The Extragalactic population of NS and the ULX paradigm revolution

GianLuca Israel (INAF Astronomical Observatory of Rome)
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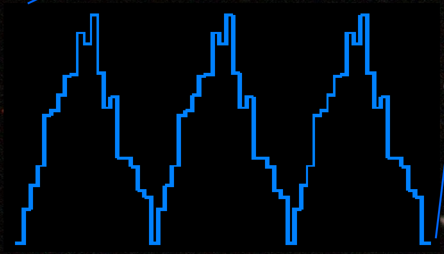
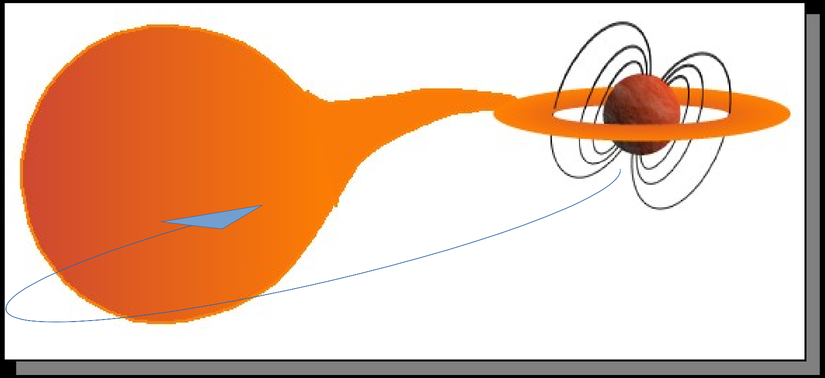


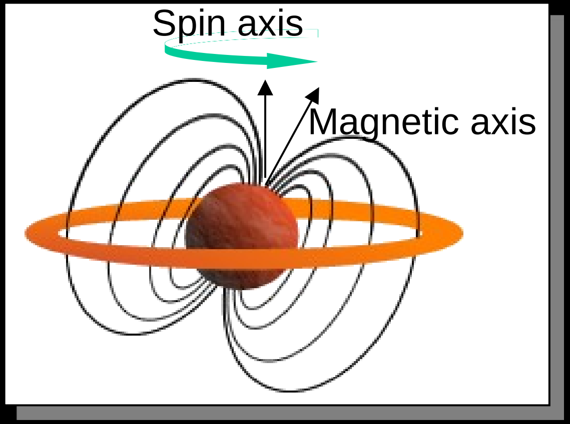
- Outline
- Data mining & periodicity search
- The CATS @ BAR and EXTraS projects
- The extragalactic pulsars (M31 and beyond): the Pulsating ULXs
- Beaming vs super-Eddington accretion
- The UNSEEN project and the next steps

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 Data Mining

About 40-60 serendipitous sources per field (Chandra and XMM) !!
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]

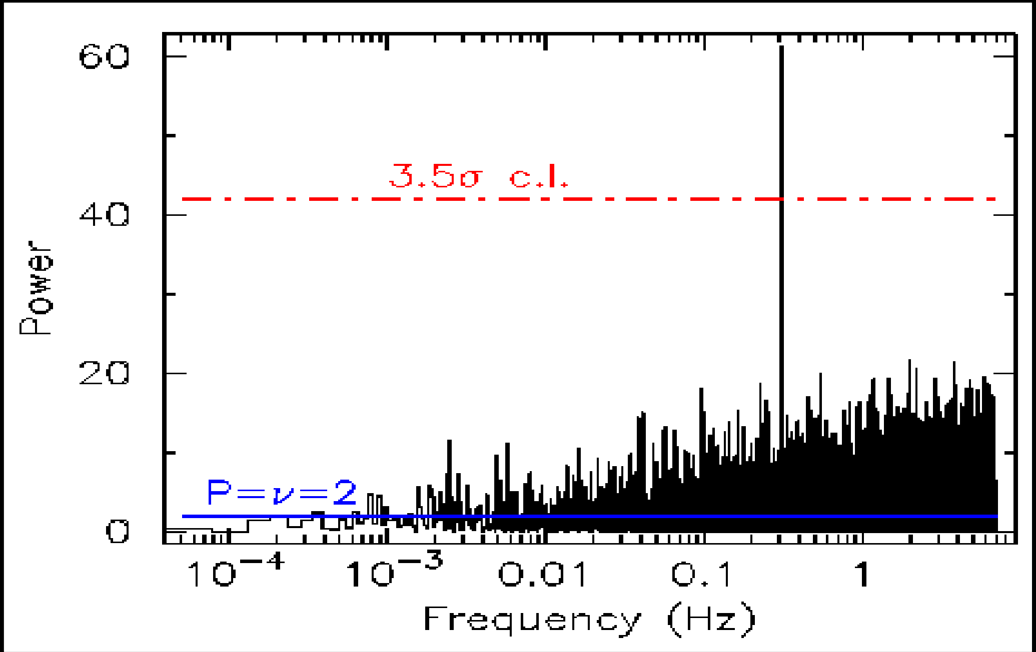
Implication: cut-off in the number of detectable NS for low Lx and/or only detection of long-period low-flux pulsators

How

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

- Well known technique;

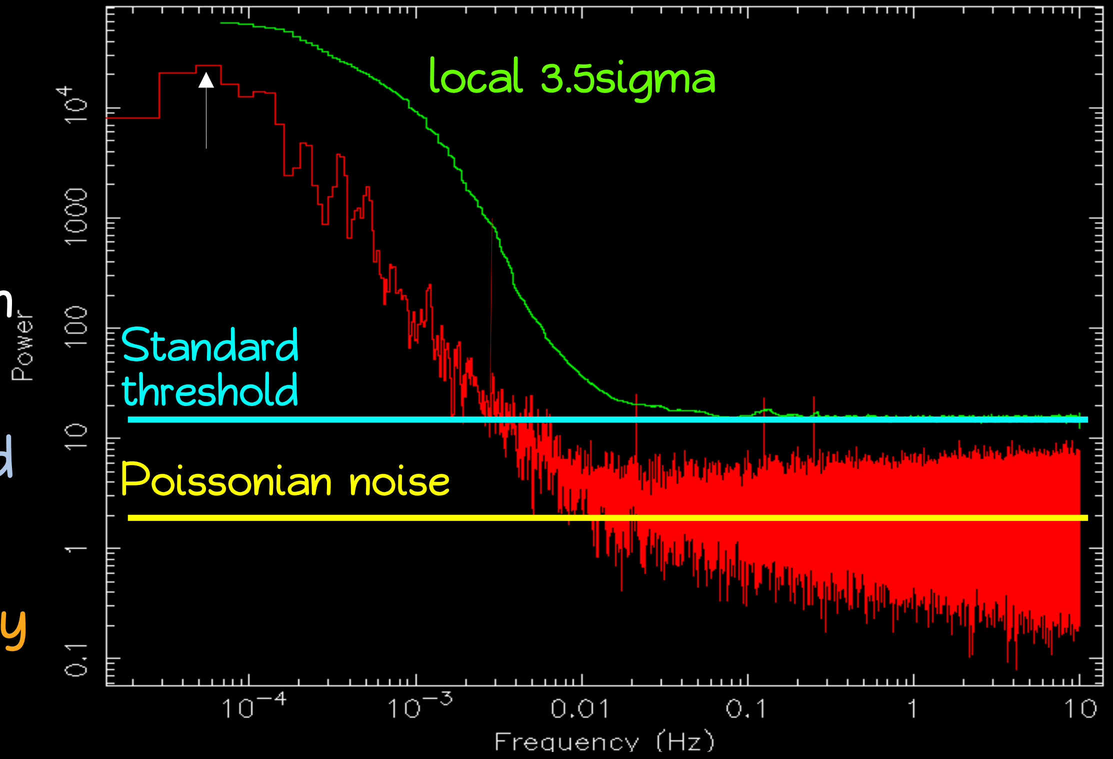
- Limits on low statistics and/or highly non sinusoidal signals



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



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

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, ~2M detections).

EXTraS WP3 (periodicity search) in numbers:

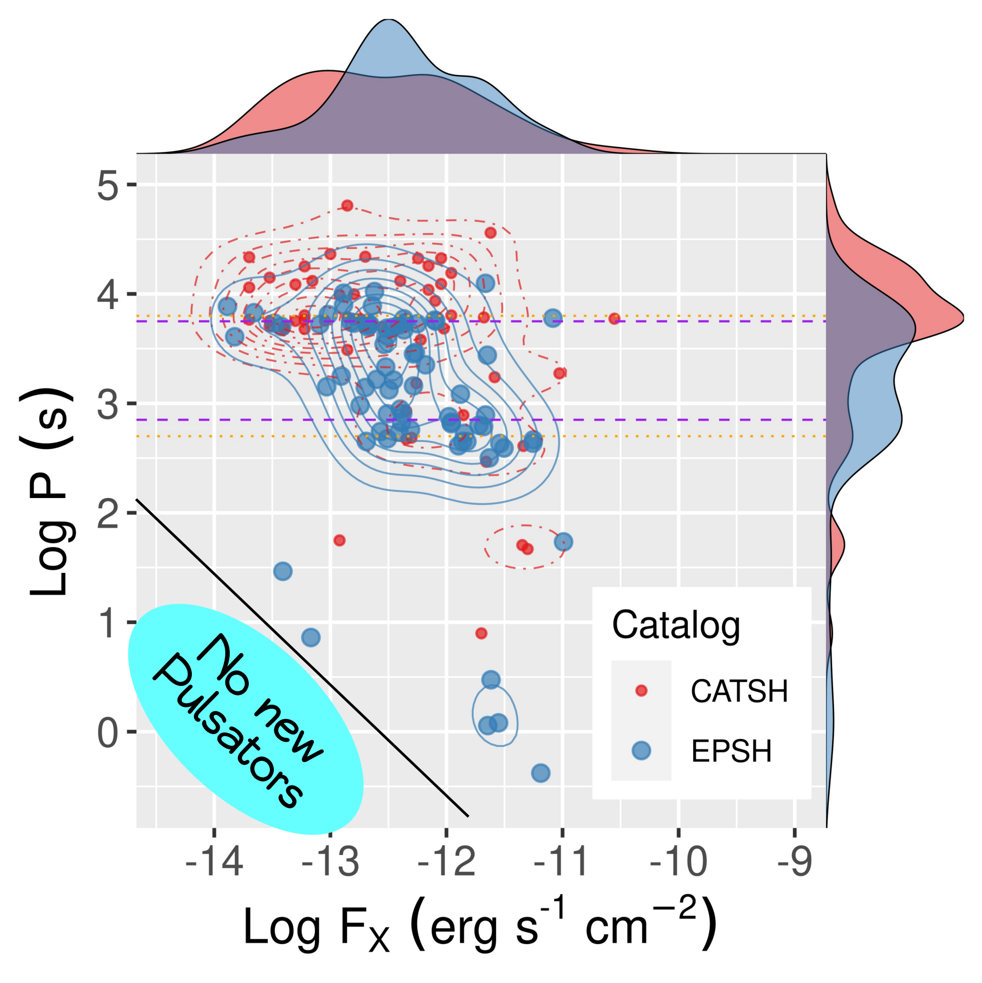
- 20 years of public data
- >10,000,000 times series (TSs)
- ~400,000 TSs with >50 photons searched for signals
- >15,000 datasets
- ~200,000 peaks
- 60 new X-ray pulsators (still counting)

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

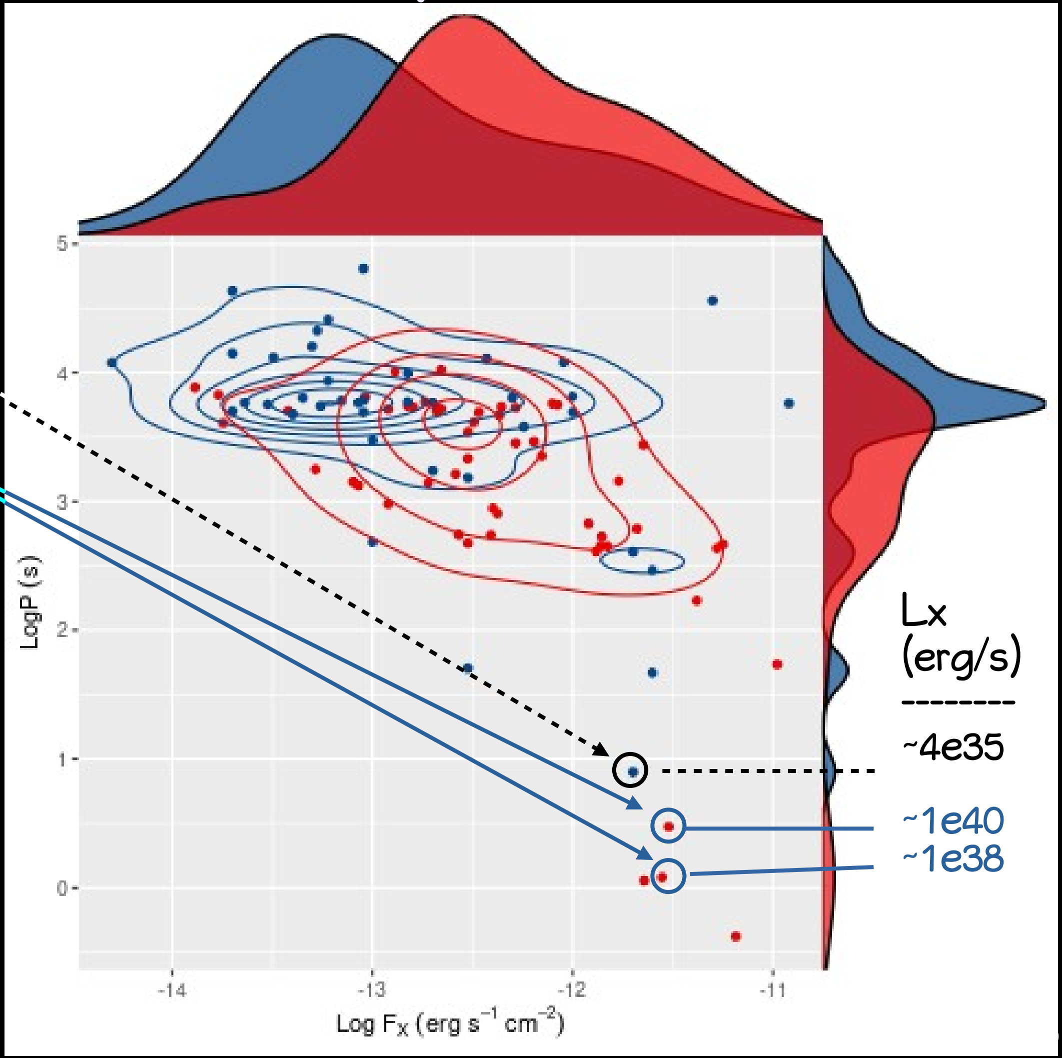
Magnetic gating/propeller ($r_m > r_c$)
Short P need high L to accrete onto NS
Low L systems need long P to accrete



The rise of a new population of pulsars

Below 10s period:

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



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EXTraS: first NS discovered in M31

ESA SPACE SCIENCE

European Space Agency

Our Universe

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

Science missions

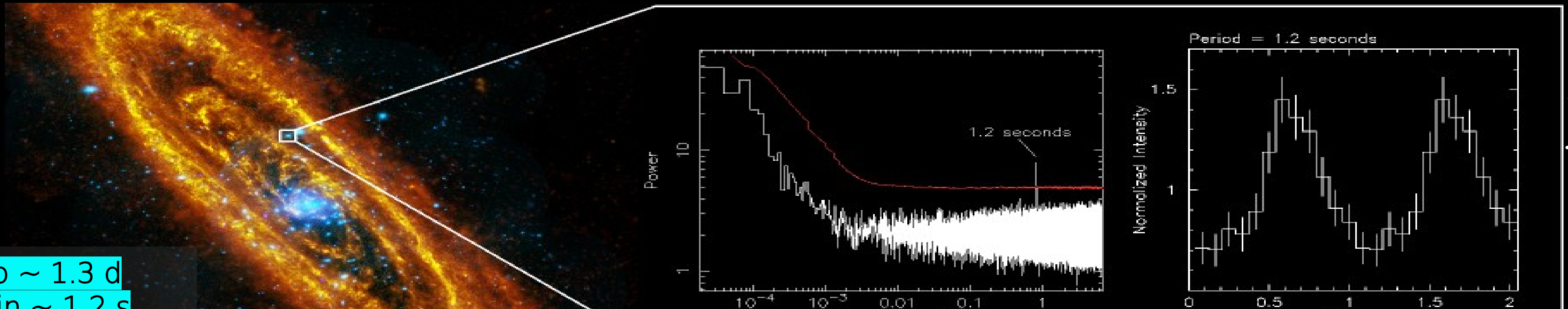
- Mission navigator

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.

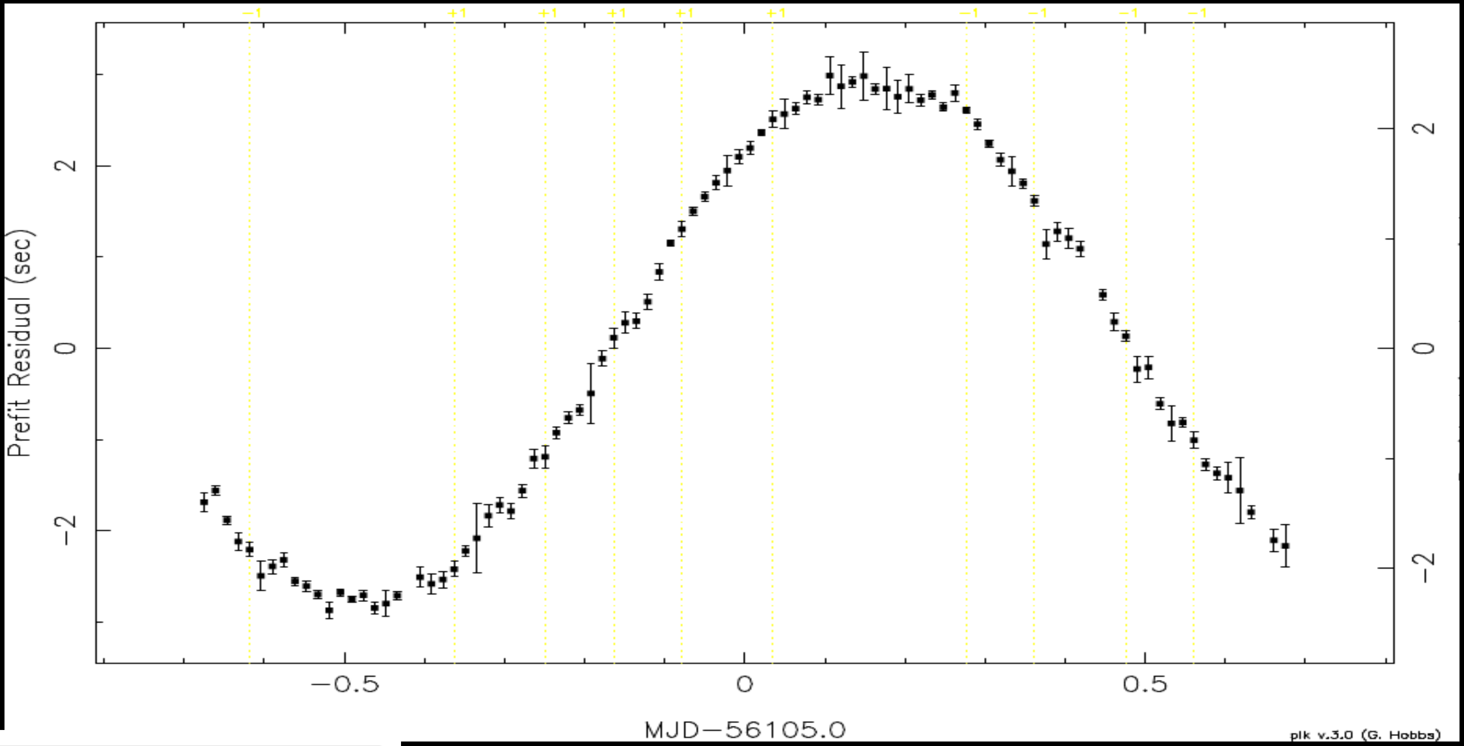


Porb ~ 1.3 d

Pspin ~ 1.2 s

(Esposito+16

- … in a 1.2d binary system



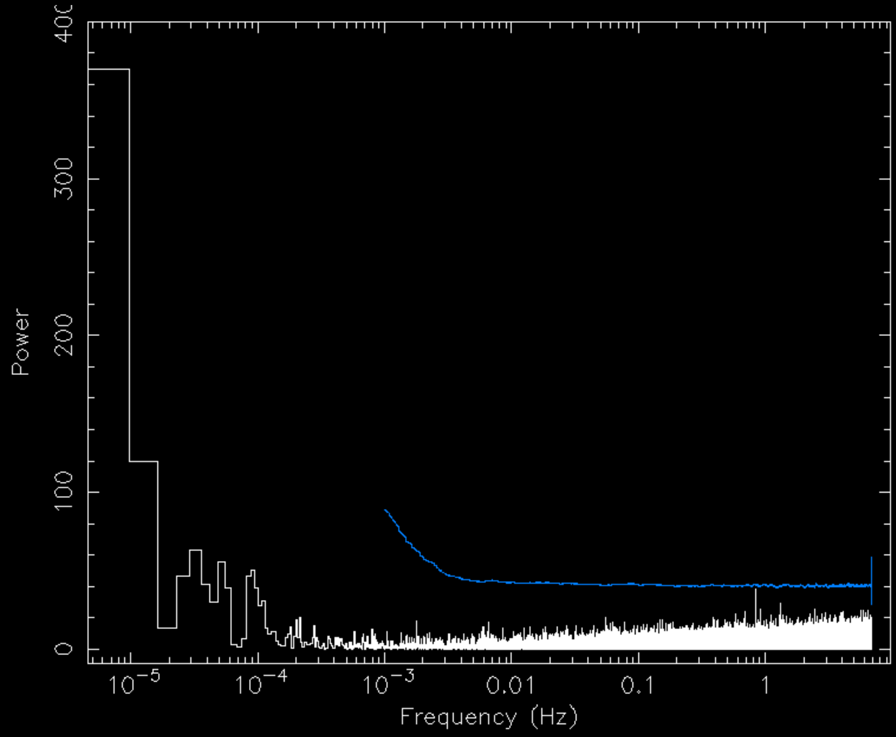
Parameter	Value
Orbital period, P_b (d)	1.27397828 ± 0.00000071
Epoch of ascending node, T_{asc} (MJD)	56104.7912 ± 0.0011
Projected semi-axis, $A_X \sin i$ (lt-s)	2.884 ± 0.017
Eccentricity, e	0.011 ± 0.009[a]
Longitude of periastron, ω (°)	276 ± 41
Mass function ($M_\odot$)	0.0159 ± 0.0008
Minimum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

[a] Upper limit at the 3σ confidence level: $e < 0.037$.

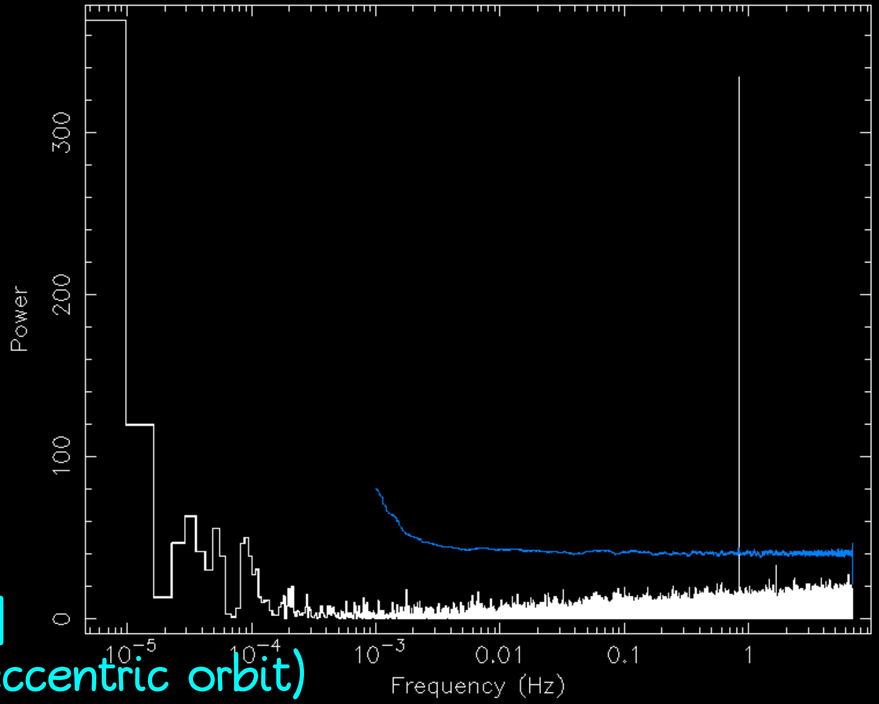
[b] Value computed for an orbit viewed edge-on, $i = 90°$.

(Esposito et al. 2016)

Recovering a signal in an orbit



Uncorrected (raw data)

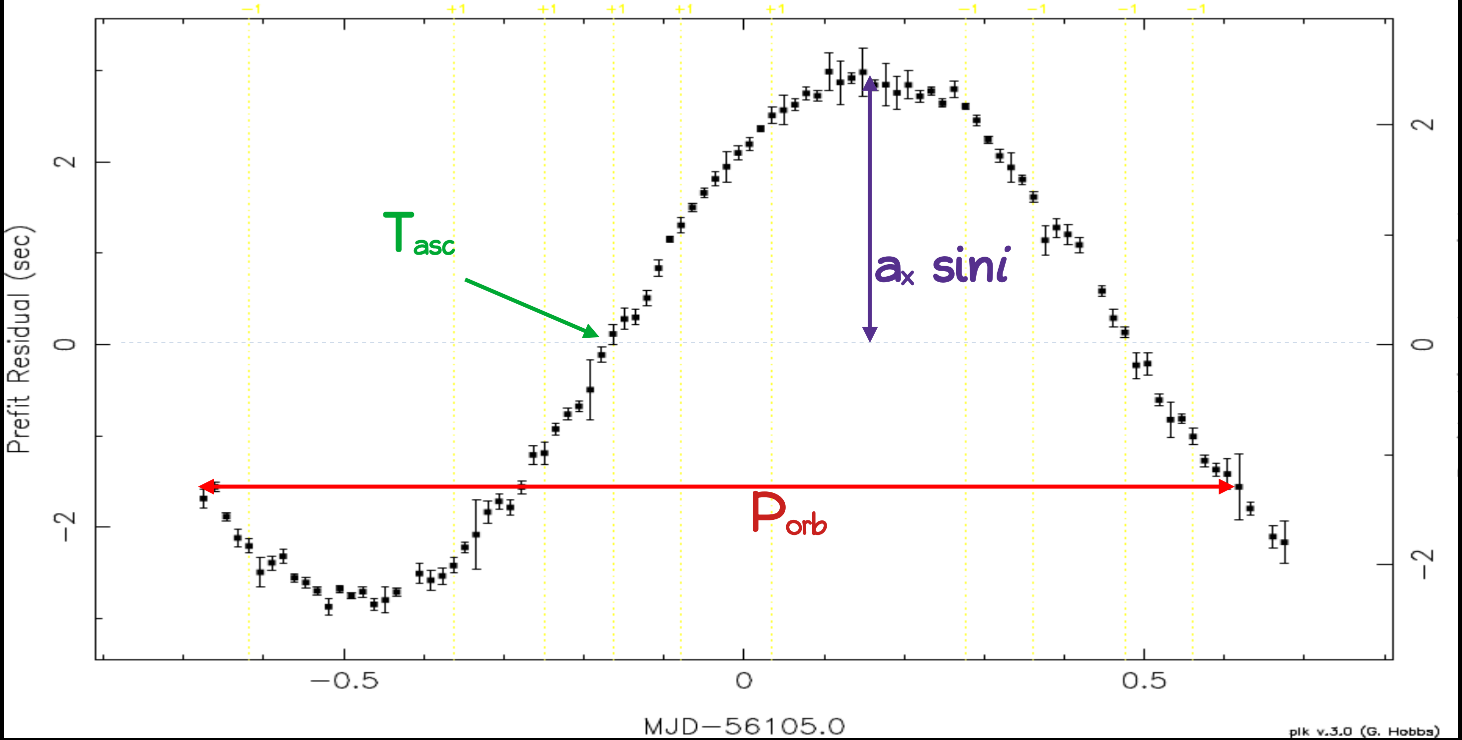


Precorrecting photon times:

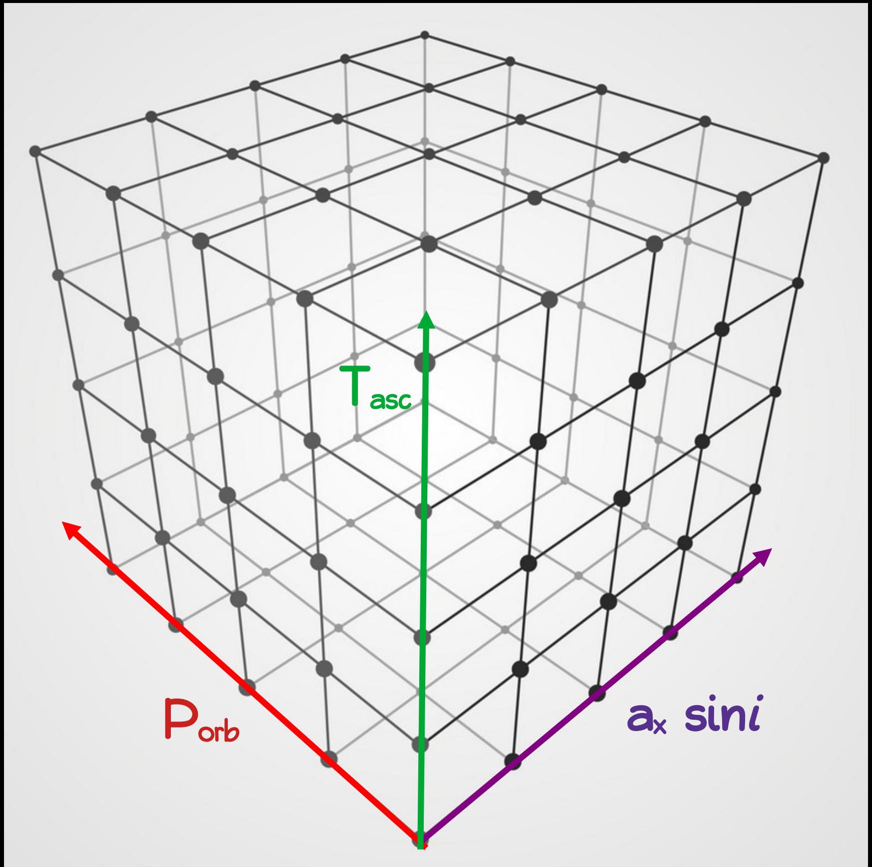
$t' = t - a_x \sin i * \sin[(2p/P_{orb})*(t-T_{asc})]$

function of: $a_x \sin i$, P_{orb}, T_{asc}, (*e if eccentric orbit*)

Recovering a signal in an orbit



Recovering a signal in an unknown orbit



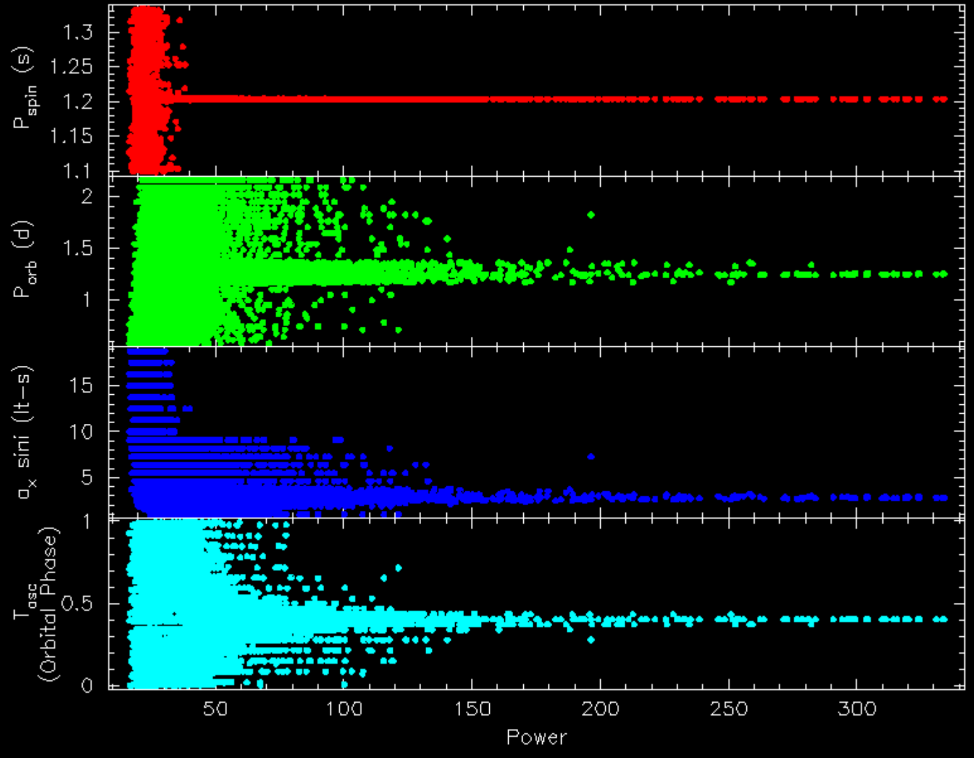
High resolution of the 3 parameters implies a higher chance of sampling the right values

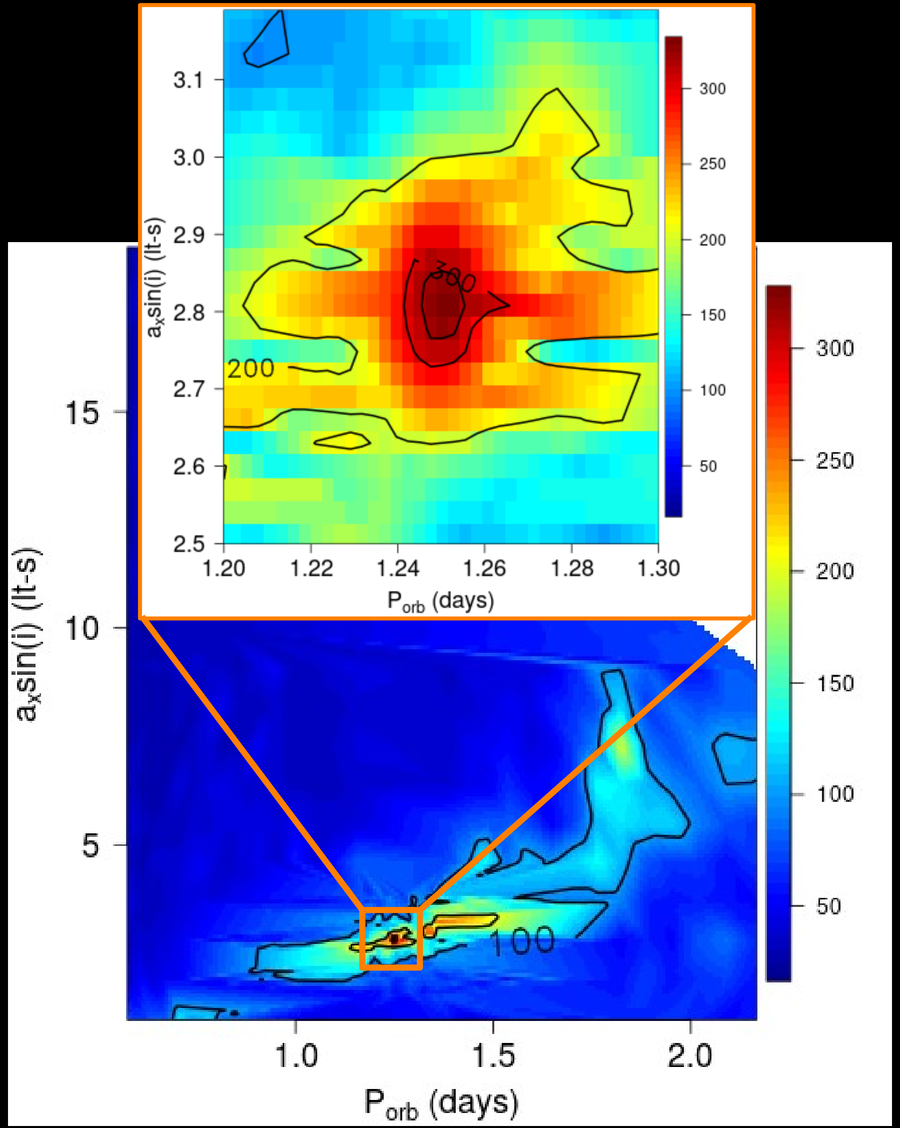
Problem: CPU-consuming

A 100x100x100 grid = 1 million FFTs (~10-30s)
Human time: 3-12months for 1 source !!!!!

Ways around:
1) working with RAM (factor of ~10)
2) working on GPU (factor of ~10)
3) More cores HPC (up to a factor of 10000)

Recovering a signal in an unknown orbit





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

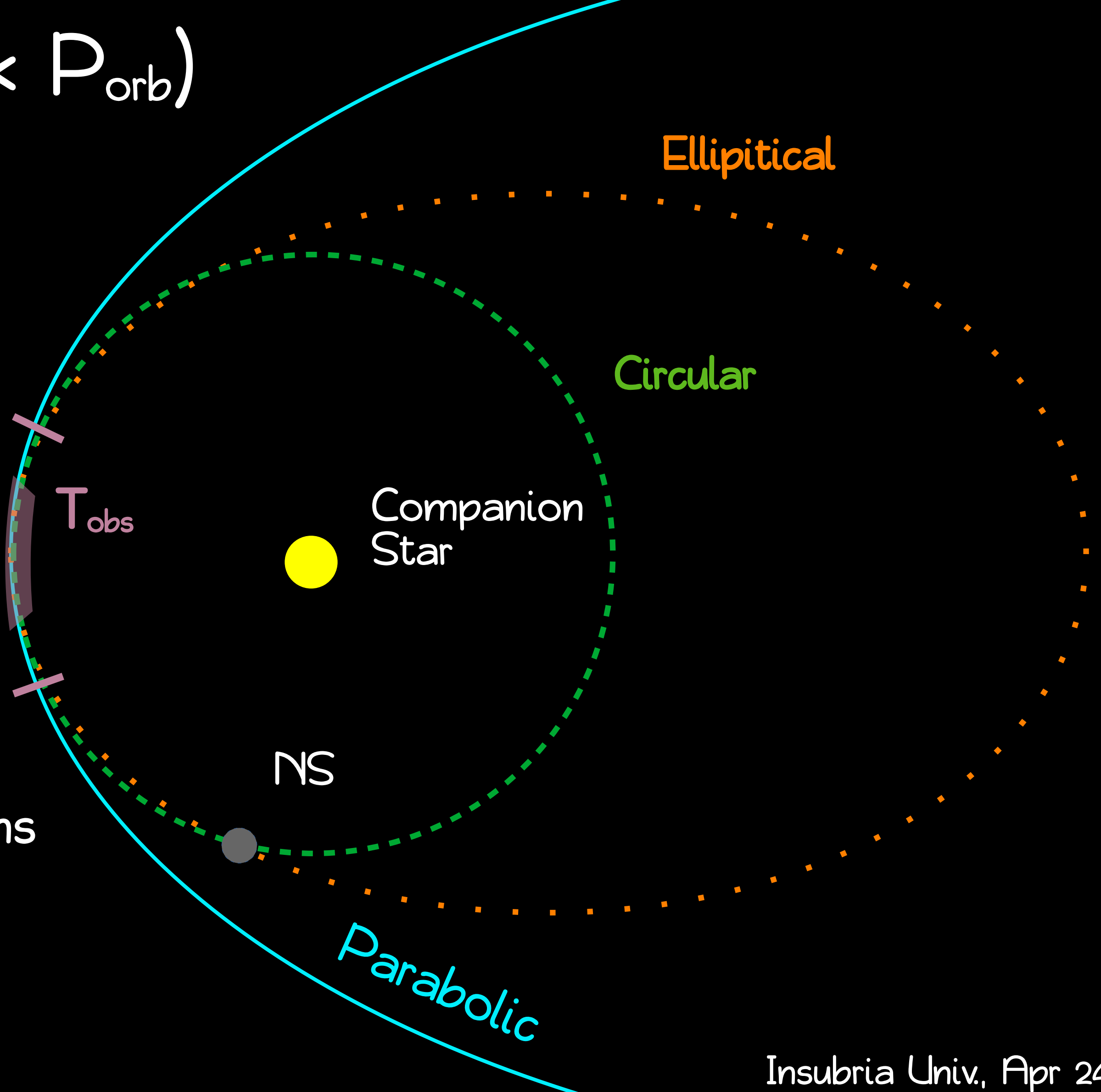
A way around ($T_{obs} << P_{orb}$)

Parabolic approximation of a circular or elliptical orbit

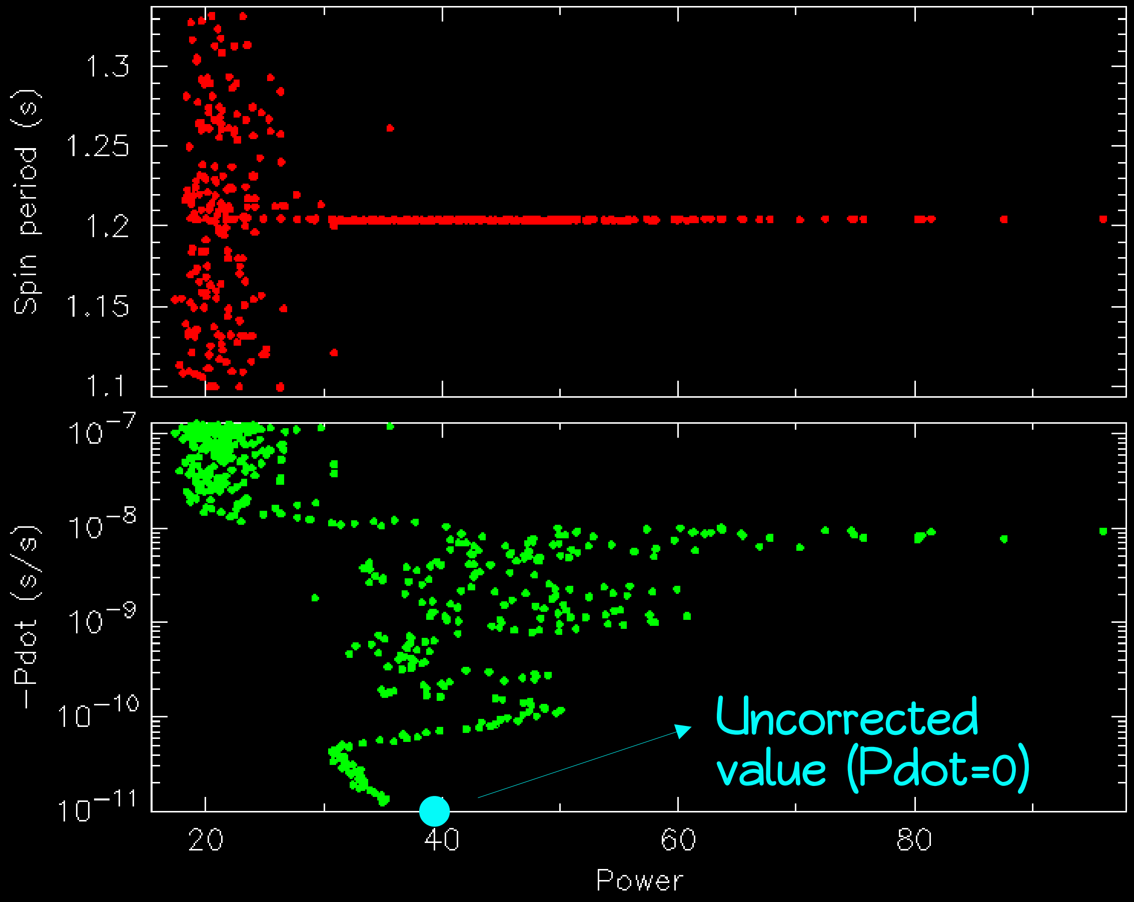
$$t' = t + \frac{1}{2}\frac{\dot{\nu}}{\nu}t^2 = t - \frac{1}{2}\frac{\dot{P}}{P}t^2$$

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

Fast wrt the orbital corrections



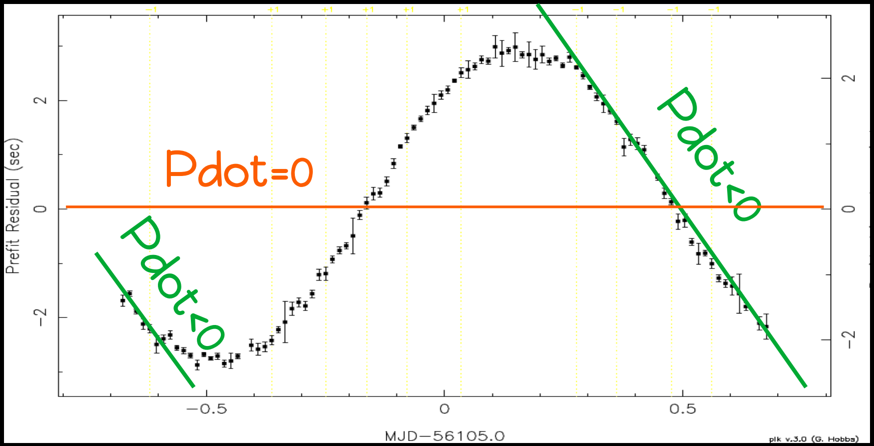
Cross-check on P1.2s pulsar



It works !!
Though a factor of about 3.5 lower in power wrt the orbital correction

Gain of >10 in CPU-time:
1 param. Versus 3 params

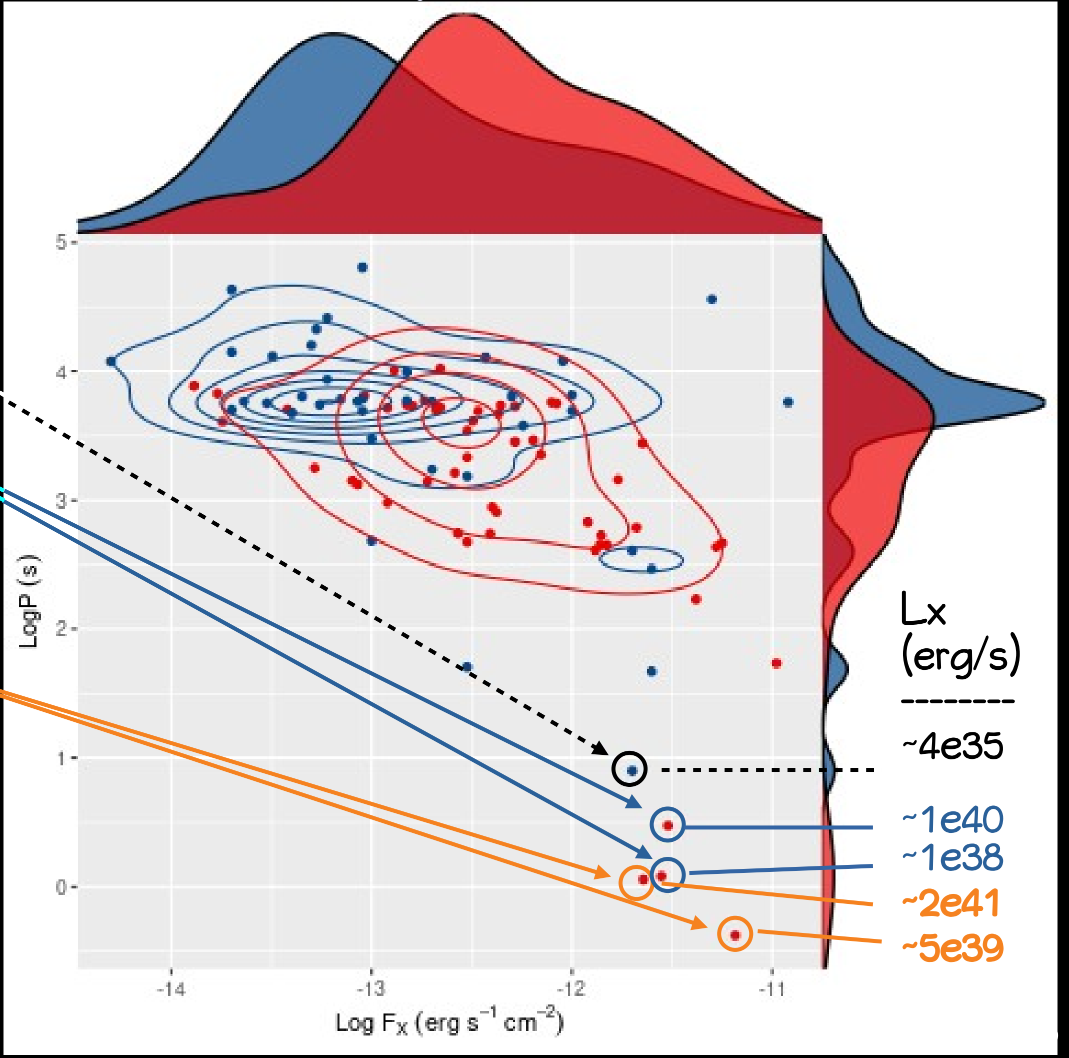
OK for large samples



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
s_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 [~1.5-3$M_\odot$] → L_{Edd} ~ 2-3.5 x 10^{38} erg/s
or
For a Lx of 1.2 x 10^{41} erg/s → M ~ 1000 $M_\odot$

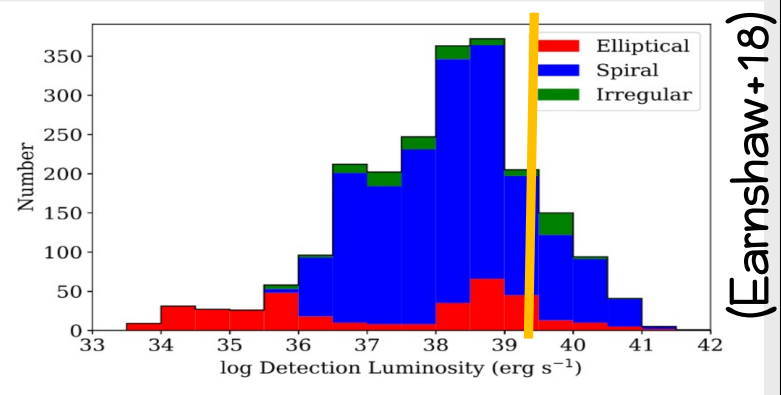
ULX class

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

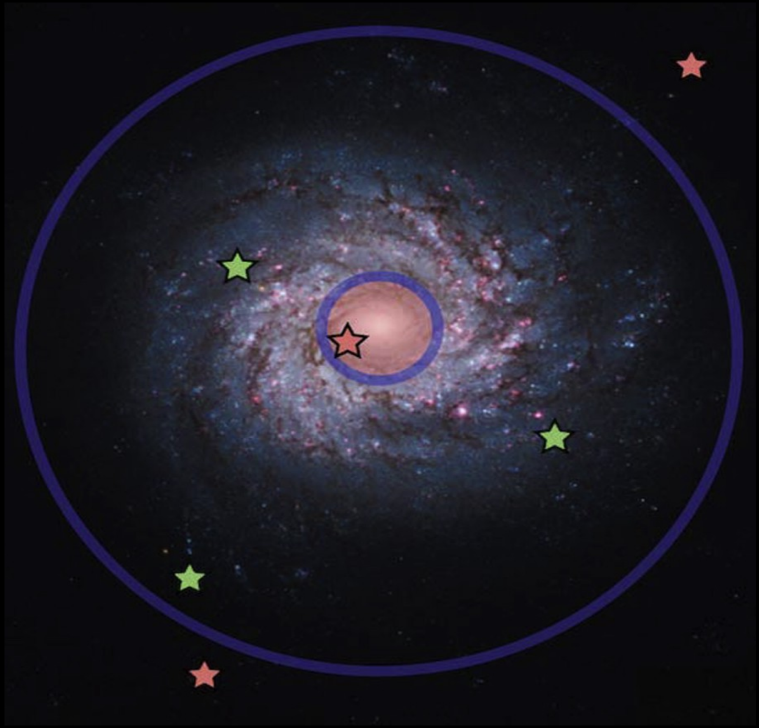
$L_{ULX} > 1\text{-}2 \times 10^{39}$ erg/s
up to ~10^{42} erg/s

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

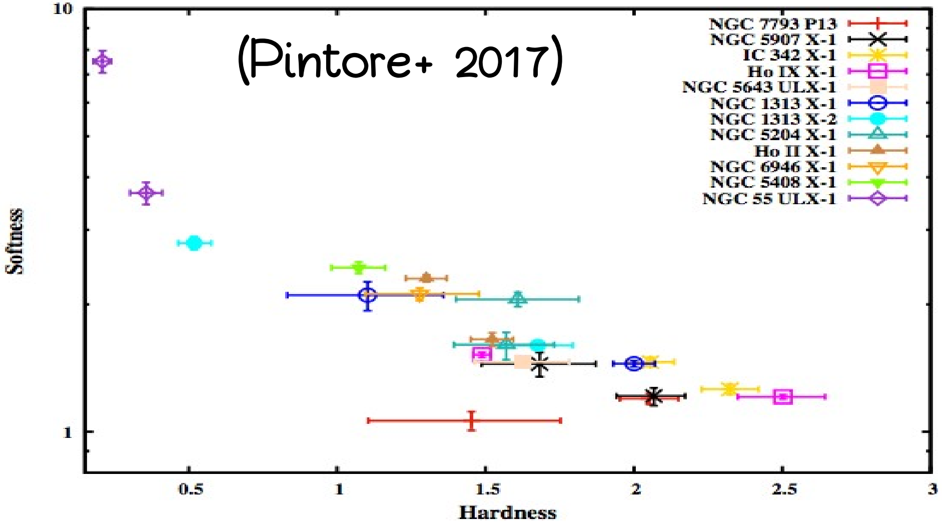
IMBHs ?



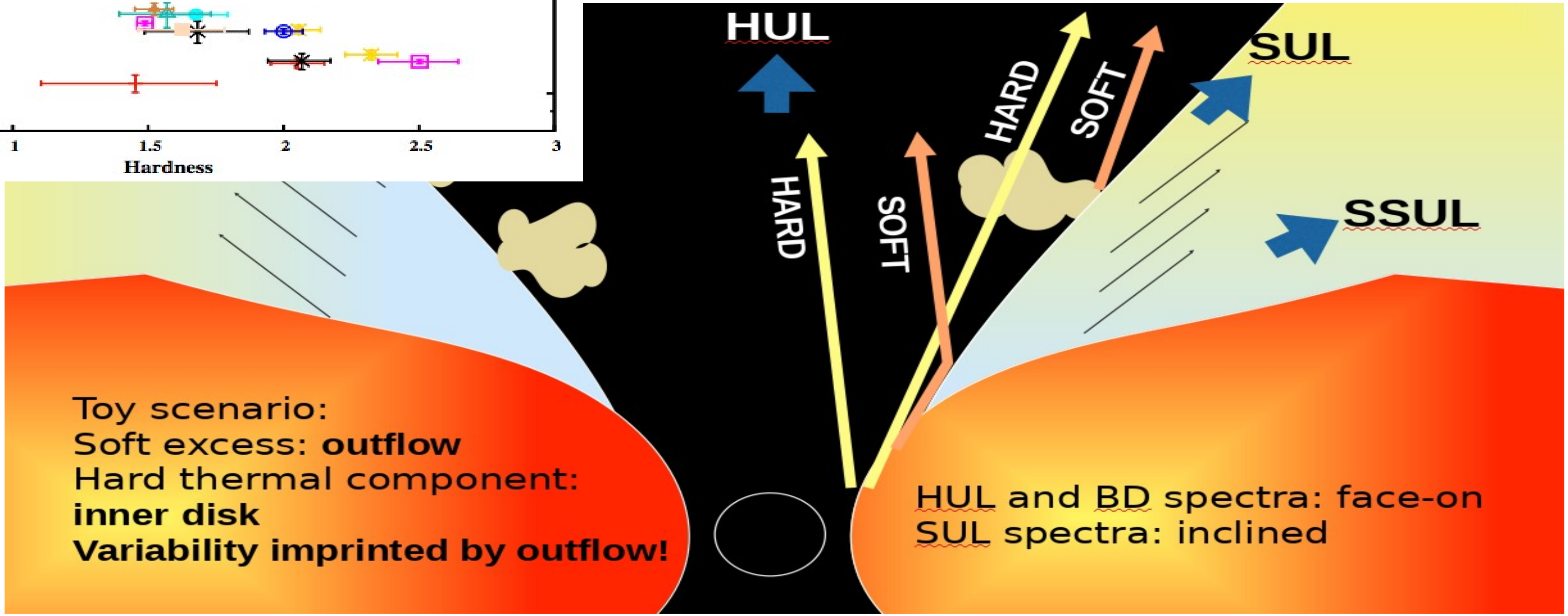
(Earnshaw+18)



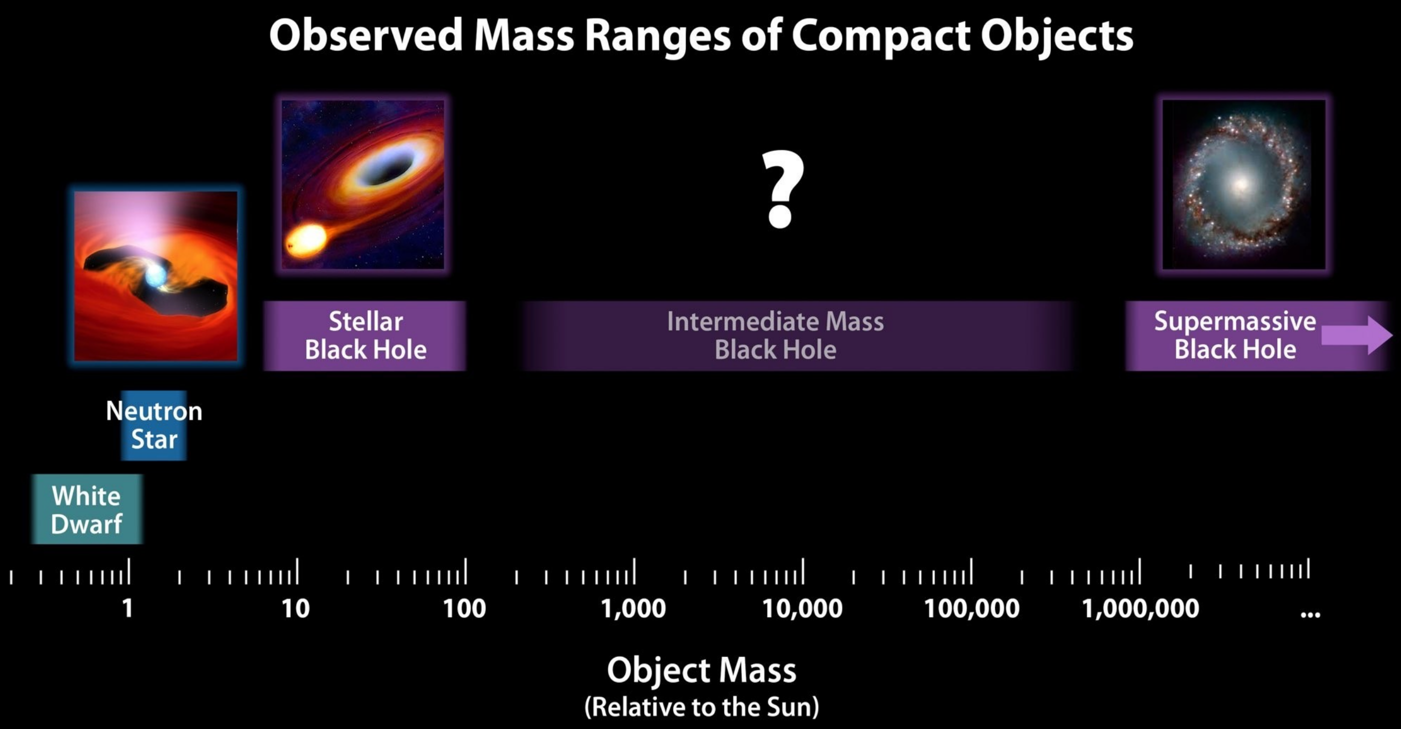
ULX class



(Pintore+ 2017)
NGC 7793 P13
NGC 5907 X-1
IC 342 X-1
Ho IX X-1
NGC 5643 ULX-1
NGC 1313 X-1
NGC 1313 X-2
NGC 5204 X-1
Ho II X-1
NGC 6946 X-1
NGC 5408 X-1
NGC 55 ULX-1
Softness
Hardness
10
1
0.5
1
1.5
2
2.5
3



HUL
SUL
SSUL
HARD
SOFT
HARD
SOFT
Toy scenario:
Soft excess: **outflow**
Hard thermal component:
inner disk
Variability imprinted by outflow!
HUL and BD spectra: face-on
SUL spectra: inclined



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

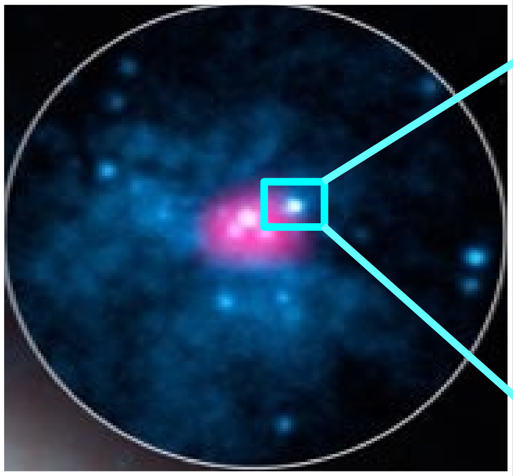
.. for 25years everybody was convinced of the BH nature of ULXs... 2017)

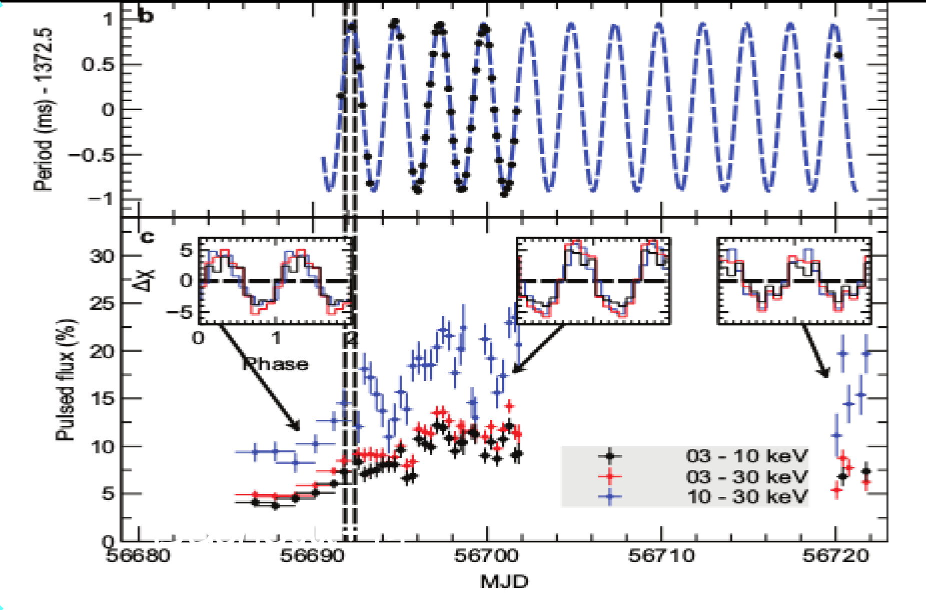
A long time ago in a galaxy far,
far away....

ULXs and M82 X-2

Pulsations at 1.37s discovered from NuSTAR obs of M82 X-2
Sinusoidal pulse shape; PF~20%
L_x~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}





Considered an odd object !

Science

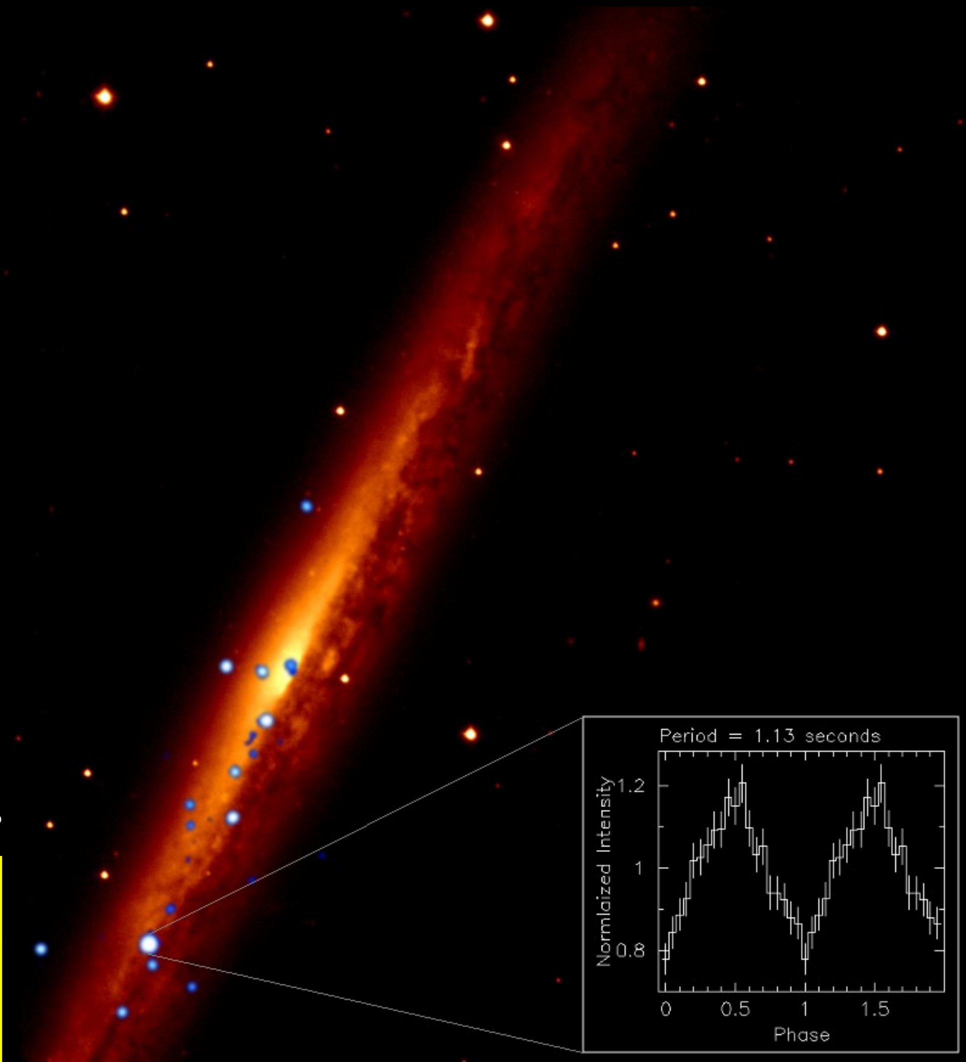
REPORT

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]

- 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



NGC 5907 ULX

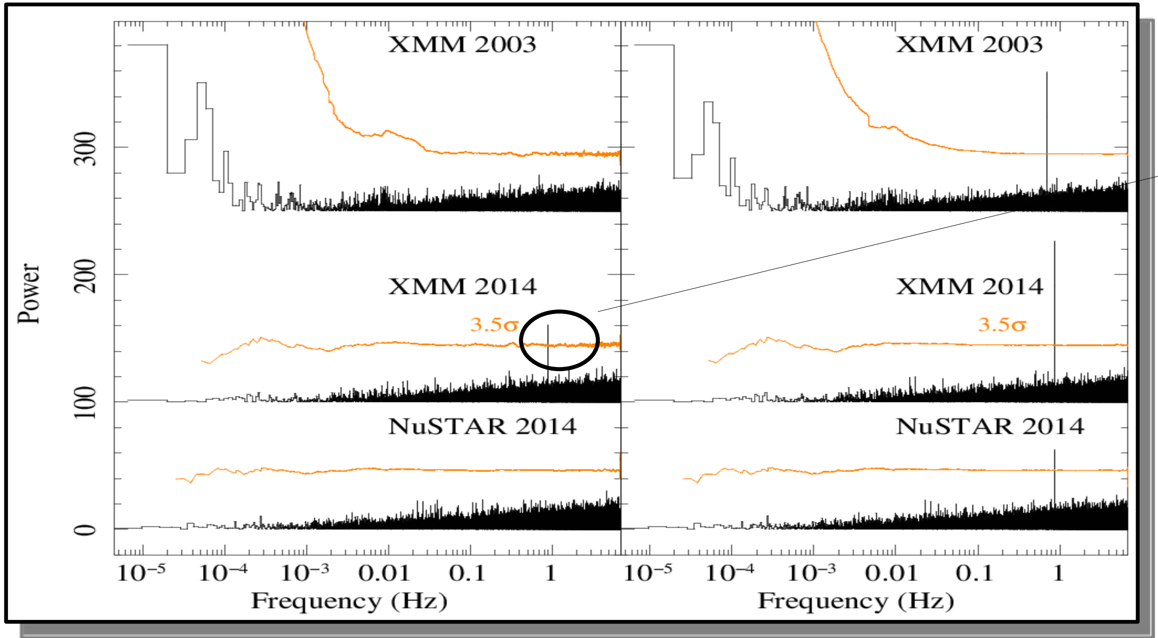
7 XMM pointings (6 source detection)+5 NuSTAR pointings (3 detection)

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

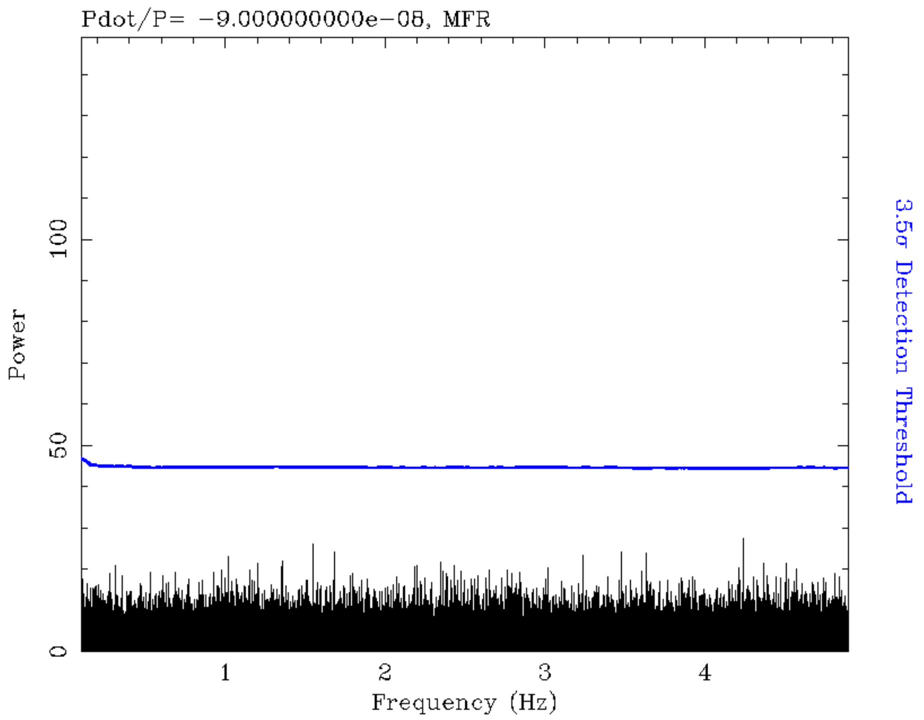
Start Date	2003 Feb. 28	2014 Jul. 09	2014 Jul. 09	2014 Jul. 12
Mission	*XMM–Newton*	*NuSTAR*	*XMM–Newton*	*NuSTAR*
Epoch (MJD)	52690.9	56848.0	56848.2	56851.5
P (s)	1.427579(3)	1.137403(1)	1.137316(2)	1.136041(1)
$\dot{P}$ (s s^{-1})^a $\times 10^{-9}$	-9.6(7)	-5.2(1)	-5.0(4)	-4.7(1)

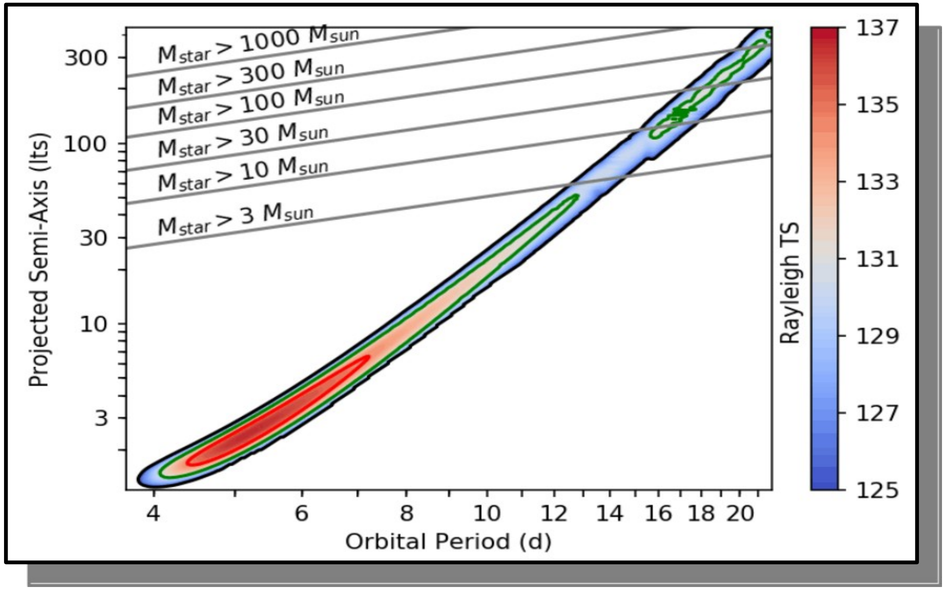
Pdot(secular) =-8.1(1)e-10 s/s

P/Pdot ~ 40 yr !!!

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

Porb=5.3[+2.0,-0.9] days (1📅)

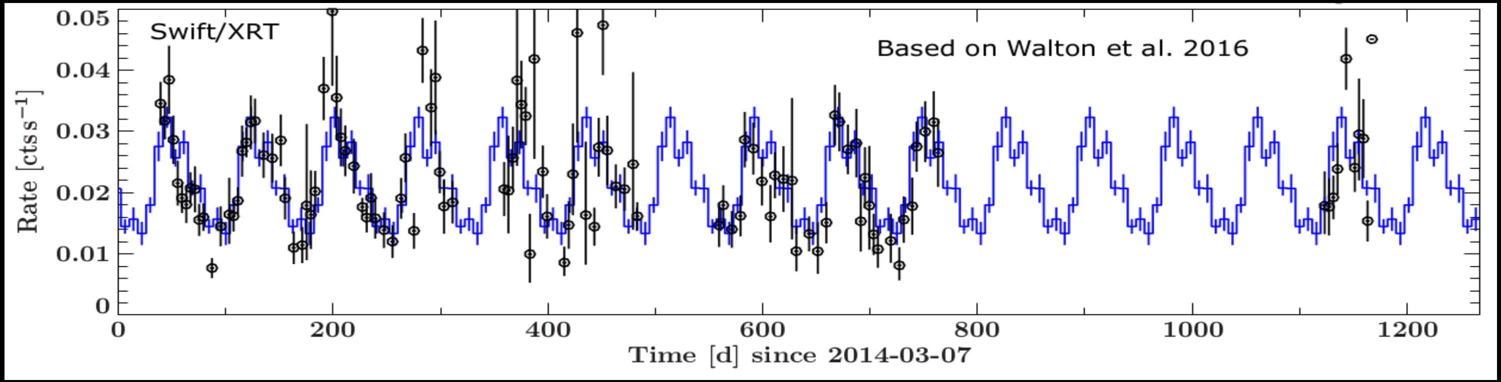




GLI+17a

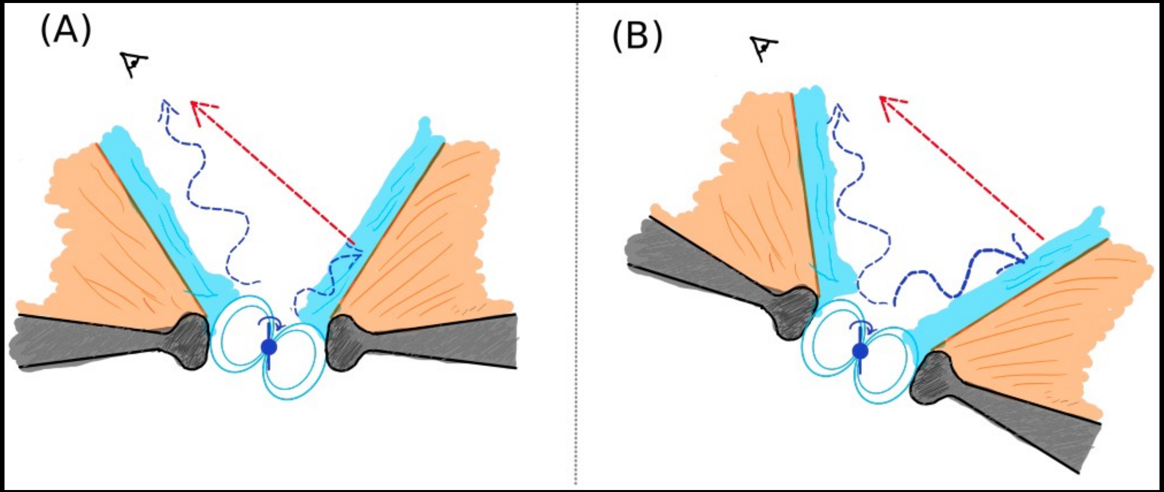
Super-orbital modulation and precession

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



Open questions

- Their luminosities challanges the “classical” models for accretion. How to account for such high luminosities ? Is there enough mass to accreate ?

- How many NS among ULXs ? Oddballs or tip of the iceberg ?

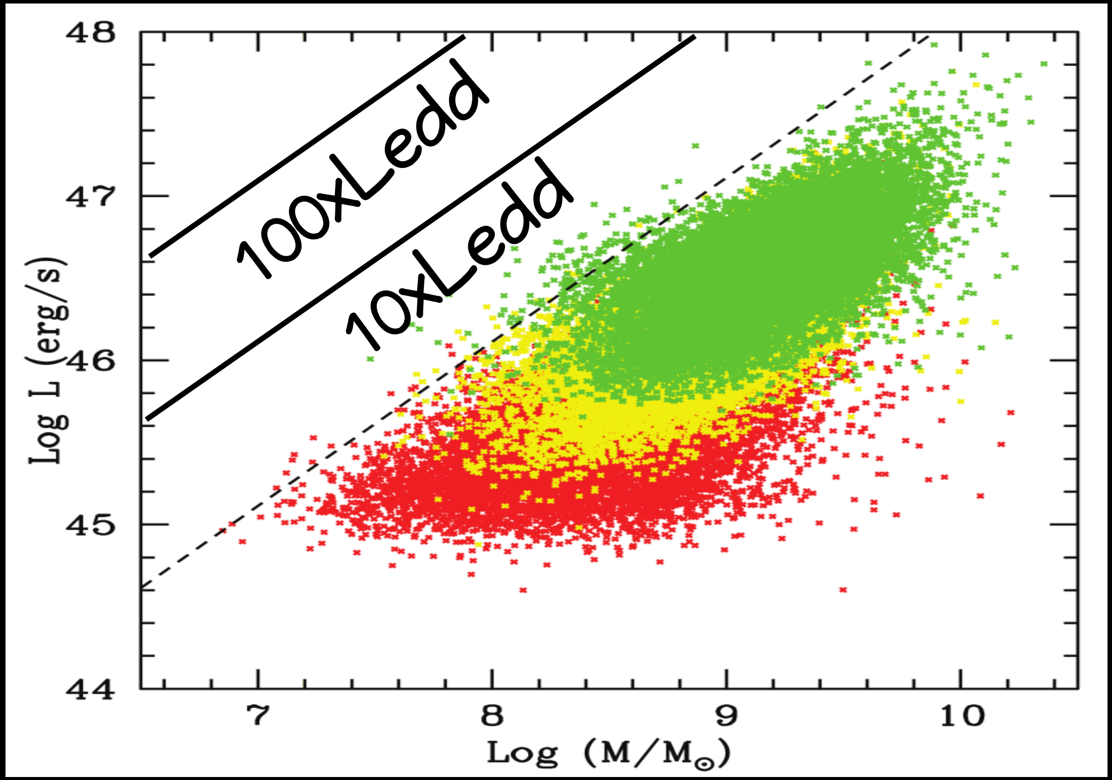
- Is the non-detection of pulsations in low states due to disk occultation or to the propeller onset ?

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)



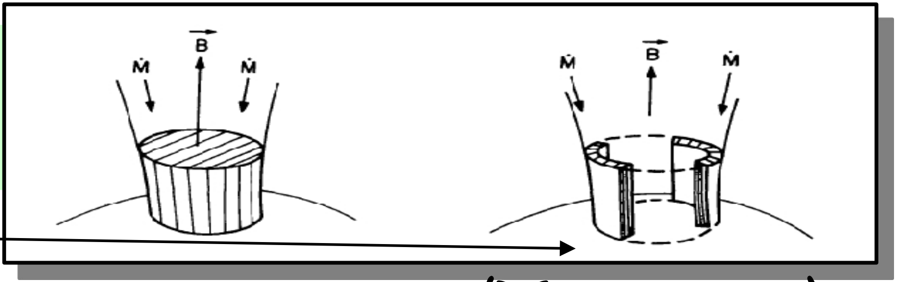
Ways to circumvent L_{Edd}

- 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 $E<E_{cyc}$).

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

For $B_{dipolar}$ = few $\times 10^{15}$ 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 ($r_m \gg r_c$)! Not accreting !!

Too B or not too B

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

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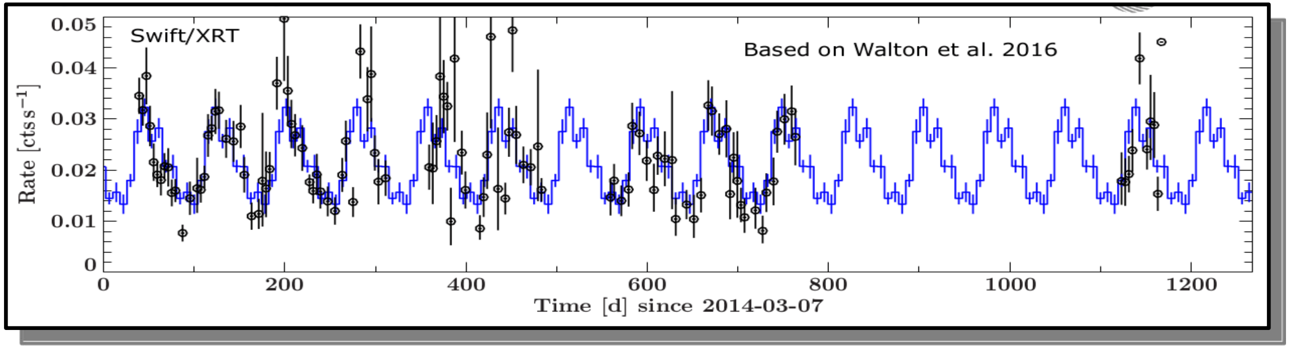
However, with that B and 1s spin period the NS in NGC5907 should be deeply in the propeller phase ($r_m >> r_c$)! Not accreting !!

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.

Too B or not too B

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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 !!

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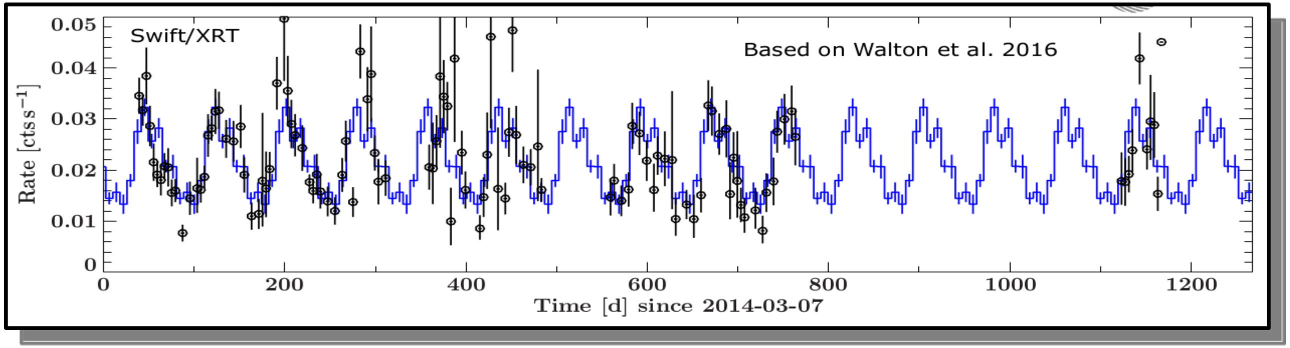
(King+ 2001, King+17, King & Lasota19)

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

Too B or not too B

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

AND

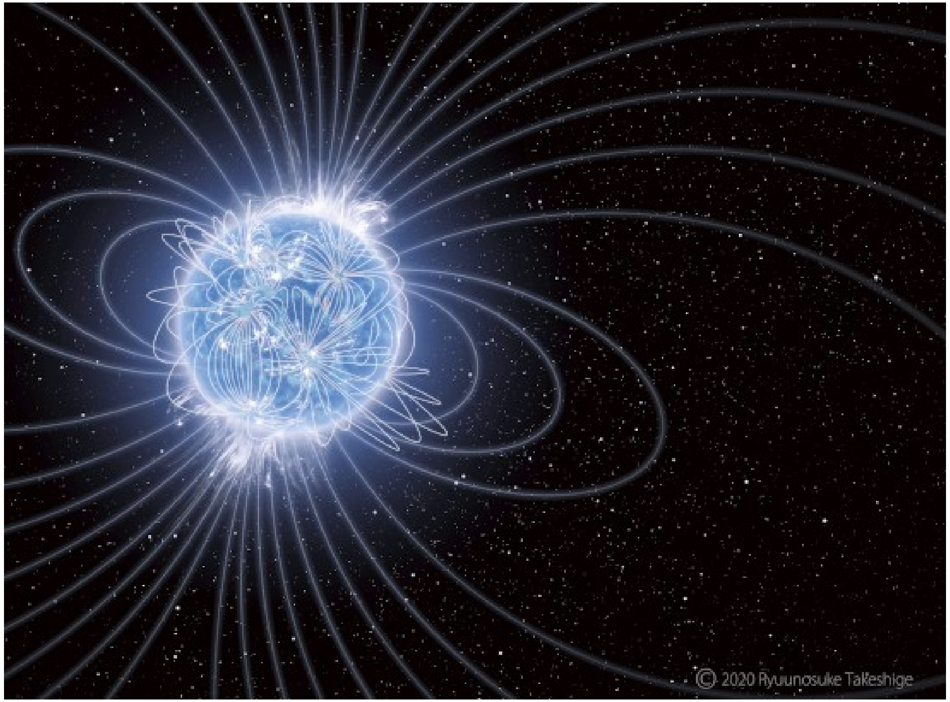
moderate $1/25<b<1/7$ beaming

AND

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

Lx OK

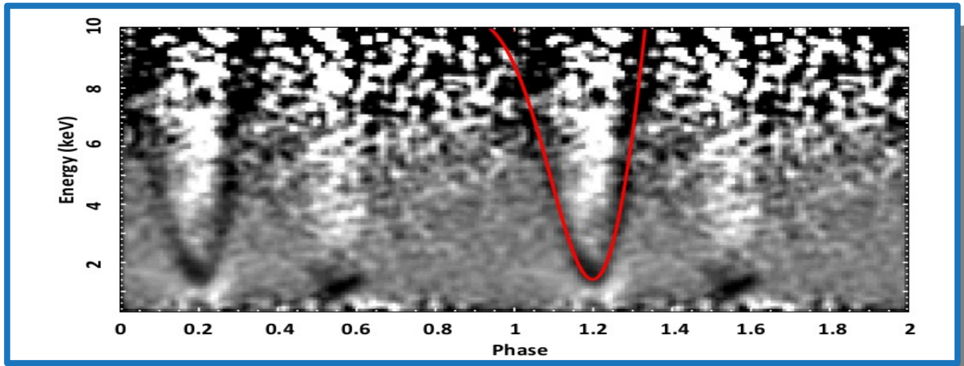
Pdot OK

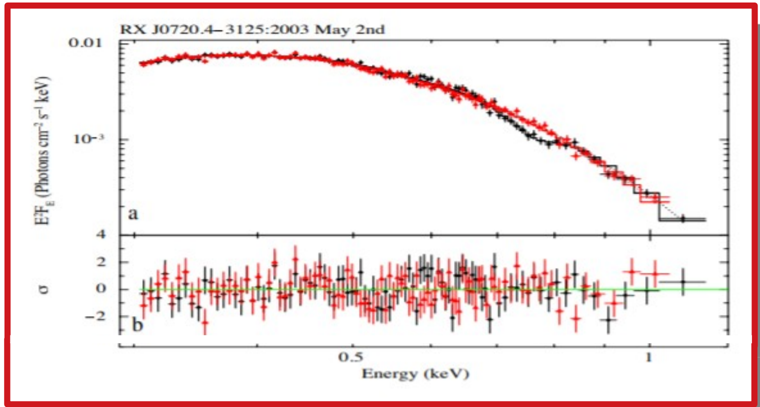


Too B or not too B

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





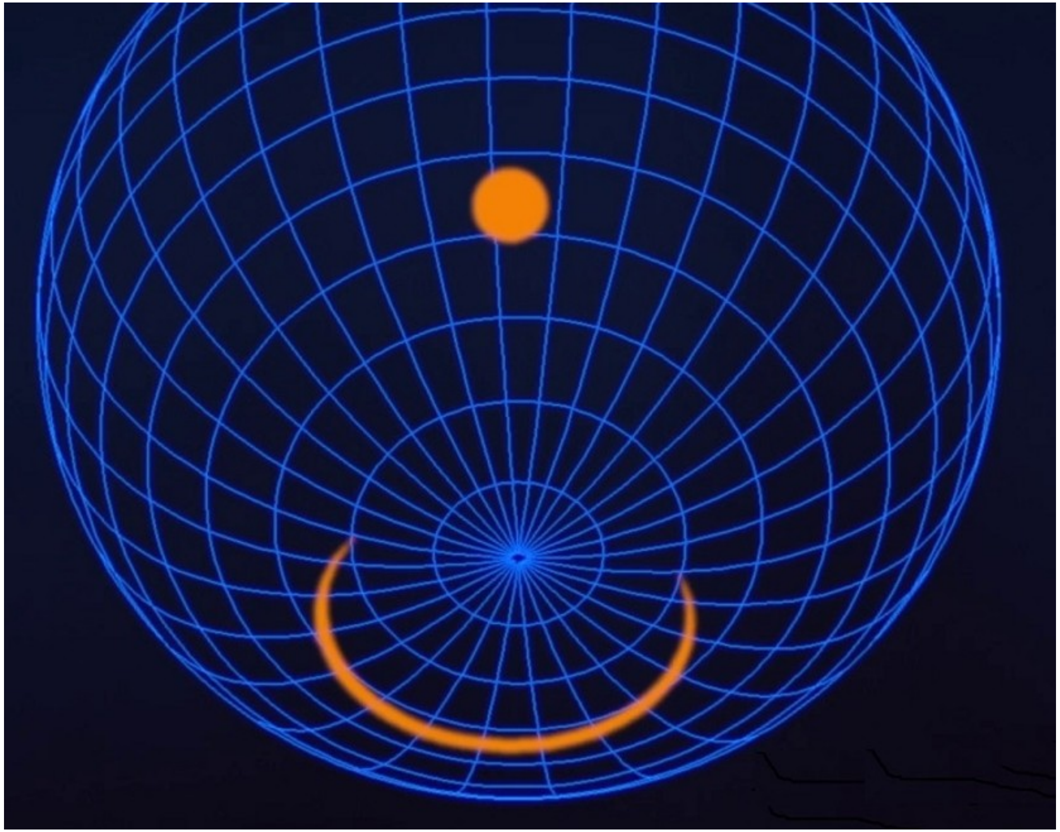
Phase-dependent p-CRSFs in young (magnetars) and old (INSs/ONSs)
high $B_{dipolar}$ isolated NSs B_{mp}~ 1-10×10^{14} G
(e-CRSF -> B < $B_{dipolar}$)
(Tiengo+13, Borghese+16)

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 7×10^{13}-3×10^{14} G

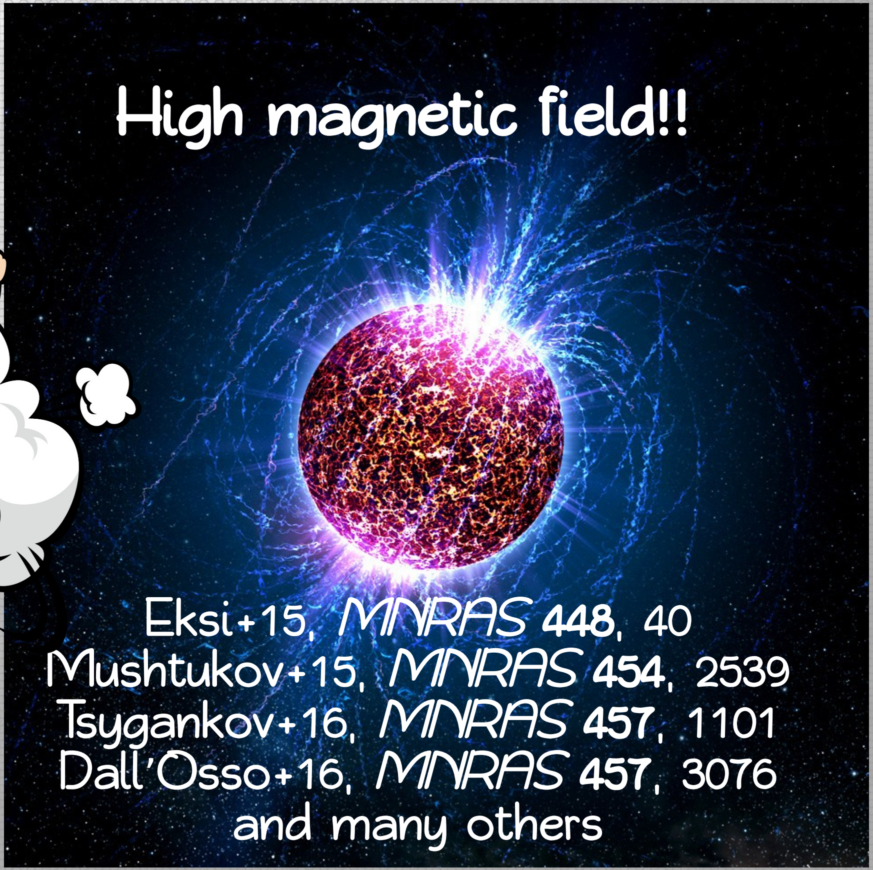
Lx OK
Pdot OK

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)

AN ONGOING FRIENDLY DEBATE

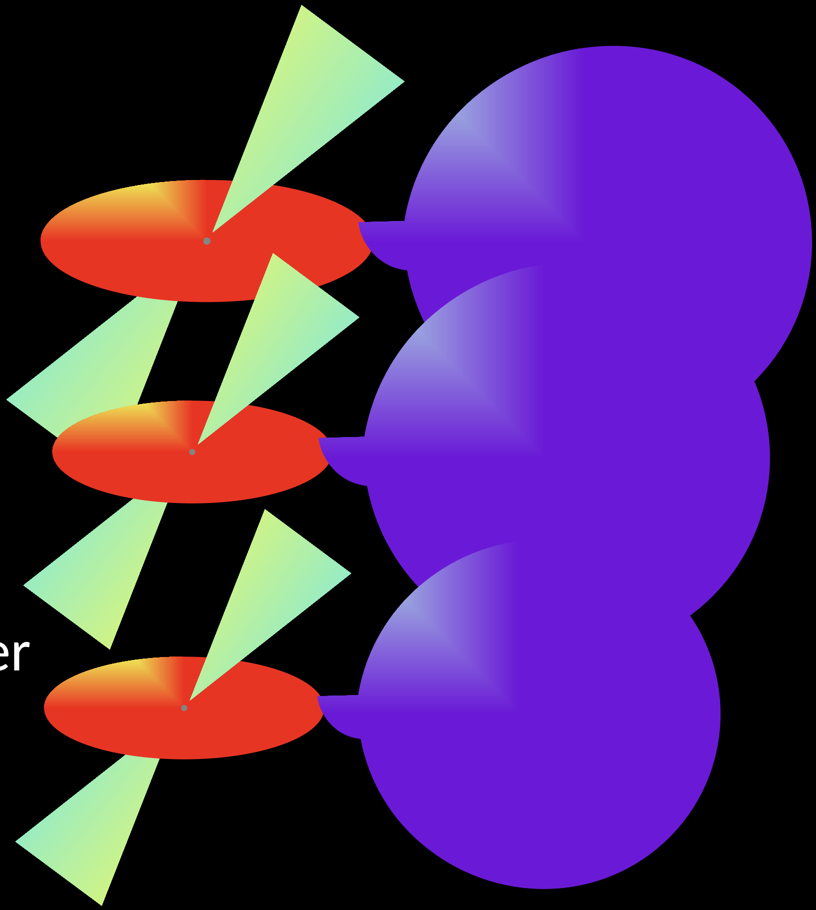


POSSIBILITY: MEASURE MASS EXCHANGE

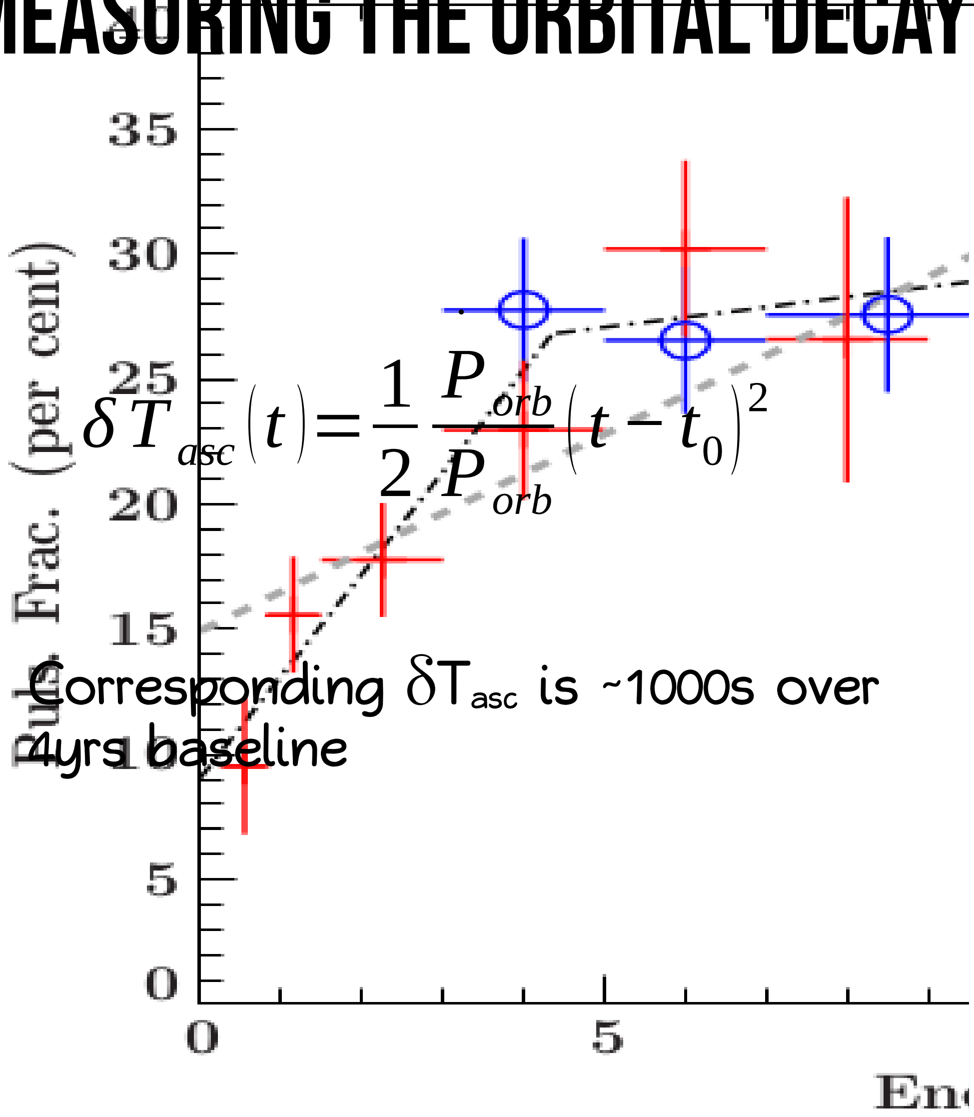
Implied highly super-Eddington mass transfer should produce orbital shrinking(assuming Roche Lobe overflow)

$$\dot{P}_{\rm orb} \sim -3.5 \times 10^{-8} \left(\frac{M_p}{1.4 M_\odot} \right)^{-1} \left(\frac{-\dot{M}_c}{100 \dot{M}_{\rm Edd}} \right)$$

For M82 X-2, hundreds of seconds of orbital drift over years. MEASURABLE!

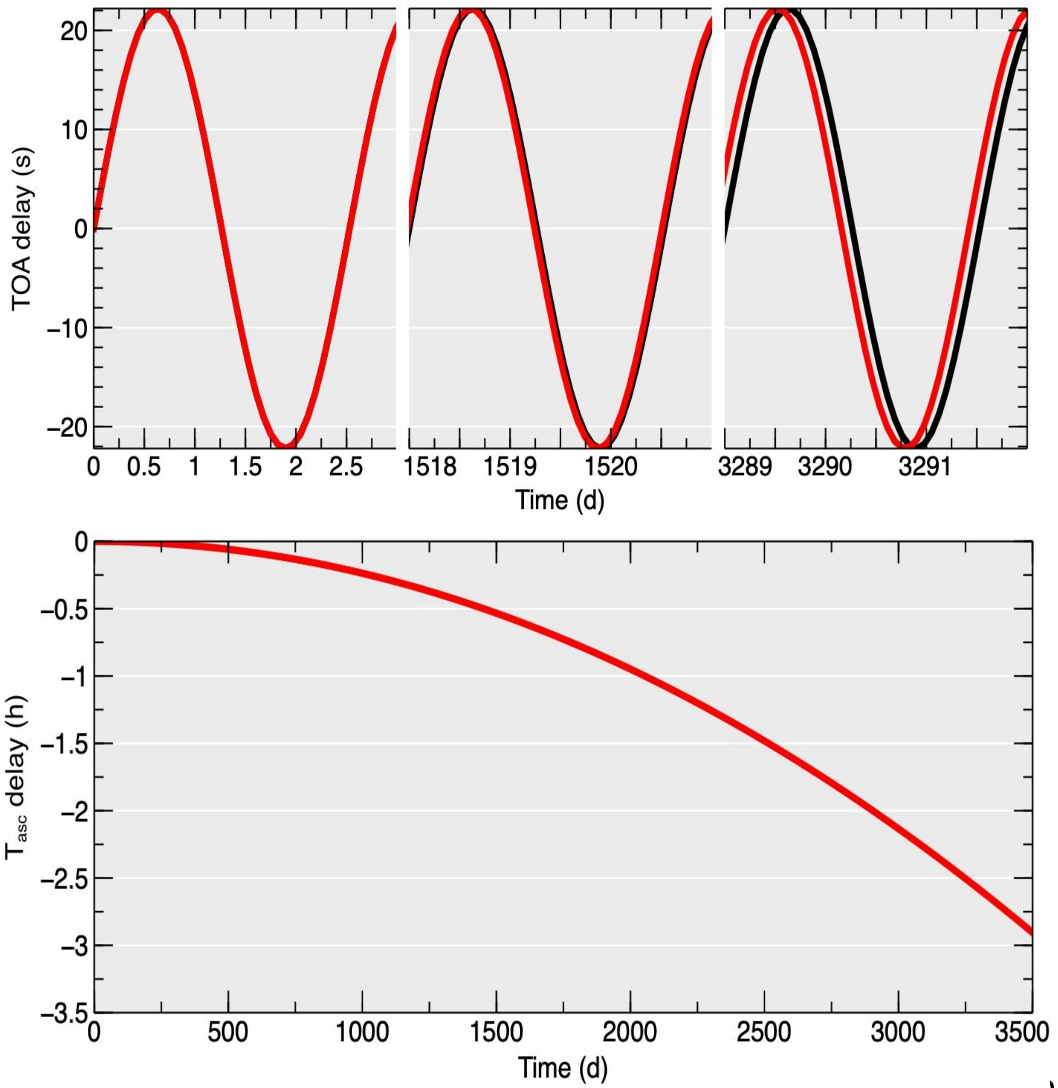


MEASURING THE ORBITAL DECAY



$$\delta T_{asc}(t) = \frac{1}{2}\frac{\dot{P}_{orb}}{P_{orb}}(t-t_0)^2$$

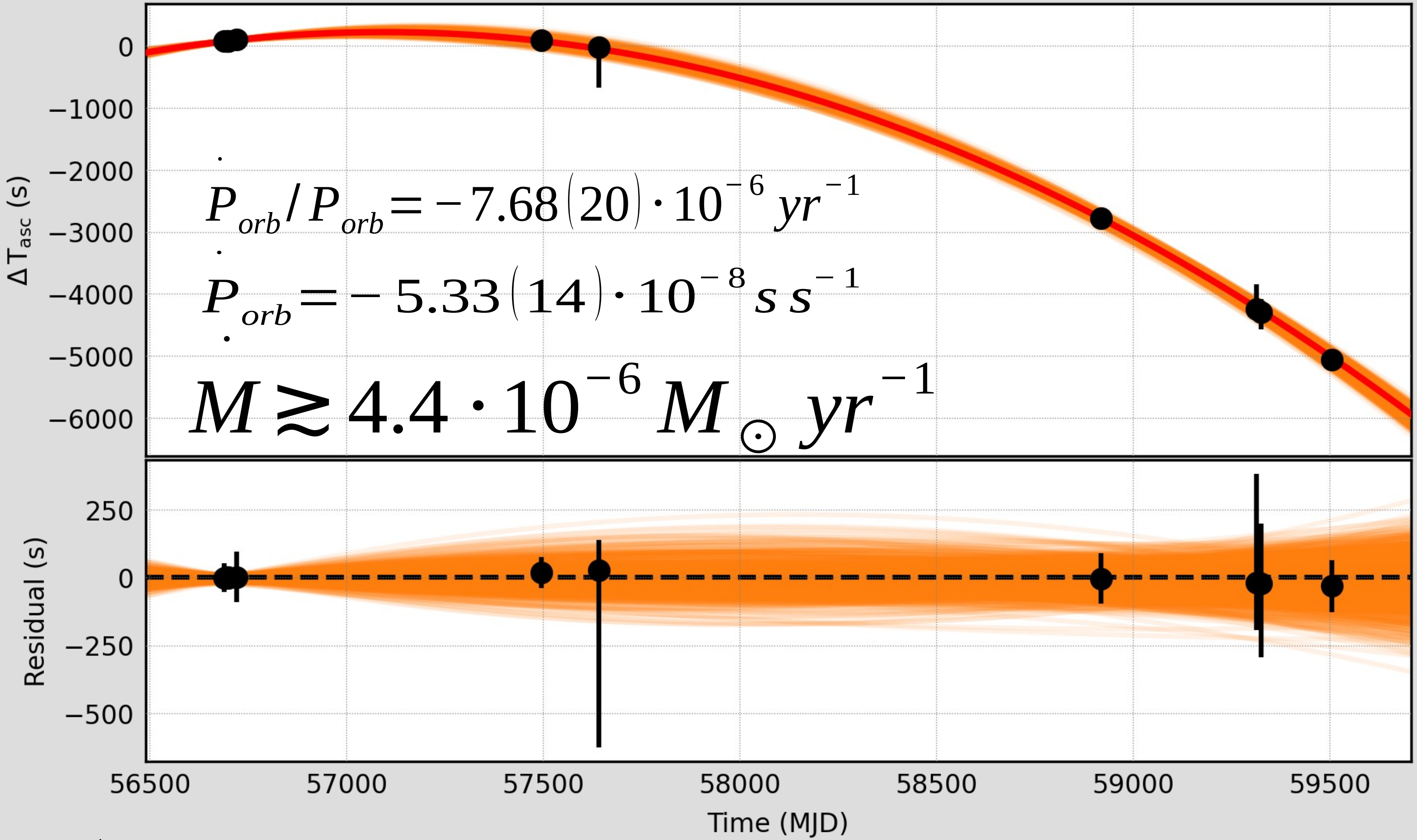
Corresponding δT_{asc} is ~1000s over 4yrs baseline



MEASURING THE ORBITAL DECAY

The orbit is shrinking over a baseline of ~8yrs!

Mdot is 150 x the Eddington limit



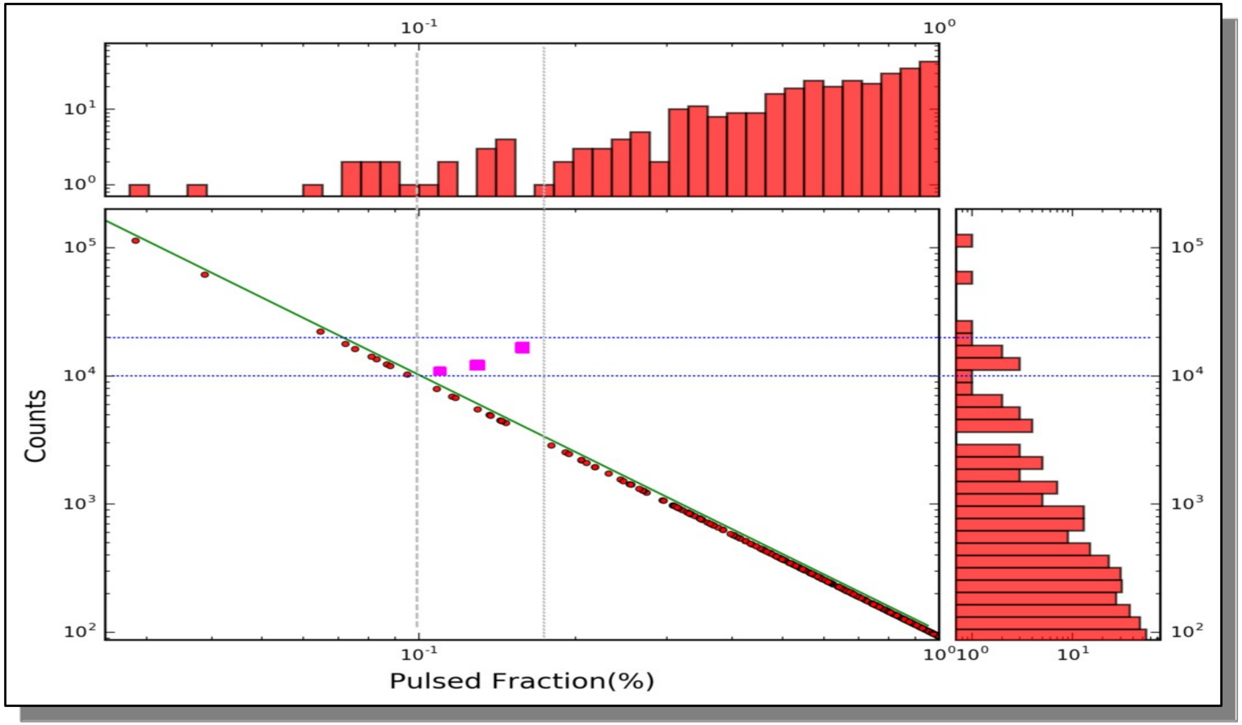
(Bachetti+22, ApJ, 937, 125)

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.

XMM LP

M51 observed in May 2018 for about 75ks

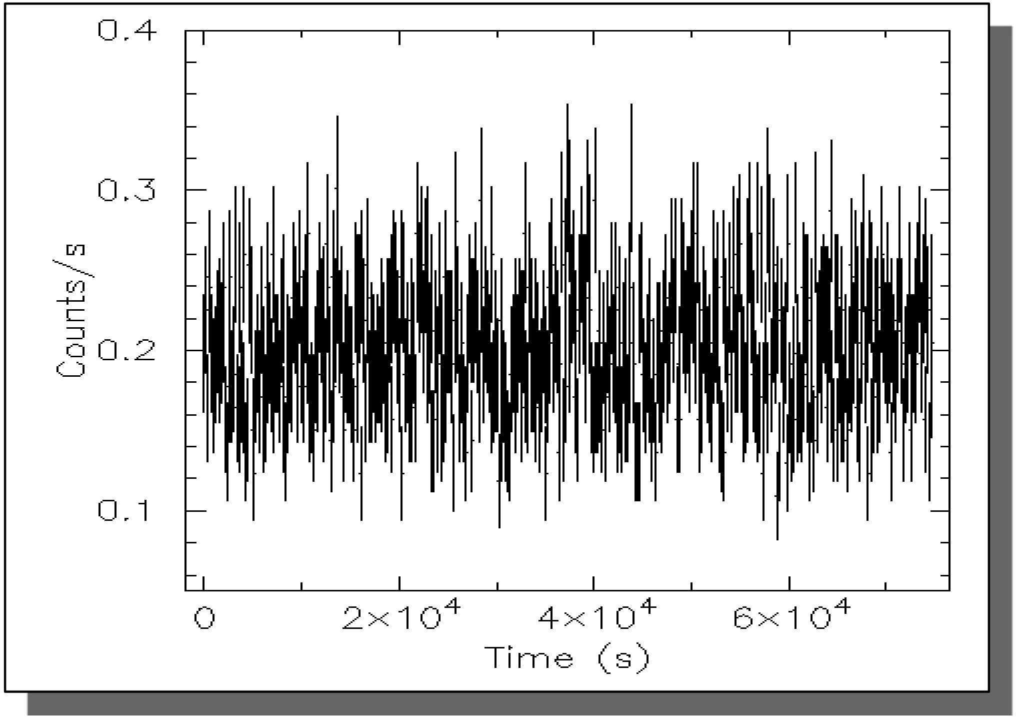
UNSEEN:
Ultraluminous
NS Extragalactic
Extreme populatioN

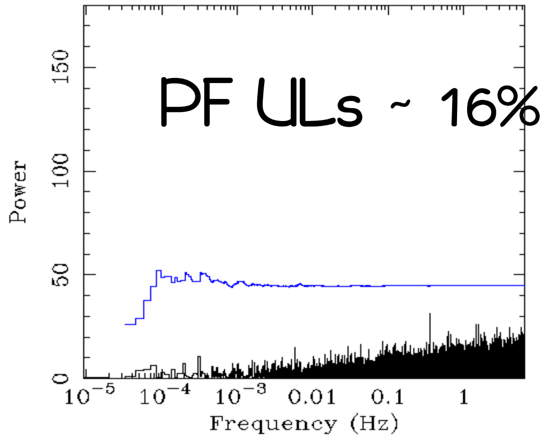
ULX7, a variable source: L_X peaks at almost 10^{40} erg/s

Observed several times by XMM
No pulsations detected.

ULX7

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





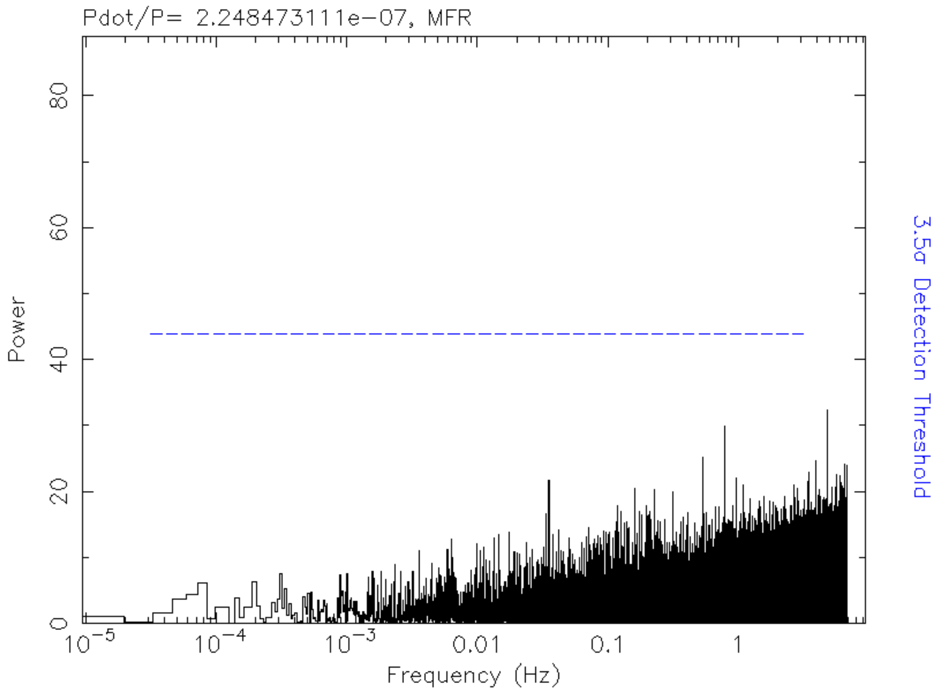
PF ULs ~ 16% [100-0.3s]

XMM LP

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

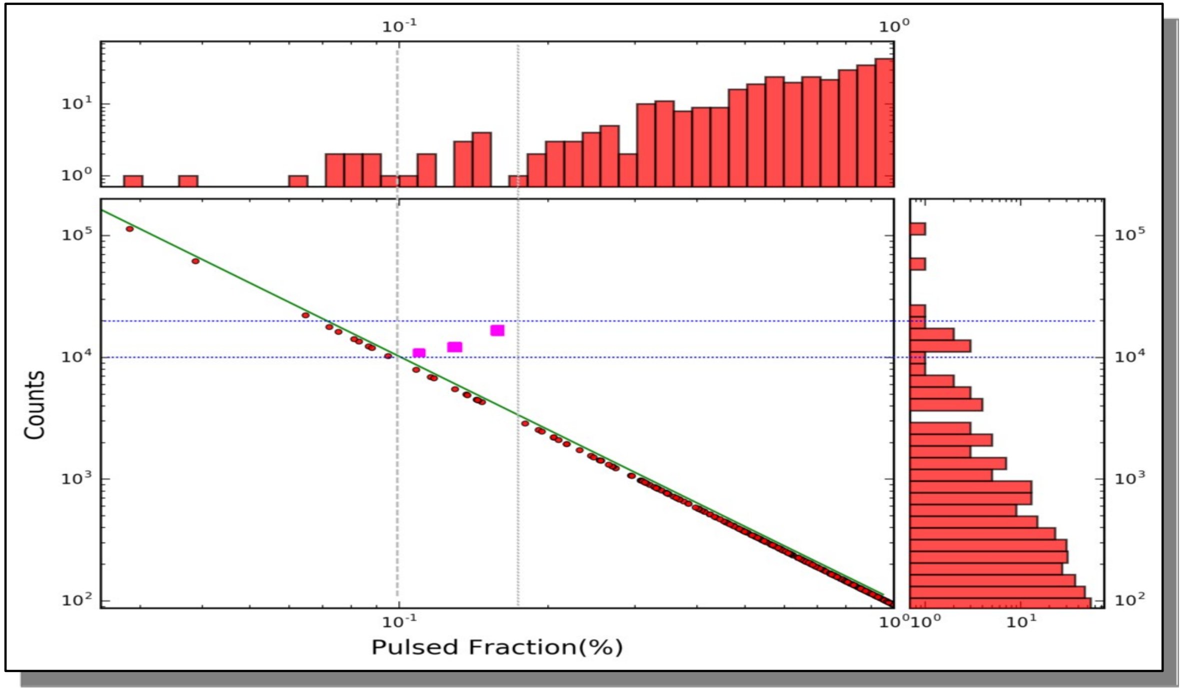
UNSEeN:
Ultraluminous
NS Extragalactic
extreme populatioN

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



How many (2020)?

7 out of 300, ~2% ?

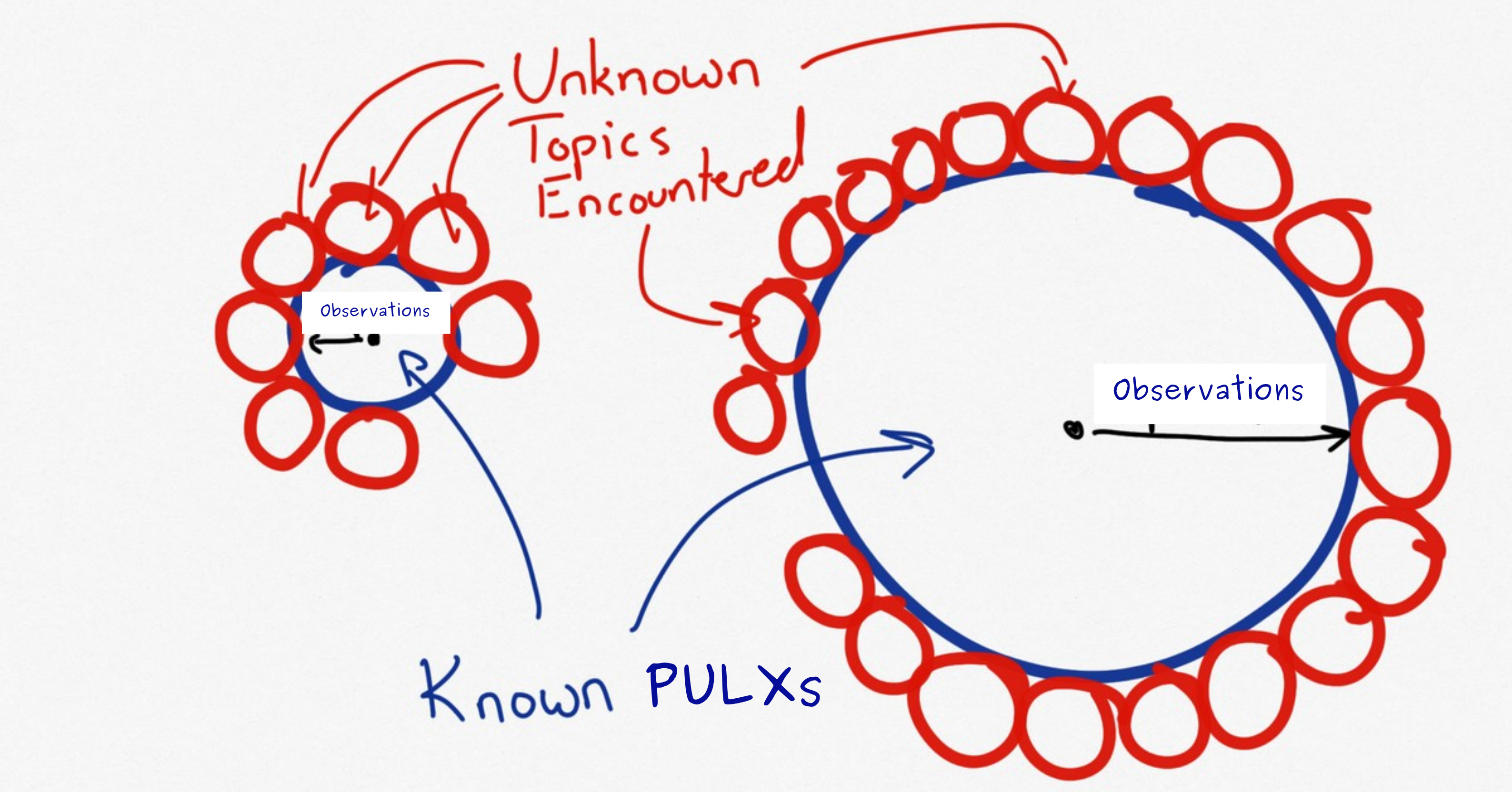


We detected PULXs in observations with at least 10,000 counts (XMM)

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


Unknown
Topics
Encountered
Observations
Observations
Known PULXs

Expectations versus Observations

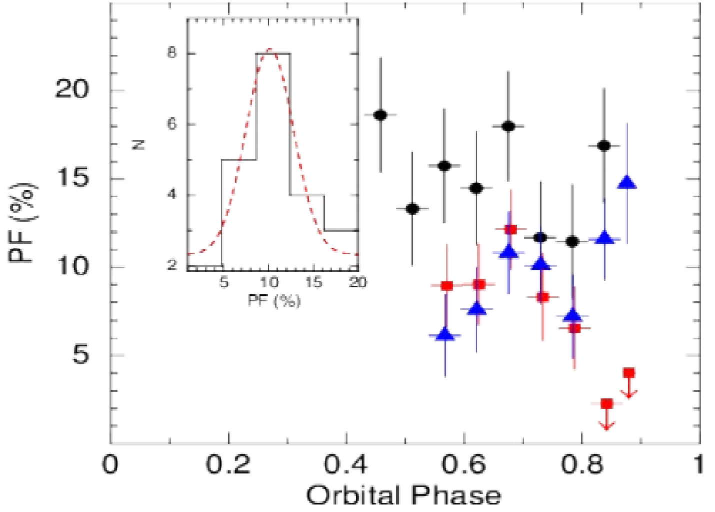
1 new PULX found so far in the XMM LP
2-3 expected based on our statistics

=

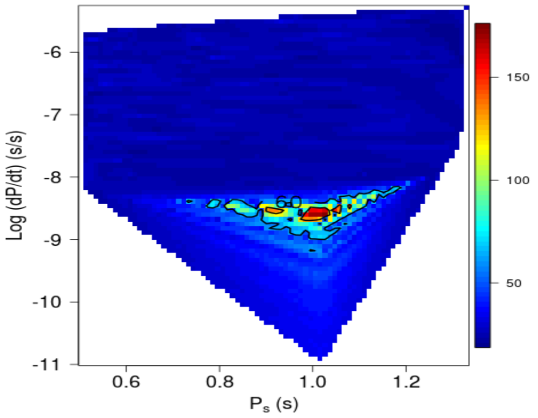
marginally consistent results

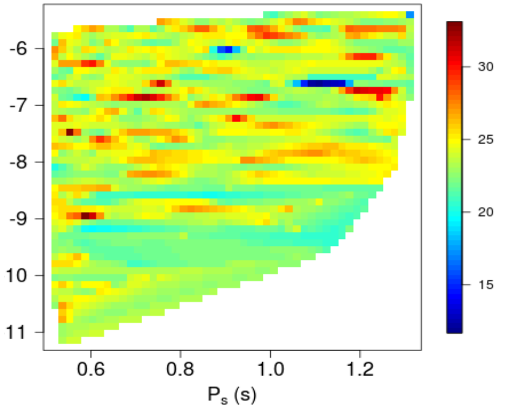
BUT
signals extremely variable.

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



NGC5907 at few days distance
same flux level

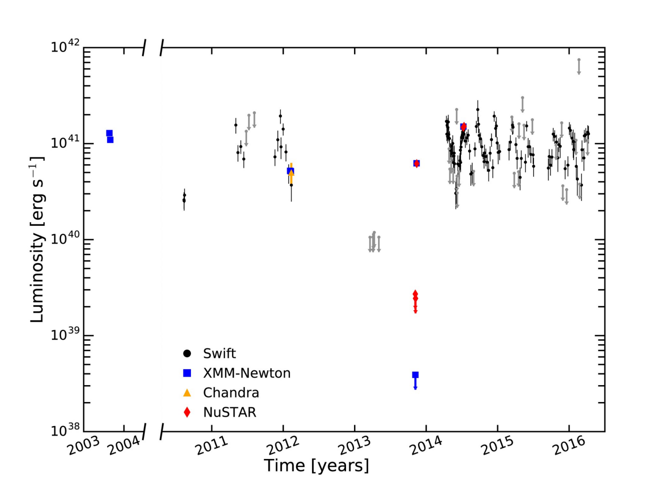


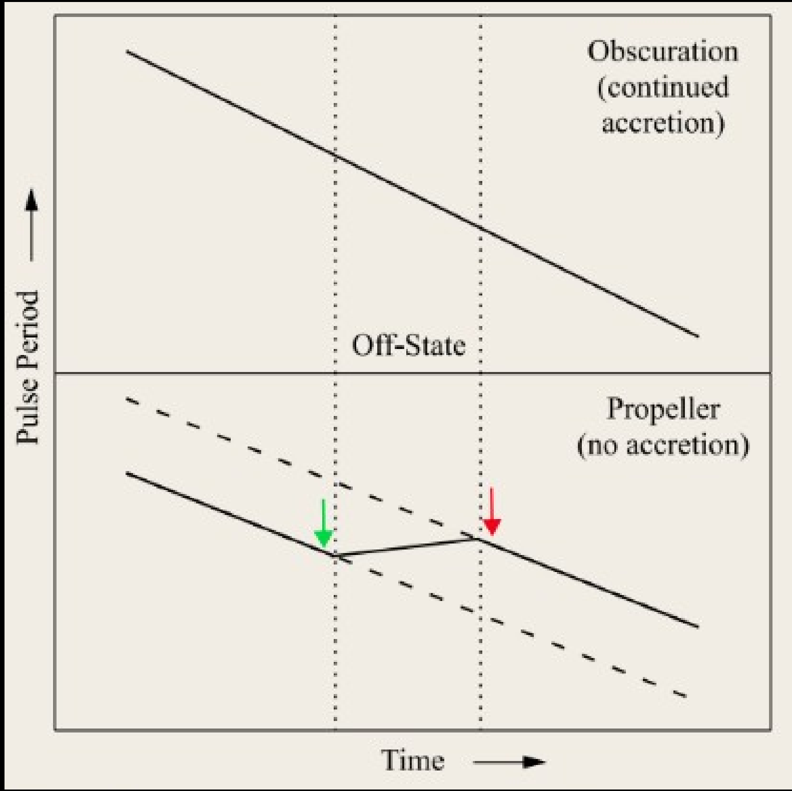


The extreme case of NGC5907 X-1

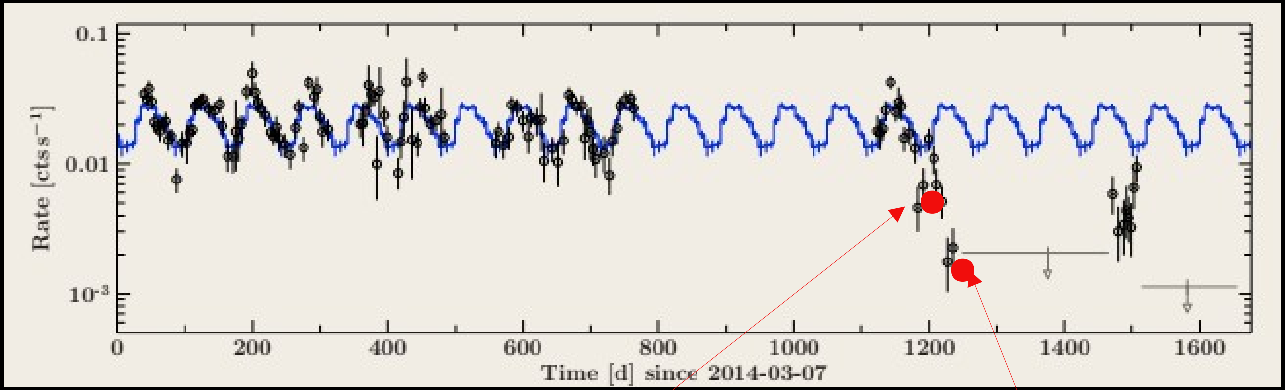
XMM LP (PI Belfiore: 380ks) to improve the orbital parameters (peak of the $P_{S\text{-}Orb}$) during high-states

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



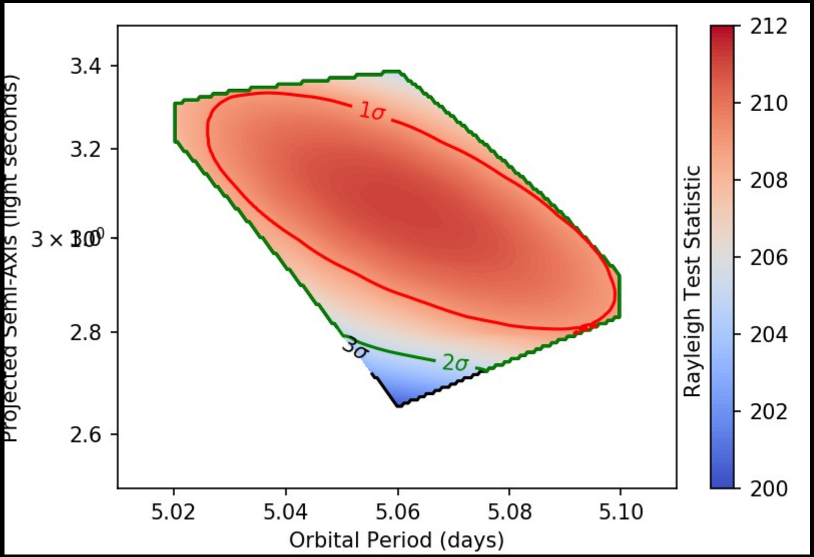


NGC5907 follow-up observations



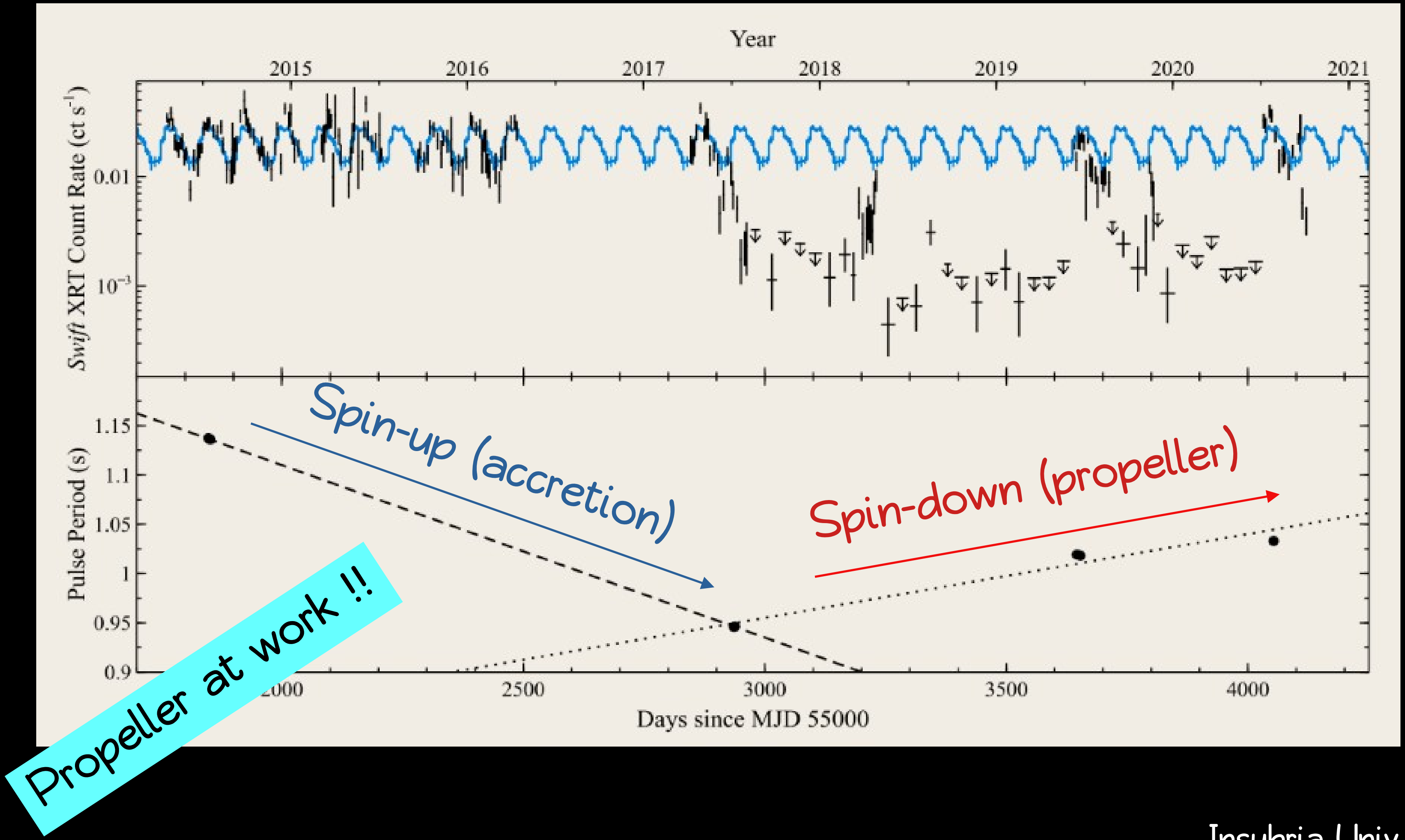
Faint signal at ~946ms

No pulsations



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

NGC5907 follow-up observations



Magnetic gating

Variable sources due to the switch between surface and magnetosphere accretion (propeller effect). L_{lim} at which the propeller magnetic gating occurs is

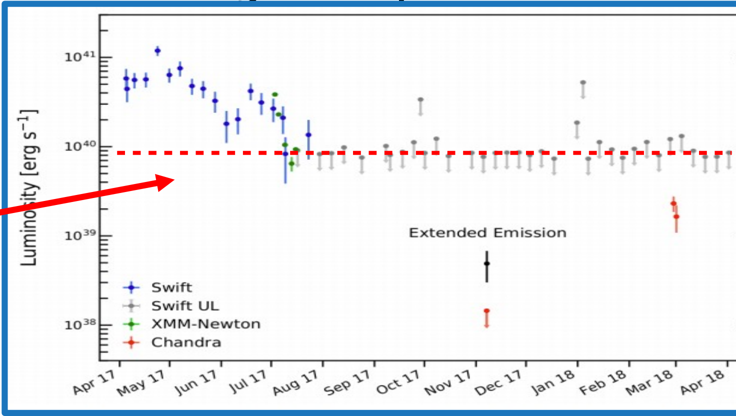
$$L_{\rm lim}(R) \simeq \frac{GM\dot{M}_{\rm lim}}{R} \simeq 4\times10^{37} k^{7/2} B_{12}^{2} P^{-7/3} M_{1.4}^{-2/3} R_6^{5}\ {\rm erg\ s^{-1}}$$

For NGC5907 ULX1 and M82 X-2

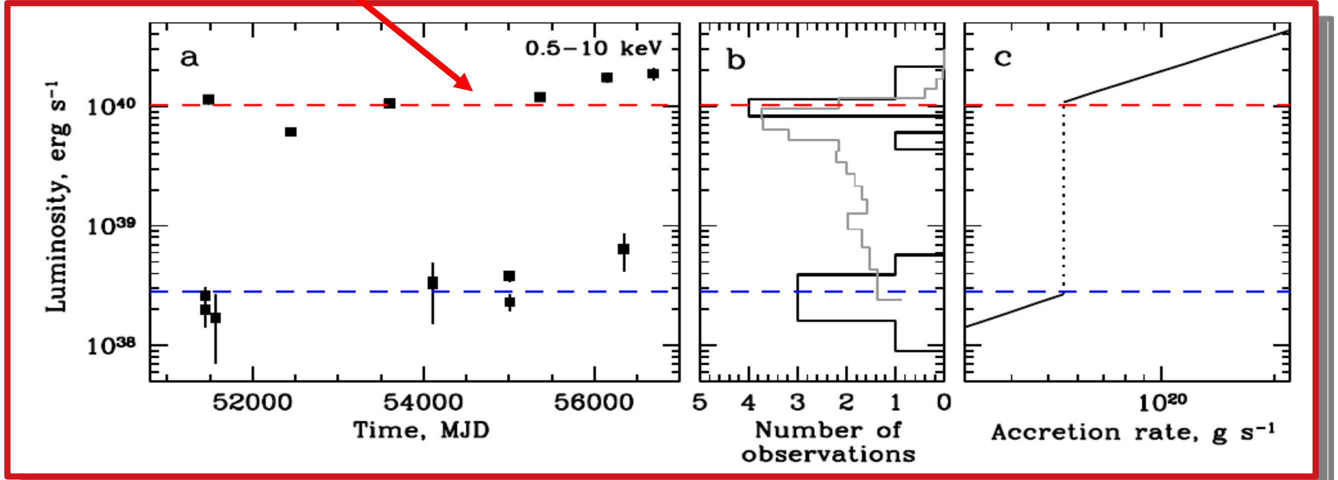
$L_{lim} \sim 10^{40}$ erg/s implying a (dipolar) magnetic field of:

$B_d \sim$ 1-10 x 10^{13} G

(See also Grebenev+17
$B_{d,max} < 7\times10^{13}$ G)



Belfiore+20



Tsygankov+16

Some implications/Conclusions

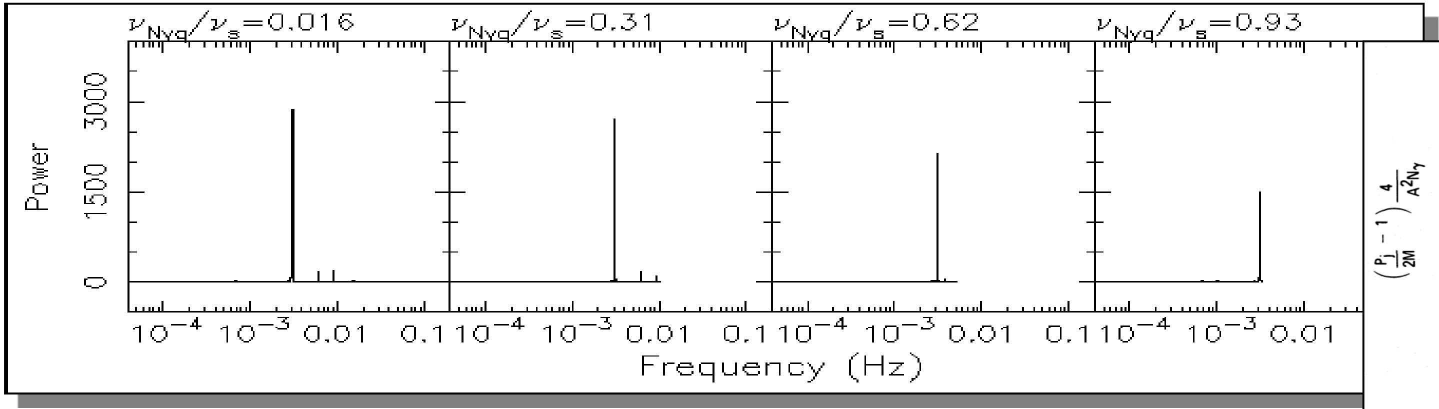
- Extreme ULXs (>1e41 erg/s), like NGC5907 ULX-1, can hosts accreting NSs. Total number of NS among ULXs could be very high. New class of X-ray pulsars identified (super-Eddington accretors)

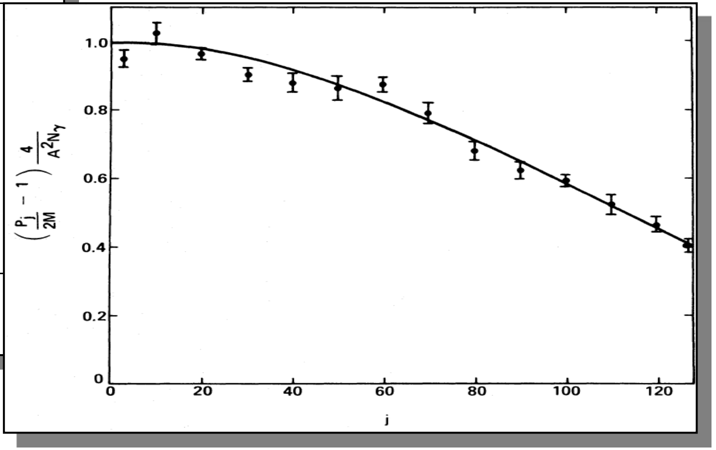
- Intrinsically difficult to find !
  The detection of these pulsars is a hard task with standard tools and current instruments. CPU-time consuming methods and HPCs at rescue....
  Athena is expected to give an important contribution to PULX studies.

- 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) and monitoring campaign during AO20.

signal detection optimization





$$A=\left\{\left[\frac{\langle P\rangle_j}{2MW}-1\right]\frac{4}{0.773N_{ph}}\frac{(\pi j/N)^2}{\sin^2(\pi j/N)}\right\}^{1/2}$$

The presence of the $x^2/\sin^2 x$ term in the amplitude relationship implies a strong correlation between signal power and its location (in terms of Fourier ν_j) with respect to ν_{Nyq}. The power-signal response function Decreases of 60% (from 1 to 0.405) from the 1st and last freq.

Implications: When searching for coherent or quasi-coherent signals It is important to use the original (if binned time series) or minimum (if arrival time series) time resolution ✉ highest ν_{Nyq}

signal detection optimization-2

$$A=\left\{\left[\frac{\langle P\rangle_j}{2MW}-1\right]\frac{4}{0.773\,N_{ph}}\frac{(\pi j/N)^2}{\sin^2(\pi j/N)}\right\}^{1/2}$$

In the greatest part of the cases the signal freq. ν_{sig} is not equal to the Fourier freq. ν_j. The signal power response as a function of the difference between ν_{sign} and the closest ν_j , is again a $x^2/\sin^2 x$ term which varies between 1 and 0.5: for a coherent periodicity 1 means that all the signal power is recovered by the PSD, 0.5 means that the signal power is equally distributed between two adjacent Fourier frequencies ν_j.

Implications: When searching for strictly coherent signals it is important to rely upon the original/maximum Fourier resolution (1/T) ✉ do not divide the observation in time sub-intervals.

Implications

Pulsations found in ULXs with $10^{38} < L_x < 10^{41}$ erg/s

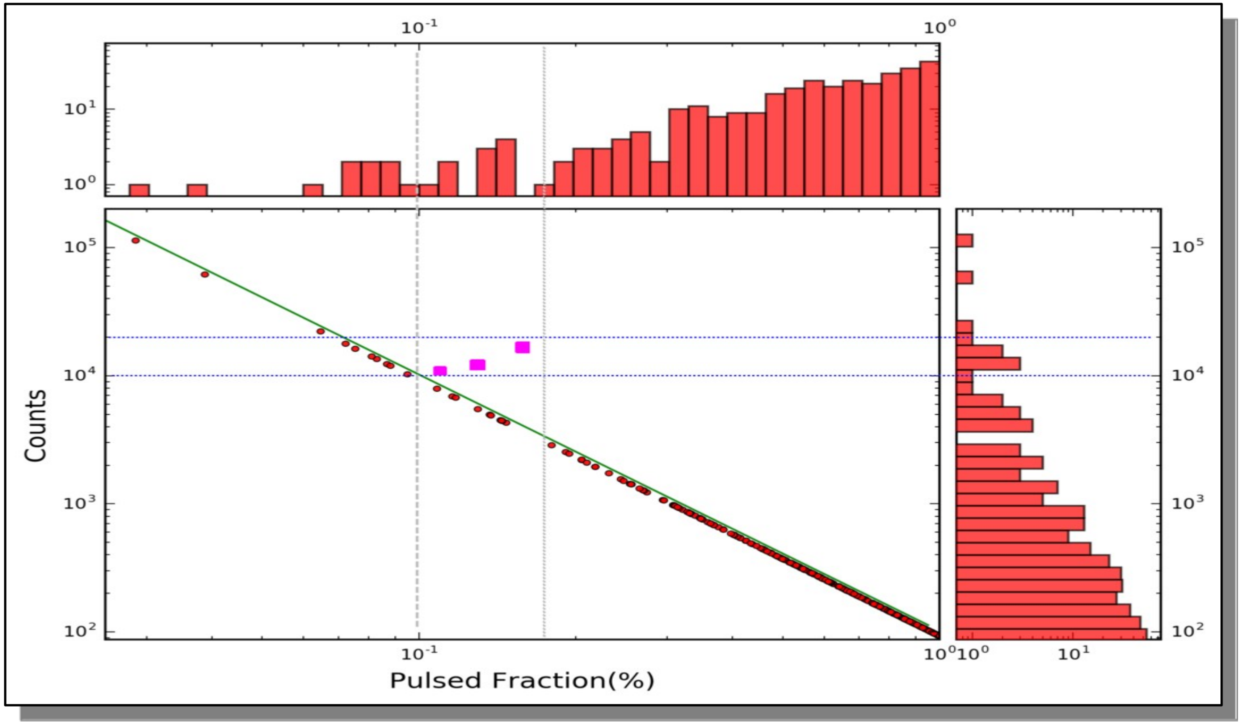
while ULXs luminosities are: 10^{39} (by definiton) $< L_x < 10^{42}$ erg/s

Note that M82 X-2, NGC5907 ULX-1 and NGC7793 P13 were all classified as BHs based on their spectral properties. Spectroscopy is not an unambiguous tool for ULX classification.

- Can we still consider ULXs as “bona fide” (IM)BHs? No
- Which is the fraction of ULXs hosting an accreting NS?
- How do we account for the super-Eddington Lx ?

How many ?

4(6) out of 300, ~1(2)% ?



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

How many ULXs with such statistics (2018)?

14 ULXs (<5% of all known ULXs) → 30(40)% are PULXs

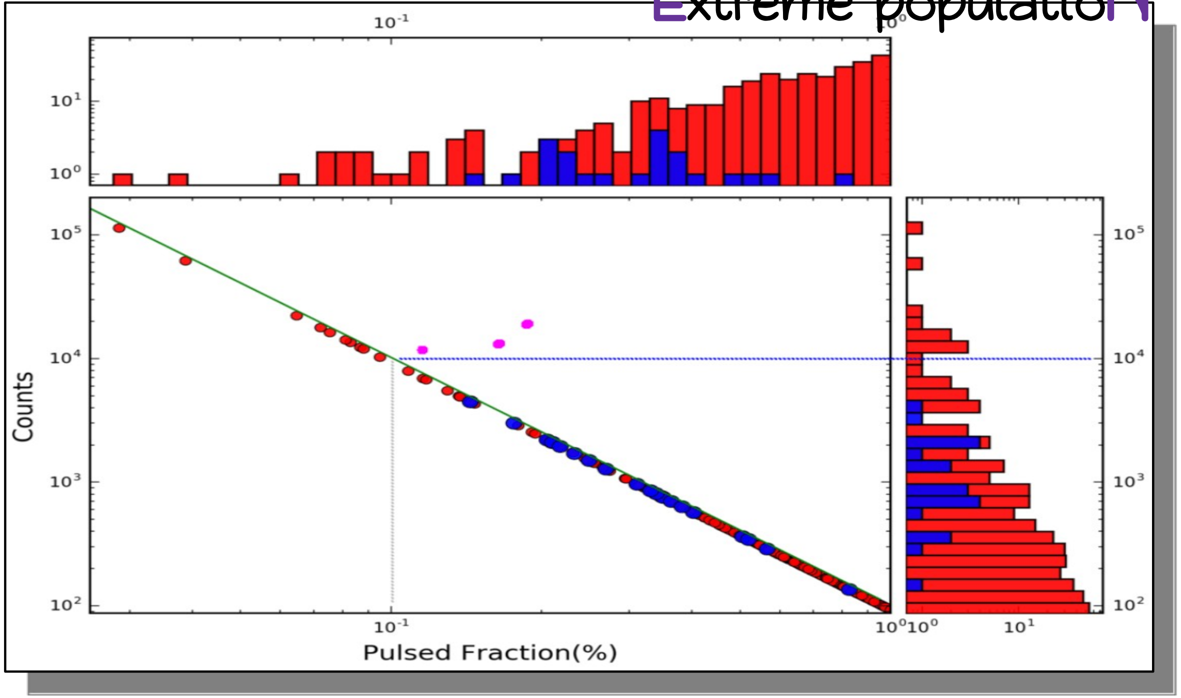
How many ULXs with a statistics such that pulsations with

Taking the beat of the UNSEEN

UNSEeN:
Ultraluminous
NS Extragalactic
Extreme populatioN

Accepted as XMM LP in AO17:

8 pointings + 3 DDTs
986 ks
~15 ULXs (>10.000 cts)
~30 additional S-Edd sources
1-3 new PULXs expected to be detected!



Observations completed
Work in progress

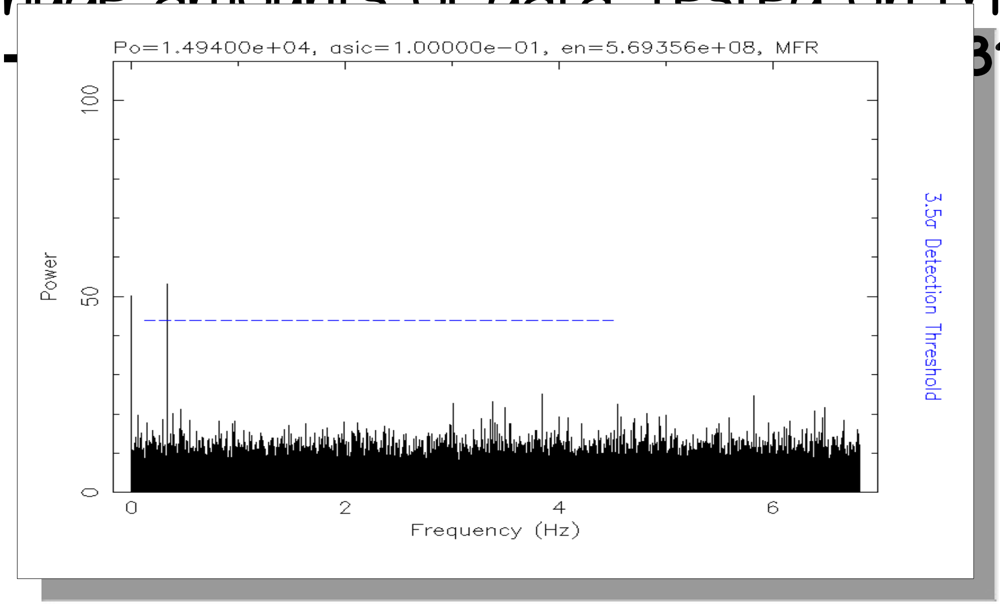
The UNSEEN Collaboration:
G.L. Israel, G. Rodriguez,

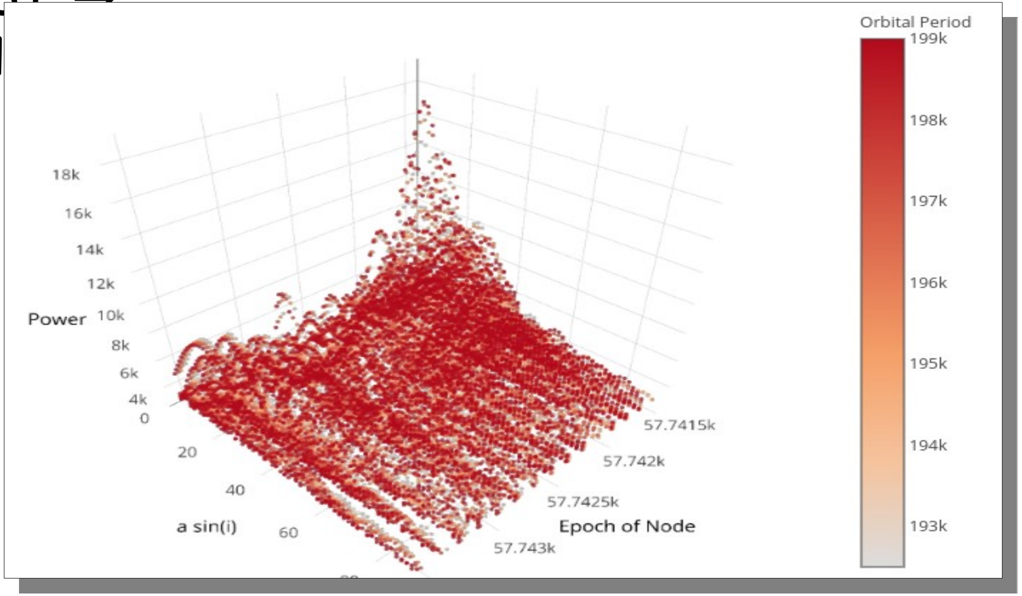
"Big data" and Computing issue

PULX signal detection strongly affected by Pdot and orbital motion:
Events corrected in a 4D parameter-space: Pdot/P , P_{orb}, $a_X \sin(i)$, T_{node}:

$$t' = t - (a_X \sin i / c) \sin[2\pi(t - T_{node})/P_{orb}]$$

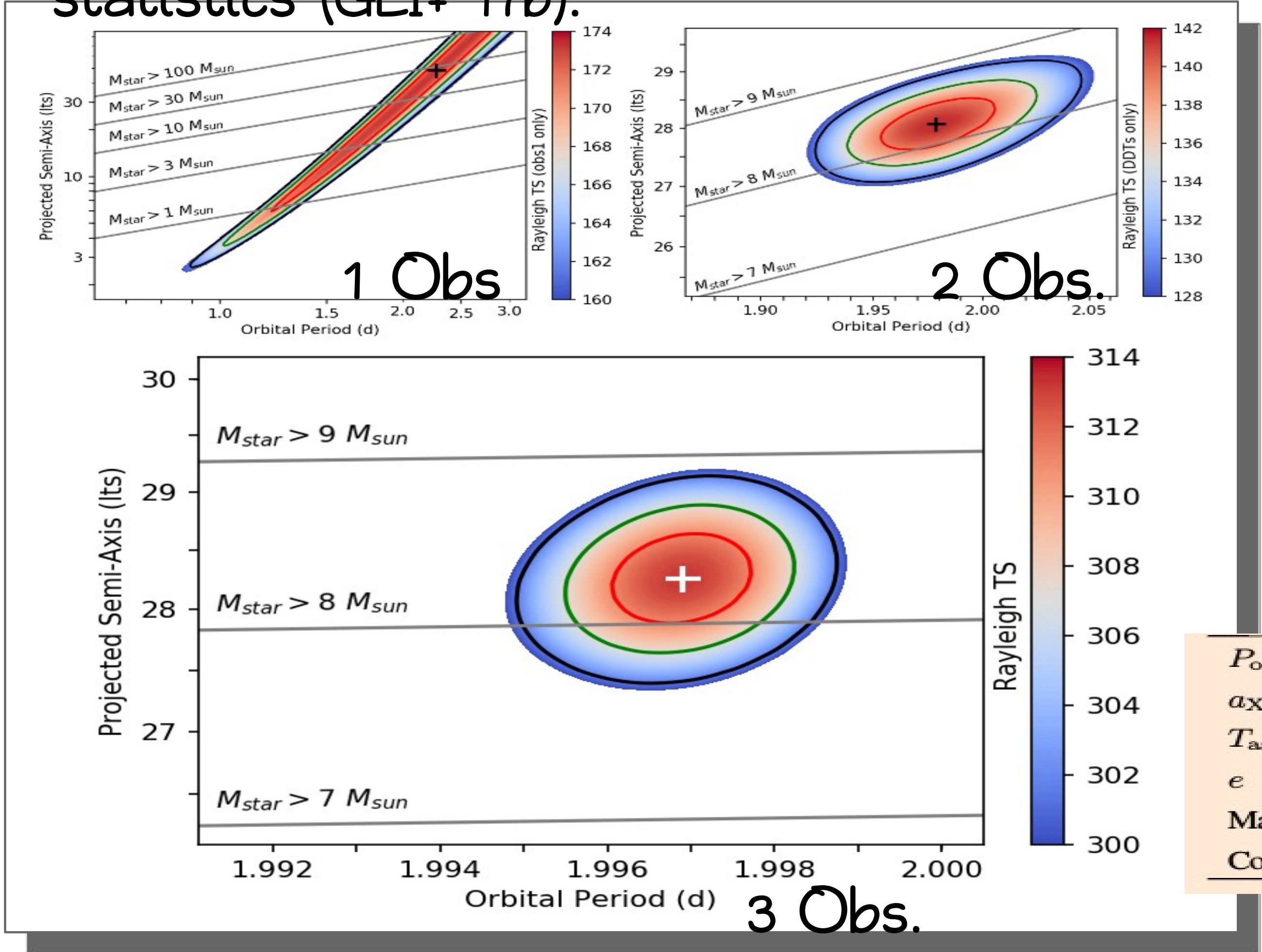
For a reasonable grid ~ **few x 10⁶** FFTs/periodograms per source →
Need for High Performing Computing (HPC) and efficient handling of huge amounts of data: tested on M31 →





The binary system hosting M51 ULX7

Orbital parameters inferred by means of likelihood Rayleigh test statistics (GLI+ 17b).



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

No eclipses/dips detected ($i \gtrsim 30°$) → $M_c < 80\ M_\odot$

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

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

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

Possible scenario (for NGC5907)

Expected **dipolar B component** (close to the Magnetospheric boundary) of the order of

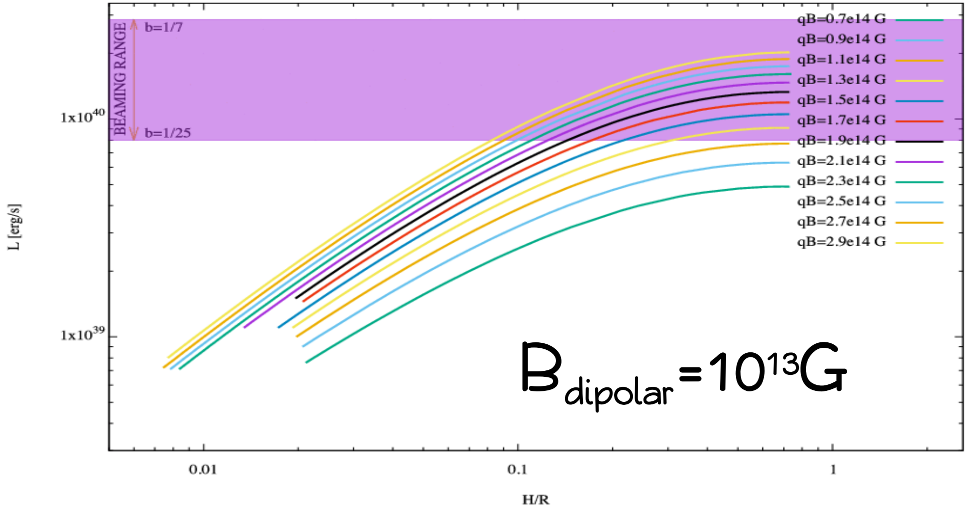
NGC5907 ULX: **(0.7 - 3.0)e12 G** @ b~1/10-1/7

Quadrupolar B component (close to the surface/bottom of the accretion column)

NGC5907 ULX: **(3-30)e13 G**

Fiore+19 show that the scenario is possible (numerical calculation) based on the formalism by Mushtukov et al. (2015a,b)

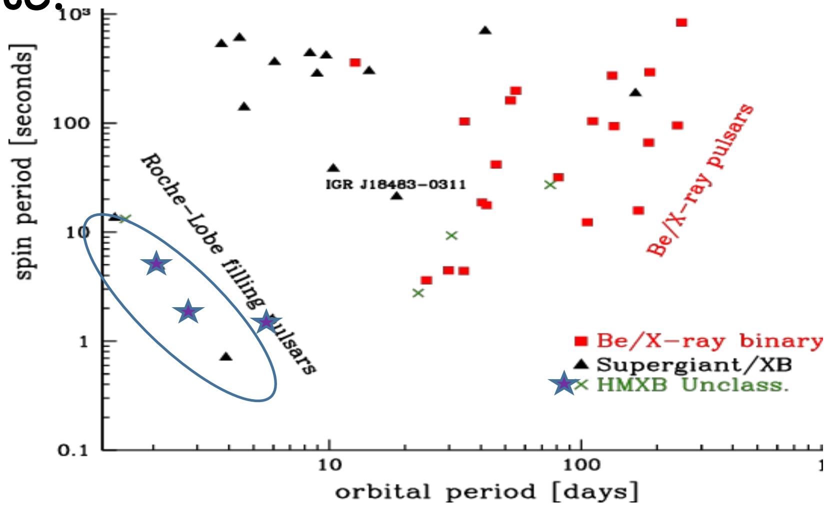
Accretion stream is channeled by the dipolar field on large scale but feels the quadrupolar component on small scales (polar region; GLI+17)



$B_{dipolar}=10^{13}G$

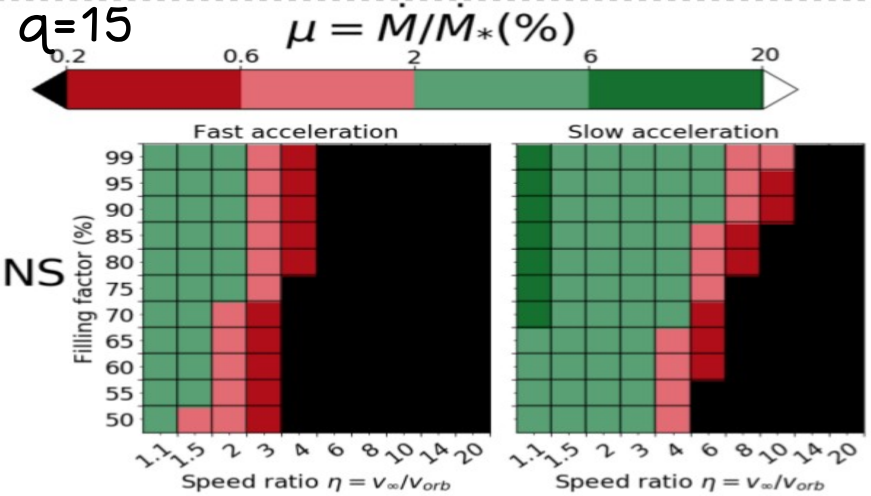
Evolutionary issues

In the Corbet's diagram 3 PULXs are in the same region of RLOF
Close to Cen X-3, SMC X-1, LMC X-4, etc.

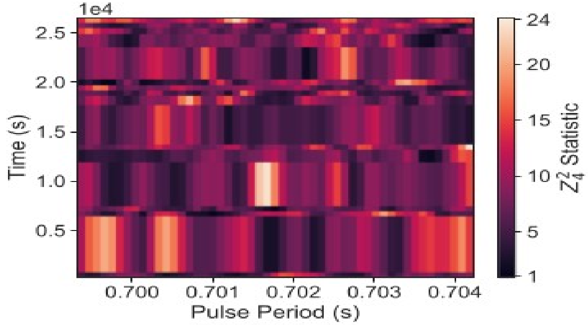


RLOF with q=Mc/Mns >> 1
mass transfer is unstable and
rapidly leading to the common
envelope phase.

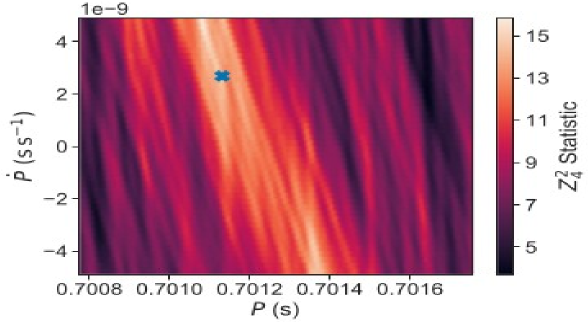
q=15



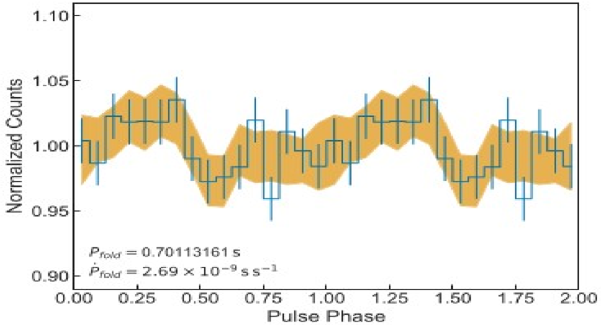
Recent studies (wind numerical
smulations) suggest that even
for large q the transfer, wind RLOF
might be stable and efficient (El
Mellah+19)



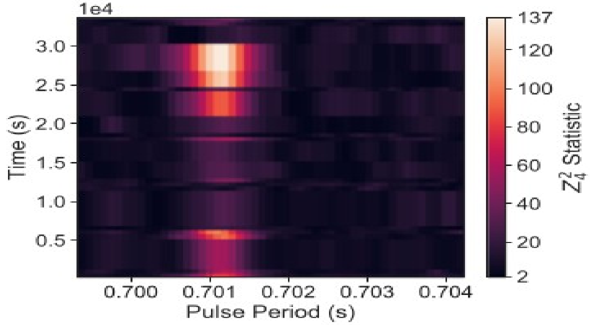
(a) Epoch I dynamic folding search



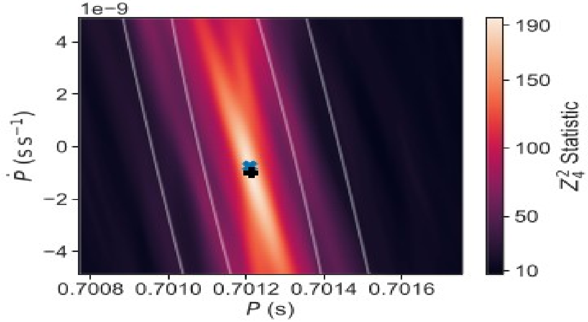
(b) Epoch I period search



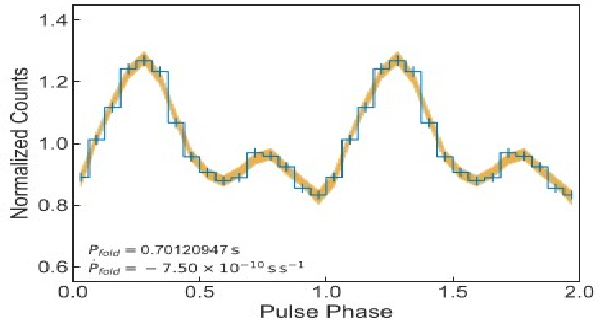
(c) Epoch I pulse profile



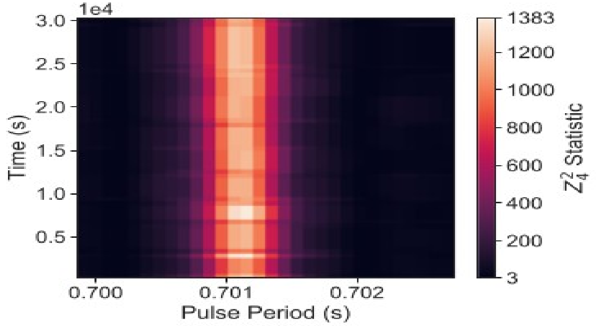
(d) Epoch II dynamic folding search



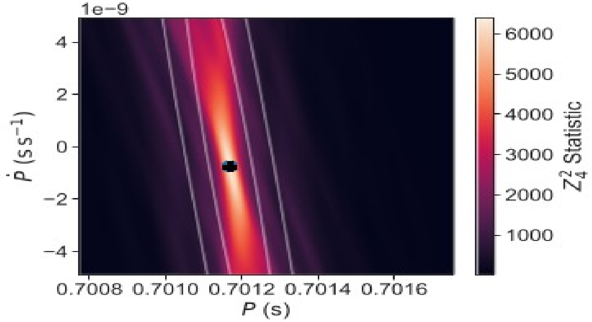
(e) Epoch II period search



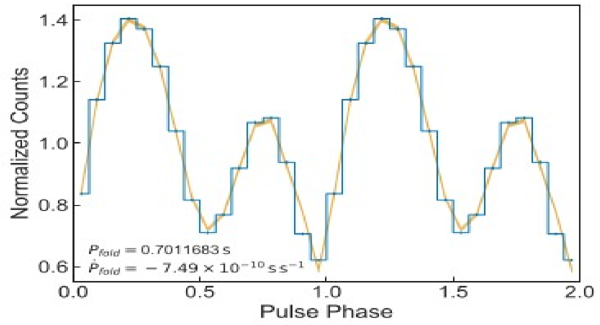
(f) Epoch II pulse profile



(g) Epoch III dynamic folding search



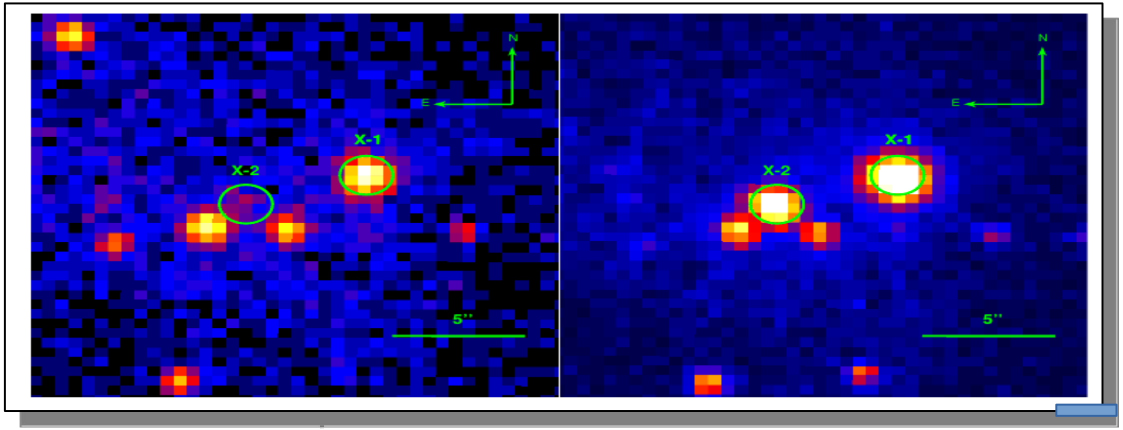
(h) Epoch III period search



(i) Epoch III pulse profile

M82 X-2: B-field

Variable source with a **bimodal Lx distribution** likely due to the switch between surface and magnetosphere accretion (propeller effect).

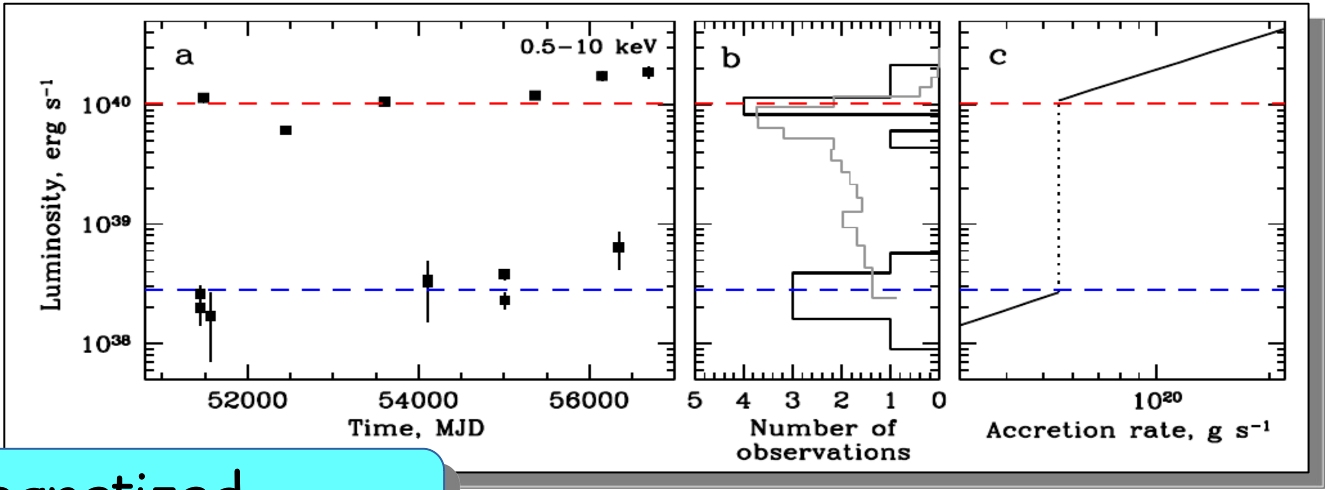


$$L_{\rm lim}(R) \simeq \frac{GM\dot{M}_{\rm lim}}{R} \simeq 4\times10^{37} k^{7/2} B_{12}^2 P^{-7/3} M_{1.4}^{-2/3} R_6^5 \ {\rm erg\ s^{-1}}$$

$$\frac{L_{\rm lim}(R)}{L_{\rm lim}(R_c)} = \left(\frac{GMP^2}{4\pi^2 R^3}\right)^{1/3} \simeq 170 P^{2/3} M_{1.4}^{1/3} R_6^{-1}$$

The propeller onset implies a magnetic field of:

$B \sim 10^{14}$ G



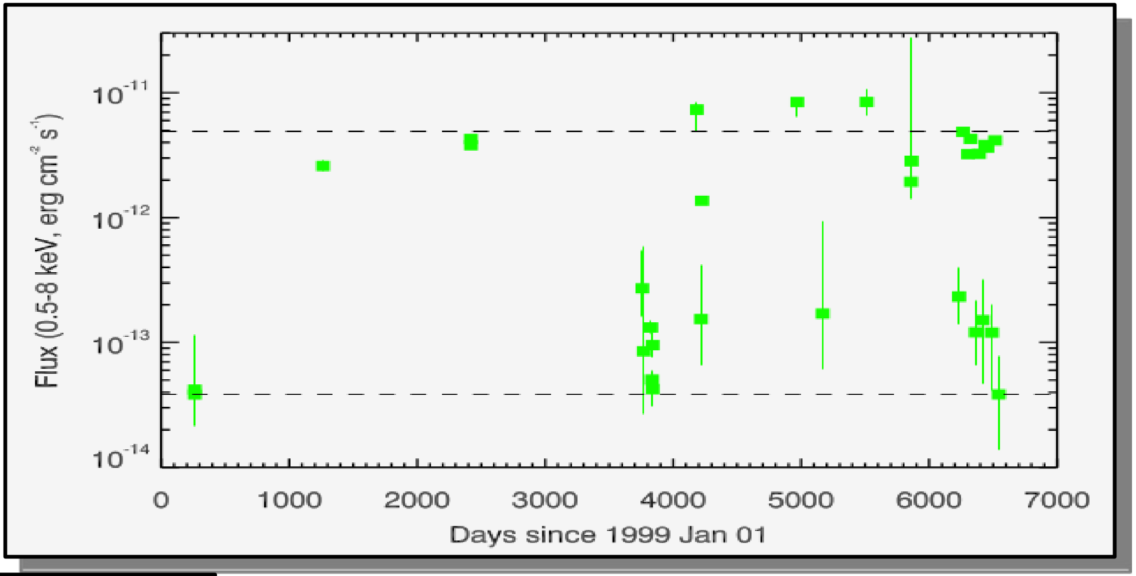
See also Grebenev 17 for a similar scenario implying

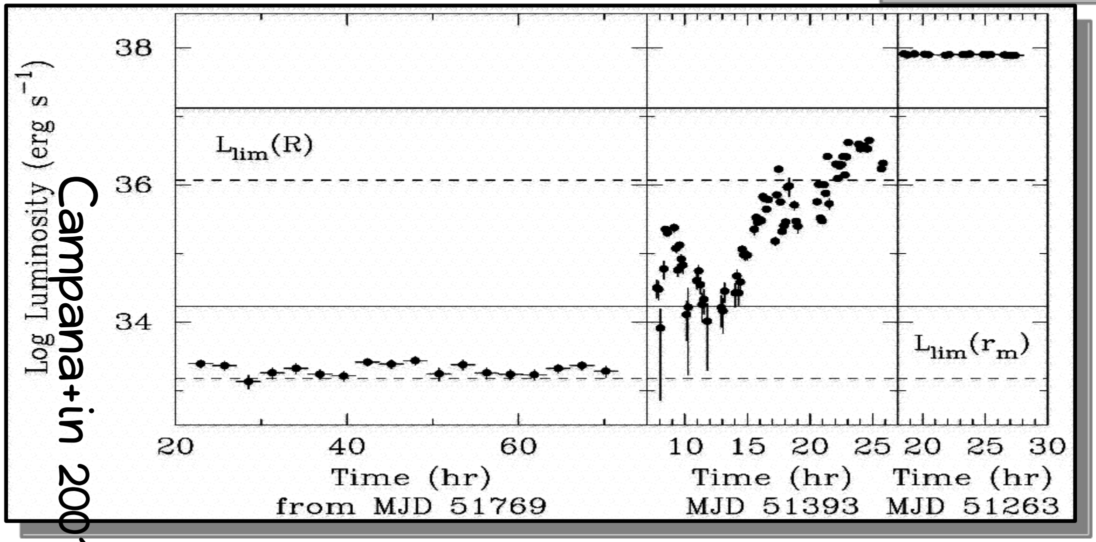
PULXs might be highly magnetized accreting NSs (not necessarly Magnetars)

M82 X-2: B-field

A reanalysis of the data shows several time intervals with flux values in the gap.

Used to weakens the propeller scenario in favor of a precession flux modulation

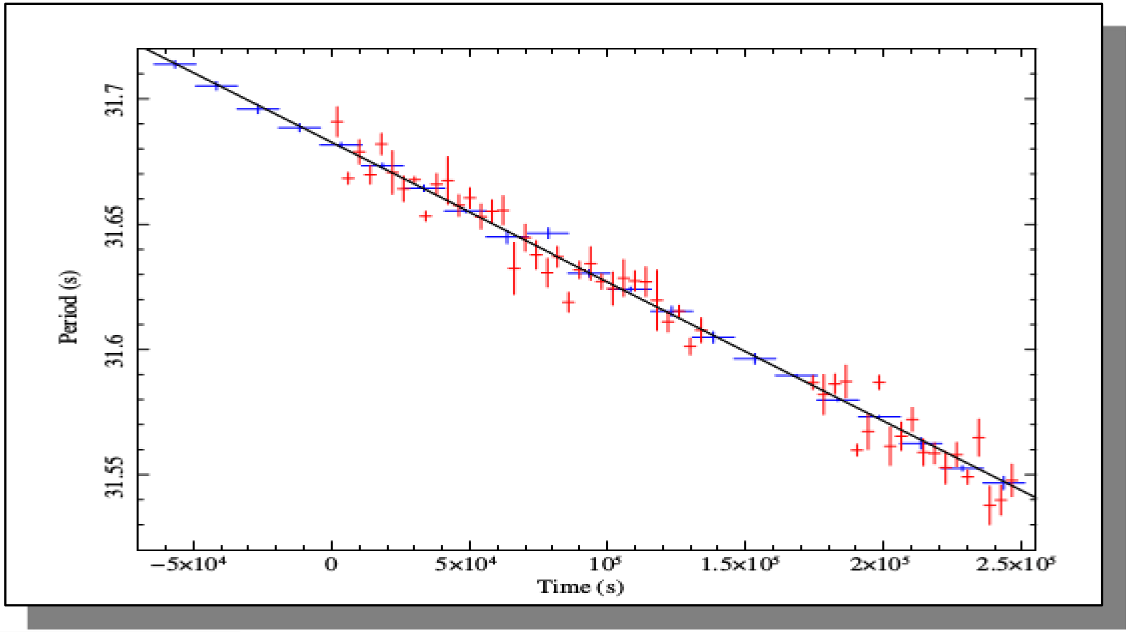


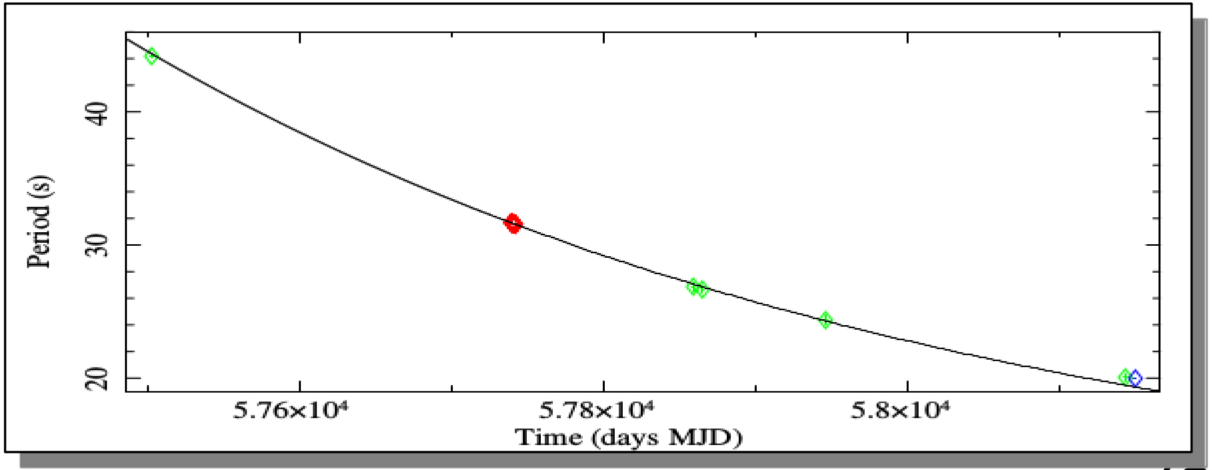


Similar behaviour observed in Galactic transient X-ray pulsars (e.g. 4U0115+63)

NGC300 X-1

Transient (SN impostor 2010da)
Lx ~ 4.5 x 1039 erg/s
P ~ 32s
Pdot ~ 6 x 10^{-7} s/s !!!!!
The highest ever observed in a pulsar = 📝P ~ 17s/yr



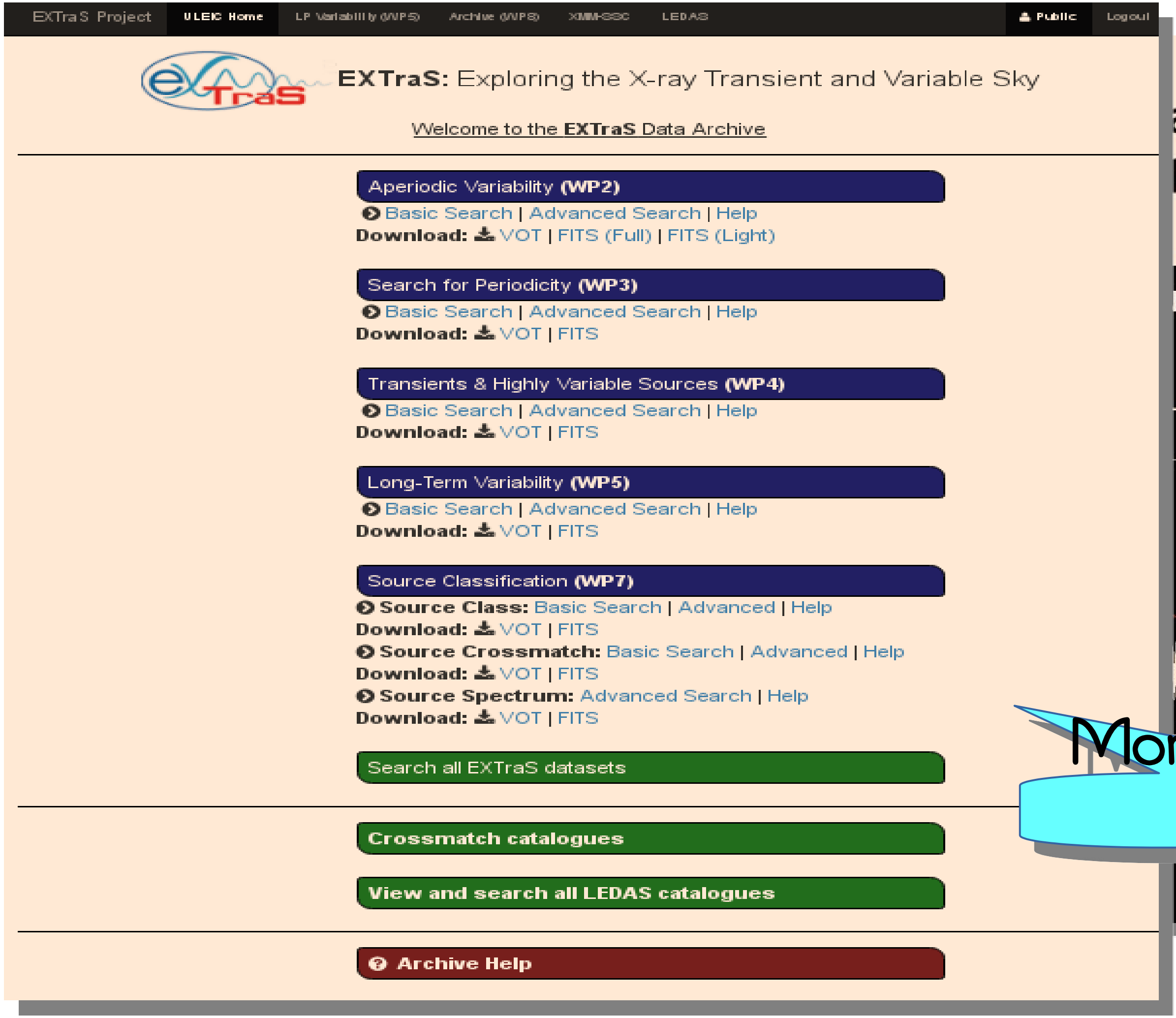


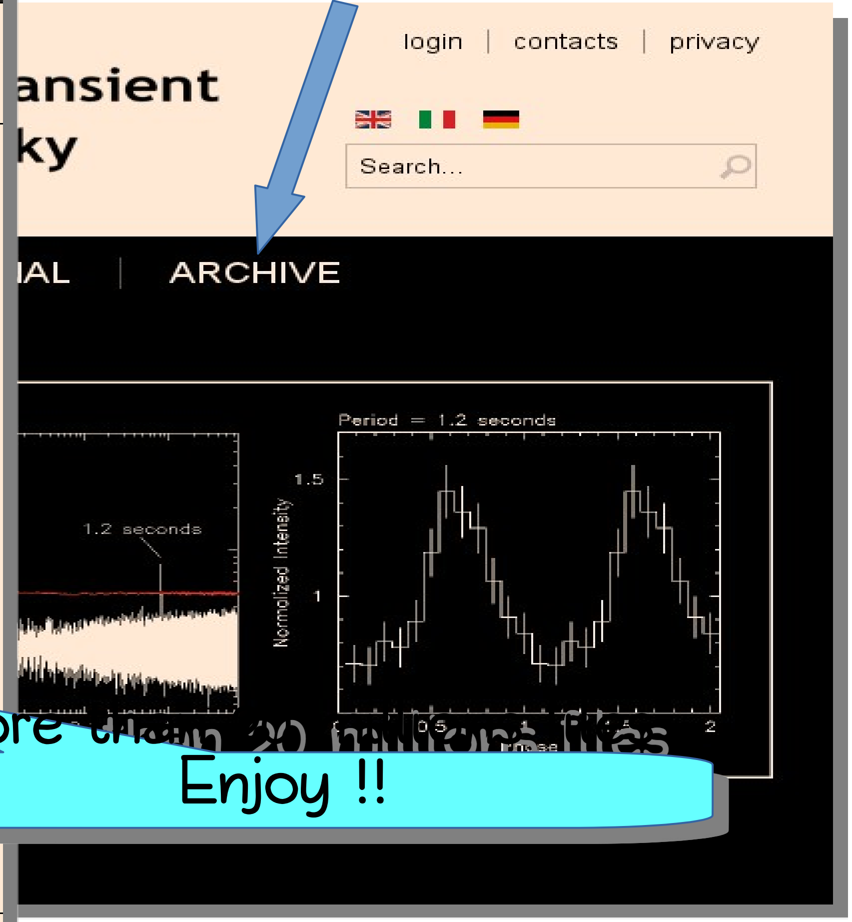
P → asymptotically approaching P_{eq} ?
📝P ~ 22s in 1.7yr

(Carpano+ 18)

EXTraS cataloges released

www.extras-fp7.eu



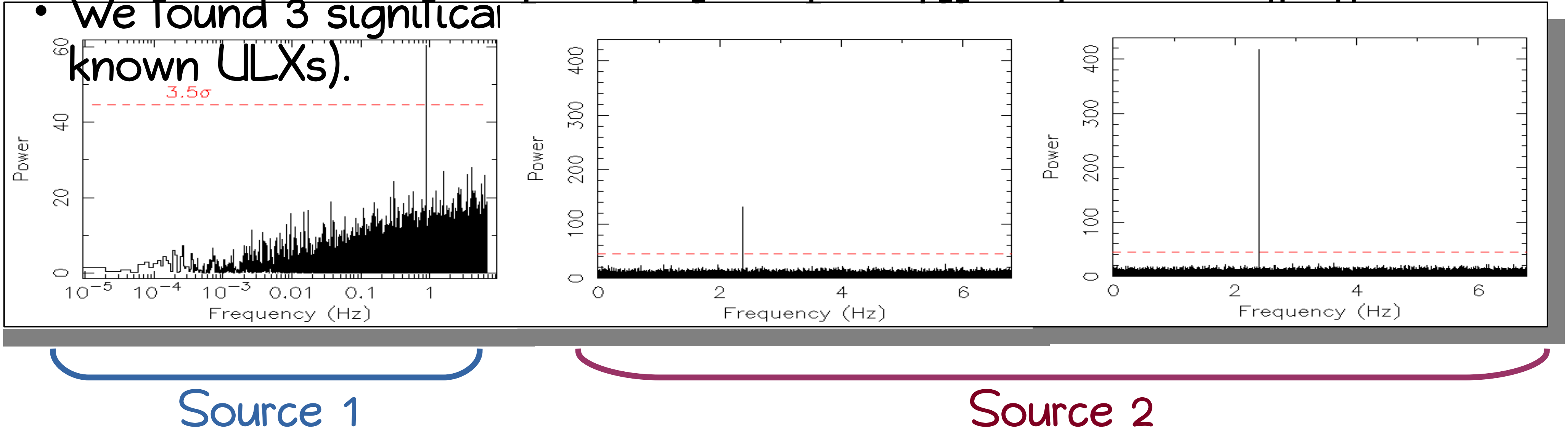


More than 20 millions files

Enjoy !!

and the ULXs

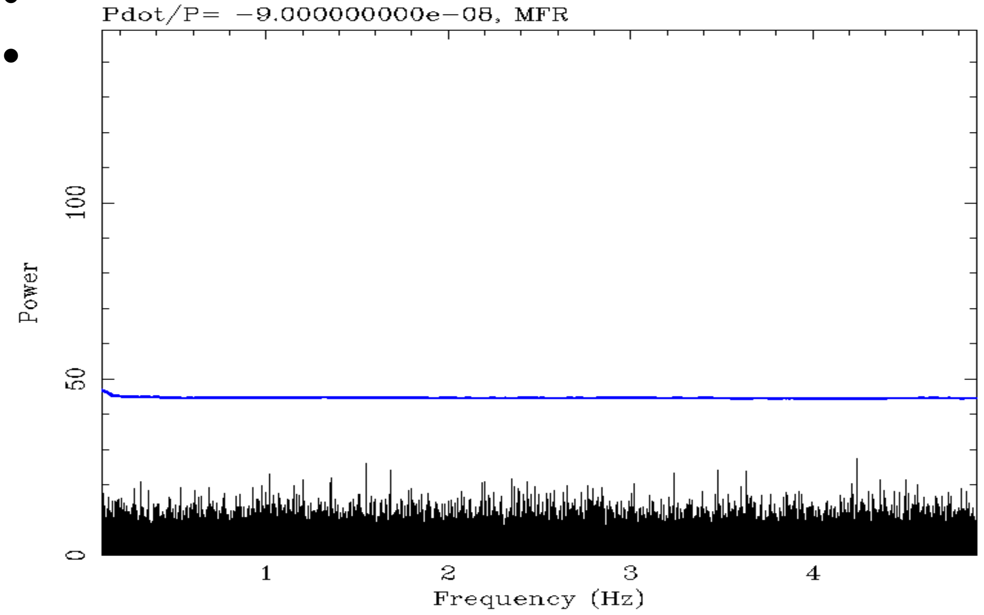
- About 500 XMM datasets including the position of cataloged or suspected ULX.
- We simply checked all the peaks detected by our pipeline in the ~500 datasets
- We found 3 significa
  known ULXs).



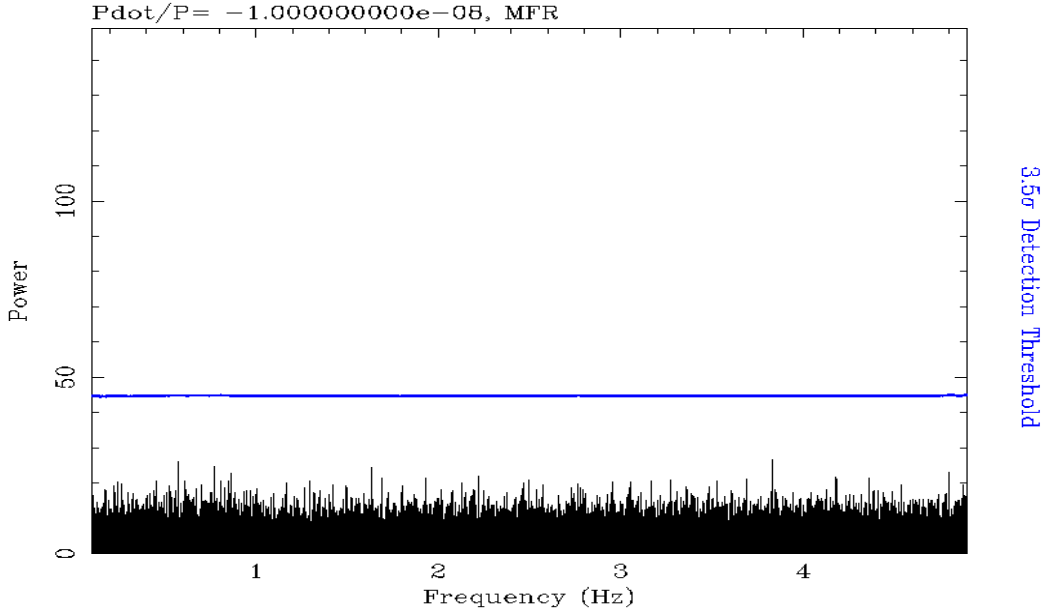
NGC 5907 ULX

- 7 XMM pointings (6 source detection)+5 NuSTAR pointings (3 detection)
- XMM data reveals a rather large "local" Pdot of several -10^{-9} s/s
- We applied an accelerated search on the 9 XMM+NuSTAR pointings
- Detection of the signal in 2 XMM and 2 NuSTAR observations

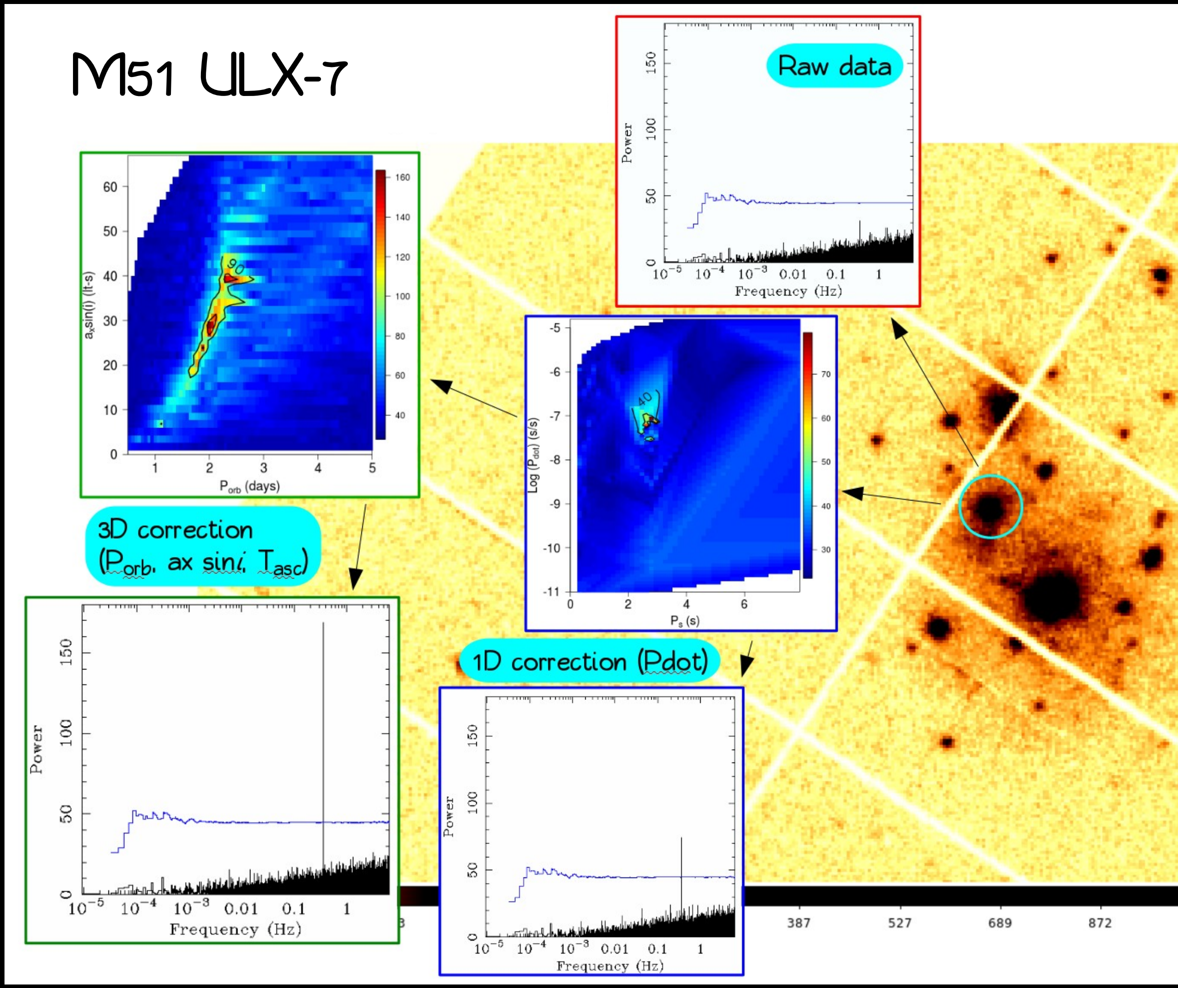
- XMM 2003



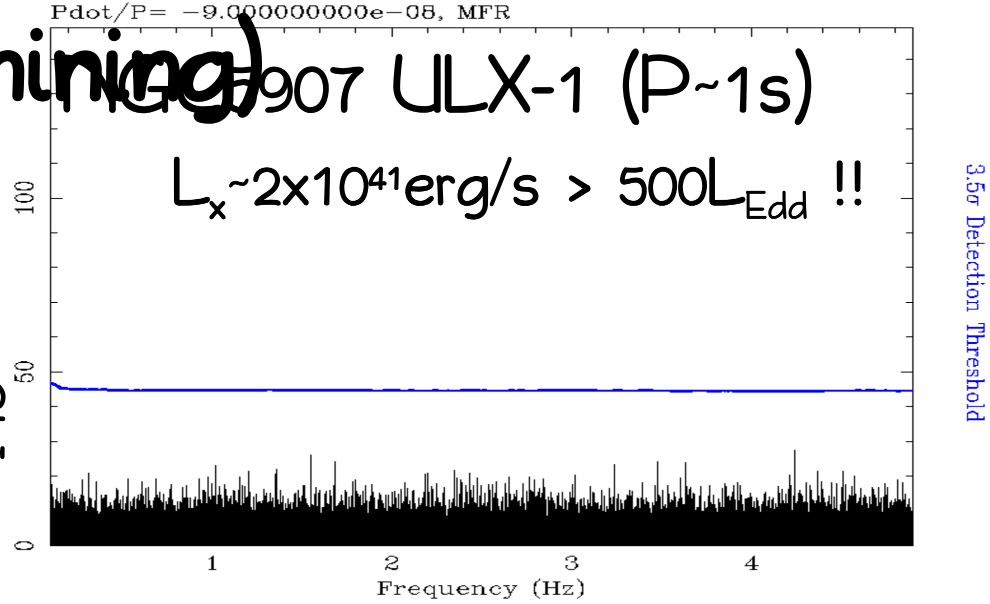
NuSTAR 2014



What's next ?


M51 ULX-7
Raw data
3D correction
(P_{orb}, ax sin$i$, T_{asc})
1D correction (Pdot)
Power
Frequency (Hz)
$a_x \sin(i)$ (lt-s)
P_{orb} (days)
Log (P_{dot}) (s/s)
P_s (s)

More PULXs discovered (data mining)



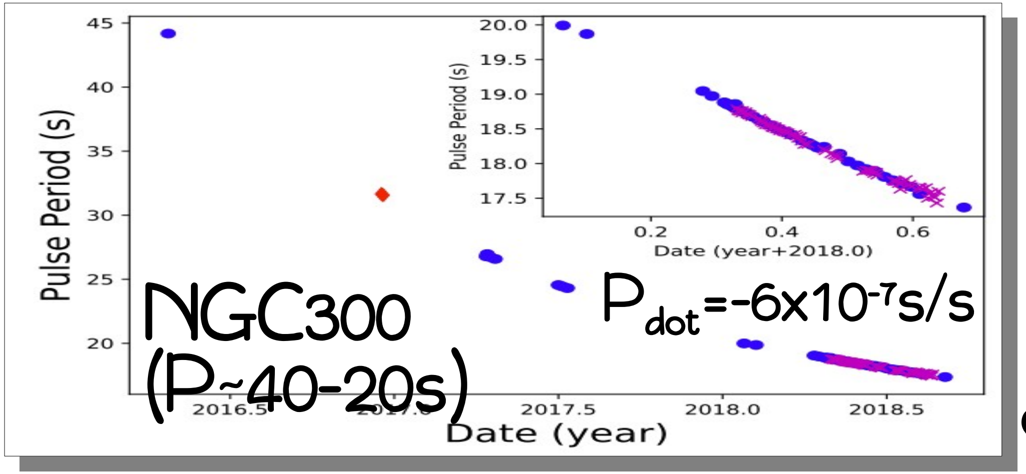
NGC5907 ULX-1 (P~1s)

L_x~$2x10^{41}$erg/s > $500L_{Edd}$!!

GLI+17a

+ 2 transient pulsars in NGC1313 (766s) and NGC2403 (18s) with L_x~few 10^{39} erg/s (Trudolyubov 2008,2010)

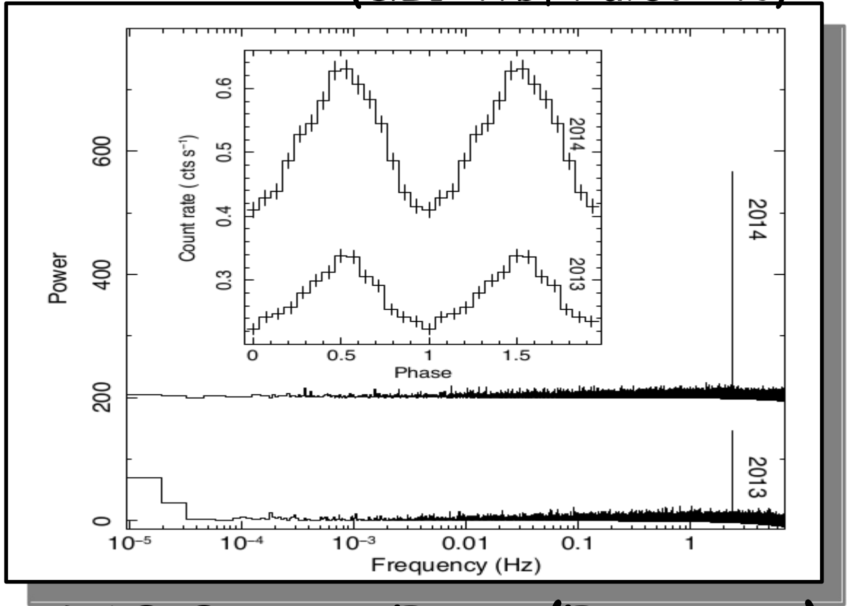
(GLI+17b, Fürst+ 16)



NGC300 (P~40-20s)

P_{dot}=-6x10^{-7}s/s

Carpano+18



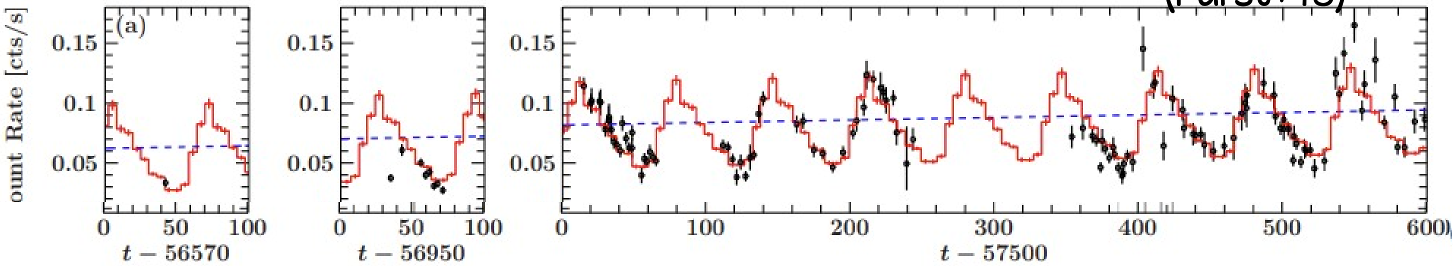
NGC7793 P13 (P~0.42s)

Nph >10.000

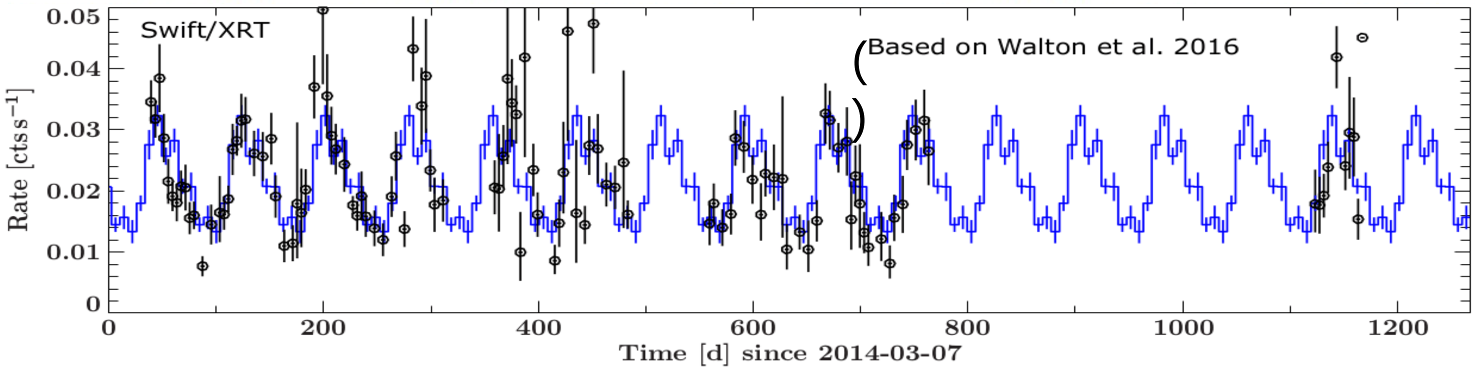
Disk precession and beaming

(Furst+18)

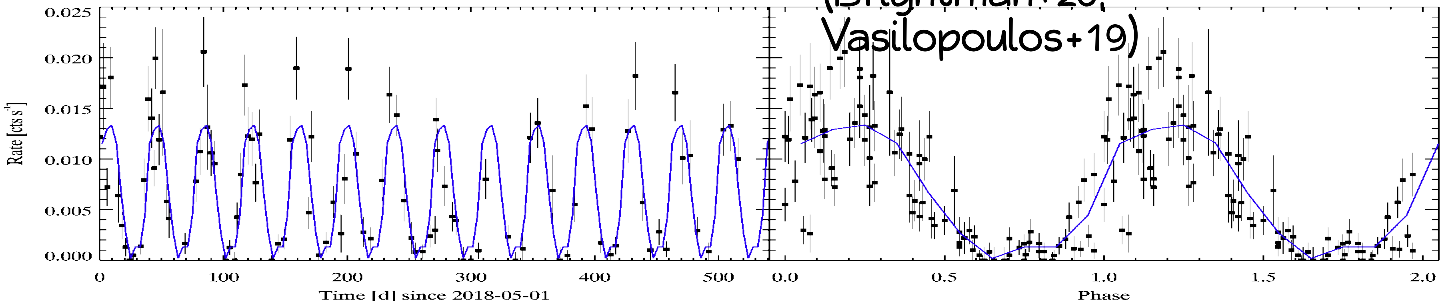
NGC7792 P13
P=66 d



NGC 5907
ULX1
P=78 d



(Brightman+20, Vasilopoulos+19)



EXTraS in a nutshell

EXTraS = Exploring the Transient x-ray Sky (fp7 funded project; 3Yr 2014-2016; PI Andrea DeLuca - INAF). Focused on the EPIC 3XMM catalog (~500,000 sources)

WP2: search and characterization of source aperiodic variability

EXTraS WP3 : <u>**search and characterization for coherent signals in the archive**</u>

WP4: search for faint and/or short transients

WP5: long term variability (more pointings and/or slew data)

WP6: Multiwavelength characterization and classification

Results (catalogs/metadata) will be released to the community as part of the 3XMM DR4 catalog (spring 2017).

Why searches ?

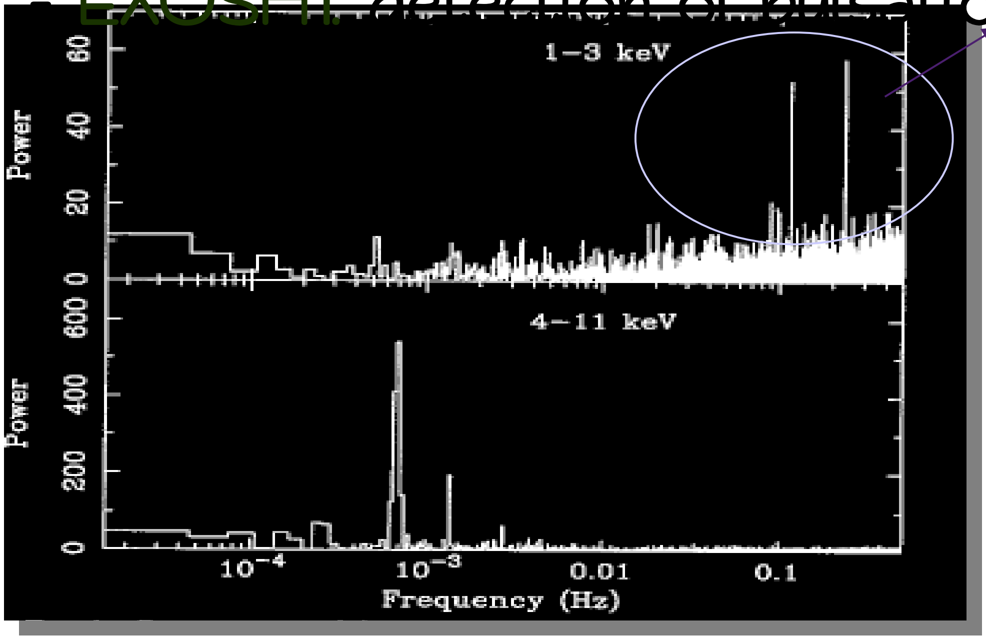
Two aims :

1) Search for new classes of X-ray pulsators

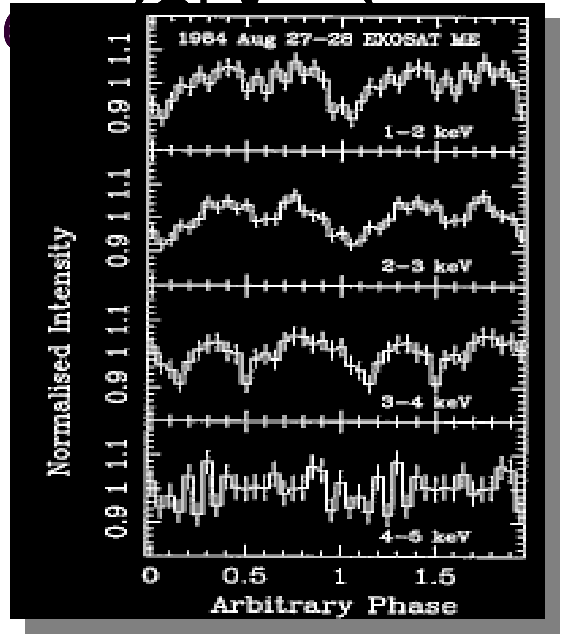
[large number of sources and photons]

Everytime we searched something…. we found something new !

- EXOSAT detection of pulsations from 4U0142+6



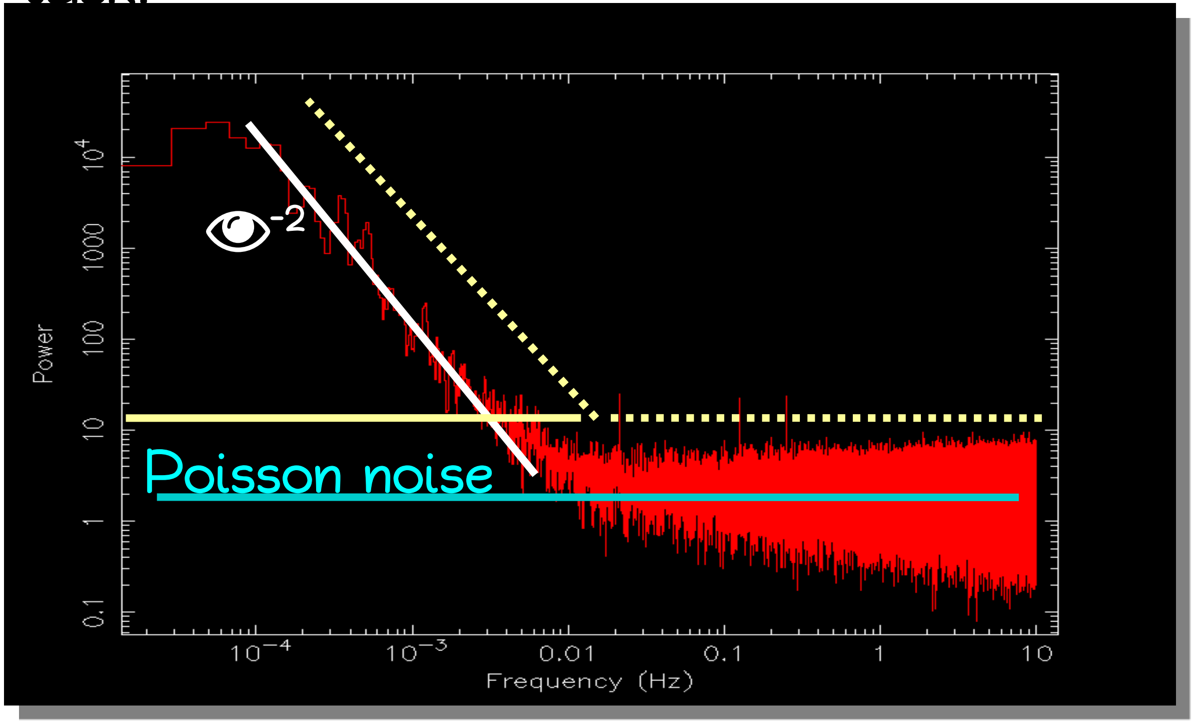
8.7s pulsar,
Ultrasoft spectrum;
$F_X/F_{opt} > 10^4$
Pdot ~ 10^{-11} s/s.
Classification ??
Magnetar



How (real data)?

In real cases PSDs of accreting objects are often dominated by "non Poissonian" noise components making the automatic detection and screening process a hard task.

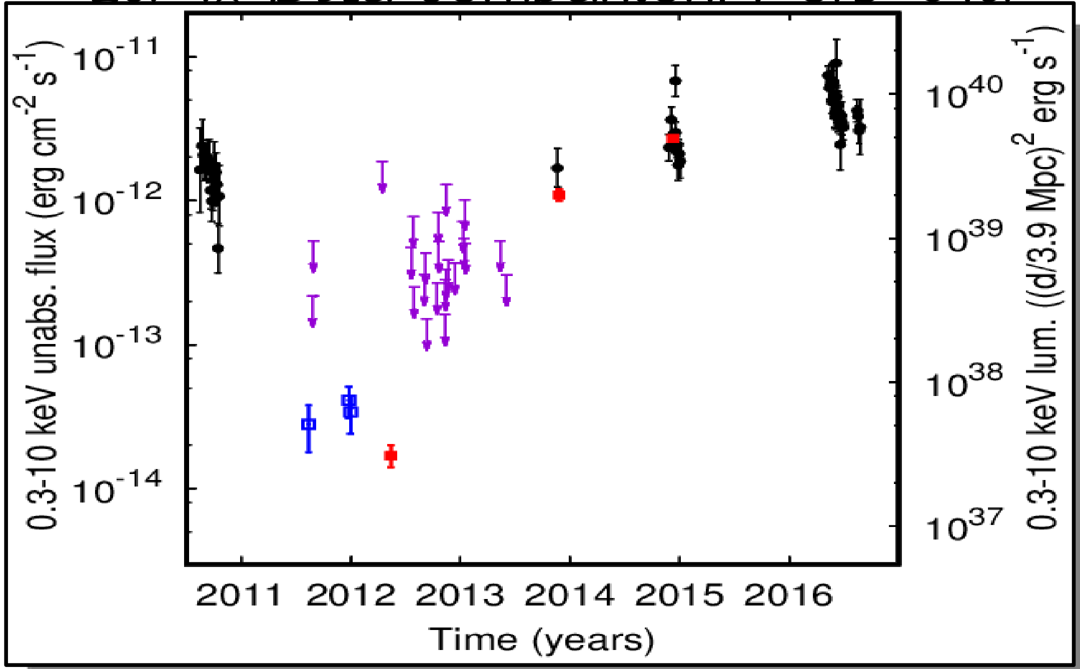
An objective tool/algorithm able to "model" the noise component was developed.

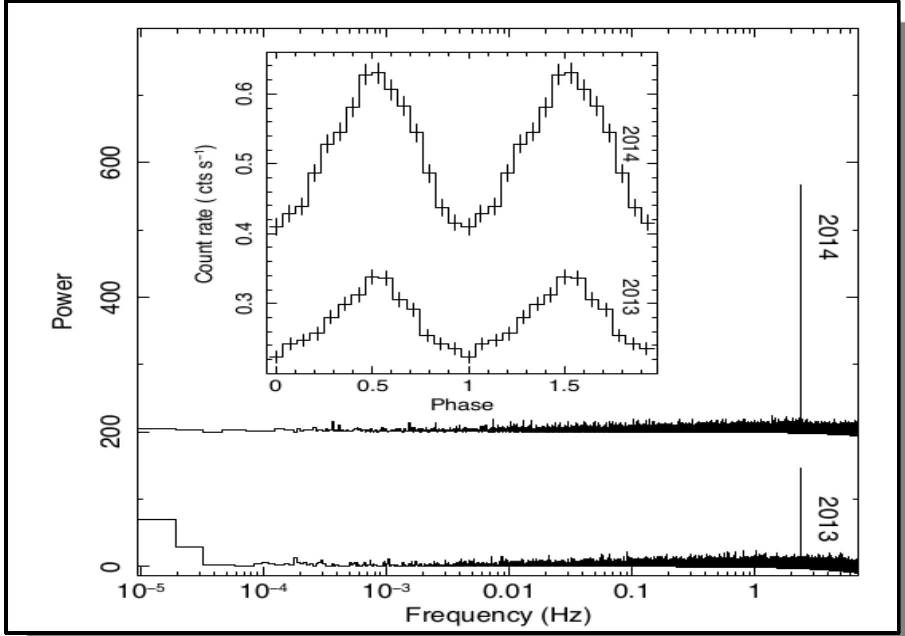


Source 2= NGC 7793 P13

Epoch (MJD TDB)	56621.0	57001.0
P (s)	0.4197119(2)	0.4183891(1)
ν (Hz)	2.382586(1)	2.3901207(6)
$\lvert\dot{P}\rvert$ (10^{-11} s s^{-1})	<10	<5
$\dot{P}_{sec}$ (10^{-11} s s^{-1})	$-4.031(4)$	
Pulsed fraction (%)[a]	18(1)	22(1)

- P/Pdot~320 yr
- 20$M_\odot$ B9Ia companion, Porb=64d



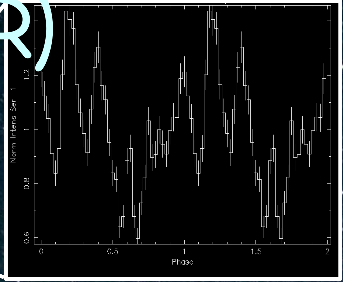


- For a distance of 3.9 Mpc the
- Isotropic Lx range is
- Lx ~ 9×10^{39} and ~1.6×10^{40} erg/s

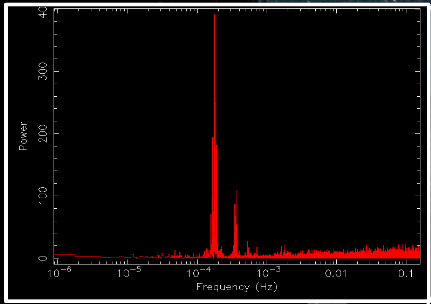
- Faint state ~ 3×10^{37} erg/s

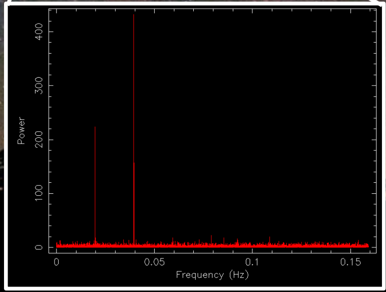
- Propeller regime expected at
- 2×10^{37} erg/s consistent with the
- lowest observed fluxes
- (GL1+17b; Fuerst+ 2016)

The Chandra ACIS Timing Survey Project (CATS@BAR)



GianLuca Israel
INAF - Rome Astronomical Observatory





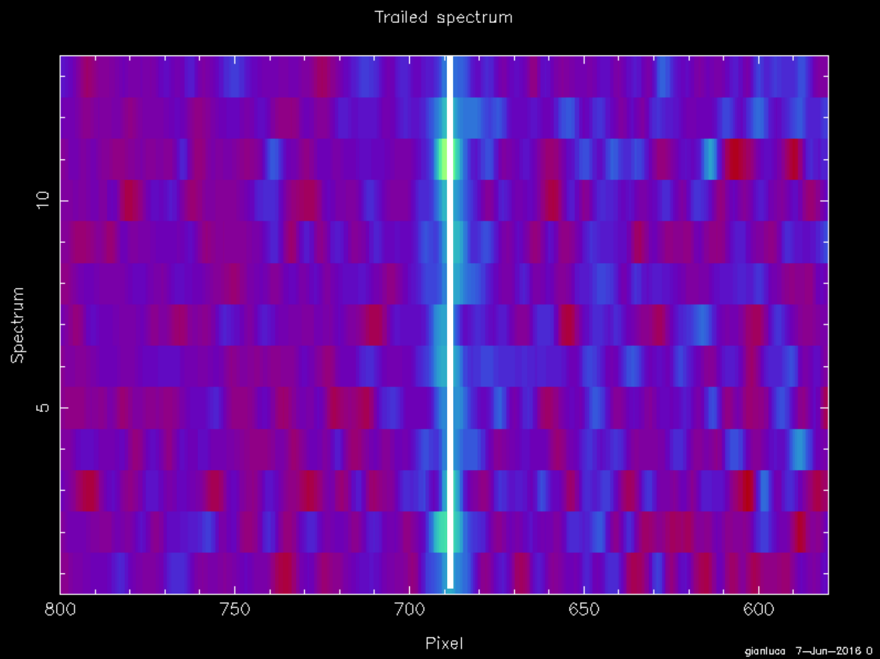
- Outline
- Why: data mining & periodicity search
- How: data analysis & overall approach
- The sample of new pulsators
- Chandra versus XMM-Newton
- Some particularly interesting cases
- The magnetic gating scenario
- Optical follow-up: origin of the signals
- What's next

- (Based on Israel+16, MNRAS, 462,4371)

Collaborators: Paolo Esposito (IUSS Pavia), Guillermo Rodriguez (INAF Palermo), Lara Sidoli (INAF Milan)

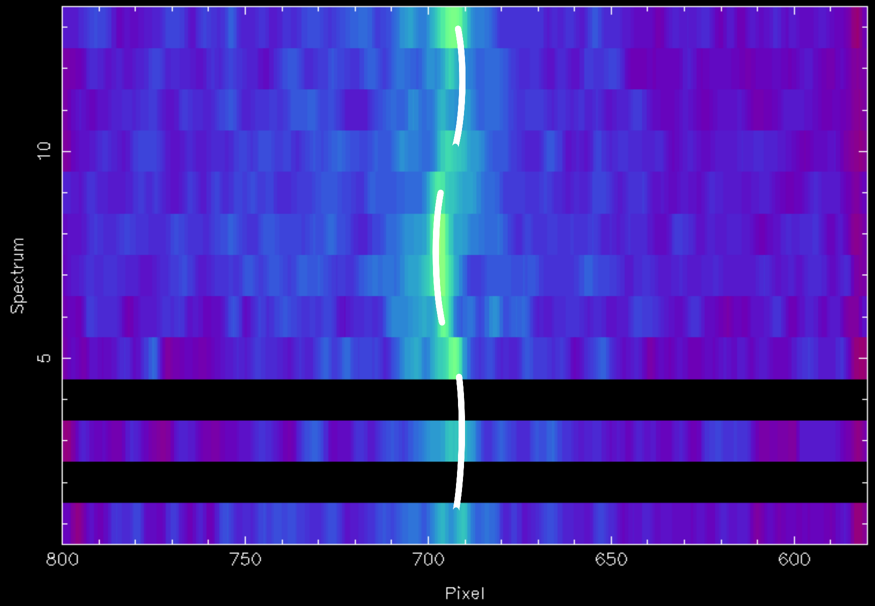
INAF ISTITUTO NAZIONALE DI ASTROFISICA

Optical studies (for CVs; 3000s<P<12000s)

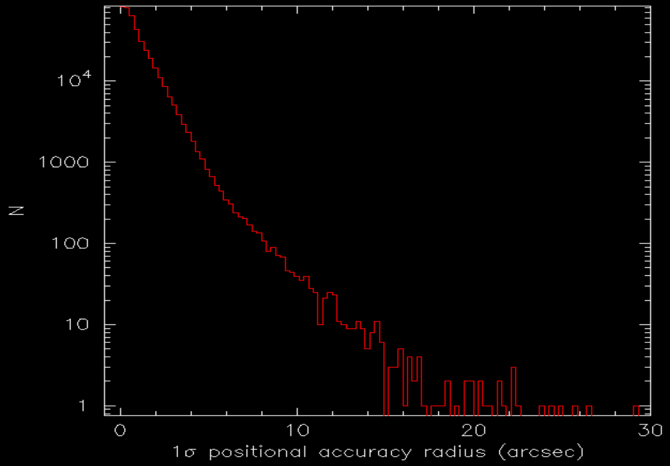


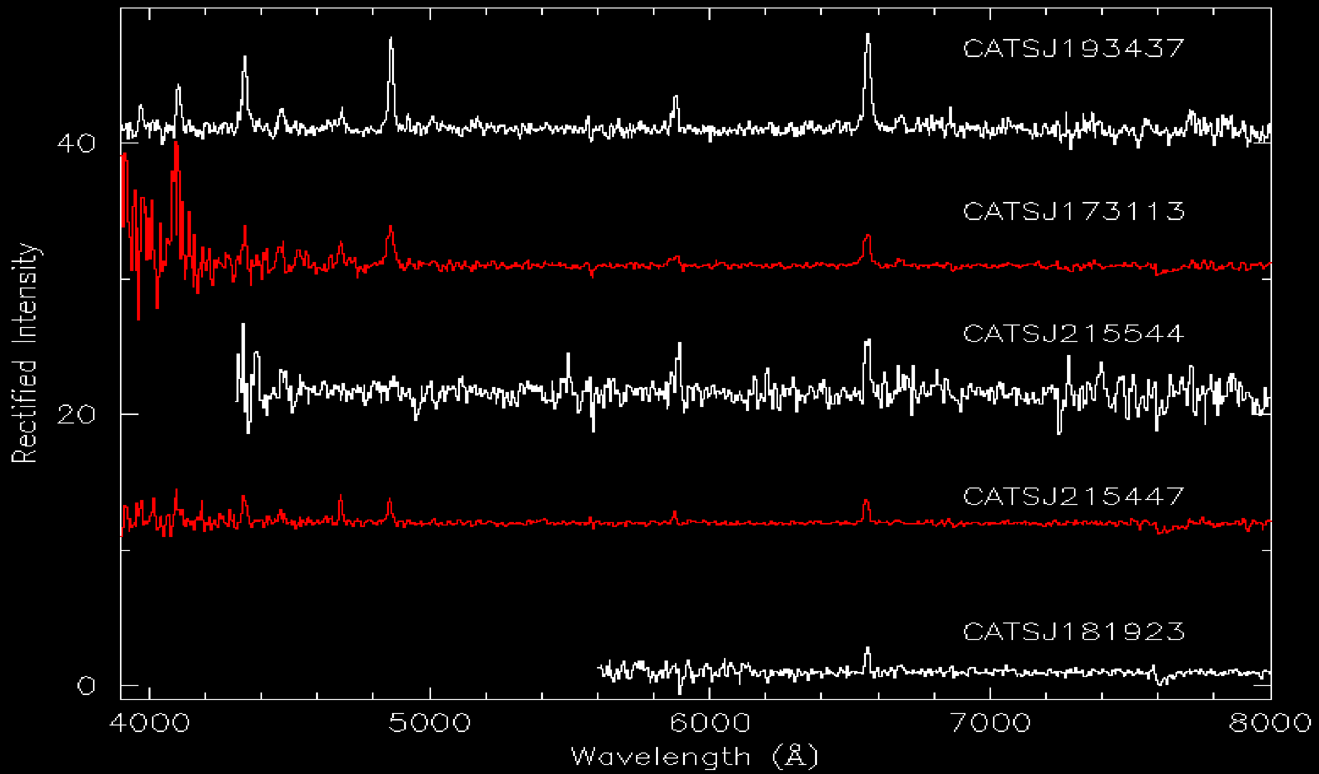
Undefined = Signal could be orbital or spin

X-ray signal = Orbital modulation



The classification process

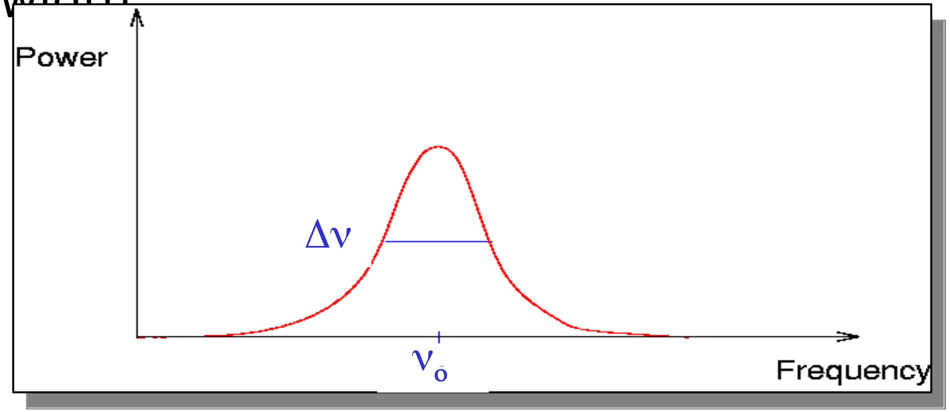




optimizing for the signal shape

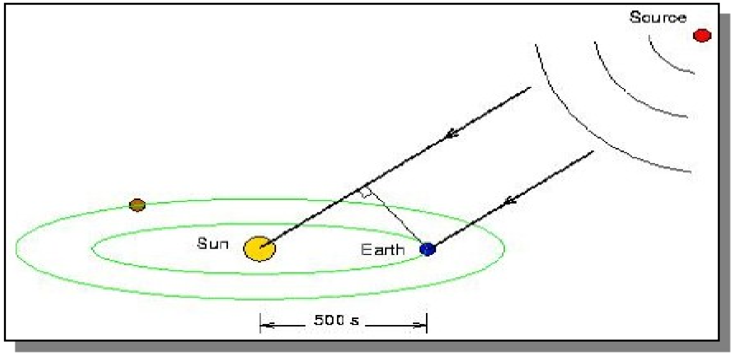
Similar reasoning shows that the signal power for a feature with finite width $\Delta\nu$ drops proportionally to *1/MW* when degrading the Fourier resolution. However, as long as feature width exceeds the frequency resolution, $\Delta\nu > MW/T$, the signal power in each Fourier frequency within the feature remains approx. constant.
When $\Delta\nu < MW/T$ the signal power begins to drop.

Implications: The search for QPOs is a three step interactive process.
Firstly, estimate (roughly) the feature width.
Secondly, run again a PSD by setting the optimal value of MW equal to $\sim T\,\Delta\nu$. Two or three iterations are likely needed.
Finally, use χ^2 hypothesis testing to derive significance of the feature, its centroid and r.m.s.



What to do

Step 1. *Barycenter* the data: corrects to arrival times at solar system's center of mass (tools: fxbary/axbary depending on the given mission). Correct for binary orbital param. (if any)

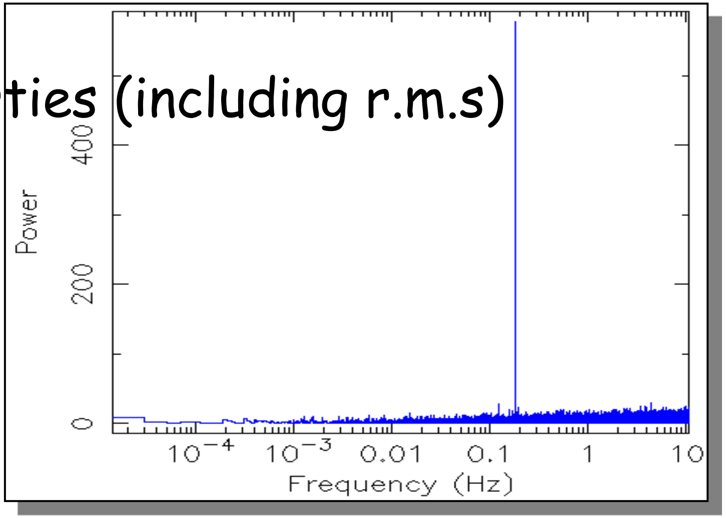


Step 2. Create light curves with lcurve for eachsource in your field of view inspect for features,e.g., eclipses, dips, flares, large long-period modulations.
lcstats give statistical info on the light curve properties (including r.m.s)

Step 3. Power spectrum. Run powspec or equivalent and search for peaks.
If no signal → calculate A_{UL} (or A_{sens})
If a peak is detected → infer

Example: ν_{sign} = 0.18 Hz → P_{sign} = 5.54s
T~48ks

One peak → likely sinusoidal pulse profile

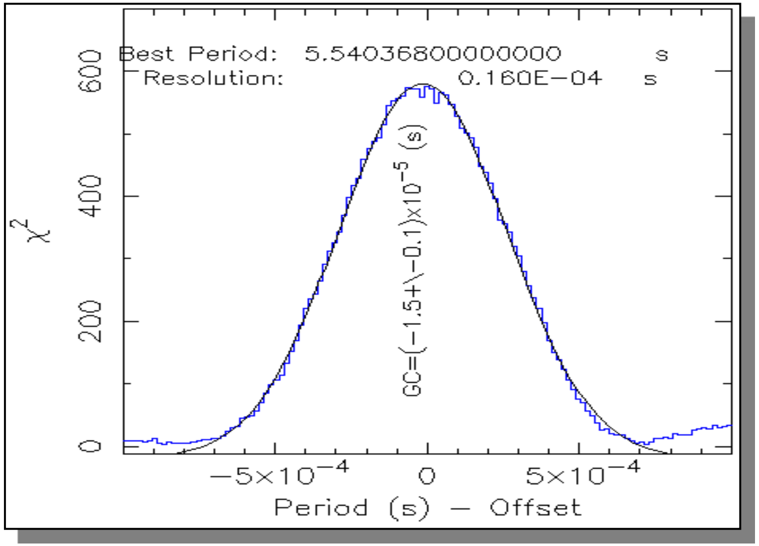


What to do-2

Step 4. Use efsearch (P vs χ^2) to refine the period. **Step 1** if you already know the period.

Note that efsearch uses the Fourier period resolution (FPR), P^2/T, as input default.
It depends from P !!!

To infer the best period the FPR has to be overestimated by a factor of several (ex. 20). Fit the resulting peak with a Gaussian and save the central value and its uncertainty.



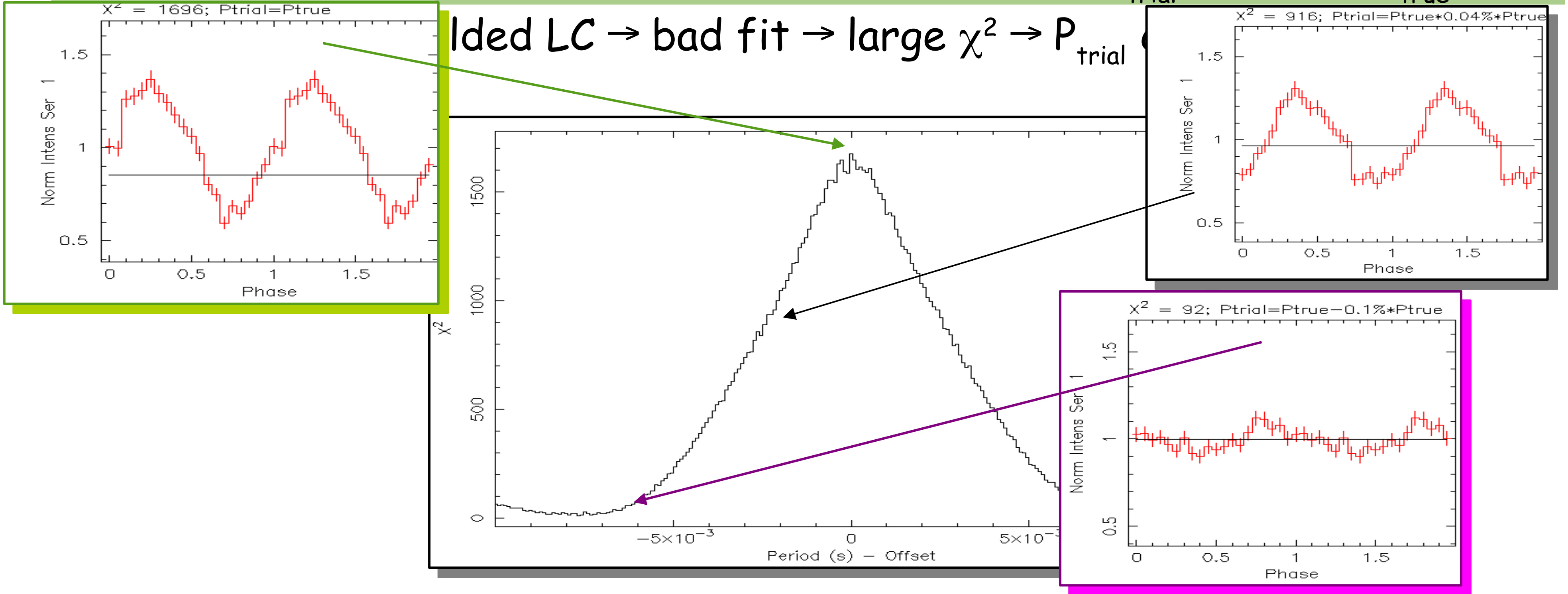
Example: for a signal at 5.54s and T=48ks ✉ FPR=3.2e-4s
FPR input = 3.2e-4/20=1.6e-5s
GC= $(-1.5\pm0.1)\times10^{-5}$s ($1\sigma$ c.l.) ✉ P=5.540368-0.000015 = 5.540353 s
For the uncertainty is often used the GC error x 20 (the overestimation factor used in input). $\Delta P = 0.1\times10^{-5} \times 20$ s = 2×10^{-4} s
Final Best Period: 5.5404(2) s (1σ c.l.)

Some details on epoch folding

The epoch folding technique (P vs χ^2), EF, checks the null hypothesis that the folded light curve (LC) modulo a given trial period is consistent with a flat (constant) component.

Flat folded LC → good fit with a const → small χ^2 → P_{trial} far from P_{true}

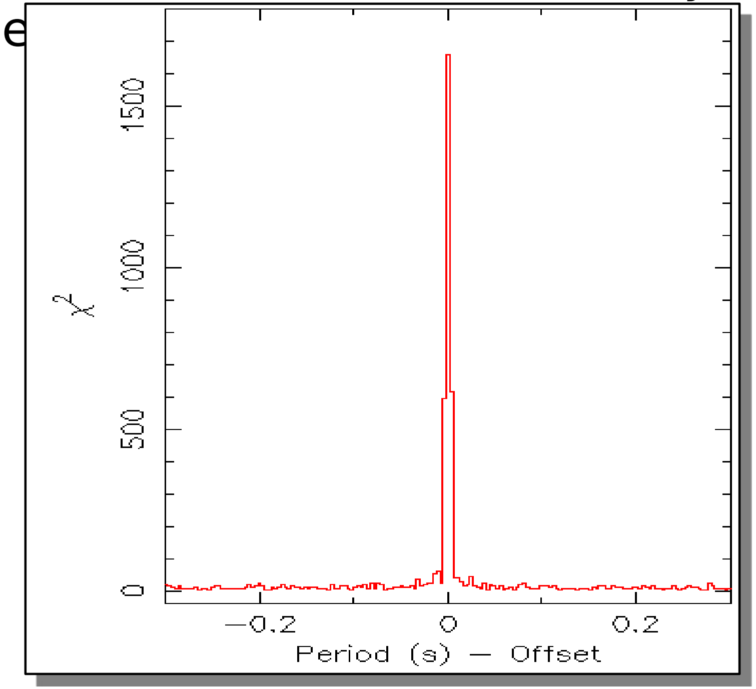
lded LC → bad fit → large χ^2 → P_{trial} c



Some details on epoch folding - 2

The EF is better suited for searching signals with small duty cycle (as a result of the fit with a constant).

Limit: the best period resolution (FRP, P^2/T) in the search depends on the period around which the search is performed. Correspondingly, a search optimized for a period of, say, 10s is less sensitive at 100s or 1000s. A way around it, is to divide the search in different pe[...] normalize for the correct N_{trial}. Not well suited for inferring the uncertainty of a (coherent) period. By definition the FRP is such that all the (coherent) signal χ^2 falls into one period "bin".

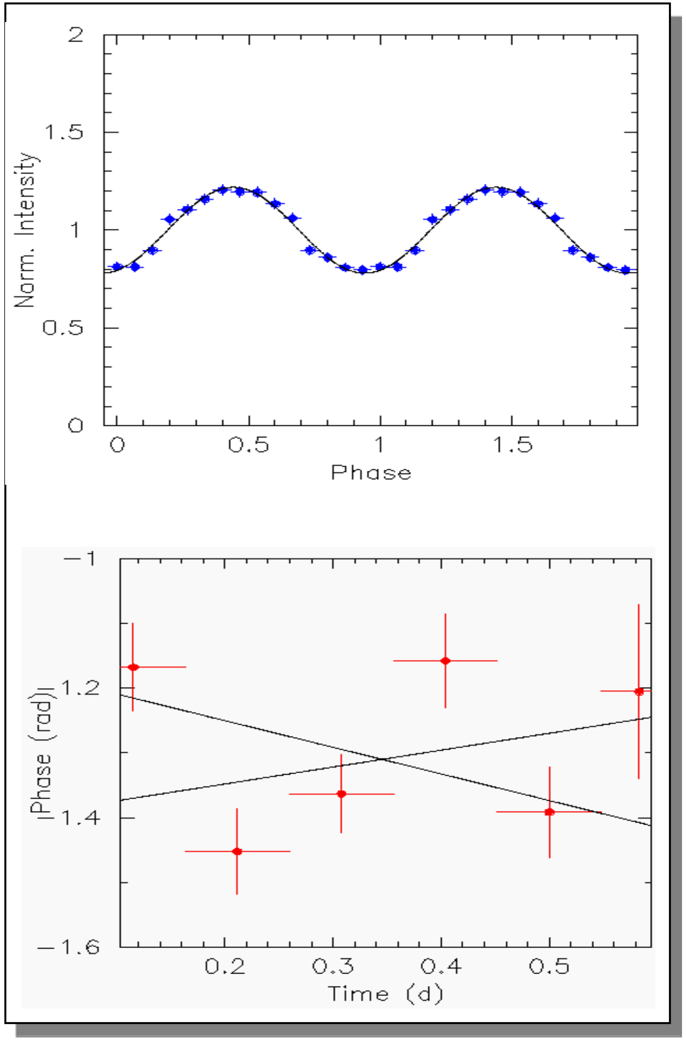


What to do-3

Step 5. Use efold to see the modulation. Fit it withone or more sinusoids. Infer the pulsed fraction (several definitions) and/or the r.m.s. Remove the BG (it works like unpulsed flux)

$$PF = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Ex: $PF = \frac{1.22 - 0.78}{1.22 + 0.78} = 0.22$



Step 4b. Apply a phase-fitting technique to your data (if enough photons). Use efold and save the sinusoid phase of pulse profiles obtained in 4 or more time intervals. Plot and fit Time vs Phase with a linear and quadratic component

- If the linear is consistent with 0 the input P is OK

- ... wrong? Correct and apply again the technique.

Example: Best Period: 5.54036(1) s 1σ c.l.
A factor of ~20 more accurate than efsearch

Some details on phase-fitting

A phase-fitting technique is an iterative procedure allowing the determination of the frequency of a coherent signal at agiven epoch, with a precision that … rvations are included in the analysis.

$$\phi(t) = \phi_0 + \int_{t_0}^{t} \omega(t')\, dt'$$

The steady variation of the period is parameterized by a series of time derivatives, truncated at the highest term that appears statistically significant. After integration, the above equation is

$$\phi(t) = \phi_0 + \omega_0 (t - t_0) + \tfrac{1}{2}\dot{\omega}_0 (t - t_0)^2 + \tfrac{1}{6}\ddot{\omega}_0 (t - t_0)^3 + \cdots$$

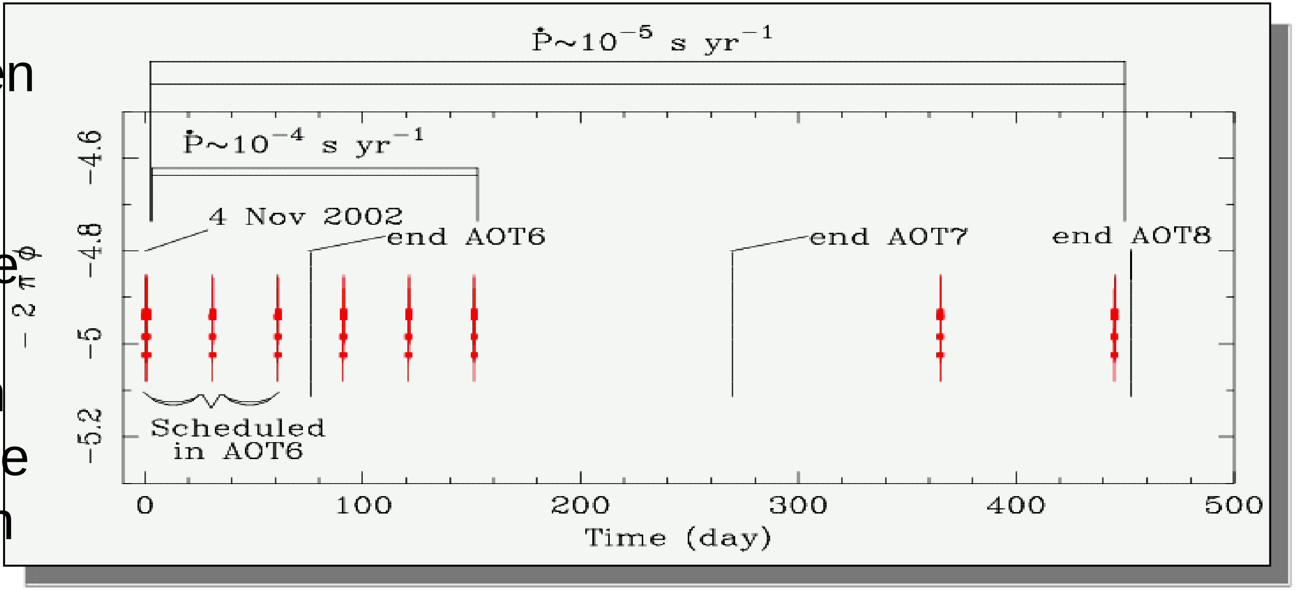
A first-guess period (P_0) was determined through an epoch-folding search of the light curve of an observation chosen as the starting point. A template pulse profile can be used if the shape of the average pulse profile does not change. Otherwise a fit with a sinusoid plus harmonics is better suited. The values of phases for N time intervals were then plotted versus the epochs and fitted by a function of (*), truncating that series at the last coefficient that was found to be statistically significant through an F-test at the 99% level (or any other value).

Phase fitting applied to the four phases provides a correction to the guess period P_0, resulting in a better estimate of the period call it $P_{0\ new}$.

To make a coherent solution you need an ad hoc observational strategy

Some details on phase-fitting

The max Δphase between the first two obs. should be less than 0.5 (better 0.4; 3.21 in the plot on the right).
The third observation can scheduled to a date where the new Δphase between the first two obs. and the third one is again <0.5
And so on….



The accuracy you can reach is order of magnitudes higher than that during the single observation.. (we have used the period AND the phase info together).

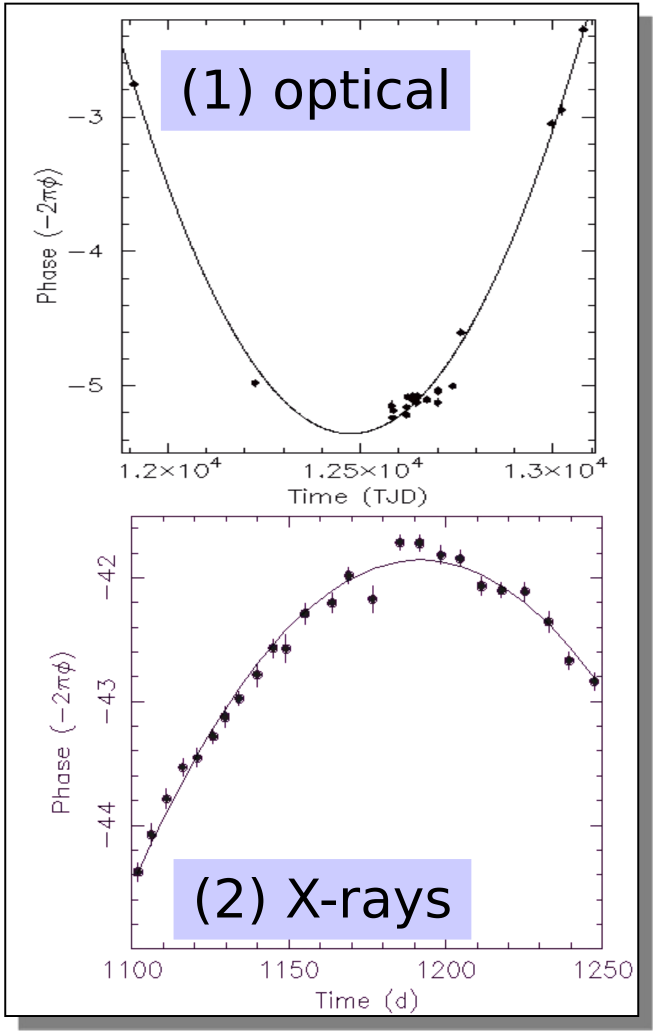
MORE on phase-fitting

It provides a phase coherent timing solution which can be extended in the future and in the past without loosing the information on the phase, therefore, providing a tool to study small changes of signals on long timescales.

- A negative quadratic term in the phase residuals implies the period is decreasing

- A positive term corresponds to an increasing period

Examples: (1) a shrinking binary – orbital period decreasing at a rate of dP/dt=1ms/yr=-3×10^{-11}s/s (2) An isolated neutron star spinning down at a rate of dP/dt=1.4×10^{-11}s/s

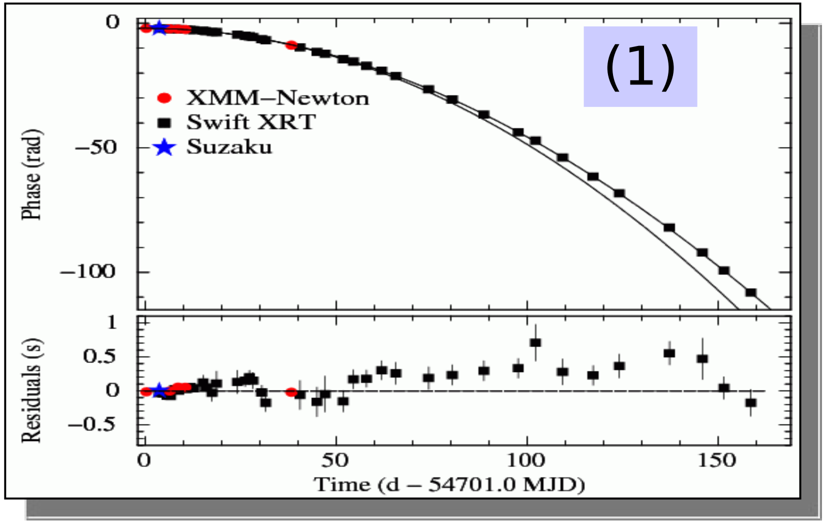


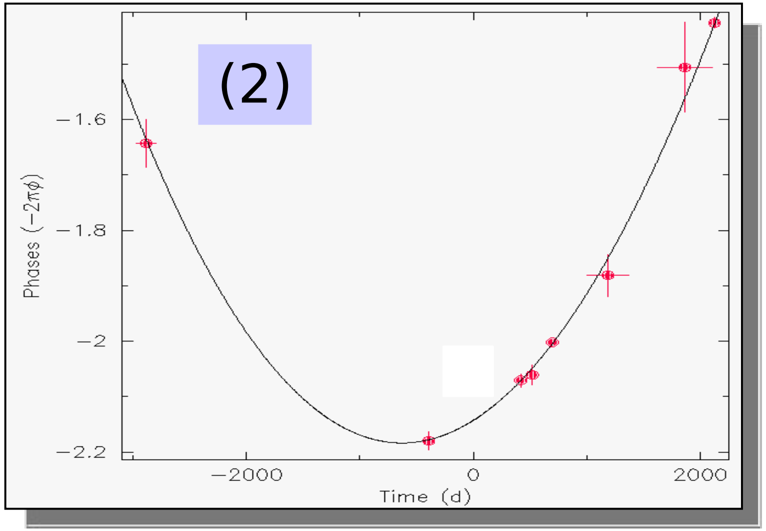
MORE on phase-fitting

When the phase coherent timing solution is accurate enough higher derivative terms may be detected as a cubic term.

- A negative cubic term in the phase residuals implies the dP/dt is decreasing

- A positive term corresponds to an increasing dP/dt

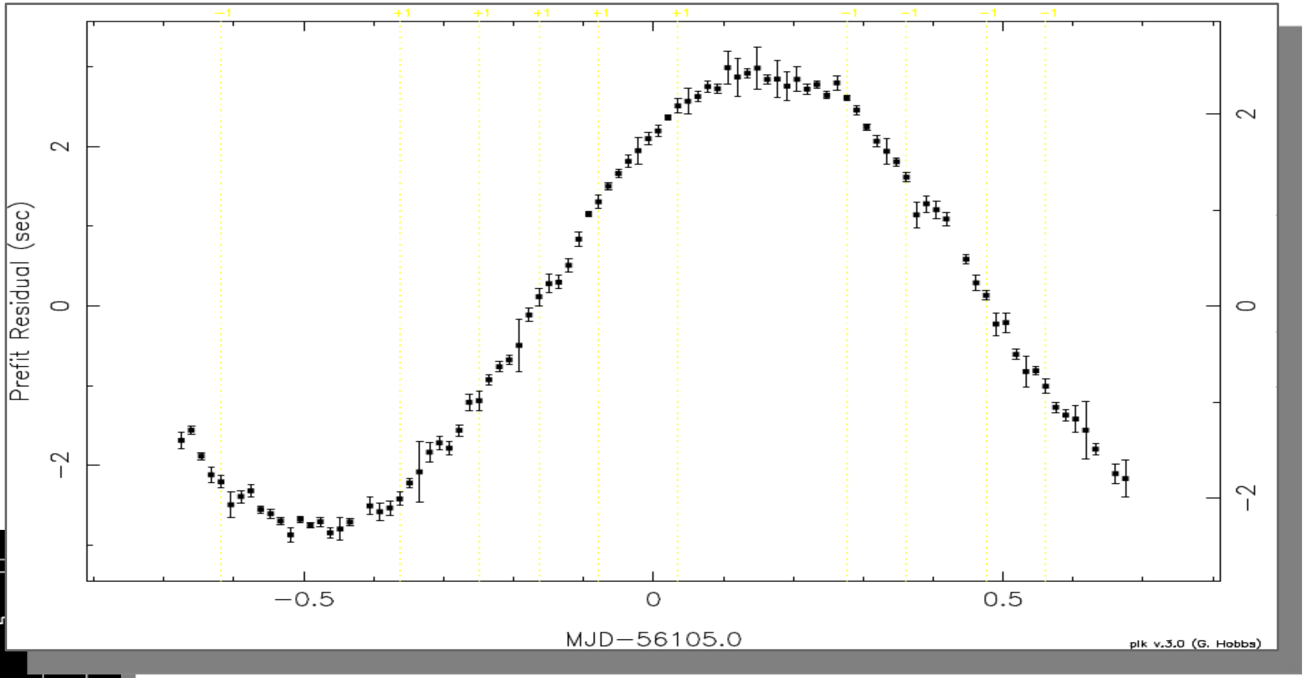


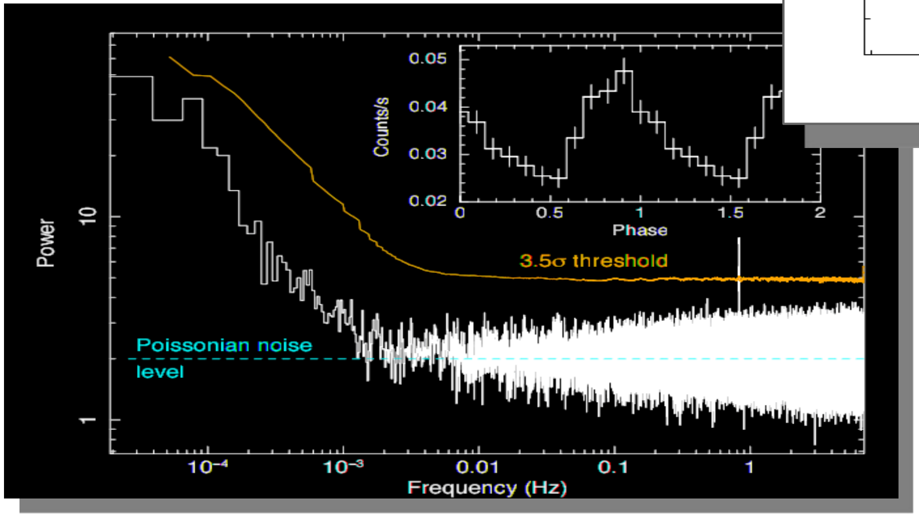


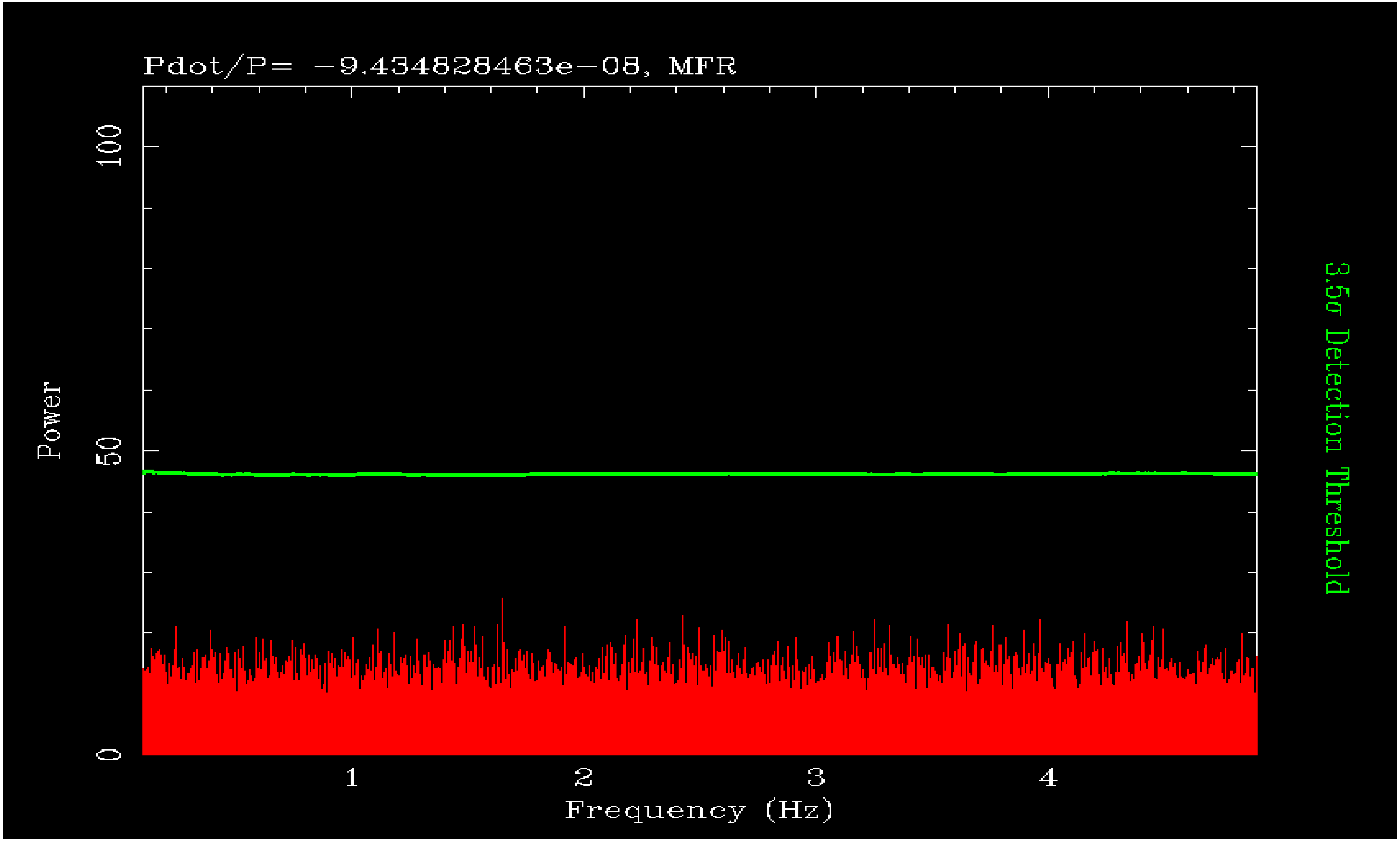
Examples: (1) An isolated neutron star spinning down at a rate of dP/dt≈6.7x10^{-12} s/s and showing a (negative) second period derivative of -1.6× 10^{-19} s s^{-2} which acts in slowing down the dP/dt. (2) 14years of monitoring of the shortest orbital period known (321.5s)

MORE on phase-fitting

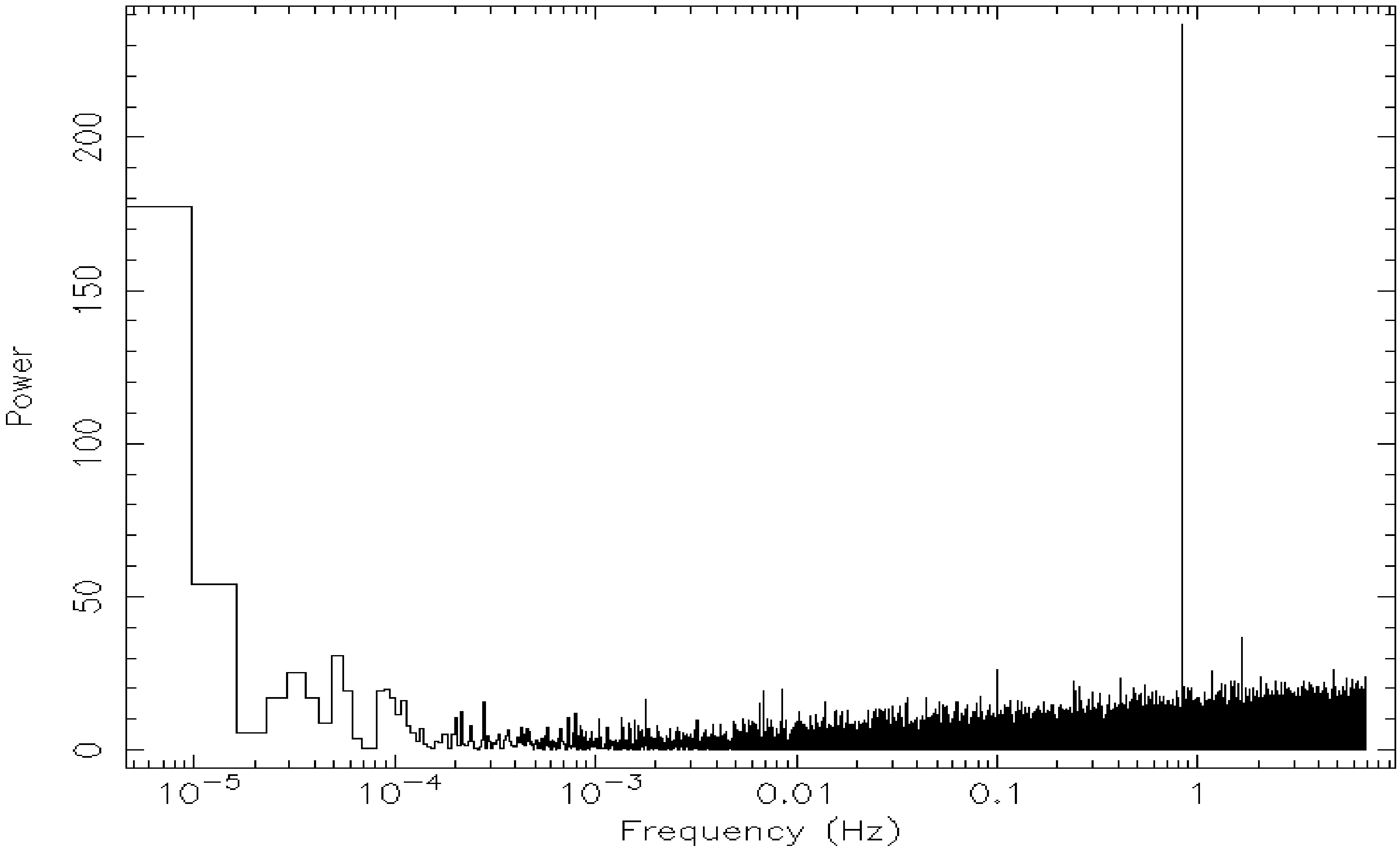
Doppler shift due
to orbital motion







Pdot/P= −9.434828463e−08, MFR
Power
100
50
0
1
2
3
4
Frequency (Hz)
3.5σ Detection Threshold

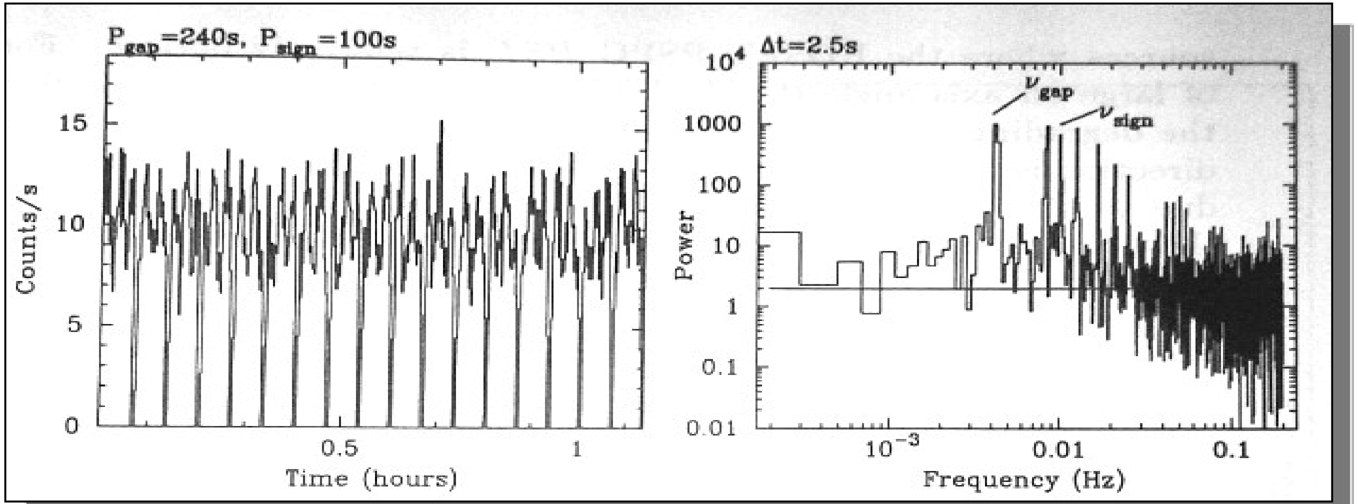


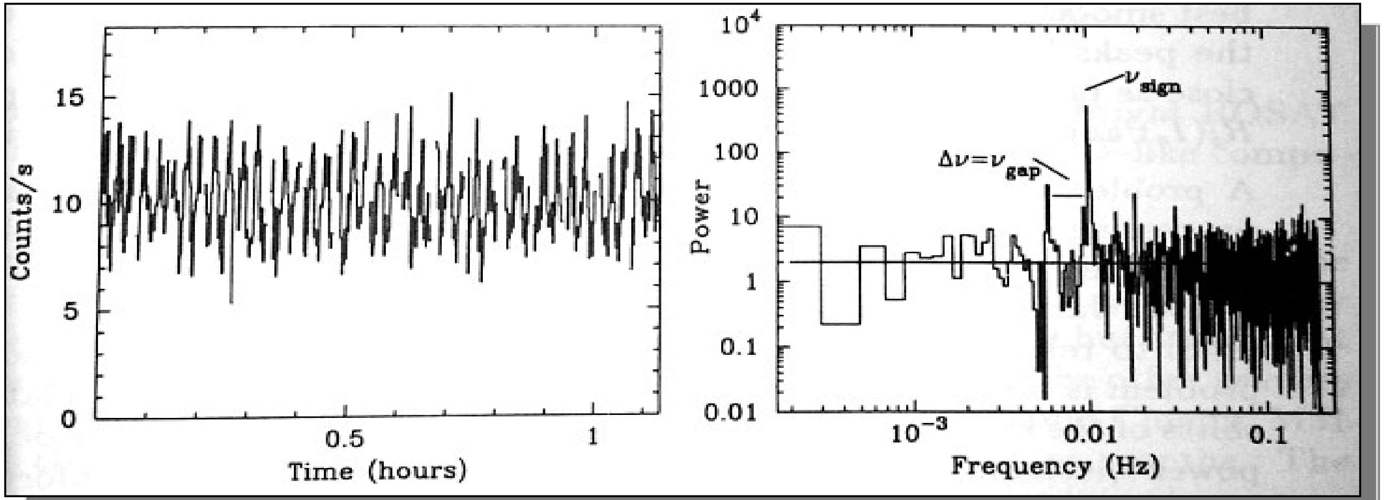
Power
0
50
100
150
200
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
1
Frequency (Hz)

The Use OF GTIs

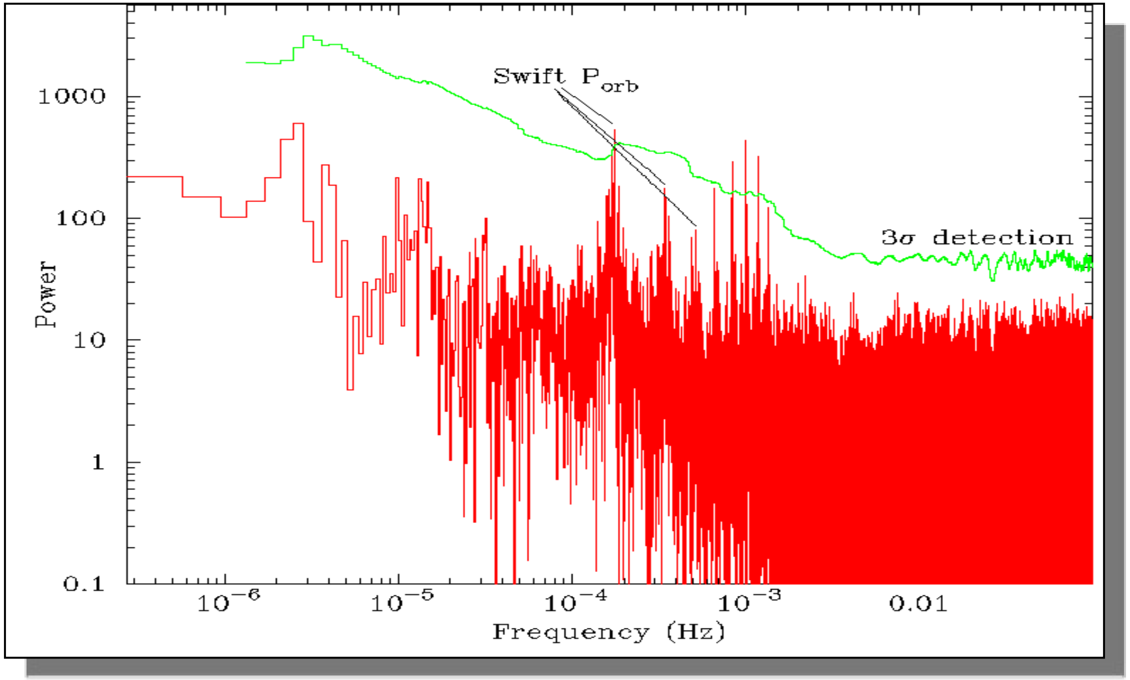
Suggestion: always check that the correct GTIs are considered (check with lcurve)

But...





The Use OF GTIs



More difficult when periodic gaps have recurrences which are longer than the typical observation.

Both in Xray (earth occultation) and optical/IR (day/night)

Sidelobes are detected around a signal

Tips

Pulsar (coherent pulsation) searches are most sensitive when *no rebinning* is done (ie., you want the maximum frequency resolution), and when the original sampling time is used (i.e. optimizing the signal power response). Always search in all serendipitous sources ($N_{ph}>300$)

QPO searches need to be done with *multiple rebinning* scales. In general, you are most sensitive to a signal when your frequency resolution matches (approximately) the frequency width of the signal.

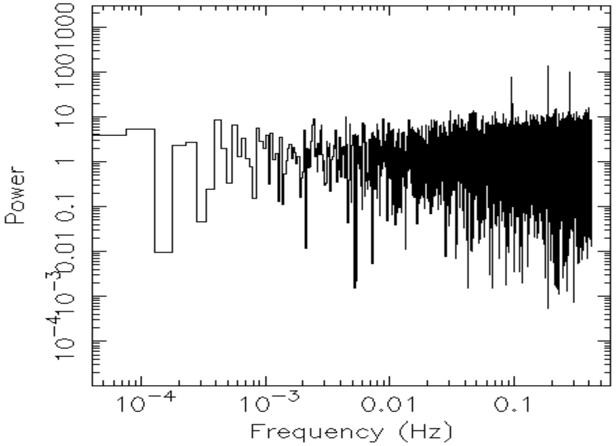
CCF: it is worth using it to study the relation among different energies

Cross-check with spectral information

Beware of signals/effects introduced by

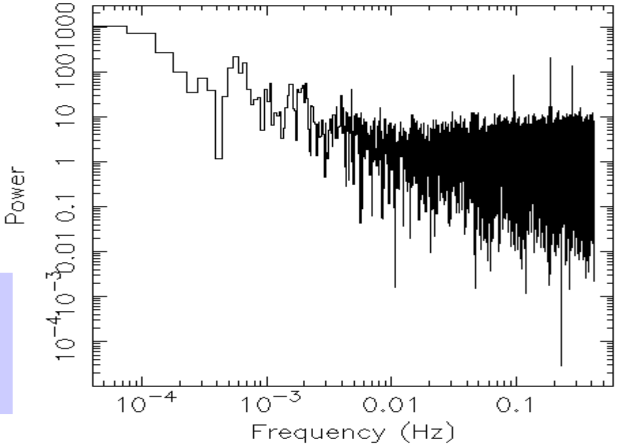
- instrument, e.g., CCD read time (check/add keyword TIMEDEL)
- Dead time
- Orbit of spacecraft
- Telescope motion (wobble,etc.)
- Pile-up (wash-out the signal)
- Orbital binary motion (“)
- The use of uncorrect GTIs (for single and merged simult. light curves)

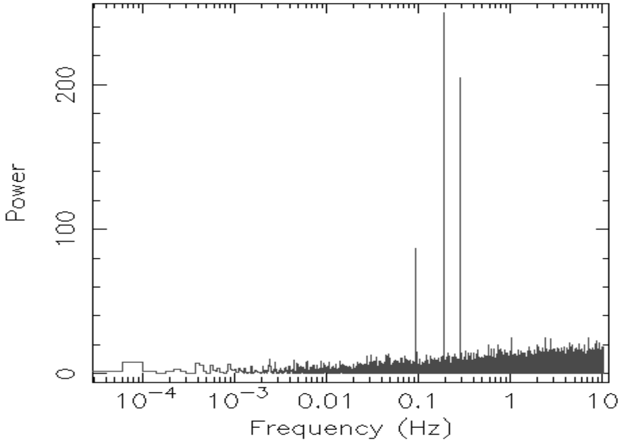
Tips-2



Right GTI table

Wrong/no GTI table





Right TIMEDEL keyword

Wrong/no TIMEDEL keyword