2 x 10^{41} erg/s → M ~ 1000 M⊙

ULX class

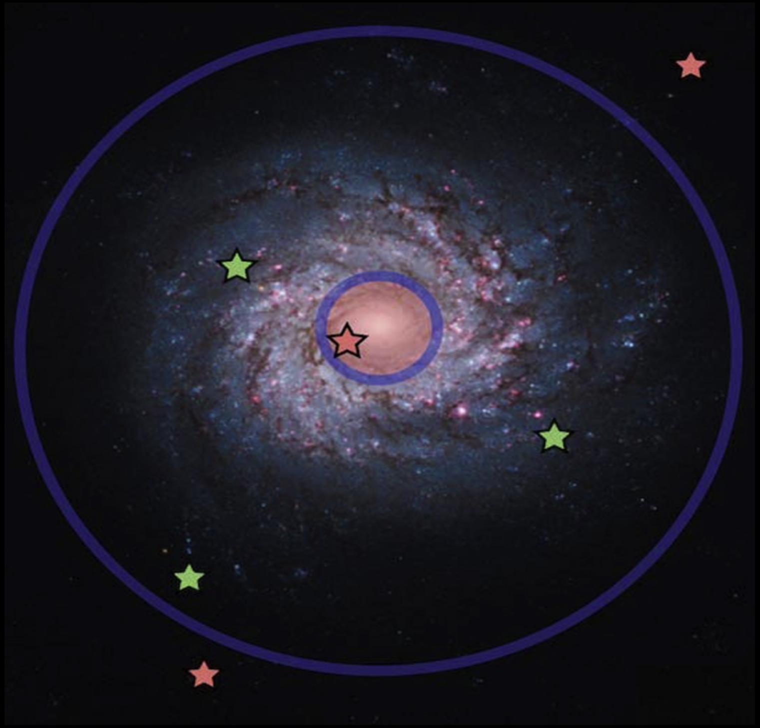
Ultraluminous X-ray sources are *off-nuclear, point-like* X-ray sources in nearby (d $\leq$100Mpc) galaxies exceeding the (isotropic) Eddington limit for a stellar-mass Black Hole (BH) of 10$M_\odot$



(Earnshaw+18)

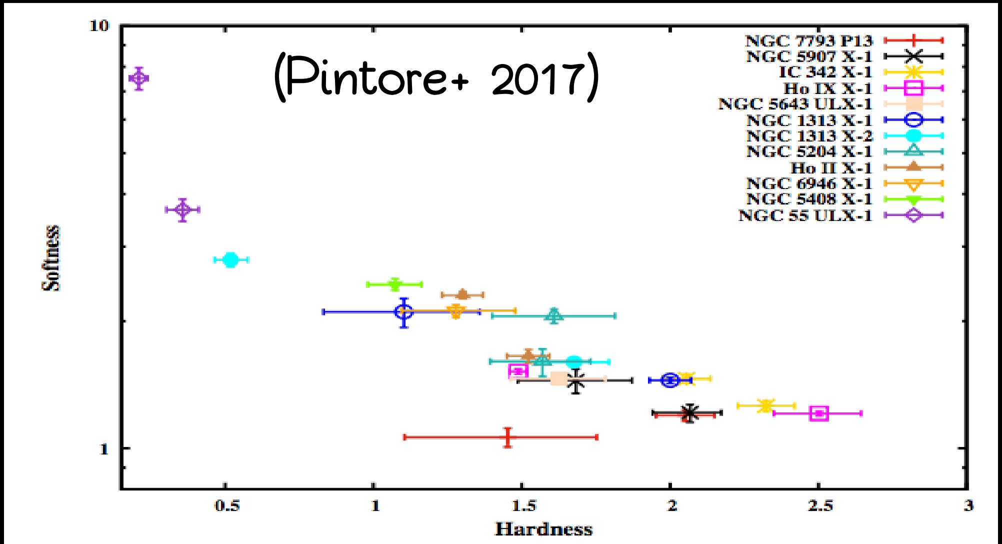
L_{ULX} > 1-2x10^{39} erg/s
up to ~10^{42} erg/s

About 300 objects
(Earnshaw+18; Liu+14)



IMBHs ?

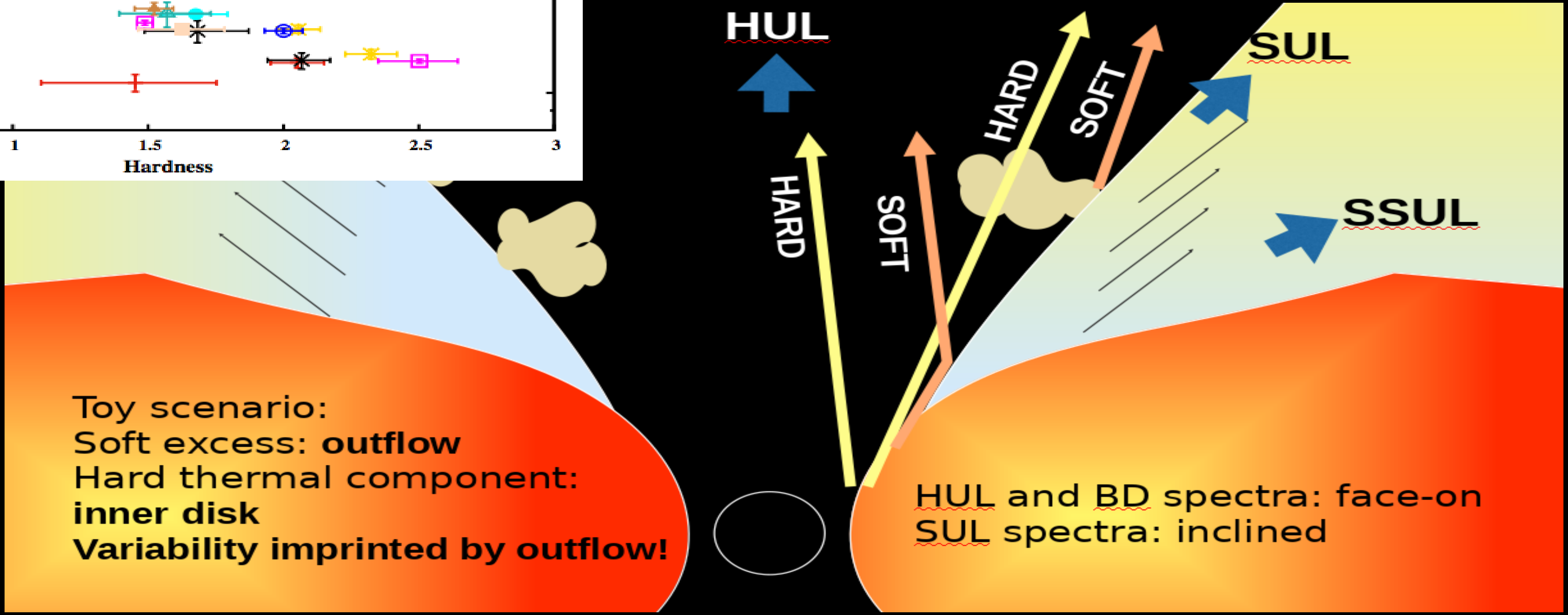
ULX class

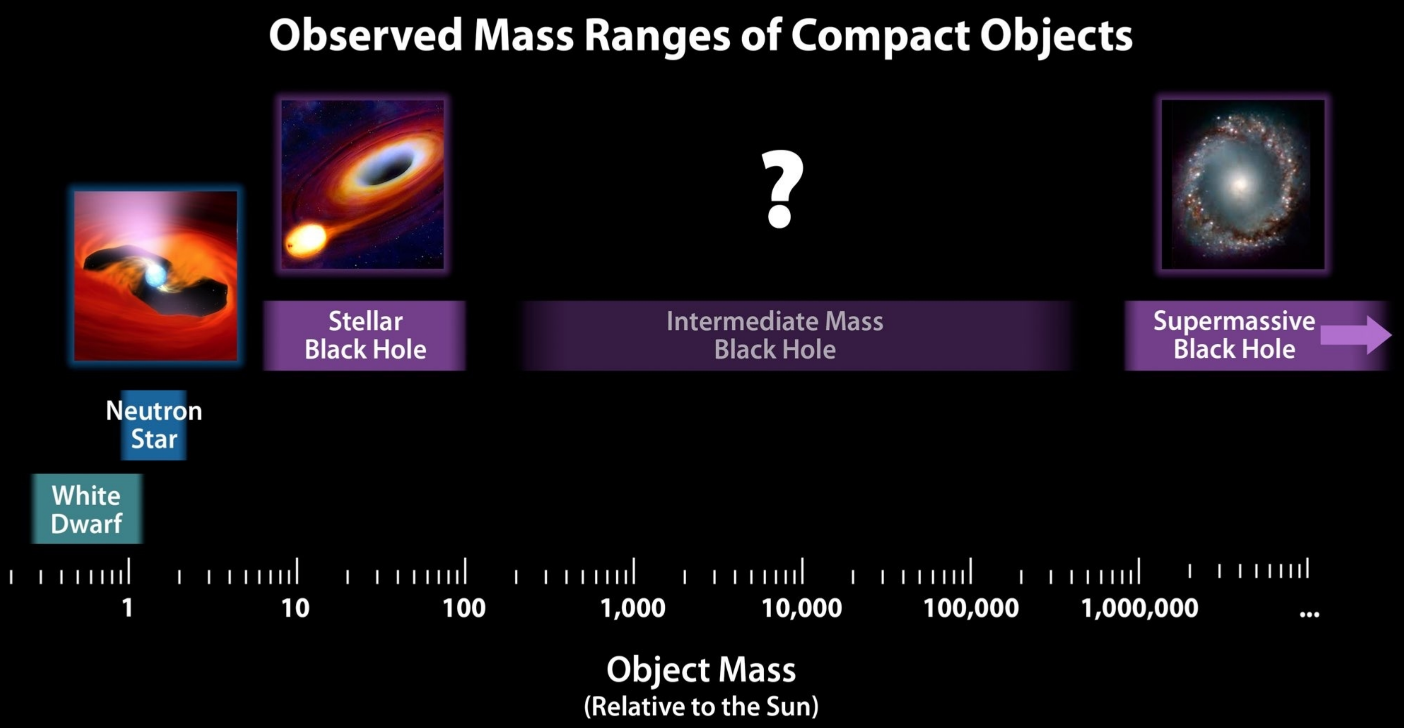


Several spectral models works well (at least 2 components needed).

Large dynamical range of parameters.

Possibly related to the emission geometry.





IMBHs needed to form SMBHs in quasars at z>6-7 (Pacucci+ 17)

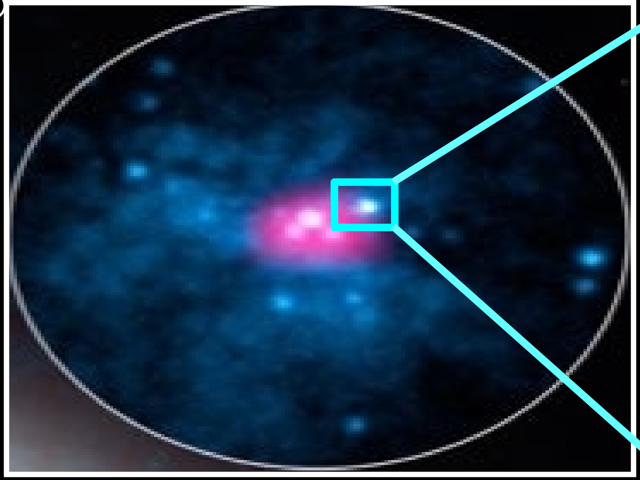
.. for 25years everybody was convinced of the BH nature of ULXs... 2017)

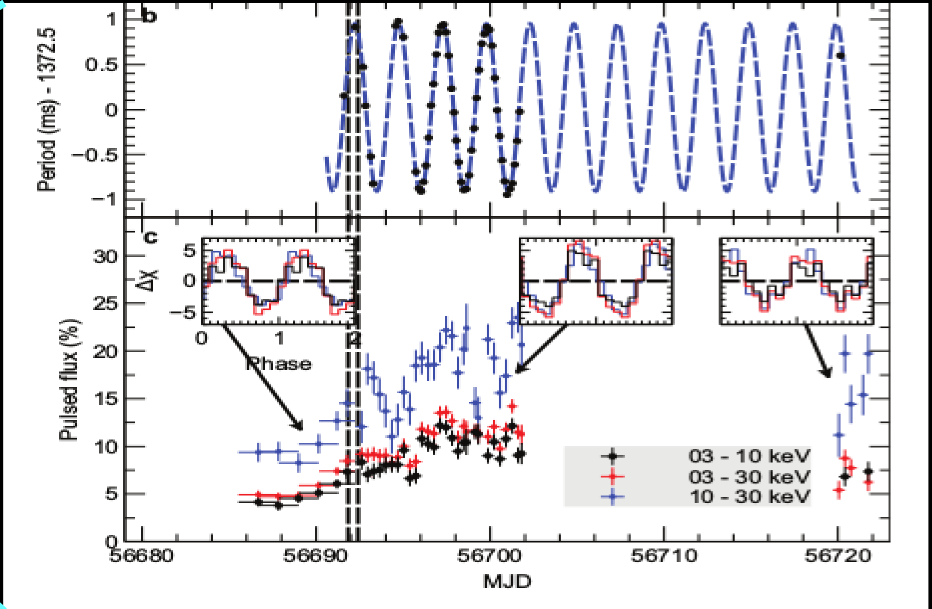
A long time ago in a galaxy far,
far away. . . .

ULXs and M82 X-2

Pulsations at 1.37s discovered from NuSTAR obs of M82 X-2
Sinusoidal pulse shape; PF~20%
Lx~2e40erg/s (@3.2Mpc)~ 100 L_{Edd}
Pdot (secular) -2e-10 s/s
P/Pdot = 300yr
Porb = 2.5days
Mc > 5.2 $M_{\odot}$

PULX emission 100 x L_{Edd}





Bachetti+14

Considered an odd object !

NGC 5907 ULX

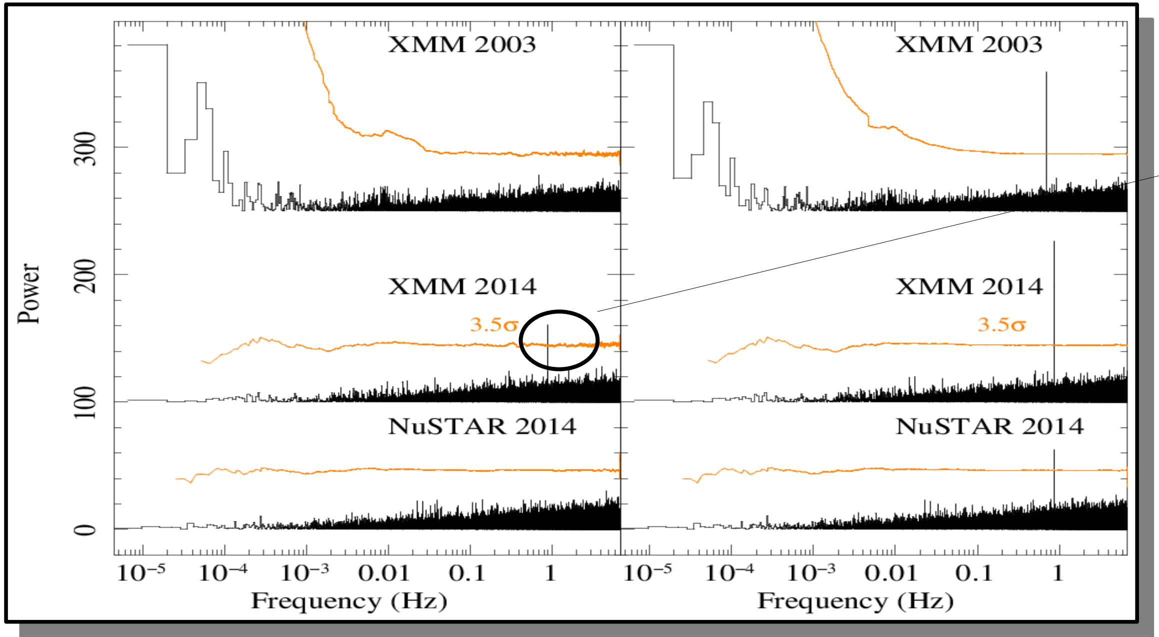
7 XMM pointings (6 source detection)+5 NuSTAR pointings (3 detection)

XMM data reveals a rather large Pdot of several -10^{-9} s/s

We applied an accelerated search on the 12 XMM+NuSTAR pointings

Detection of the signal in 2 XMM and 2 NuSTAR observations

Raw data | P-Pdot Corrected



Only one peak detected out of 9 datasets !!!

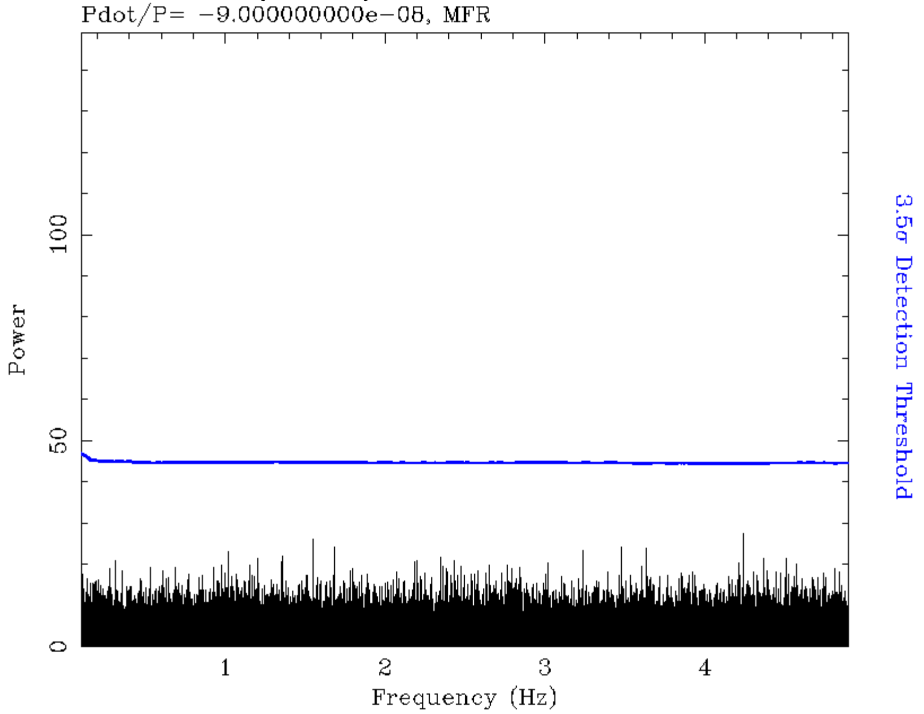
Main parameters

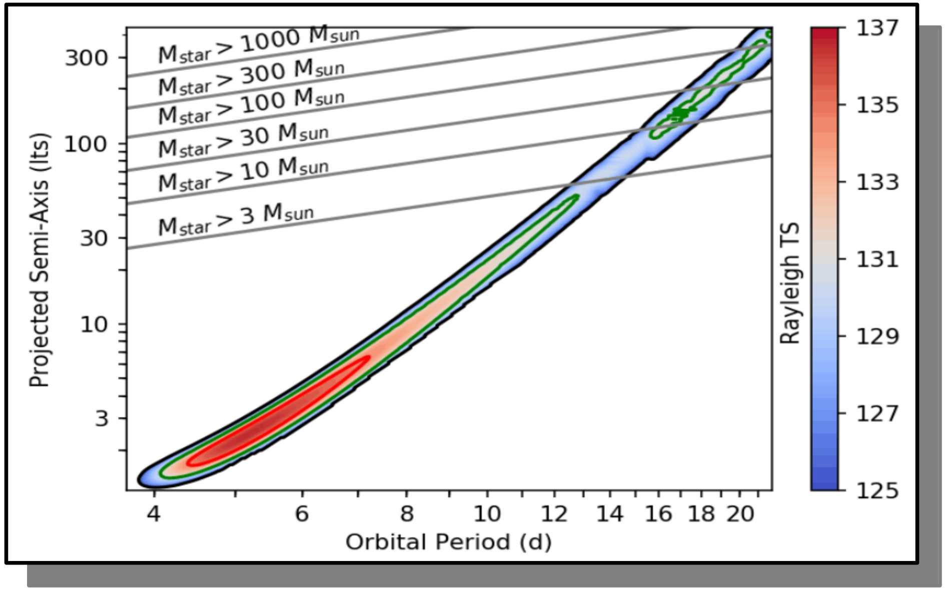
Start Date	2003 Feb. 28	2014 Jul. 09	2014 Jul. 09	2014 Jul. 12
Mission	*XMM–Newton*	*NuSTAR*	*XMM–Newton*	*NuSTAR*
Epoch (MJD)	52690.9	56848.0	56848.2	56851.5
P (s)	1.427579(3)	1.137403(1)	1.137316(2)	1.136041(1)
$\dot{P}$ (s s^{-1})^a $\times 10^{-9}$	-9.6(7)	-5.2(1)	-5.0(4)	-4.7(1)

Pdot(secular) =-8.1(1)e-10 s/s P/Pdot ~ 40 yr !!!

$t' = \frac{1}{2} (\dot{P}/P)\, t^2$

Porb=5.3[+2.0,-0.9] days (1σ)





GLI+17a

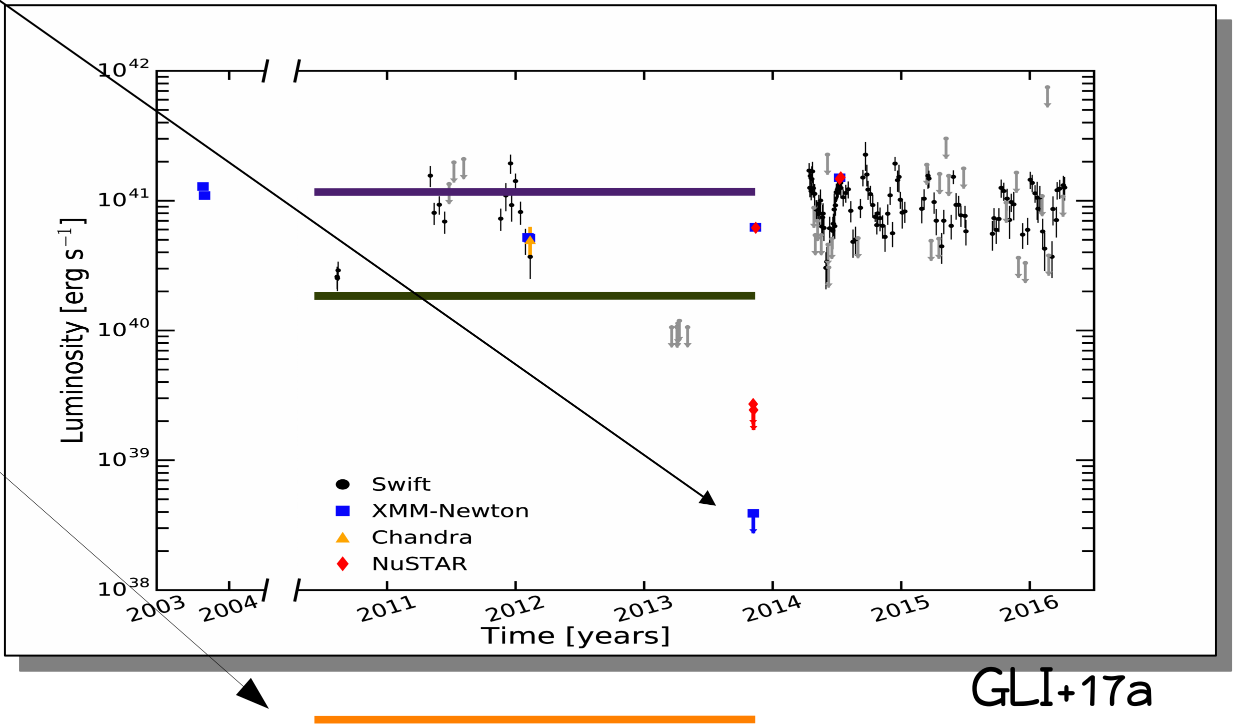
Luminosities

For a distance of 17.1Mpc the (isotropic) luminosity range is

Lx ~ 0.2x10^{41} -1.6x10^{41} erg/s

With an upper limit of 3x10^{38} erg/s

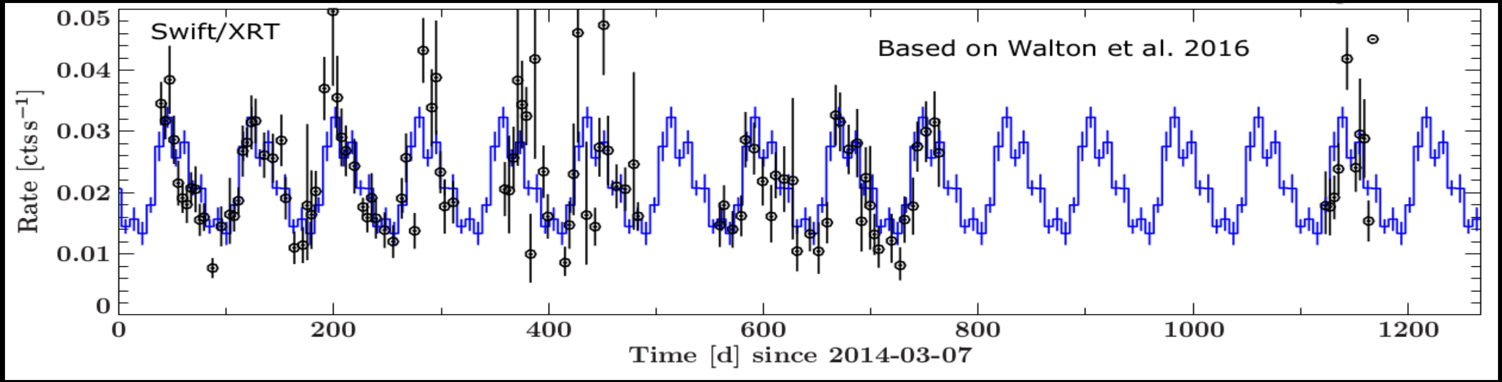
Propeller regime expected
at about 10^{37} erg/s



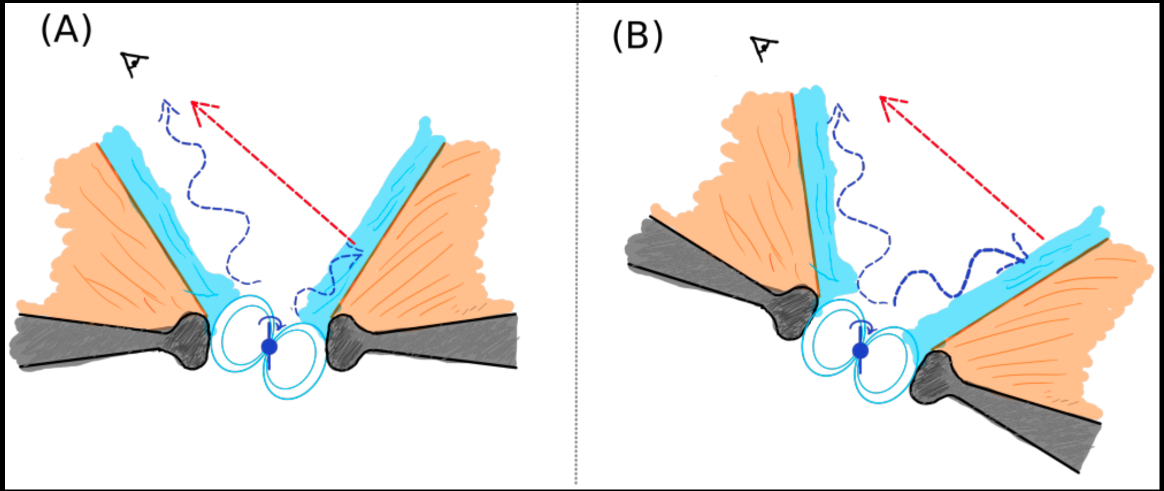
GLI+17a

Super-orbital modulation and precession

NGC5907 X-1
$P_{S\text{-}Orb}$ = 78 days



Interpreted as precession of the disk in agreement with pulse detection at the peak of $P_{S\text{-}Orb}$



A beaming effect should be present too

Science

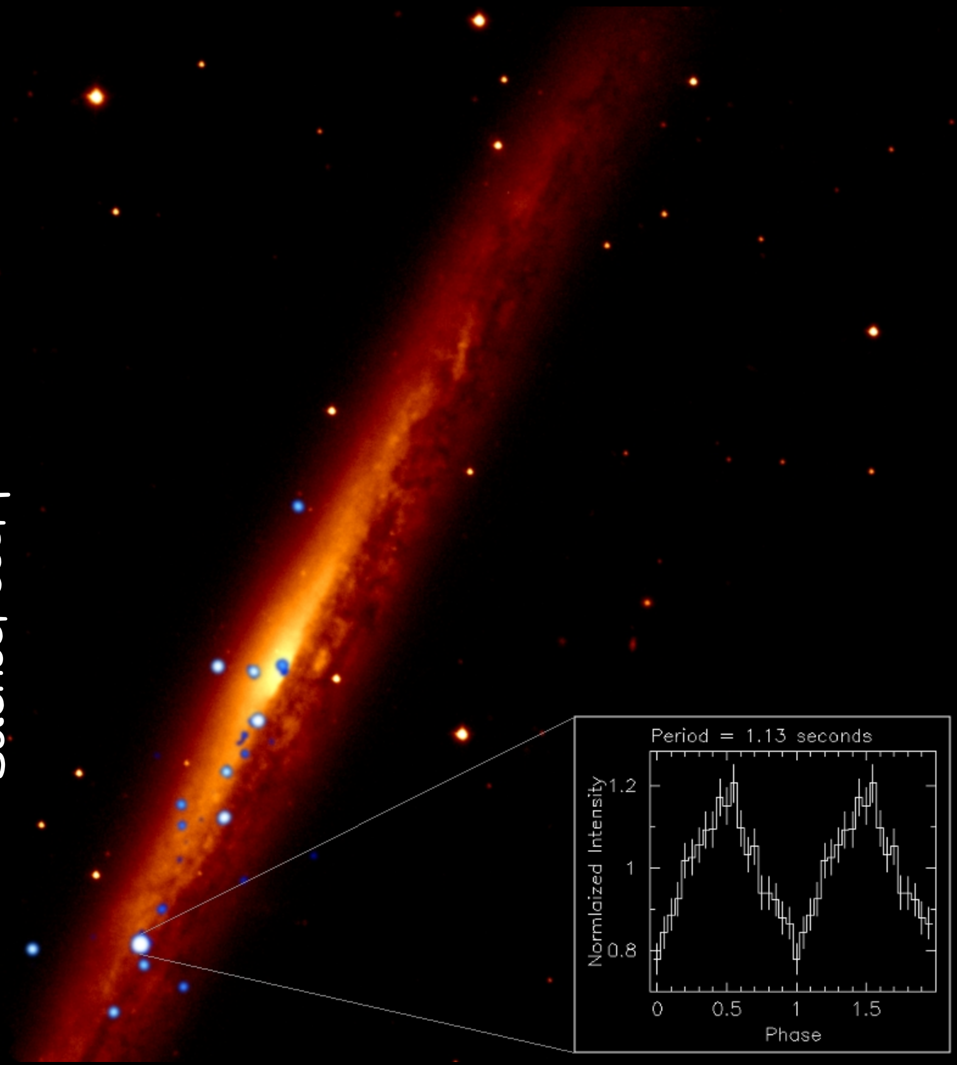
REPORT

EXTREME ASTROPHYSICS

An accreting pulsar with extreme properties drives an ultraluminous x-ray source in NGC 5907

Gian Luca Israel,[1*] Andrea Belfiore,[2] Luigi Stella,[1] Paolo Esposito,[3,2] Piergiorgio Casella,[1] Andrea De Luca,[2,4] Martino Marelli,[2] Alessandro Papitto,[1] Matteo Perri,[5,1] Simonetta Puccetti,[5,1] Guillermo A. Rodríguez Castillo,[1] David Salvetti,[2] Andrea Tiengo,[6,2,4] Luca Zampieri,[7] Daniele D'Agostino,[8] Jochen Greiner,[9] Frank Haberl,[9] Giovanni Novara,[6,2] Ruben Salvaterra,[2] Roberto Turolla,[10] Mike Watson,[11] Joern Wilms,[12] Anna Wolter[13]

Science, 355, p817



- NGC5907 X-1 is the most luminous and distant X-ray pulsar
- Extreme ULXs can host an accreting NS
- The peak luminosity is ~1000xL_{Edd} for a NS

Open questions

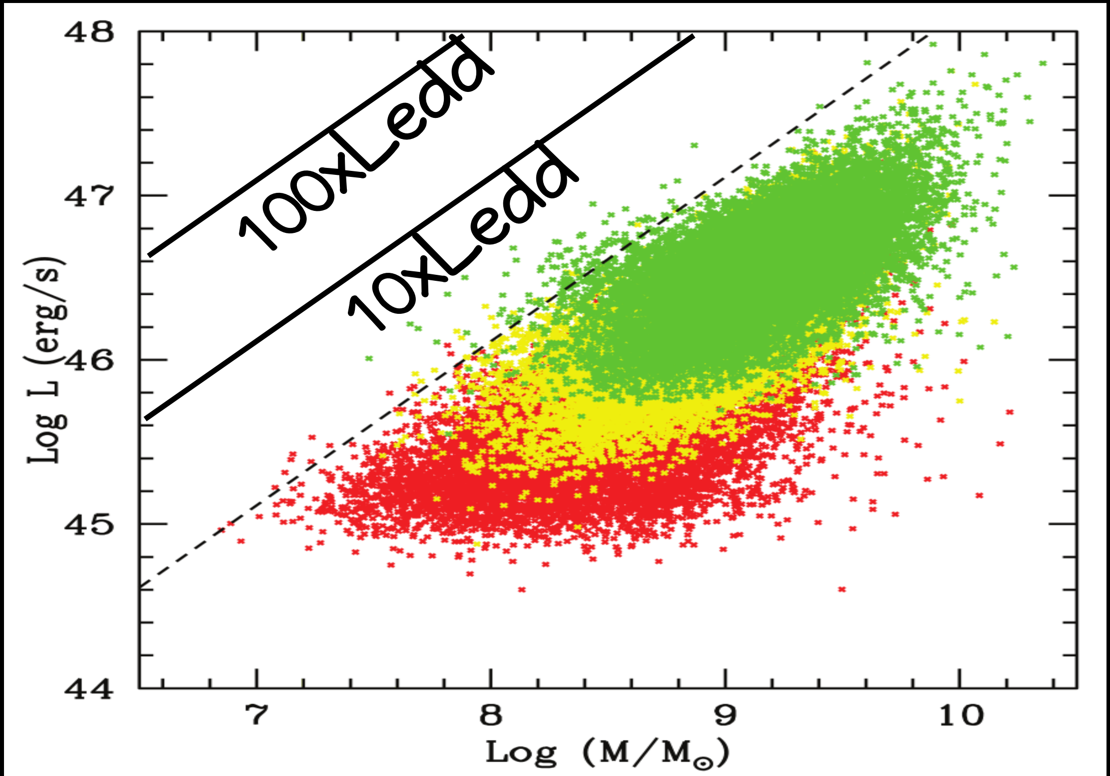
- Their luminosities challanges the “classical” models for accretion. How to account for such high luminosities ?
- Is the non-detection of pulsations in low states due to disk occultation or to the propeller onset ?
- How many NS among ULXs ? Oddballs or tip of the iceberg ?

BHs and Ledd

62,000 quasars (BHs) at different z. Even assuming the uncertainties in the distances and in the virial mass determination NONE of them is above the Ledd by a factor of 10.

Magnatic field might be an important ingredient.

(Steinhardt & Elvis 10)



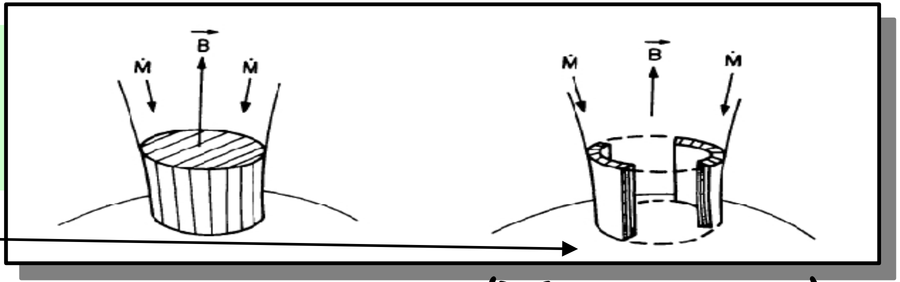
Ways to circumvent L_{Edd}

- No isotropic emission (beaming)
- Accretion geometry
- Radiation not transferred by photons
- Changes in the σ_T cross section (B-field)
- Chemical composition of the infalling matter (metallicity)

Maximum L_{edd} ?

- The maximum X-ray luminosity depends (at least) from the accretion rate, the magnetic field, the geometry of accretion and beaming.

- up to a factor of about 10 higher in L can be reached if $B_{dipolar} > 10^{13}$ G assuming a thin hollow funnel



(Mészáros 84)

- In principle, if B is high enough the electron scattering cross section is reduced (in the extraordinary mode for $E<E_{cyc}$).

$$L_{\mathrm{Edd},B}(r) \simeq 2L_{\mathrm{Edd}}\left(\frac{B}{10^{12}\ \mathrm{G}}\right)^{4/3}$$

For $B_{dipolar}$ = few x10^{15} G up to 10^{41} erg/s can be released on the NS surface ...

- A beaming factor b<1 (b*Liso=Lacc) is also likely present. 1/10<b<1/100 from King+2001

“Too B or not too B” or “too b or not too b”

- $B_{dipolar}$ > 10^{14}-10^{15} G

Lx OK

However, with that B and 1s spin period the NS in NGC5907 should be deeply in the propeller phase ($r_m >> r_c$)! Not accreting !!

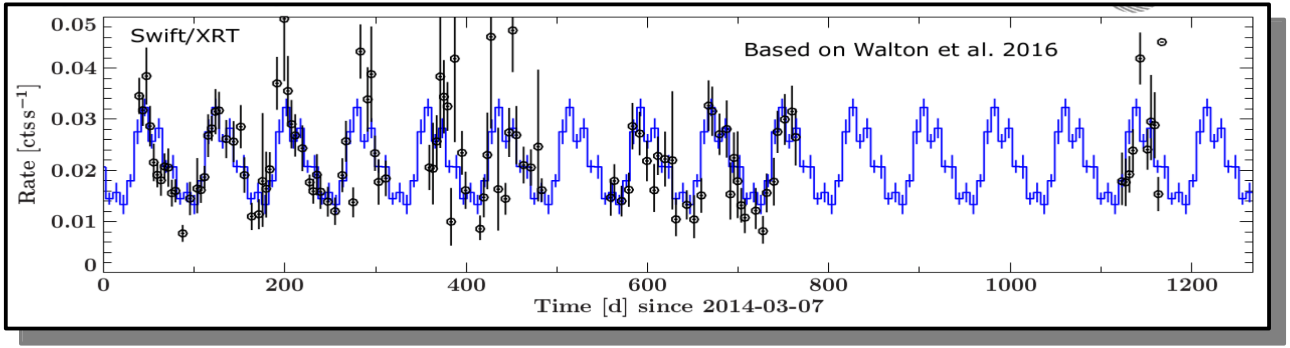
Too B or not too B

- $B_{dipolar}$ > 10^{14}-10^{15} G

Lx OK
However, with that B and 1s spin period the NS in NGC5907 should be deeply in the propeller phase ($r_m >> r_c$)! Not accreting !!

1. $B_{dipolar}$ > 10^{12}-10^{13} G

AND
high beaming factor b~1/100 (b*Liso=Lacc)
(King+ 2001, King+17, King & Lasota19)
Lx OK



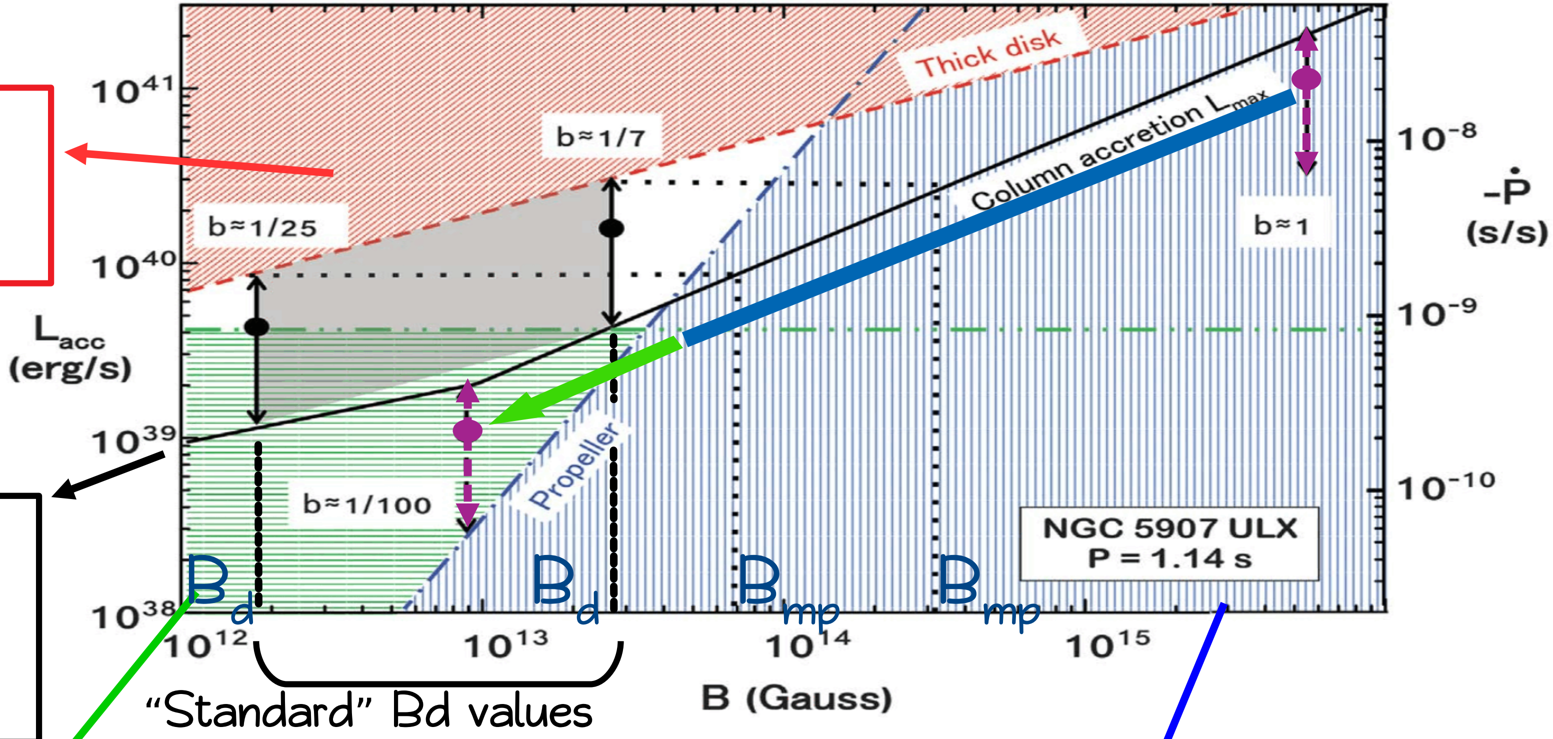
Beaming should be at work
due to super-orbital modulations detected in PULXs likely originated by disk precession and due to non detection of pulsations in different super-orbital phases.

Possible scenario for NGC5907 ULX

Super-Eddington emission from the disk; escaping radiation stopped

Maximum Lx atteinable by the accretion column for the dipolar B component

Minimum Mdot in order to obtain the observed Pdot



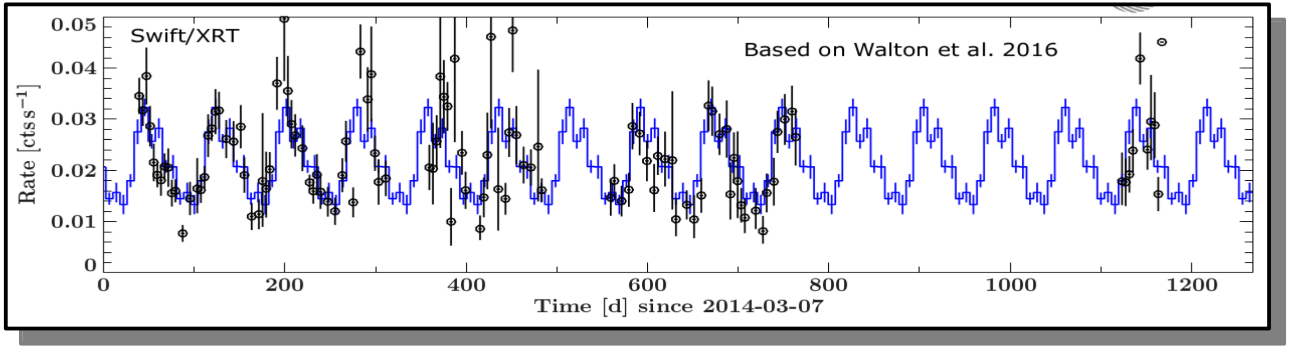
Propeller regime: no accretion possible on the NS surface, no pulsations

Too B or not too B

- $B_{dipolar}$ > 10^{14}-10^{15} G

Lx OK
However, with that B and 1s spin period the NS in NGC5907 should be deeply in the propeller phase ($r_m >> r_c$)! Not accreting !!

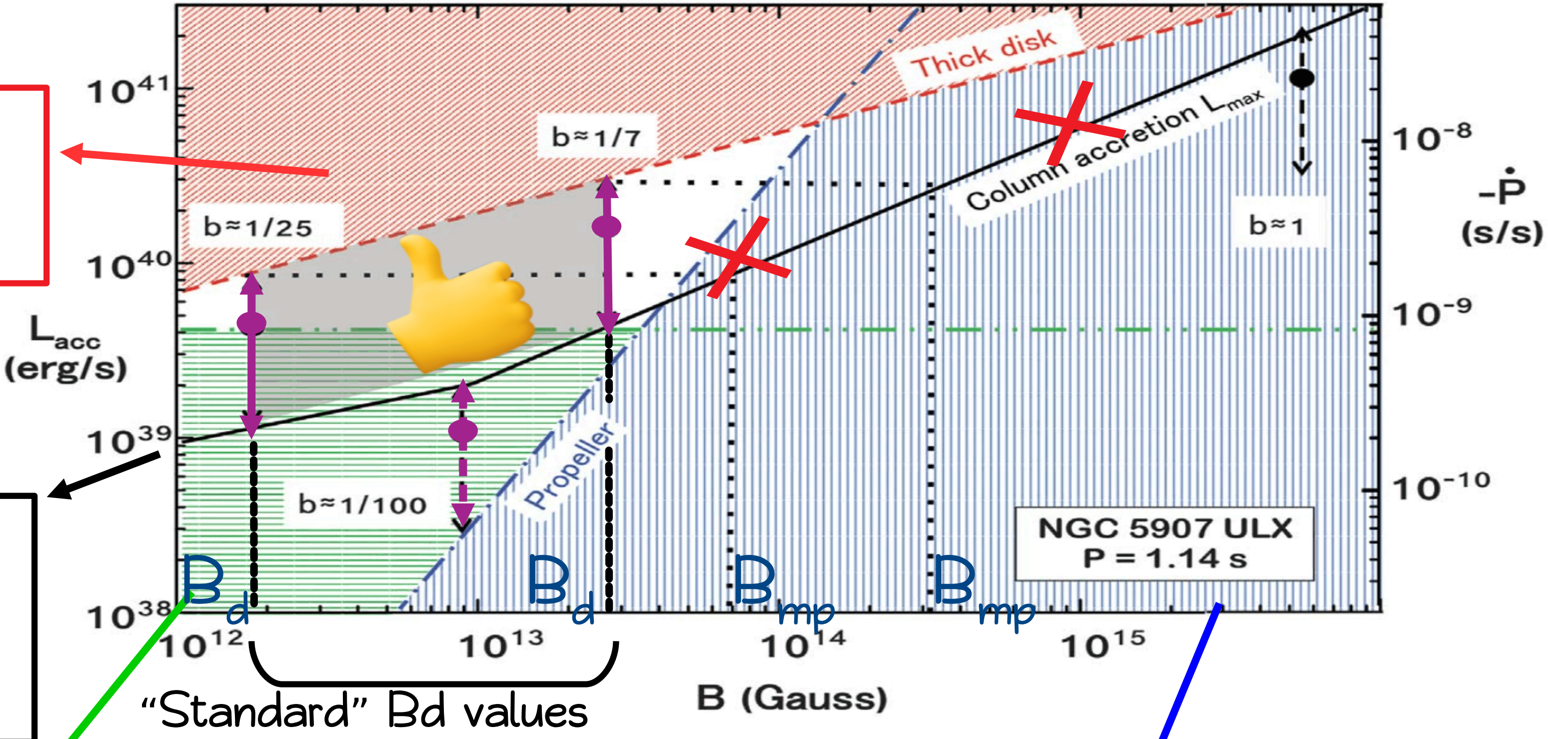
1. $B_{dipolar}$ > 10^{12}-10^{13} G
AND
high beaming factor b~1/100 (b*Liso=Lacc)
(King+ 2001, King+17, King & Lasota19)
Lx OK



b=1/100 pushes NGC5907 out from the propeller but with Lx~10^{39} erg/s not able to account for the observed Pdot
Pdot NO

Possible scenario for NGC5907 ULX

Super-Eddington emission from the disk; escaping radiation stopped



Maximum Lx atteinable by the accretion column for the dipolar B component

Minimum Mdot in order to obtain the observed Pdot

Propeller regime: no accretion possible on the NS surface, no pulsations

Too B or not too B

2. $B_{dipolar} > 10^{12}$-10^{13} G

AND

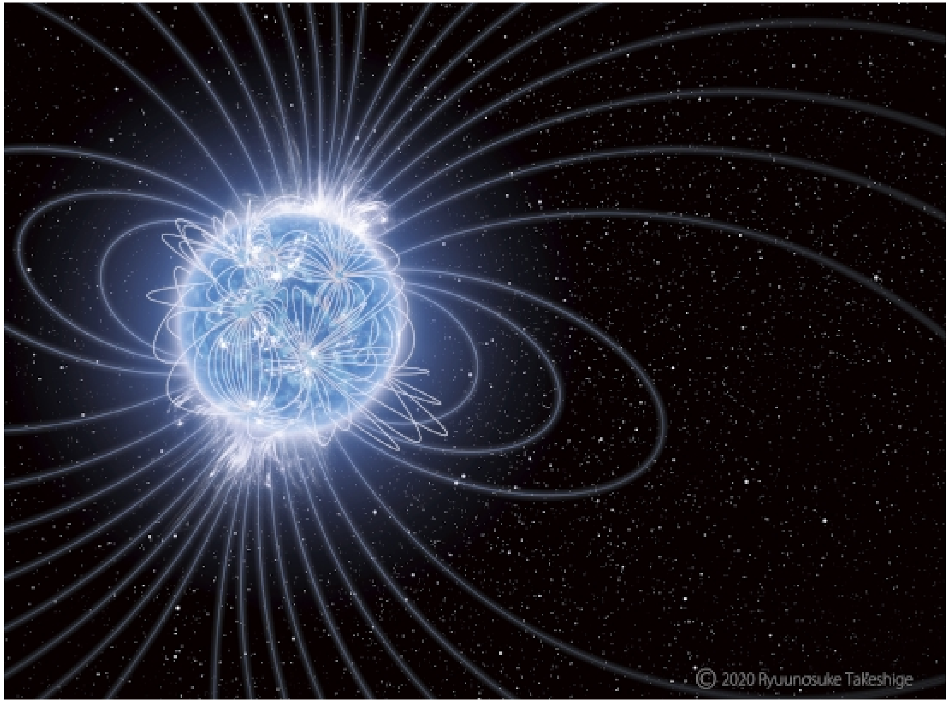
moderate 1/25<b<1/7 beaming

AND

multipolar B component close to the NS surface (accretion column base) in the 7×10^{13}-3×10^{14} G

Lx OK

Pdot OK



Too B or not too B

2. $B_{dipolar}$ > 10^{12}-10^{13} G

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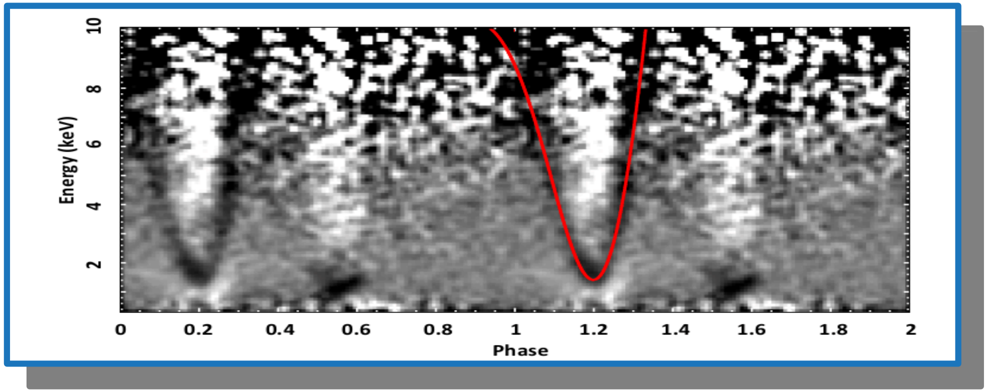
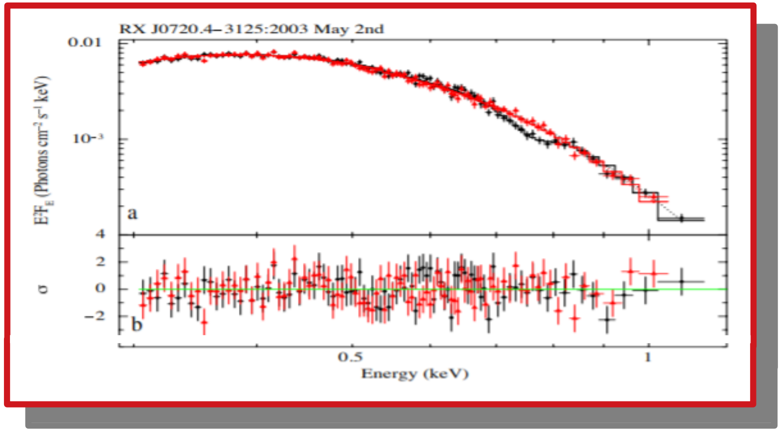
AND

multipolar B component close to the NS surface (accretion column base) in the 7×10^{13}-3×10^{14} G

Lx OK

Pdot OK





Phase-dependent p-CRSFs in young (magnetars) and old (INSs/ONSs)

high $B_{dipolar}$ isolated NSs B_{mp}~ 1-10x10^{14} G

(e-CRSF -> B < $B_{dipolar}$)

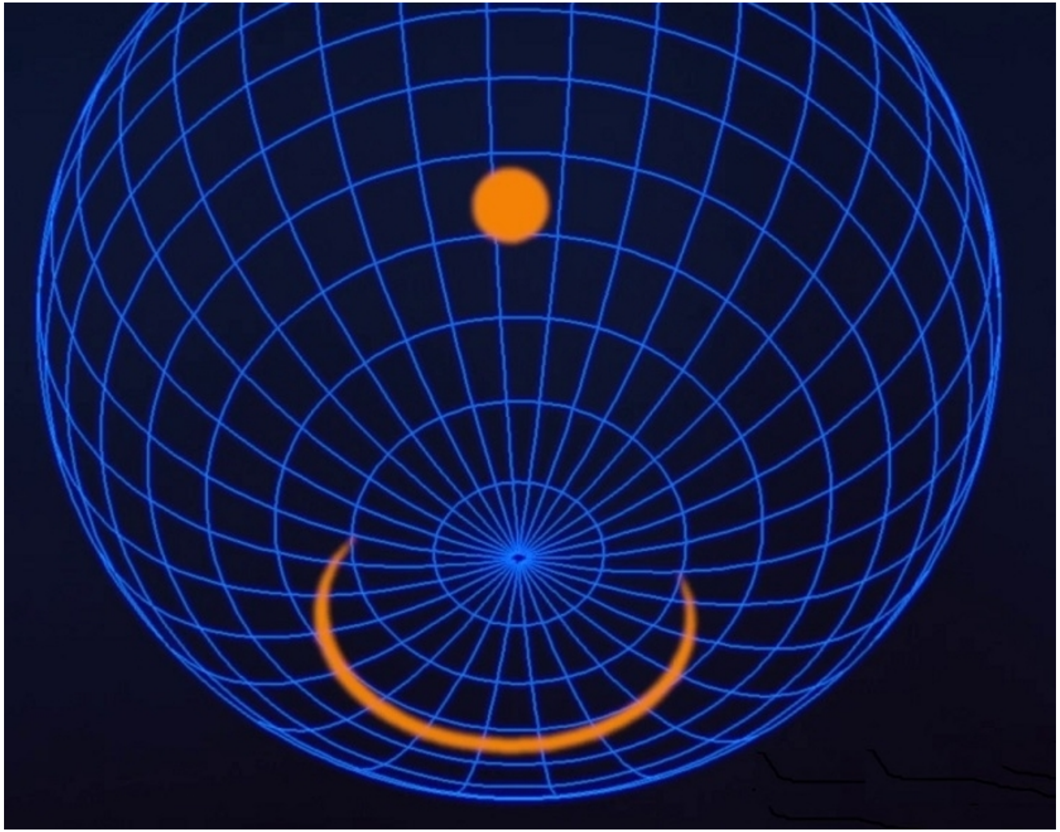
(Tiengo+13, Borghese+16)

Too B or not too B

2. $B_{dipolar} > 10^{12}$-10^{13} G
AND
moderate 1/25<b<1/7 beaming
AND
multipolar B component close to the NS surface (accretion column base) in the $7x10^{13}$-$3x10^{14}$ G

Lx OK
Pdot OK

Not necessarly a magnetars !!
[though 10^{12}-10^{13} G dipolar B does not exclude a magnetar]



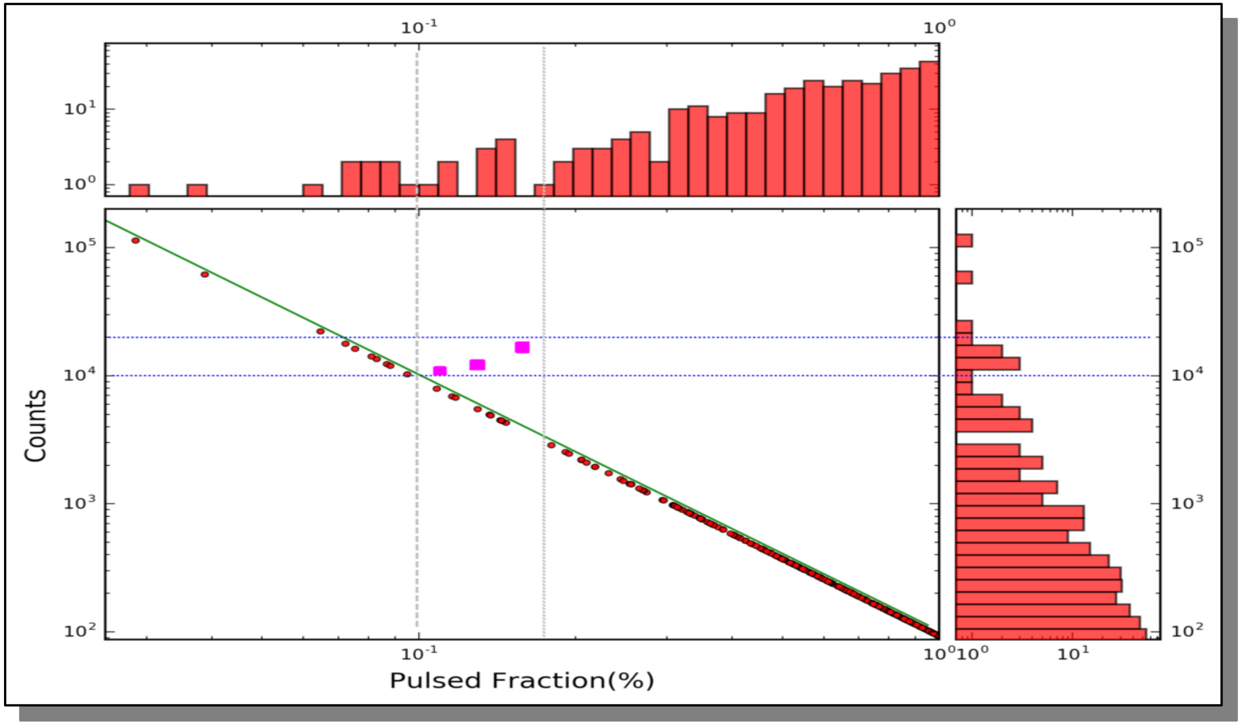
NICER studies of J0030+0045 (P=4.9ms, old NS) implies that the magnetic field structure is much more complex than previously imagined (Riley+ 19; Raaijmakers+ 19)

How many (2018)?

4 out of 300, ~1% ?
Who cares ?

We detected PULXs in observations with at least 10,000 counts (XMM)

How many ULXs with such statistics?



14 ULXs (<5% of all known ULXs) → **29%** are PULXs

How many ULXs with a statistics such that pulsations with 20% pulsed fractions might be detected?

18 ULXs → **21%** are PULXs

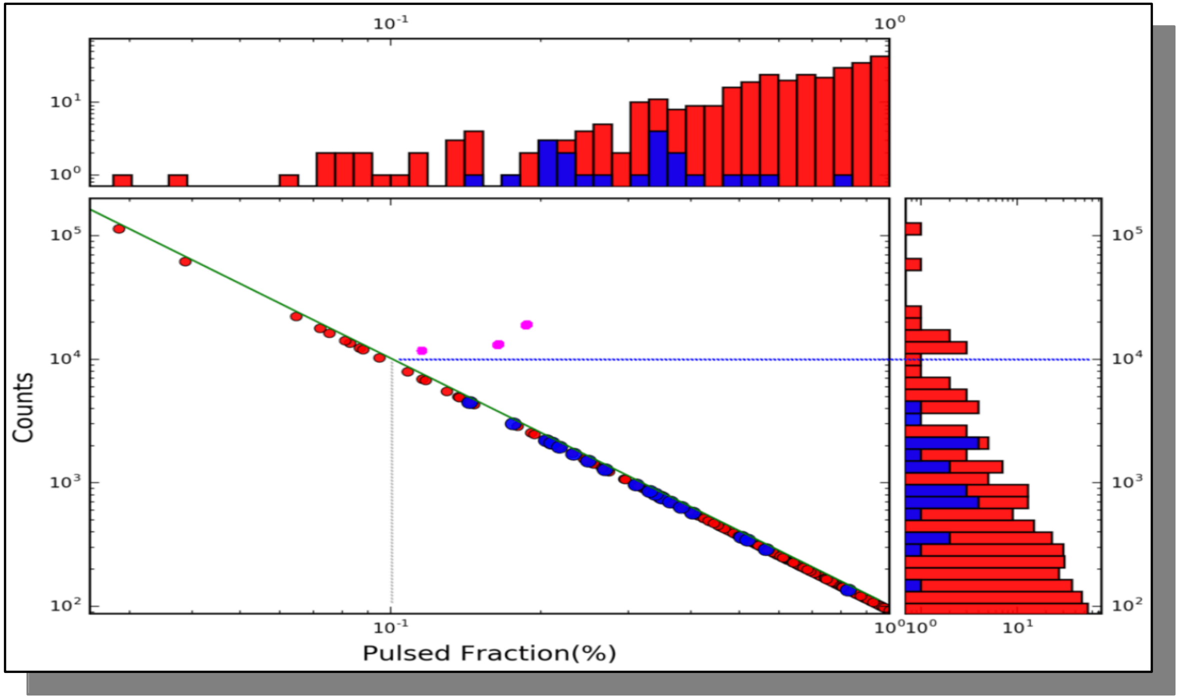
Not all pulsars are expected to be beamed towards us.

Taking the beat of the UNSEEN

UNSEEN:
Ultraluminous
NS Extragalactic
Extreme populatioN

Accepted as XMM LP in AO17:

8 pointings + 3 DDTs
986 ks
~10 ULXs (>10.000 cts)
~30 additional S-Edd sources
~2 new PULXs
expected to be detected!



XMM LP

M51 observed in May 2018 for about 75ks

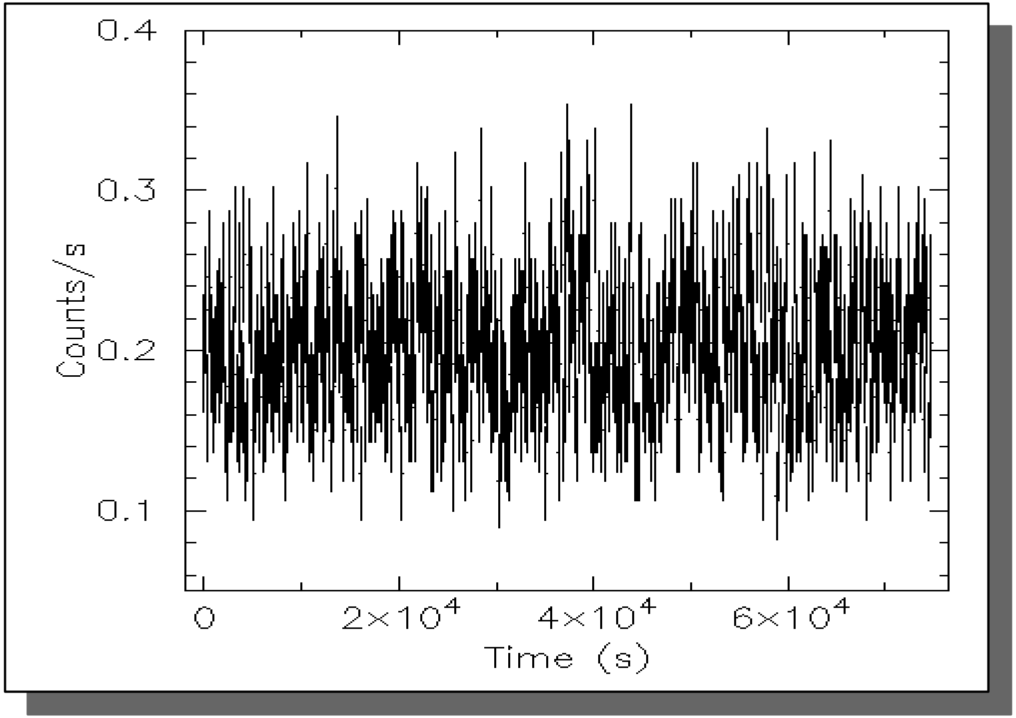
UNSEEN:
Ultraluminous
NS **E**xtragalactic
Extreme populatio**N**

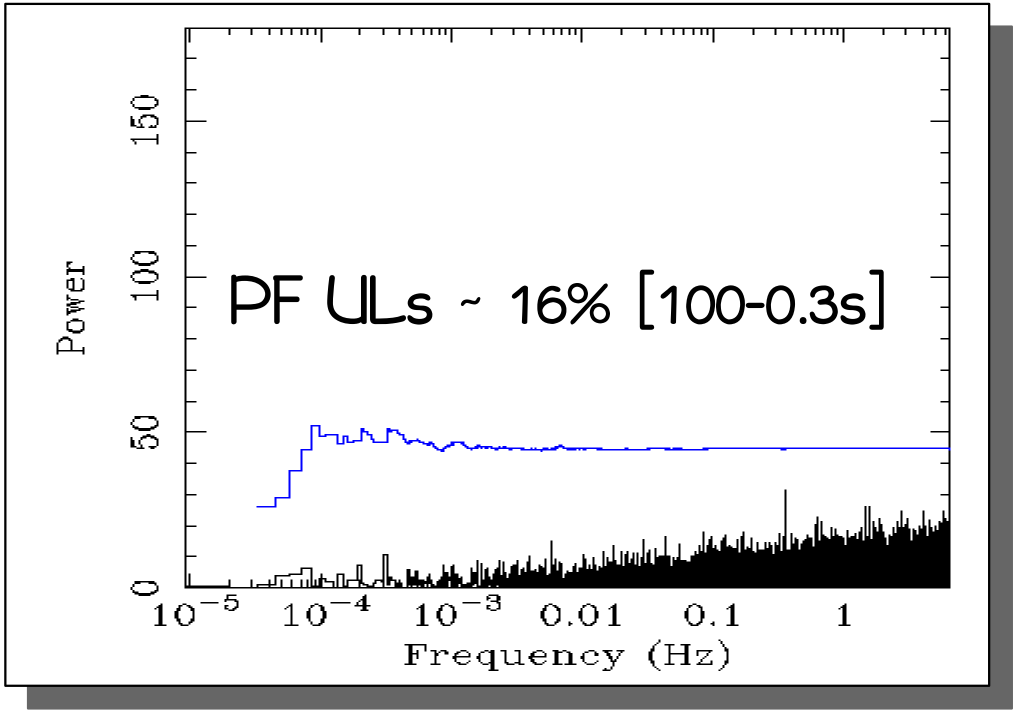
ULX7, a variable source: L_X peaks at almost 10^{40} erg/s

Observed several times by XMM
No pulsations detected.

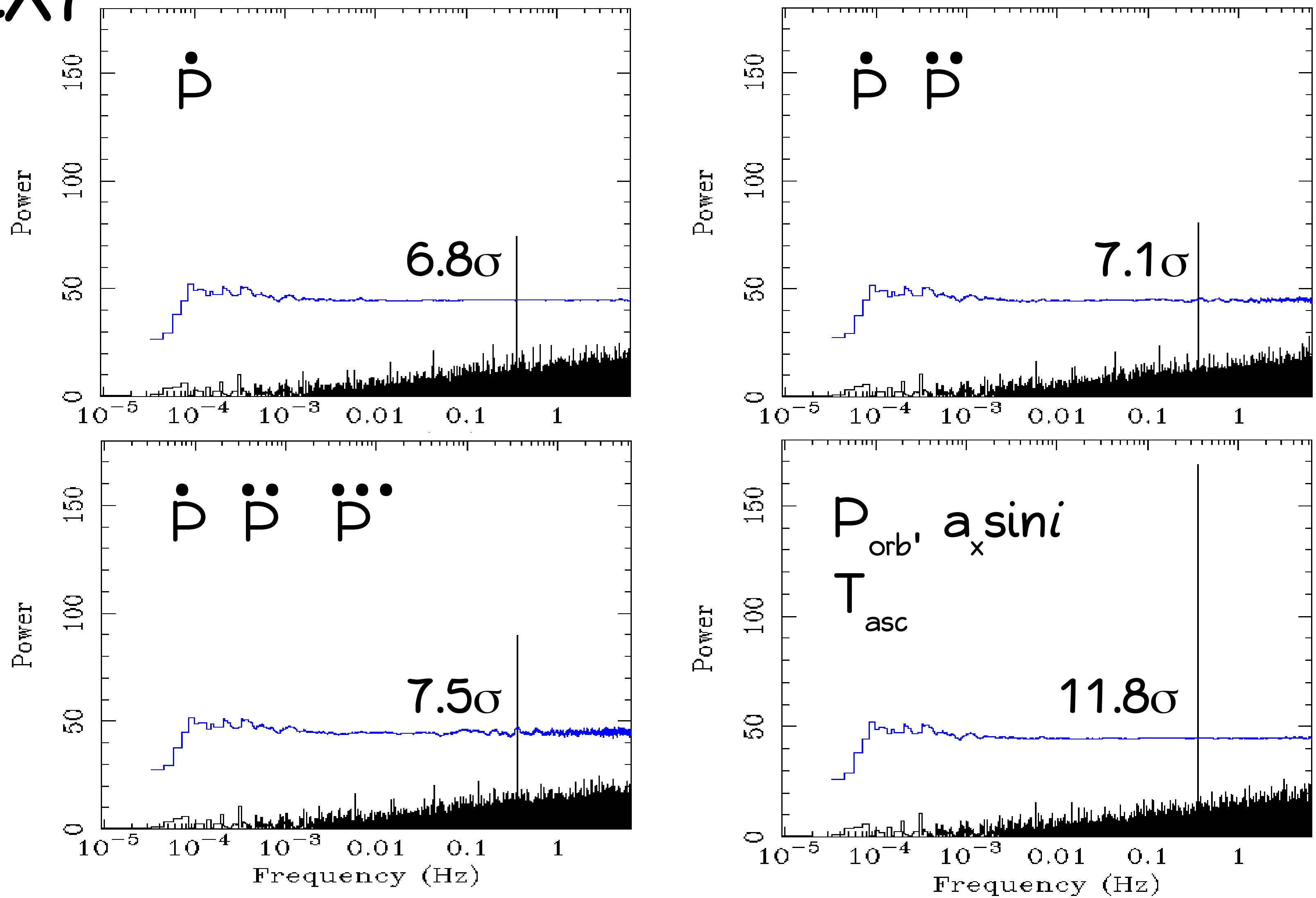
ULX7

One of the best example of Poissonian process
and white noise !





ULX7



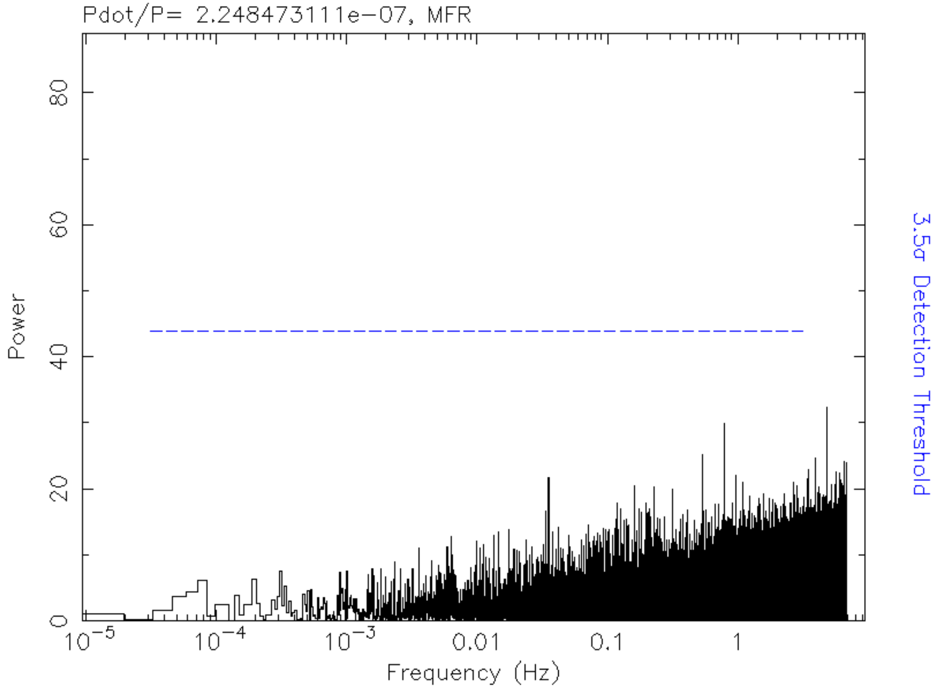
$\dot{P}$
6.8σ
$\dot{P}$ $\ddot{P}$
7.1σ
$\dot{P}$ $\ddot{P}$ $\dddot{P}$
7.5σ
P_{orb}, $a_x sin\,i$
T_{asc}
11.8σ
Power
Frequency (Hz)

XMM LP

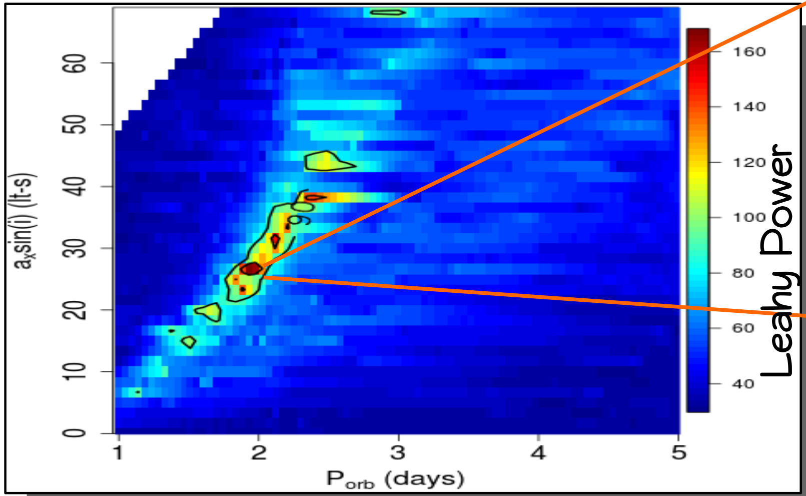
M51 observed in May 2018 for about 75ks
+ 3 DTT (96+63+64ks) requested on in June 2018

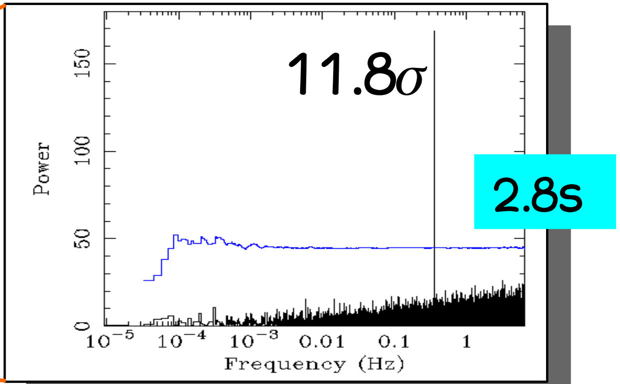
UNSEeN:
Ultraluminous
NS **E**xtragalactic
extreme populatio**N**

ULX7, a variable source: L_X peaks at almost 10^{40} erg/s



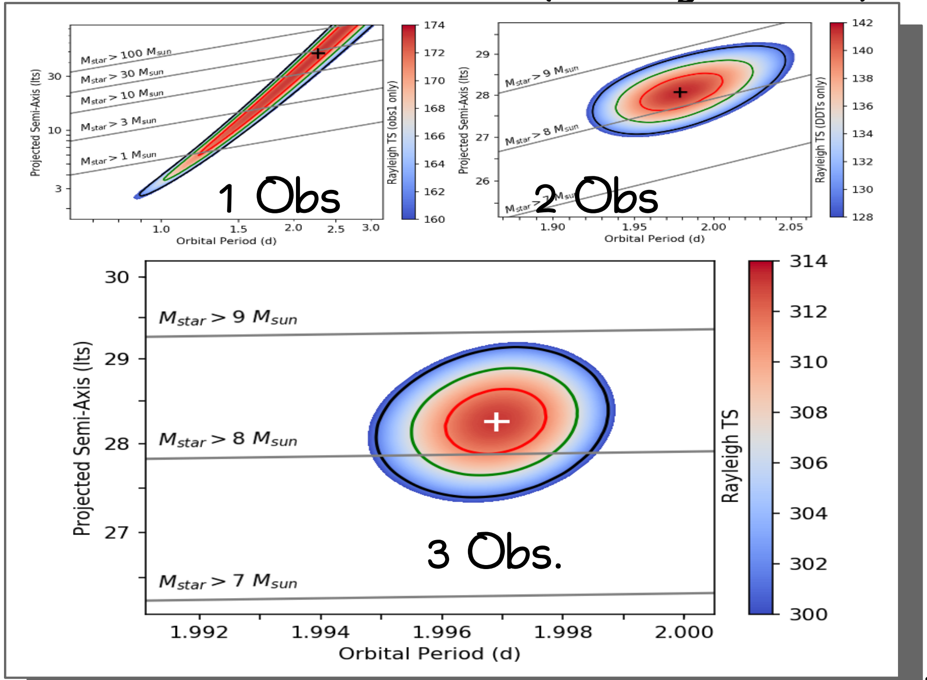
M51 ULX-7





$\dot{P}_{sec} \simeq -10^{-9}$ s/s

(Rodriguez+ 19)



$M_c/M_\odot = 8.3/\sin i$

$M_c \simeq 13\ M_\odot$ for average sine values -> HMXB

$P_{\rm orb}$ (d)	1.9969(7)
$a_{\rm X} \sin i$ (lt-s)	28.3(4)
$T_{\rm asc}$ (MJD)	58285.0084(12)
e	<0.22
Mass function ($M_\odot$)	6.1(3)
Companion mass ($M_\odot$)	$8.3(3)/\sin i$

PULXs overall properties (2021)

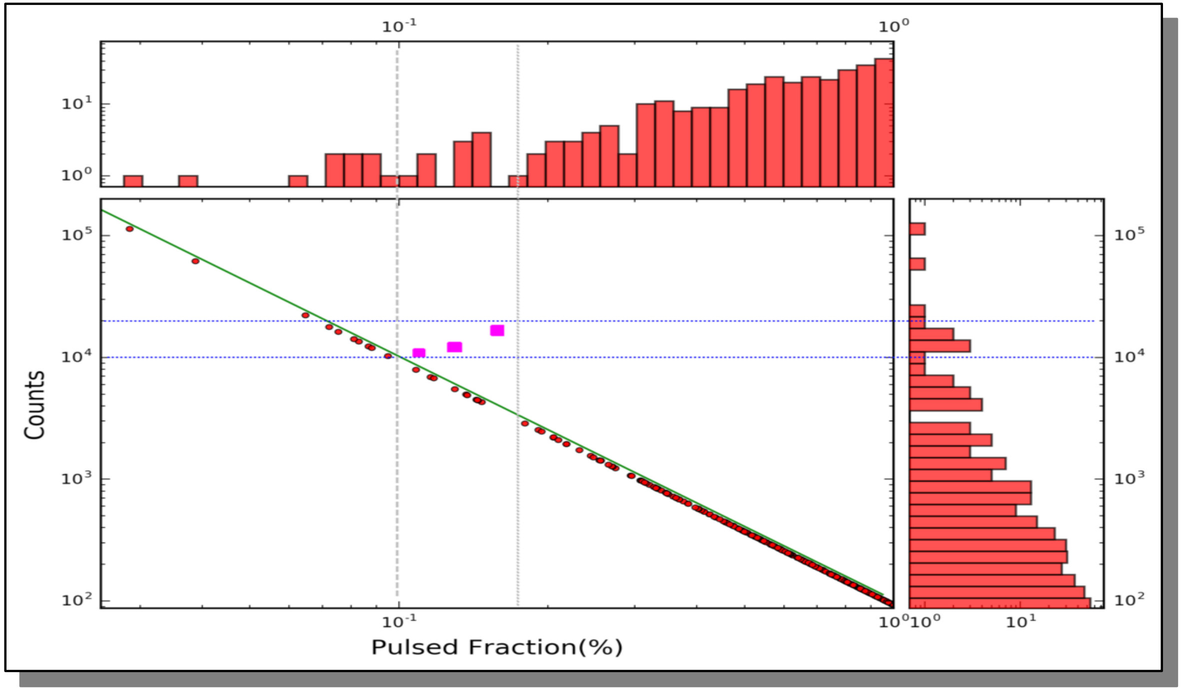
	M82 X-2	NGC 7793	NGC 5907	NGC 300	M51 ULX7
Pspin (s)	1.37	0.416	1.4-0.95	45-16	2.8
Pdot (s/s)	up / down	-3.5e-11	up / down (-8e-10)	-6e-7	-1e-9/e-10
Porb (d)	2.53	63.9	~5.1	< 35	1.99
Super orbital P (d)	63.8	66.9	78	-	38
Max. Lx (erg/s)	2e+40 ~100 L_{Edd}	6e+39	1.6e+41 ~1000 L_{Edd}	5e+39	8e+39
Min Lx (erg/s)	< 2.5e+38	6e+37	<1.2e+38	1e+38	3e+38
Optical Companion	5-20M⊙	18-23M⊙ B9I	M⊙>1M⊙	M<20M⊙ supergiant	~(8-13)M⊙

How many (2020)?

7 out of 300, ~2% ?

We detected PULXs in observations with at least 10,000 counts (XMM)

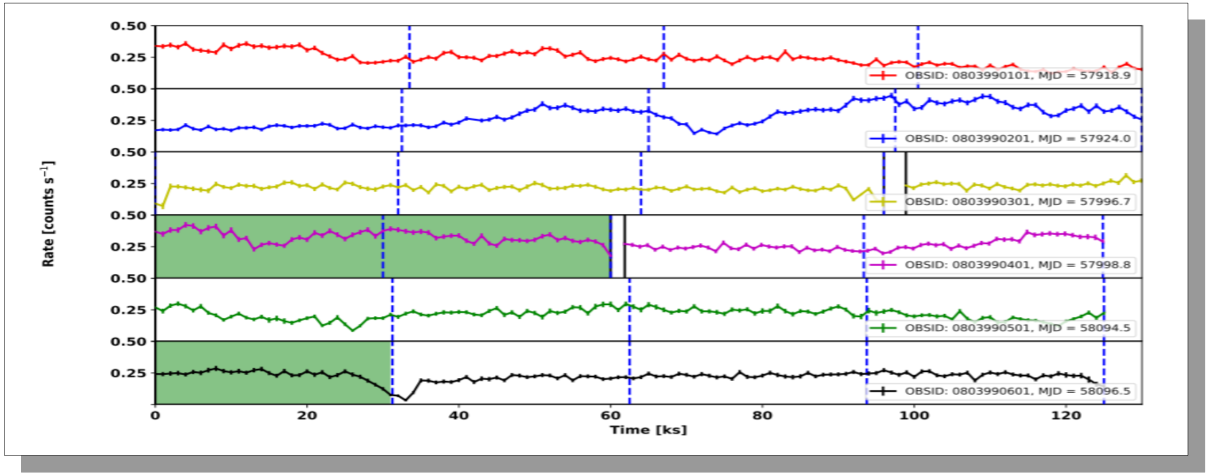
How many ULXs with such statistics (2020)?



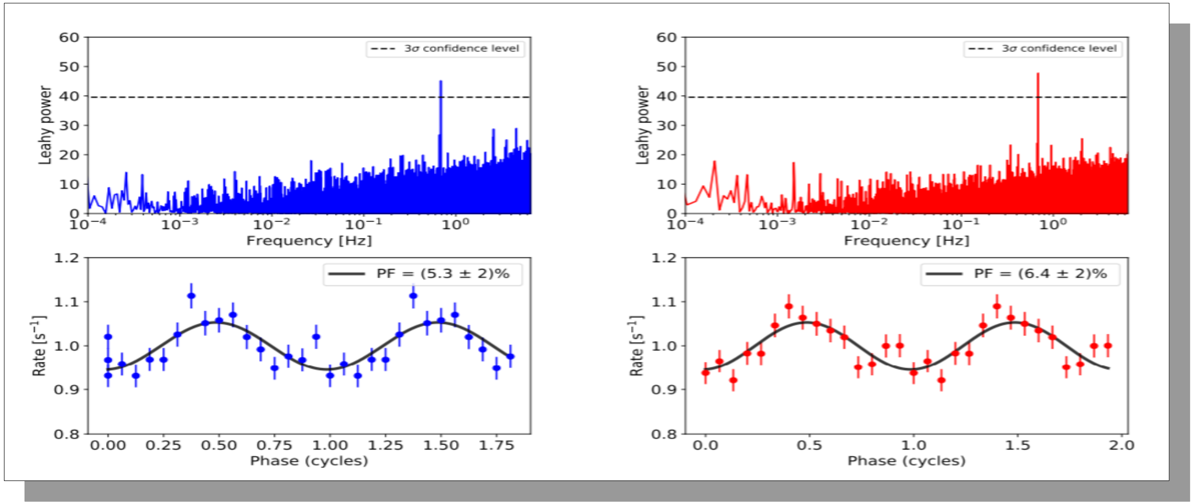
~25 ULXs (8% of all known ULXs) → 30% are PULXs

Not all pulsars are expected to be beamed towards us:
30% must be taken as a lower limit

… and the latest discovered intermittent PULX



NGC1313 X-2
P = 1.5s
PF ~ 5%
Signal duty cycle ~14%



(Sathyaprakash+19)

Expectations versus Observations

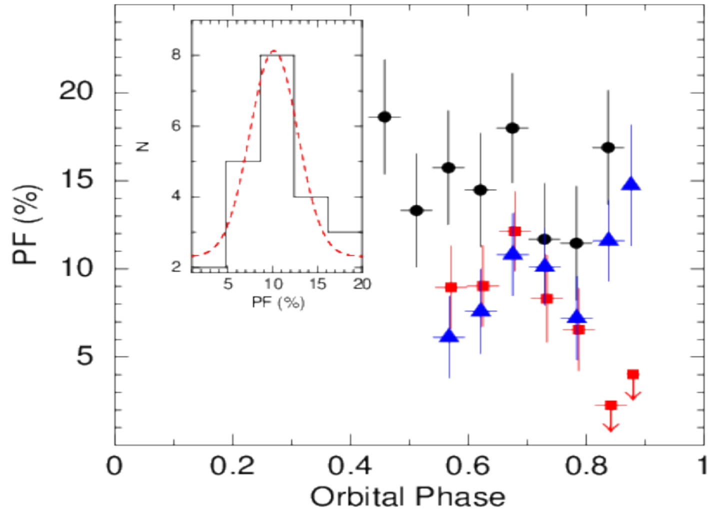
1 new PULX found so far in the XMM LP
2-3 expected based on our statistics

=

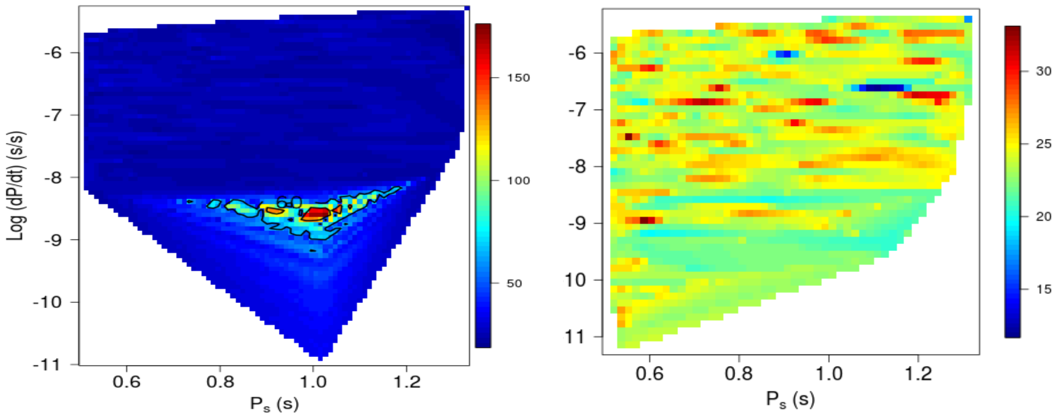
marginally consistent results

BUT
signals extremely variable.

large variability in the signals PF.
undetected for about 3hr



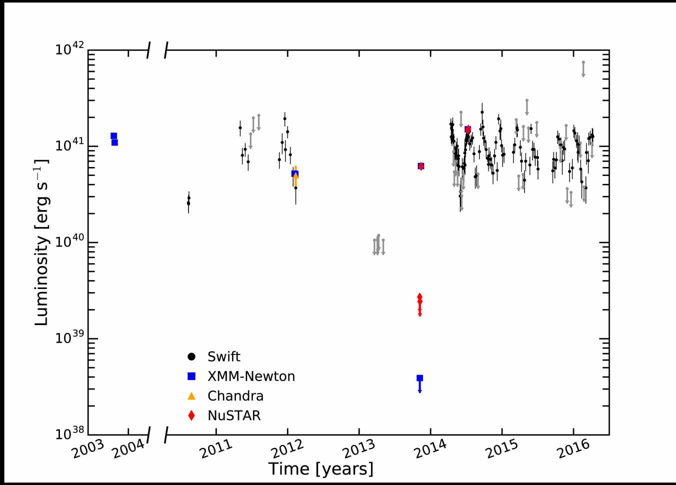
NGC5907 at few days distance
same flux level

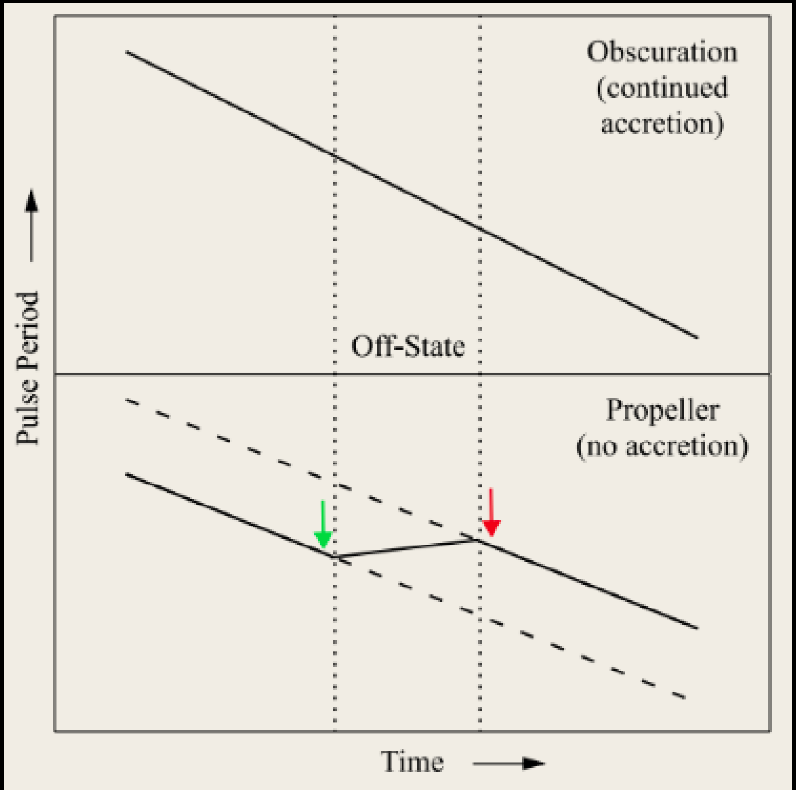


The extreme case of NGC5907 X-1

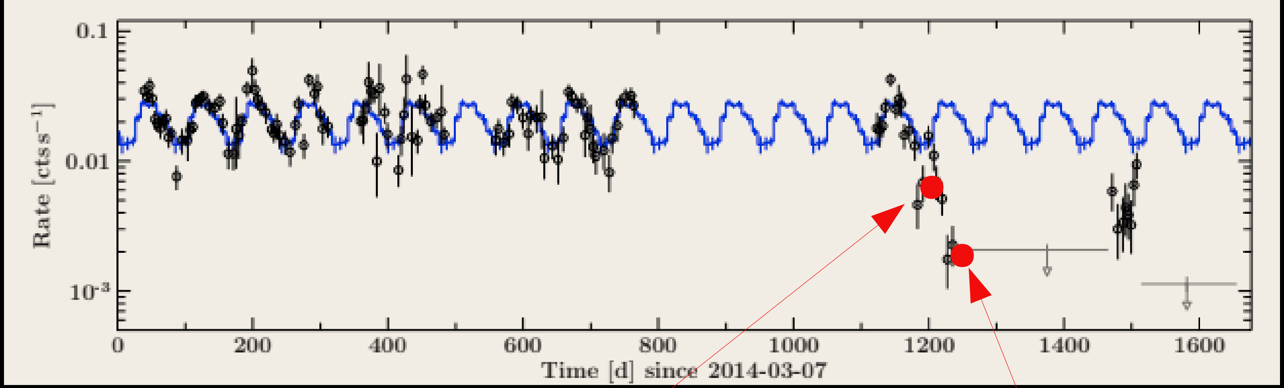
XMM LP (PI Belfiore: 380ks) to improve the orbital parameters (peak of the $P_{S\text{-}Orb}$) during high-states

XMM LP (PI Walton: 380ks) to check P_{spin} after low-states: testing the occultation scenario versus the propeller one



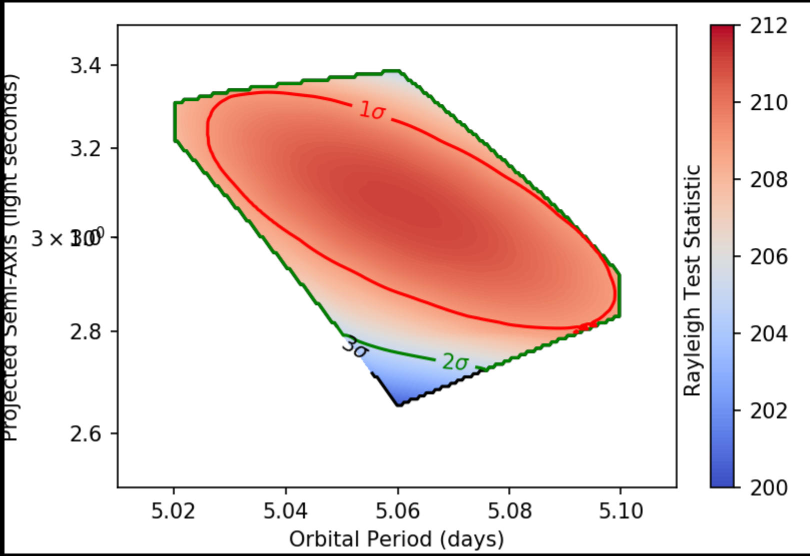


NGC5907 follow-up observations



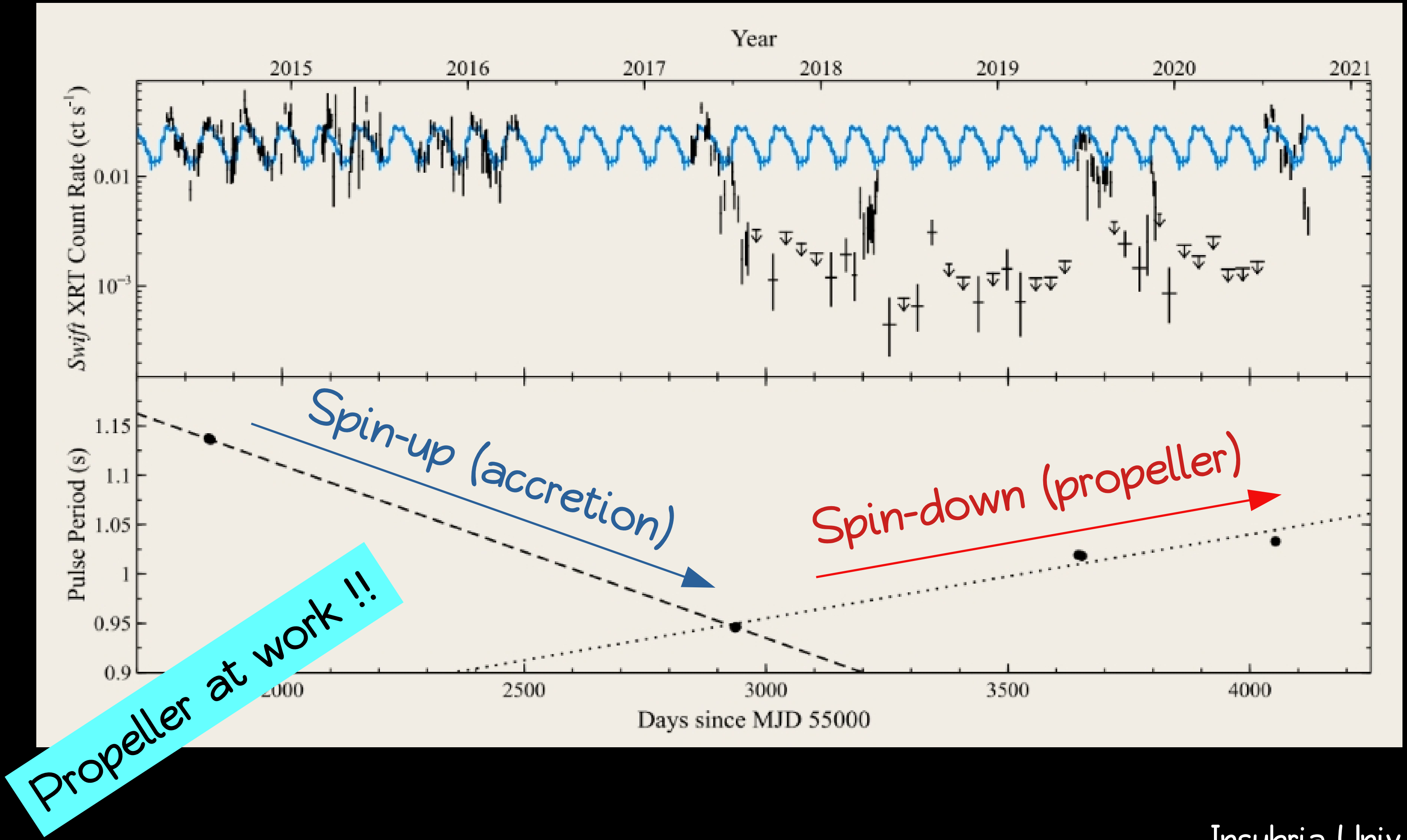
Faint signal at ~946ms

No pulsations



Porb = 5.06+\-0.15 d
Ax sin*i* = 3.1+\-0.4 lt-s

NGC5907 follow-up observations



Some implications/Conclusions

+ Extreme ULXs (>1e41 erg/s), like NGC5907 ULX-1, can hosts accreting NSs. Total number of NS among ULXs could be very high

+ Intrinsically difficult to find !
  The detection of these pulsars is a hard task with standard tools and current instruments. CPU-time consuming methods and HPCs at rescue….
  Athena is expected to give an important contribution to PULX studies.

+ B versus b
  PULXs challange the current models of accretion, even assuming a large beaming.
  A "normal" dipolar B component plus a multipolar B component (and moderate beaming) might account for both the observed Lx and Pdot.

+ Next challenge is the Porb variation in M82 X-2 and M51 ULX-7. XMM LP (390ks) in AO20.