Taking the beat of the UNSEEN: a new Ultraluminous Neutron Star Extreme Extragalactic populatioN

Main questions:

Why PULXs are so Luminous ?

How many NSs among ULXs ?

GianLuca Israel
& Guillermo Rodriguez
(AO Roma)
.... and any many other colleagues
(EXTraS and UNSEEN collaboration)

Outline:

- ULX/PULX class
- too B or not too B
- UNSEEN preliminary results

EXTraS in a nutshell

= 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

WP3: **search and characterization for coherent signals in the archive**

WP4: search for faint and/or short transients

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

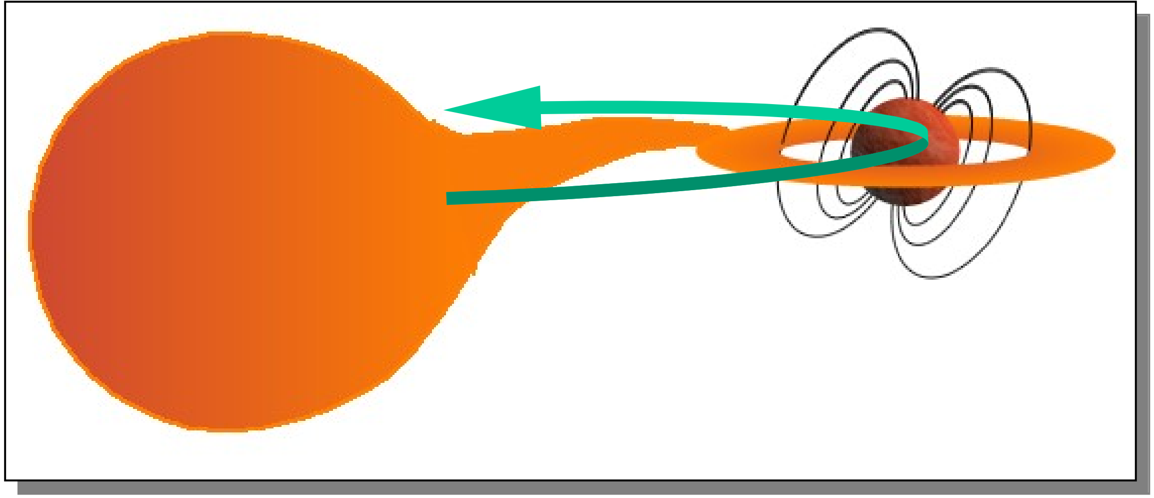
WP6: Multiwavelength characterization and classification

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

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS
IUSS Sapere Aude Istituto Universitario di Studi Superiori Pavia
imati
University of Leicester
MPE
ecap ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

What can coherent signals tell Us? (or, why should we be interested?)

Timing => characteristic timescales = PHYSICS
Timing => measurements can be extremely accurate!!

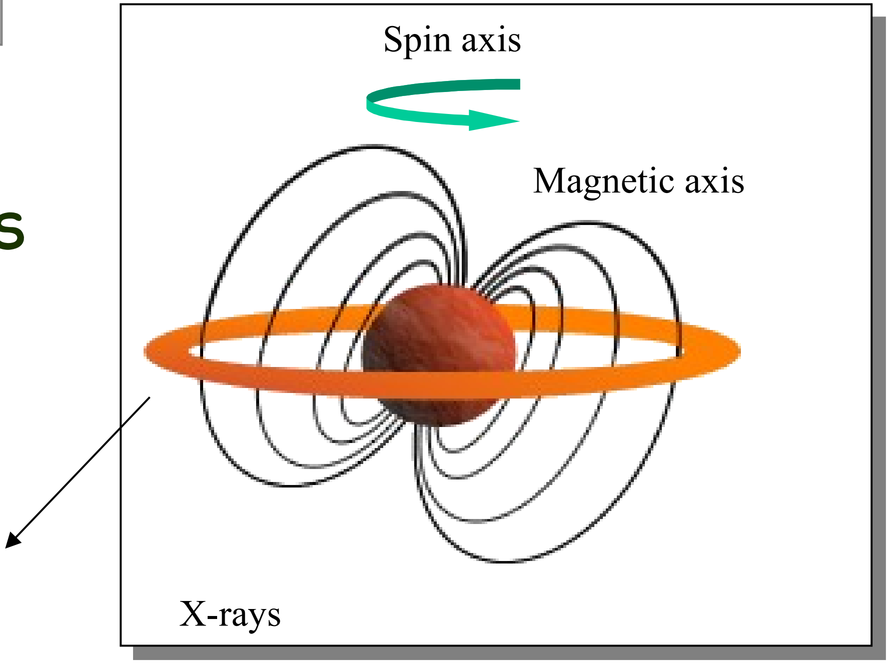


Binary orbits

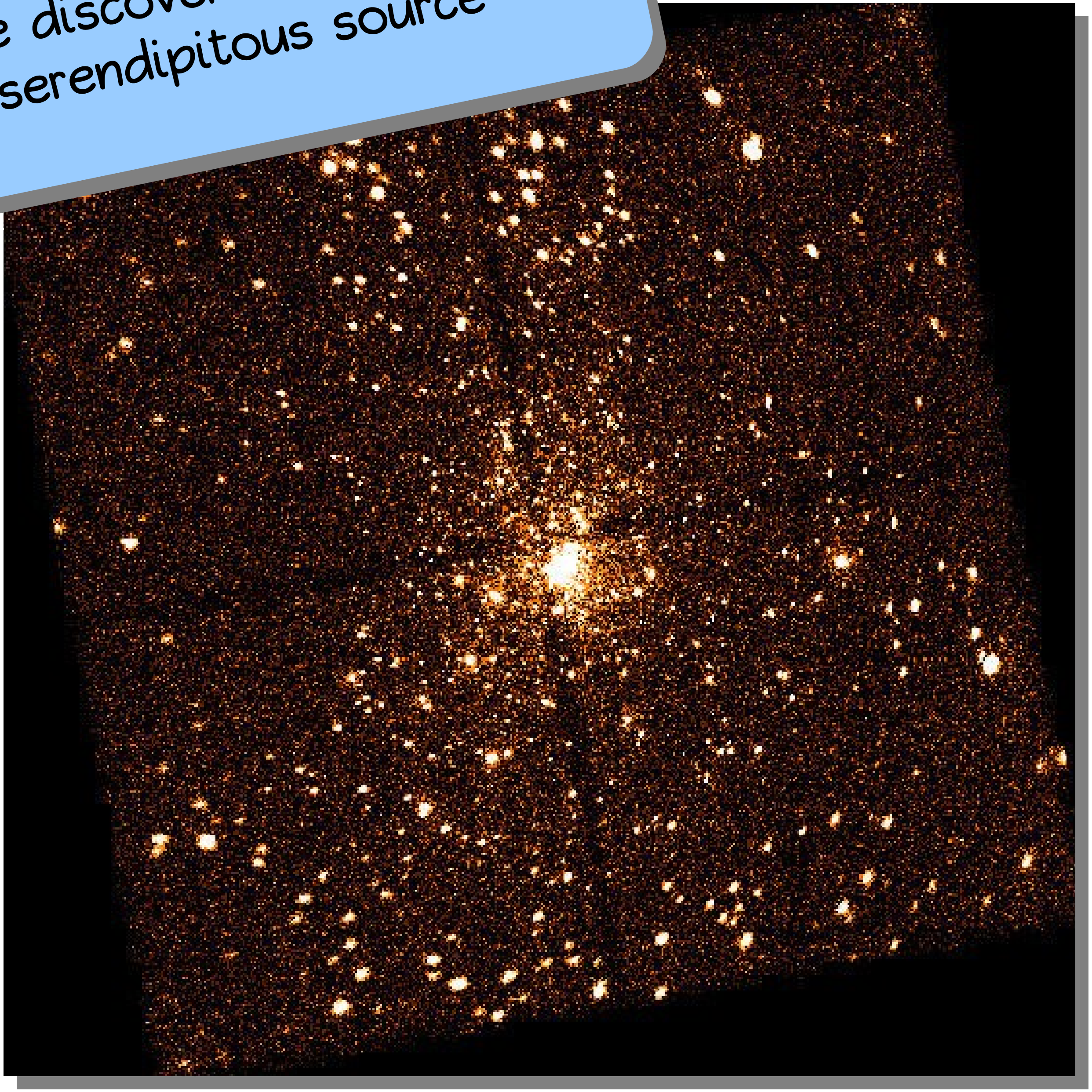
orbital period
sizes of emission regions and occulting objects
orbital evolution

Rotation of stellar bodies

pulsation periods
stability of rotation
torques acting on system, Lx, etc.
Isolated or accreting neutron stars



Why searches in X-ray archive ?



In many cases pulsations are discovered by applying timing analysis software to serendipitous source timeseries

In almost all cases
The PI does not look
at serendipitous sources

About 40-60 serendipitous
sources in each field
(Chandra and XMM) !!

For about 95% of detected
sources no timing info are
inferred

Why searches ?

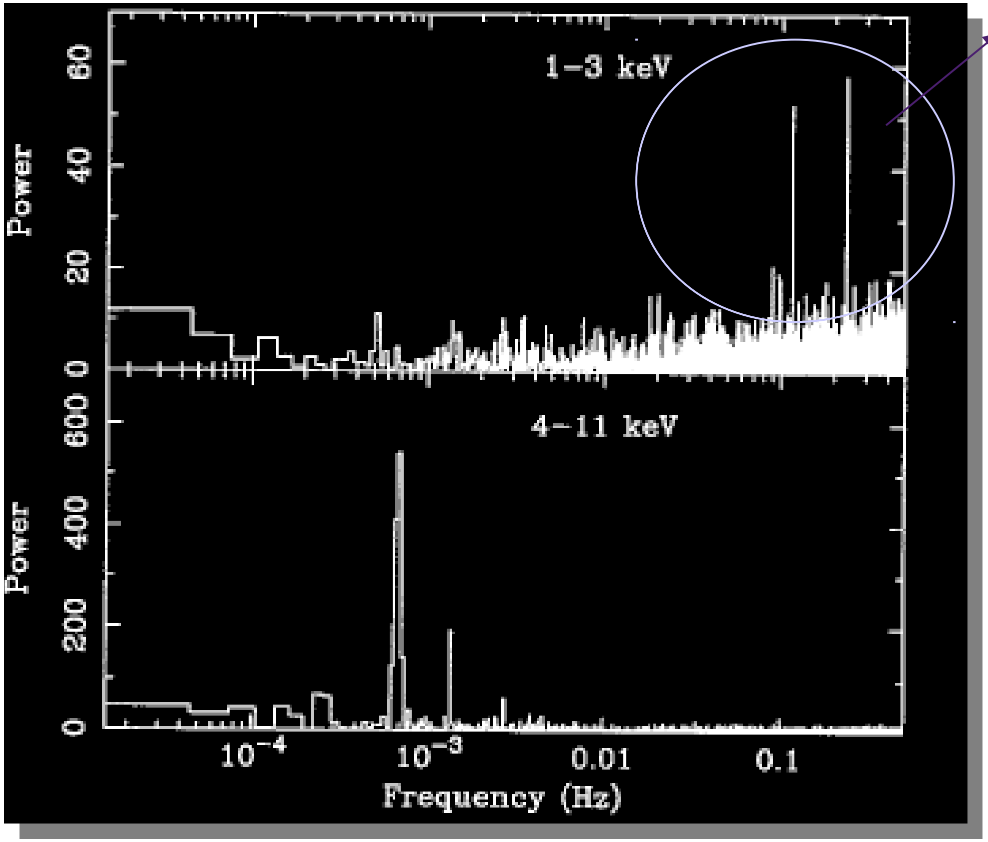
Two aims :

1) Search for new classes of X-ray pulsators

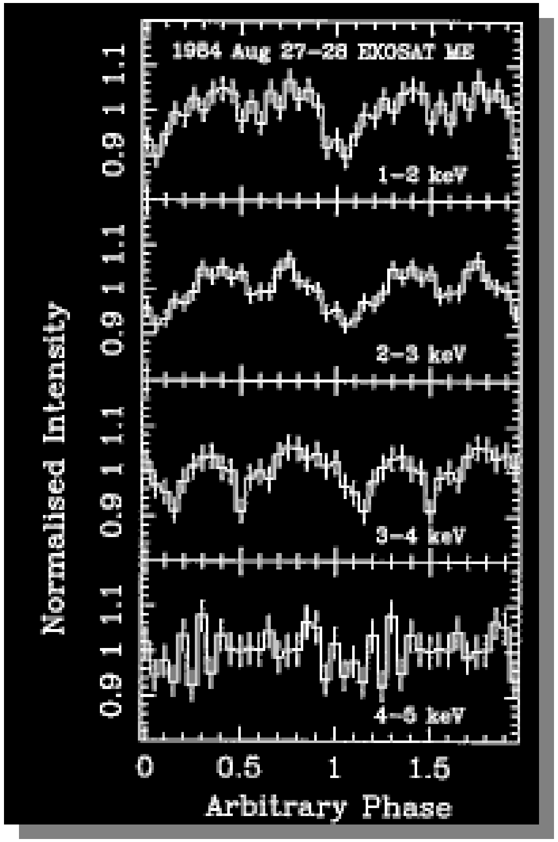
[large number of sources and photons]

Everytime we searched something.... we found something new !

- EXOSAT: detection of pulsations from 4U0142+614 (GLI+94);



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



Why searches ?

2) Extending the luminosity interval over which the physics of the (accretion) emission mechanism can be investigated

[large throughput and narrow psf]

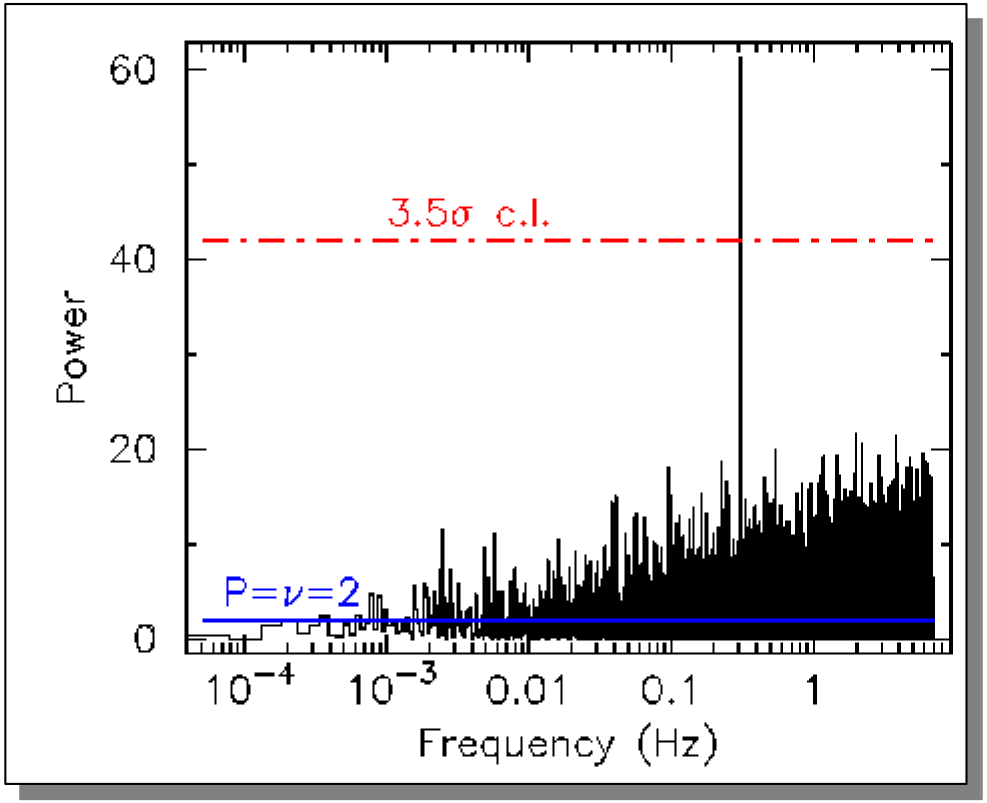
In particular, at lower luminosities (therefore lower accretion rates M) only NS with long spin periods and/or low magnetic fields can satisfy the condition that corotation radius is larger then the magnetospheric one (rc >rm), such that the matter can reach the NS surface at polar caps and spin pulses can be detected. Though this is a widely assessed theoretical scenario, so far it has not been possible to explore the low luminosity tail of the distribution of accreting compact objects.

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

How ?

We (mainly) rely upon (Fast) Fourier trnsforms

- Well known technique
- Fast routines available
- Optimized for long pulse duty-cycles
- Limits on statistics/highly non sin signal



Leahy Normalization

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

- N_{ph} is the total number of photons
- With this normalization, the Poisson noise level 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)

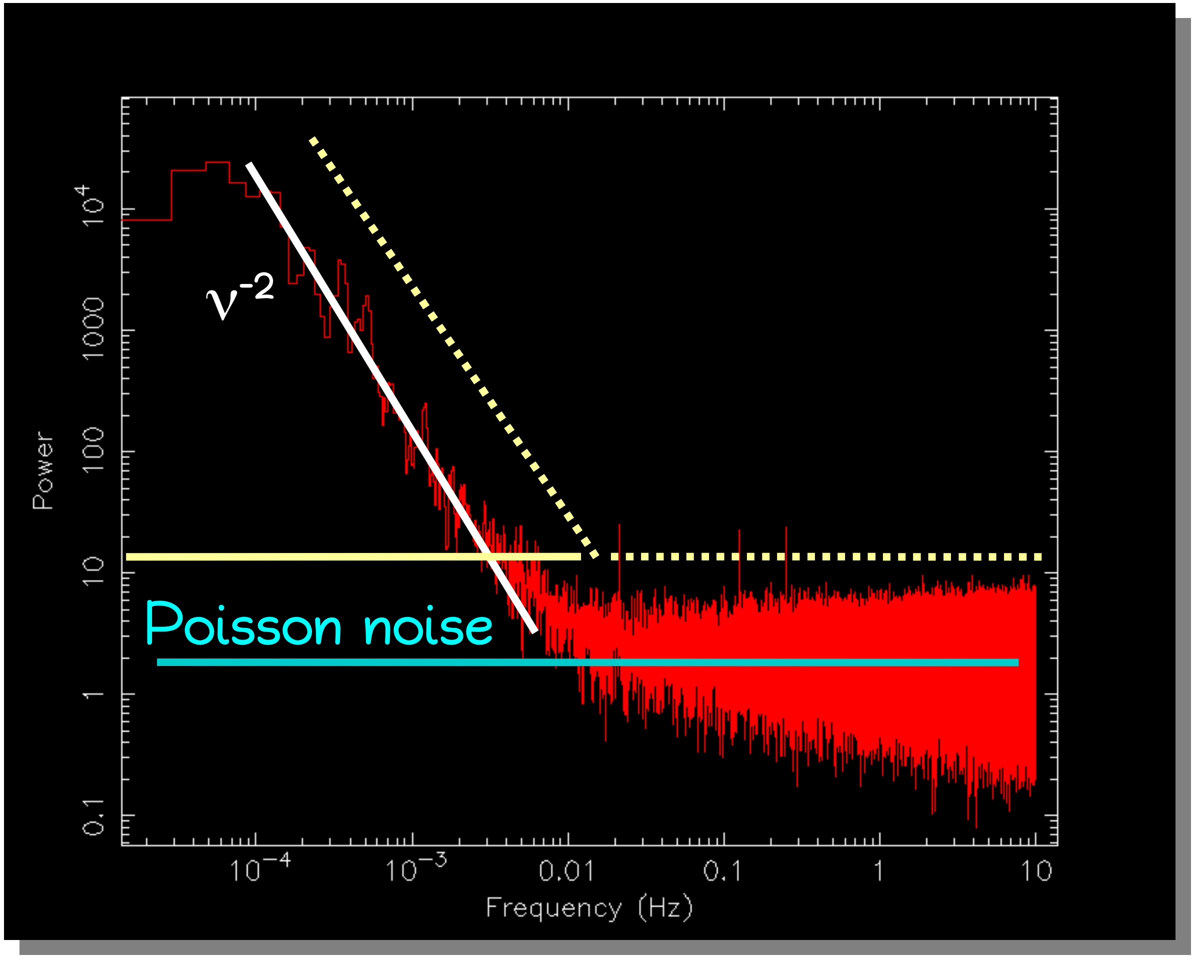
- $E[\chi^2|\nu] = \nu = 2$ for $N_{PSD}=1$
- $\sigma[\chi^2|\nu] = \mathrm{sqrt}(2\nu) = 2$ for $N_{PSD}=1$ -> noisy

Detection threshold for given confidence level (>3σ)

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.



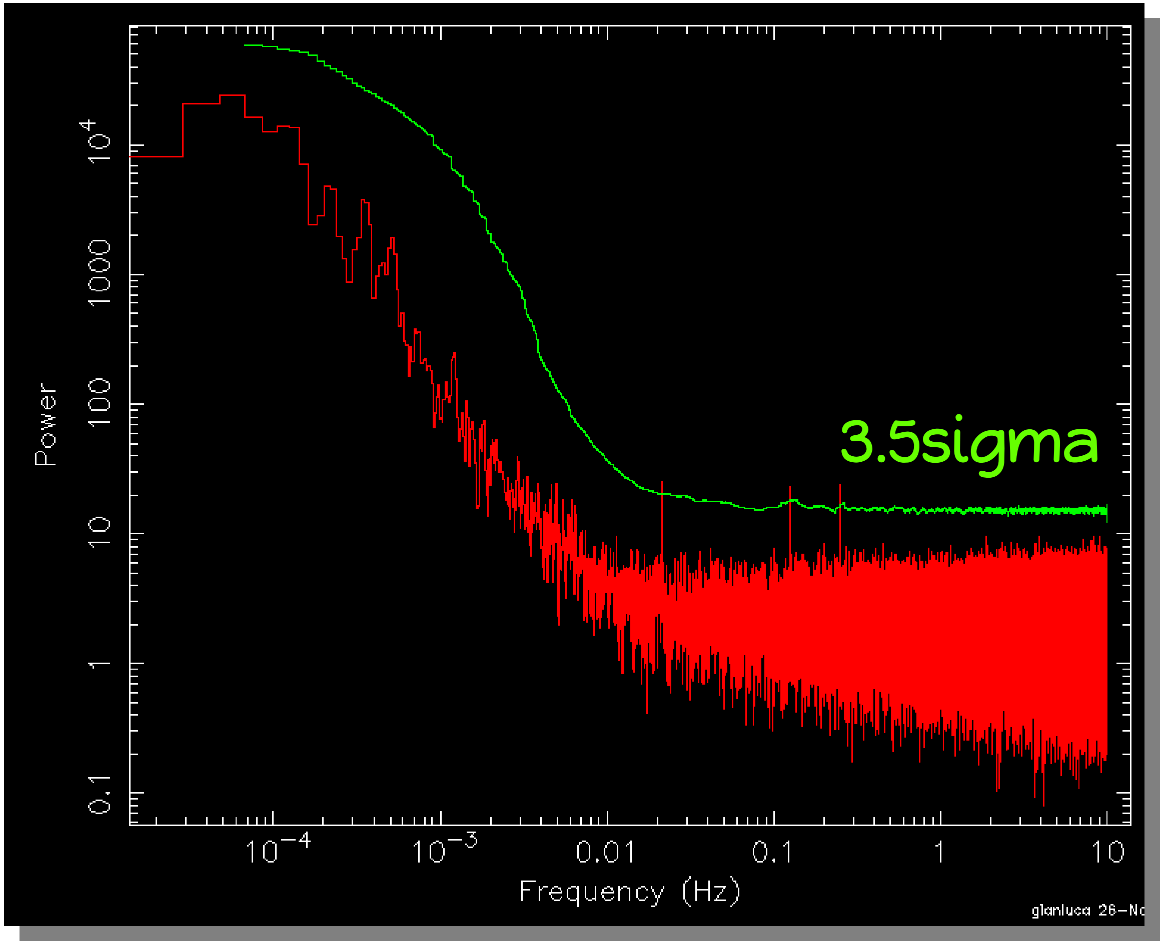
How (real data)?

Algorithm well suited for automatic searches of significant peaks in the presence of different noise components in PSD.

At least 50 photons are needed

Limits: low sensitivity at low frequency and/or poor statistics.

Low sensitivity for non sinusoidal signals



Blind mining XMM for pulsations

EXploring the Transient 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)

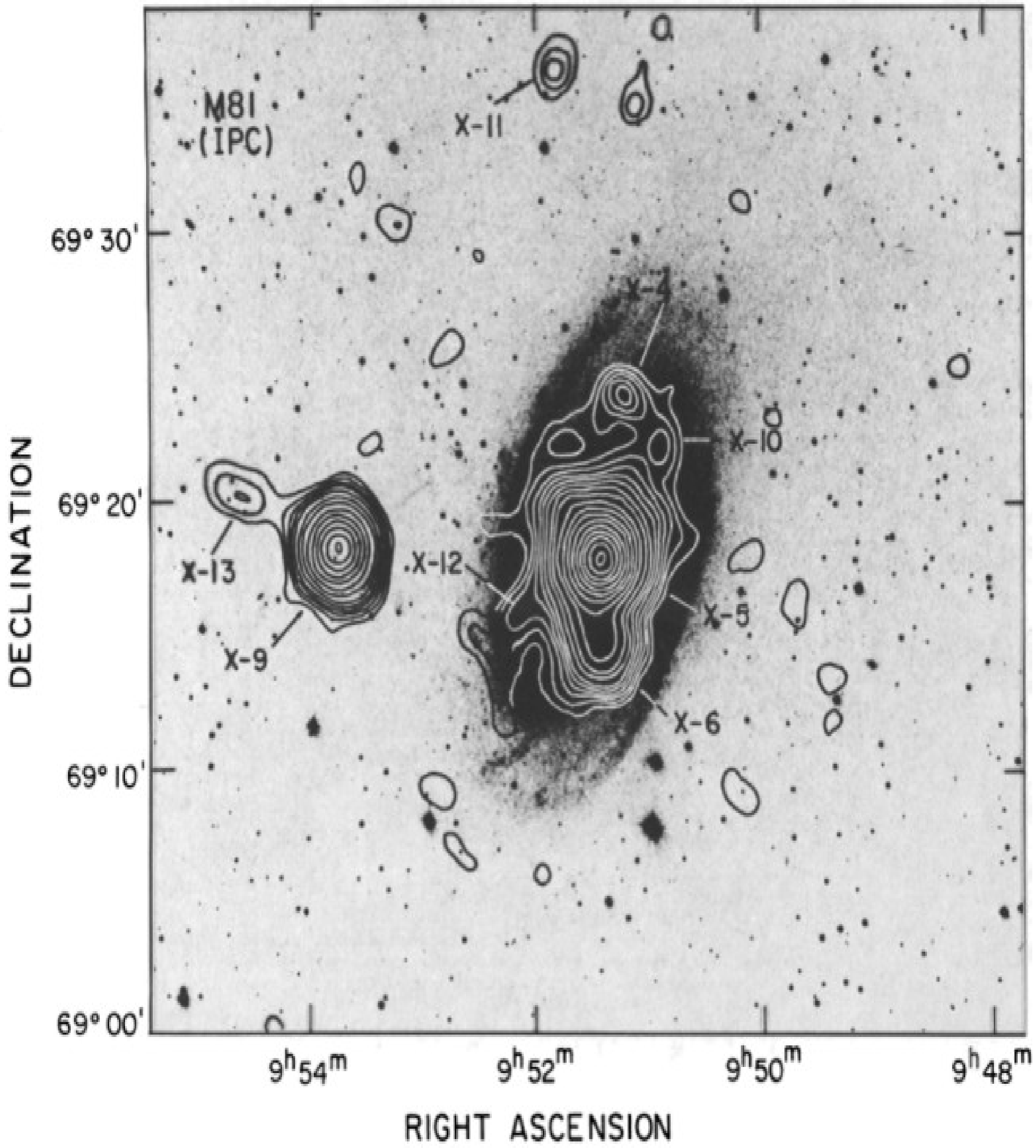
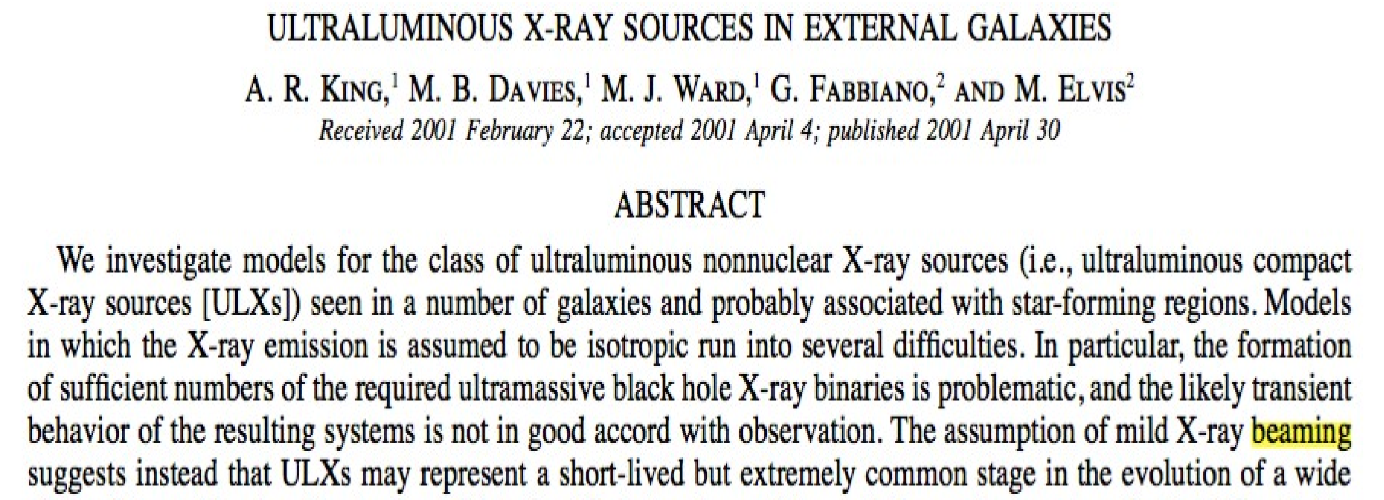


FIG. 2.—IPC contour map of M81 overlaid on the POSS O plate. The first contour is at 2 σ above the field background. Discrete sources detected in the IPC image are indicated by an X followed by a number. Data were smoothed with a Gaussian with $\sigma_G = 35''$. The equivalent Gaussian sigma of a point source in this map is $\sigma_G \sim 57''$.

EINSTEIN - Fabbiano 1988



ULTRALUMINOUS X-RAY SOURCES IN EXTERNAL GALAXIES

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ABSTRACT

We investigate models for the class of ultraluminous nonnuclear X-ray sources (i.e., ultraluminous compact X-ray sources [ULXs]) seen in a number of galaxies and probably associated with star-forming regions. Models in which the X-ray emission is assumed to be isotropic run into several difficulties. In particular, the formation of sufficient numbers of the required ultramassive black hole X-ray binaries is problematic, and the likely transient behavior of the resulting systems is not in good accord with observation. The assumption of mild X-ray beaming suggests instead that ULXs may represent a short-lived but extremely common stage in the evolution of a wide class of X-ray binaries. The best candidate for this is the phase of thermal-

in many intermediate- and high-mass X-ray binaries. This in turn sugges

The short lifetimes of high-mass X-ray binaries would explain the ass

formation. These considerations still allow the possibility that *individua*

black holes.

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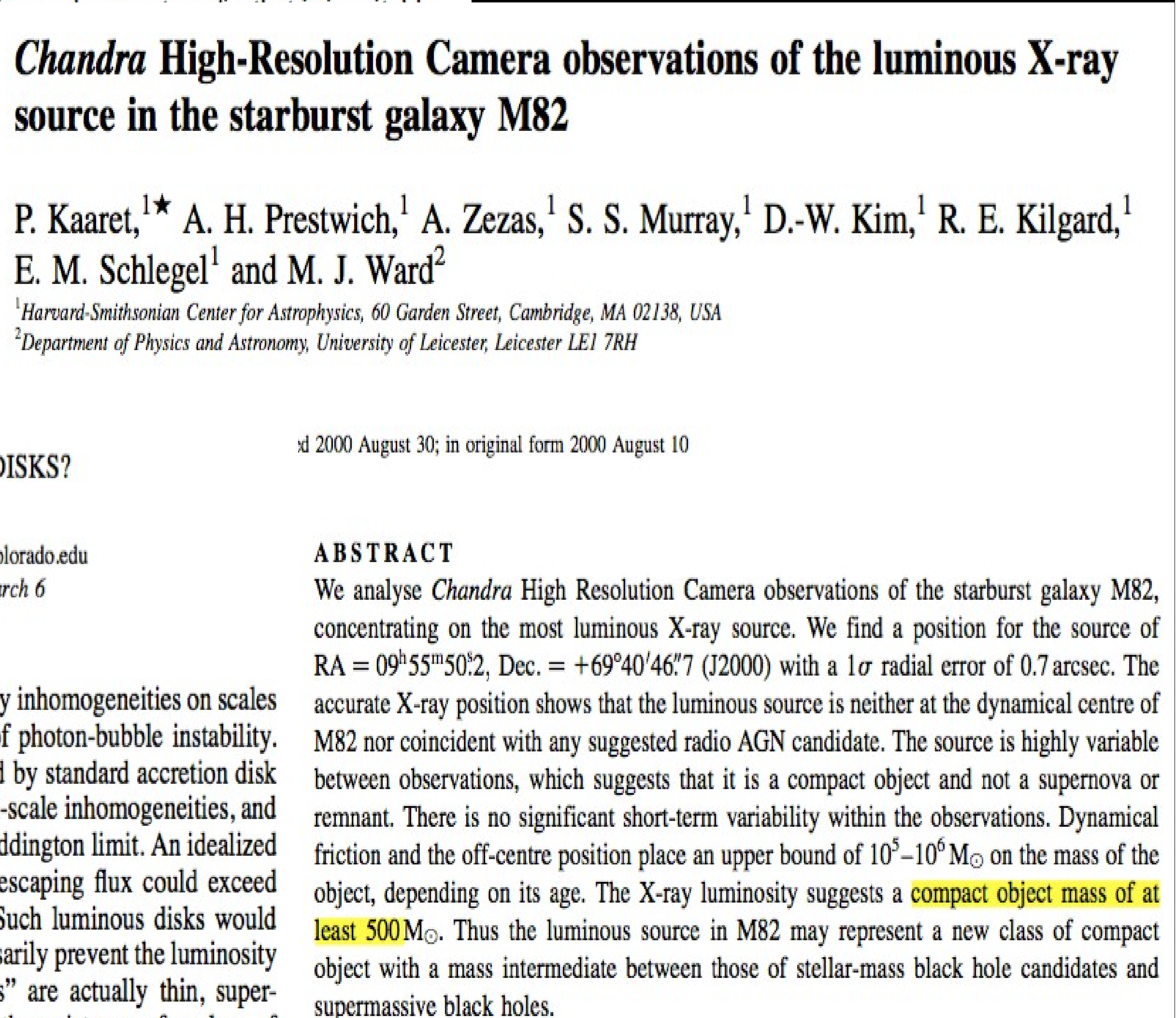

Chandra High-Resolution Camera observations of the luminous X-ray source in the starburst galaxy M82

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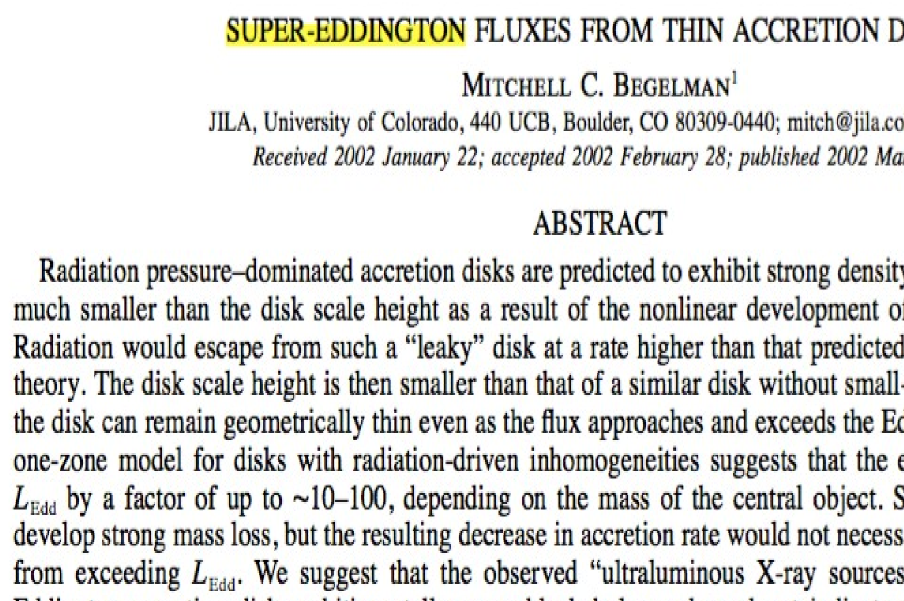
d 2000 August 30; in original form 2000 August 10

ABSTRACT

We analyse *Chandra* High Resolution Camera observations of the starburst galaxy M82, concentrating on the most luminous X-ray source. We find a position for the source of RA = $09^{\rm h}55^{\rm m}50^{\rm s}.2$, Dec. = $+69^{\circ}40'46''.7$ (J2000) with a 1σ radial error of 0.7 arcsec. The accurate X-ray position shows that the luminous source is neither at the dynamical centre of M82 nor coincident with any suggested radio AGN candidate. The source is highly variable between observations, which suggests that it is a compact object and not a supernova or remnant. There is no significant short-term variability within the observations. Dynamical friction and the off-centre position place an upper bound of 10^5–$10^6\,M_\odot$ on the mass of the object, depending on its age. The X-ray luminosity suggests a compact object mass of at least $500\,M_\odot$. Thus the luminous source in M82 may represent a new class of compact object with a mass intermediate between those of stellar-mass black hole candidates and supermassive black holes.



SUPER-EDDINGTON FLUXES FROM THIN ACCRETION DISKS?

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ABSTRACT

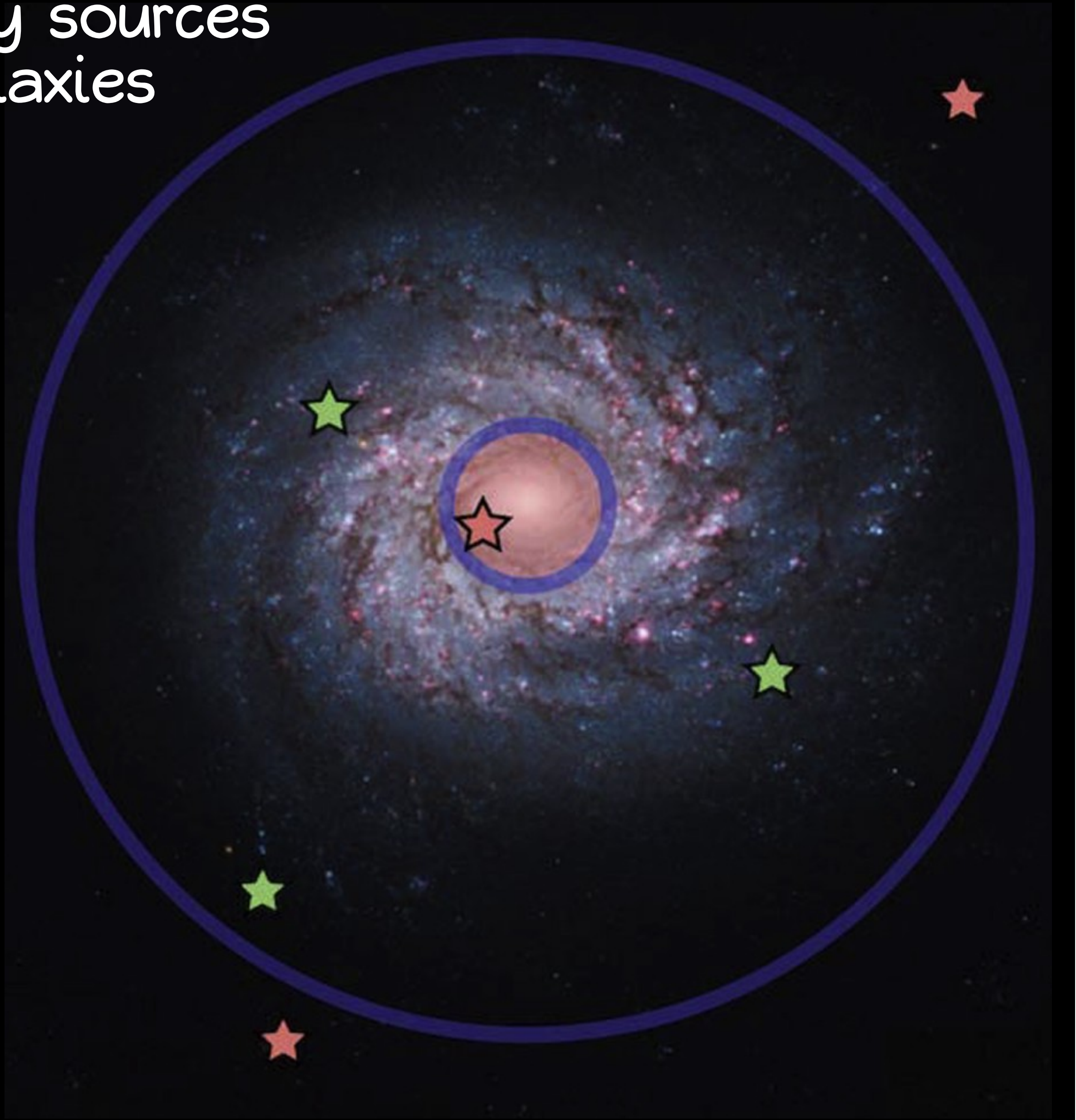
Radiation pressure–dominated accretion disks are predicted to exhibit strong density inhomogeneities on scales much smaller than the disk scale height as a result of the nonlinear development of photon-bubble instability. Radiation would escape from such a "leaky" disk at a rate higher than that predicted by standard accretion disk theory. The disk scale height is then smaller than that of a similar disk without small-scale inhomogeneities, and the disk can remain geometrically thin even as the flux approaches and exceeds the Eddington limit. An idealized one-zone model for disks with radiation-driven inhomogeneities suggests that the escaping flux could exceed $L_{\rm Edd}$ by a factor of up to ~10–100, depending on the mass of the central object. Such luminous disks would develop strong mass loss, but the resulting decrease in accretion rate would not necessarily prevent the luminosity from exceeding $L_{\rm Edd}$. We suggest that the observed "ultraluminous X-ray sources" are actually thin, super-

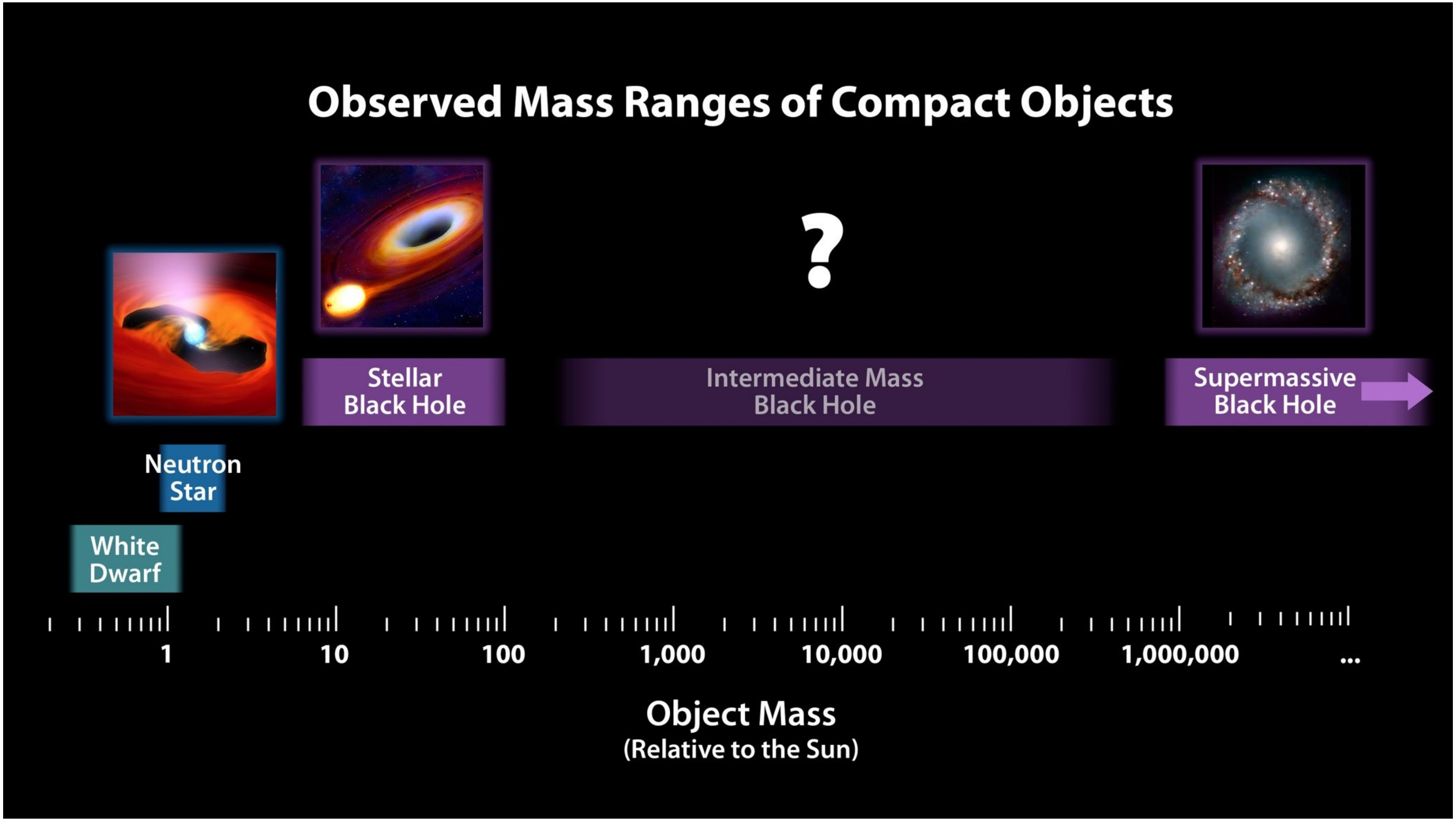
ULX class

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 (StBH) of $10M_\odot$

$L_{ULX} > 3\times10^{39}$ erg/s up to $\sim10^{42}$ erg/s

About 300 objects (Earnshaw+ 18)

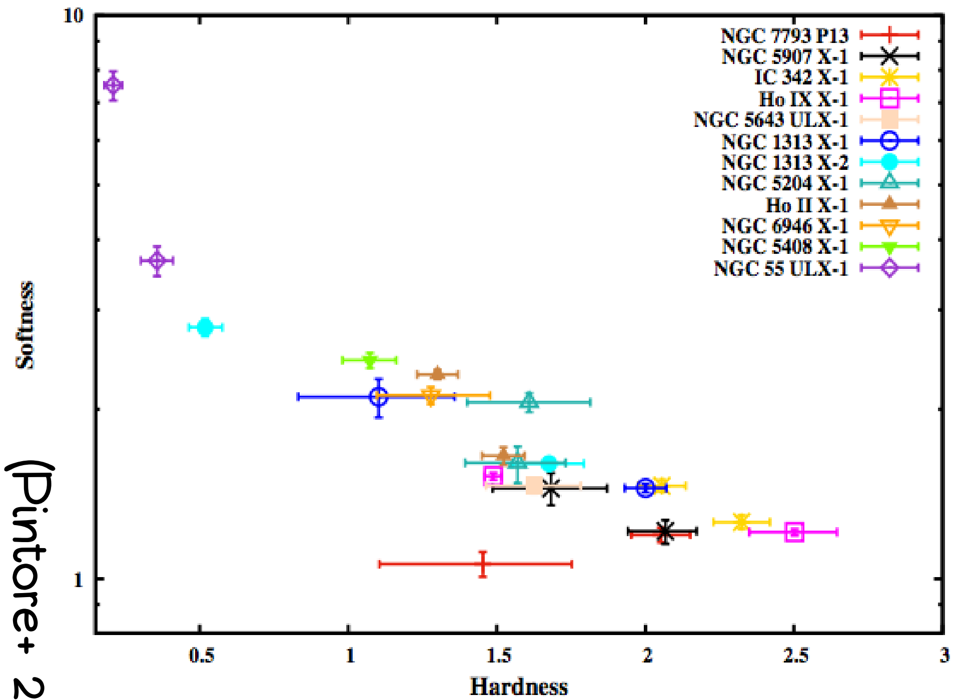




IMBHs needed to form SMBHs in quasars at $z>6-7$
(Pacucci+ 17)

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

ULX class

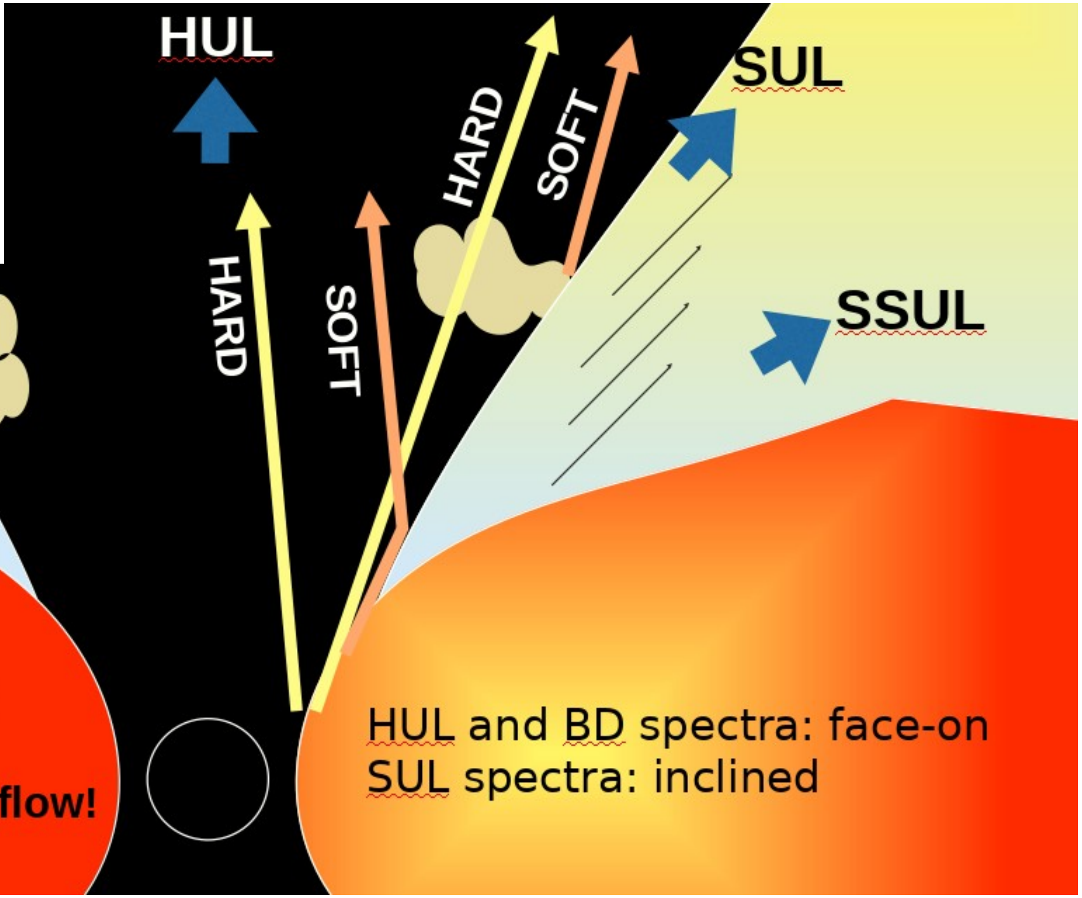


(Pintore+ 2017)

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

Large dynamical range of parameters.

Possibly related to the emission geometry.



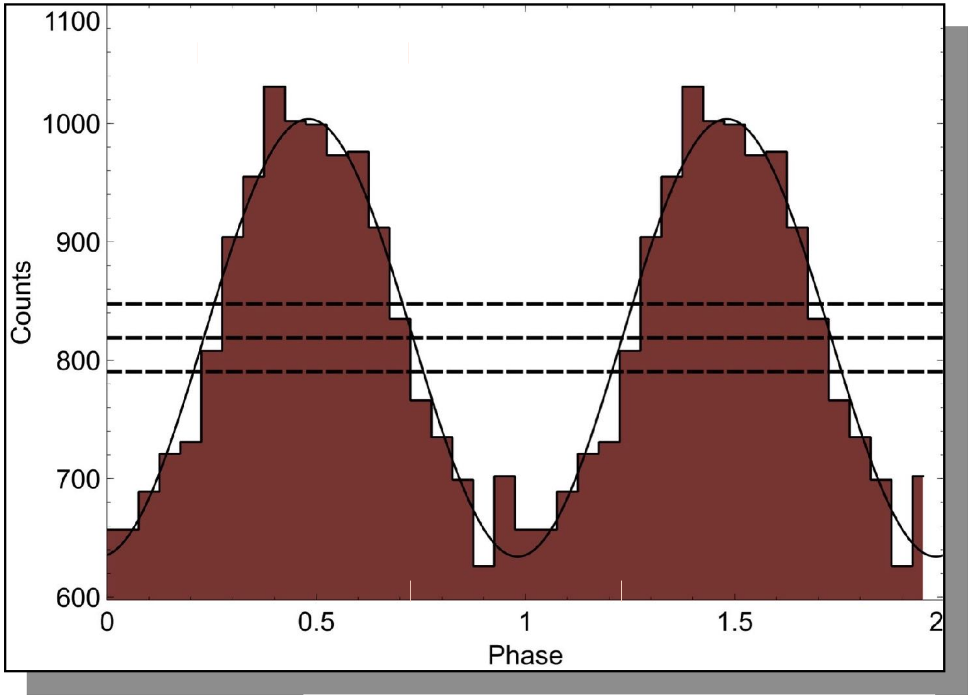
Toy scenario:
Soft excess: **outflow**
Hard thermal component:
inner disk
Variability imprinted by outflow!

HUL and BD spectra: face-on
SUL spectra: inclined

In 2014

~~A long time ago~~ in a galaxy far, far away.... namely M82

ULXs and M82 X-2



Pulsations at 1.37s discovered from NuSTAR obs of M82 X-2

Sinusoidal pulse shape; PF~20%

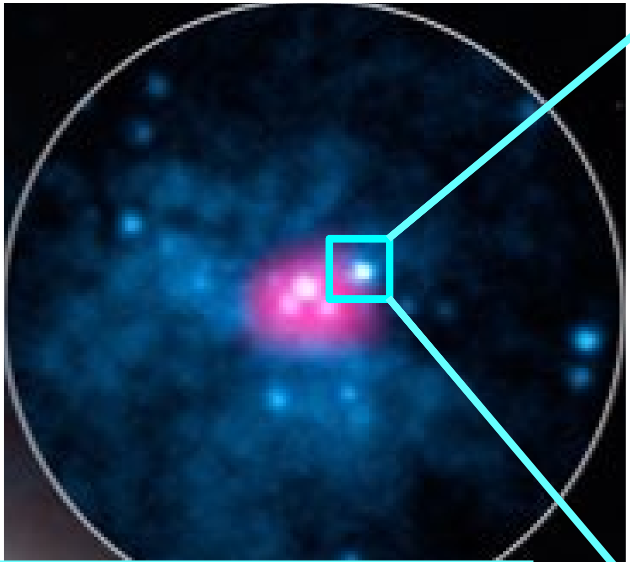
Lx~2e40erg/s (@3.2Mpc)~ 100 L_{Edd}

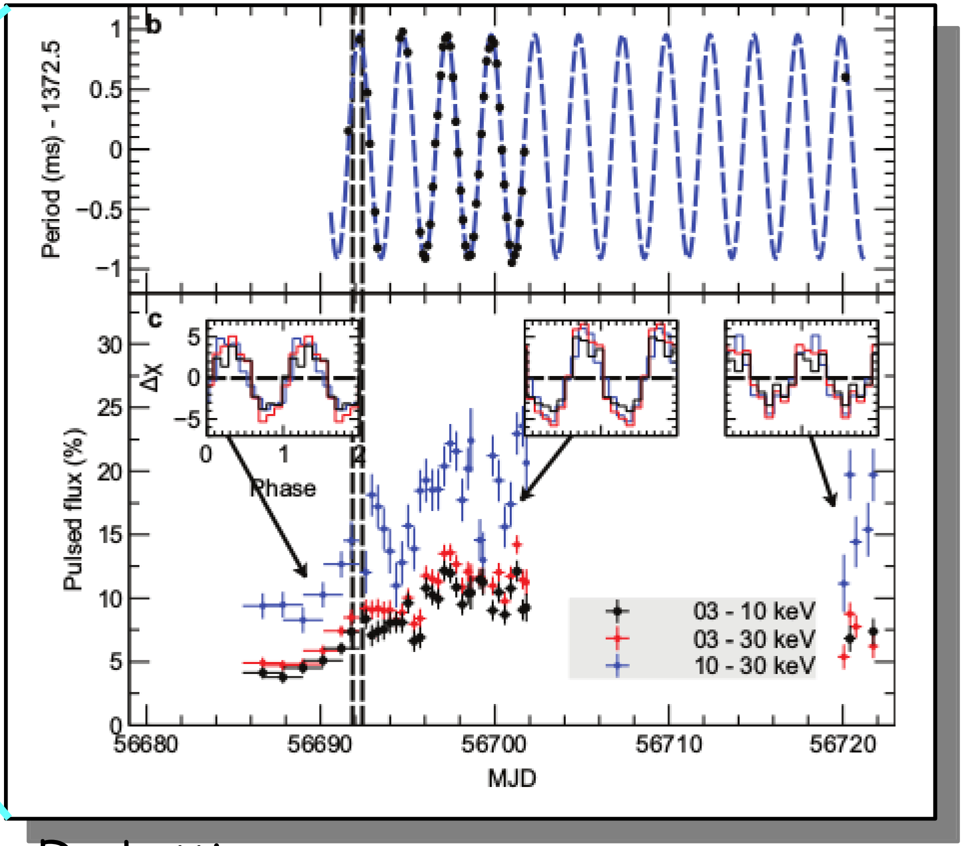
Pdot (secular) -2e-10 s/s

P/Pdot = 300yr

Porb = 2.5days

Mc > 5.2 $M_\odot$



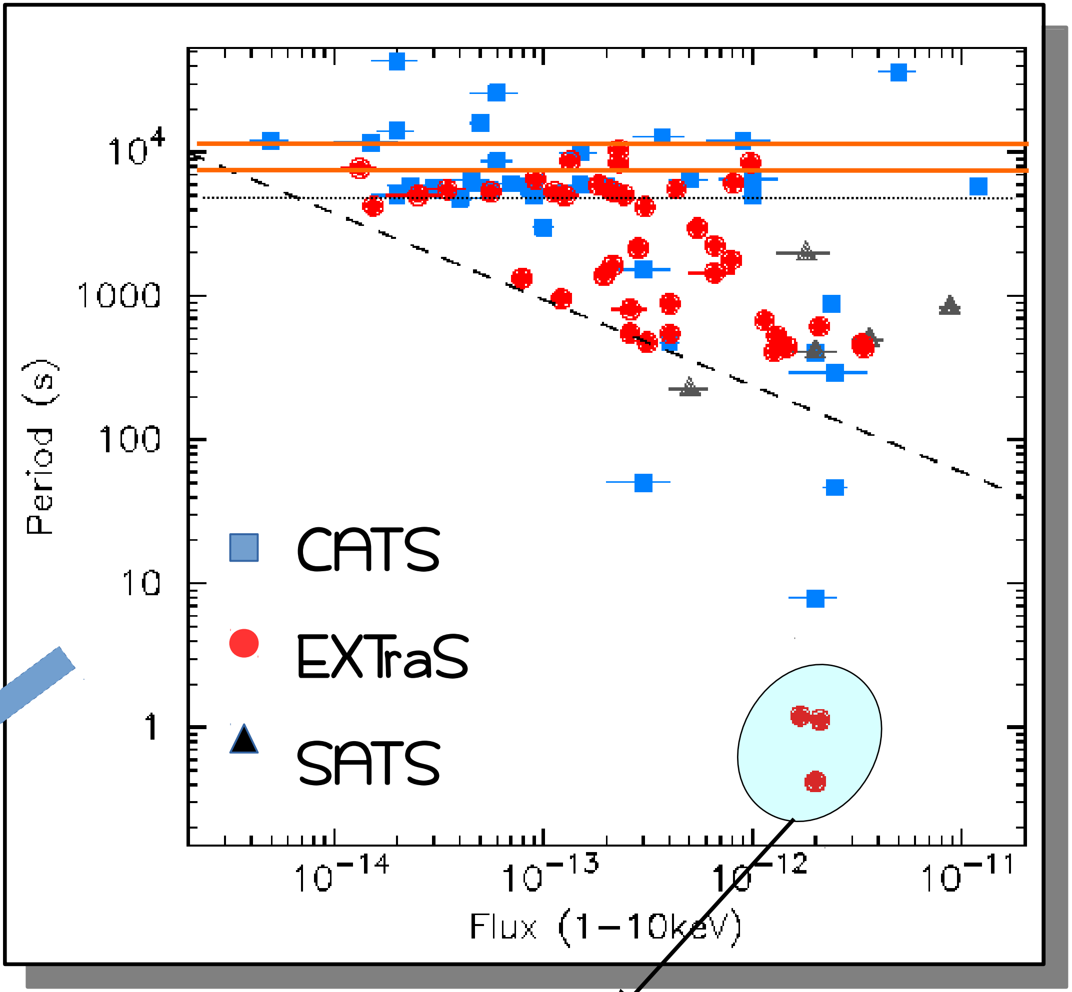


PULX emission 100 x L_{Edd}

ULXs are not BHs only !!

Bachetti+14

60 new pulsators (out of 120000 “spurious” detections)!! and still counting



ULX ??

Fastest signals are extragalactic !!

EXTraS: first NS discovered in M31

ESA SPACE SCIENCE

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

Science missions

- Mission navigator

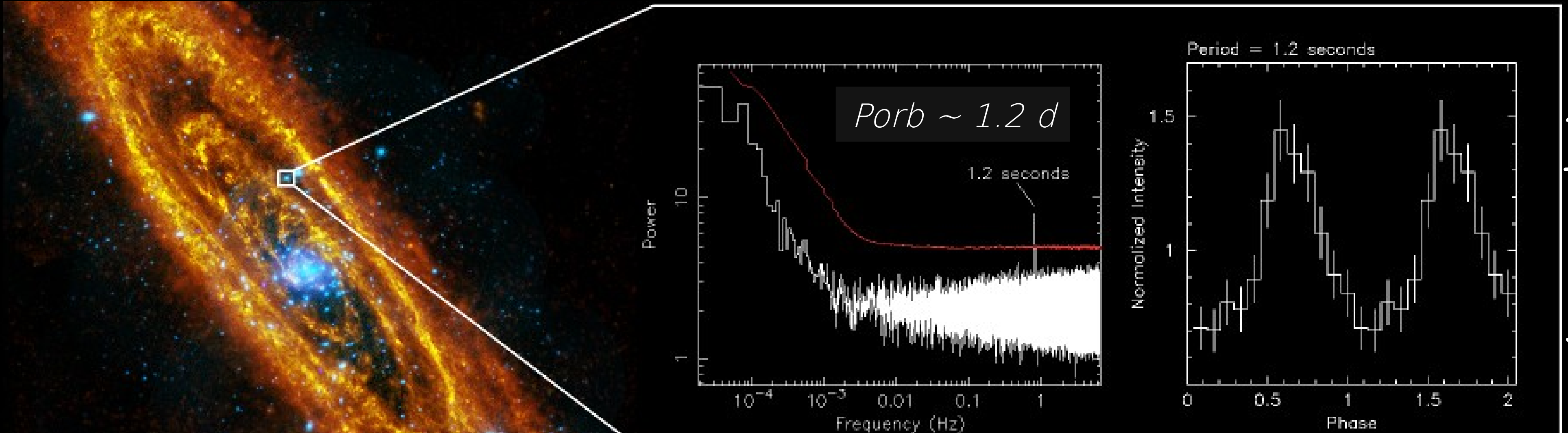
Target groups

ESA > Our Activities > Space Science

European Space Agency

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.



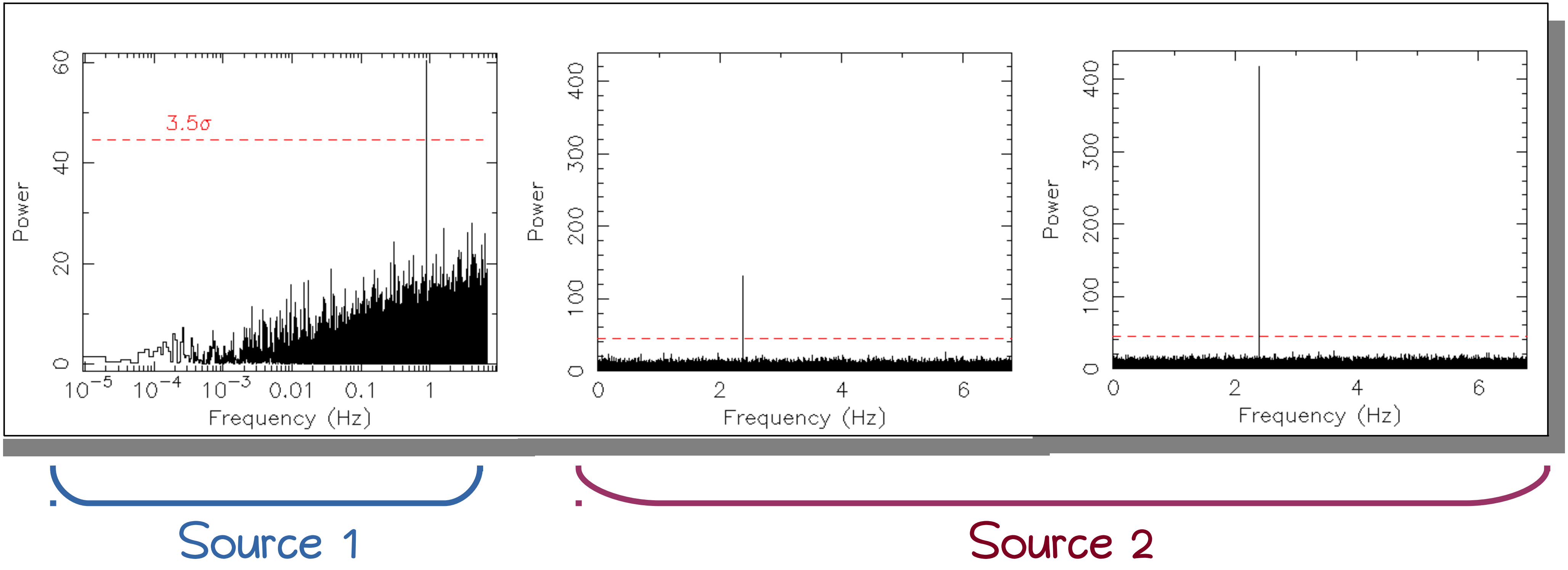
(Esposito+16)

EXTraS 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 significant peaks from two different sources (both known ULXs).



Source 1= NGC 5907 ULX

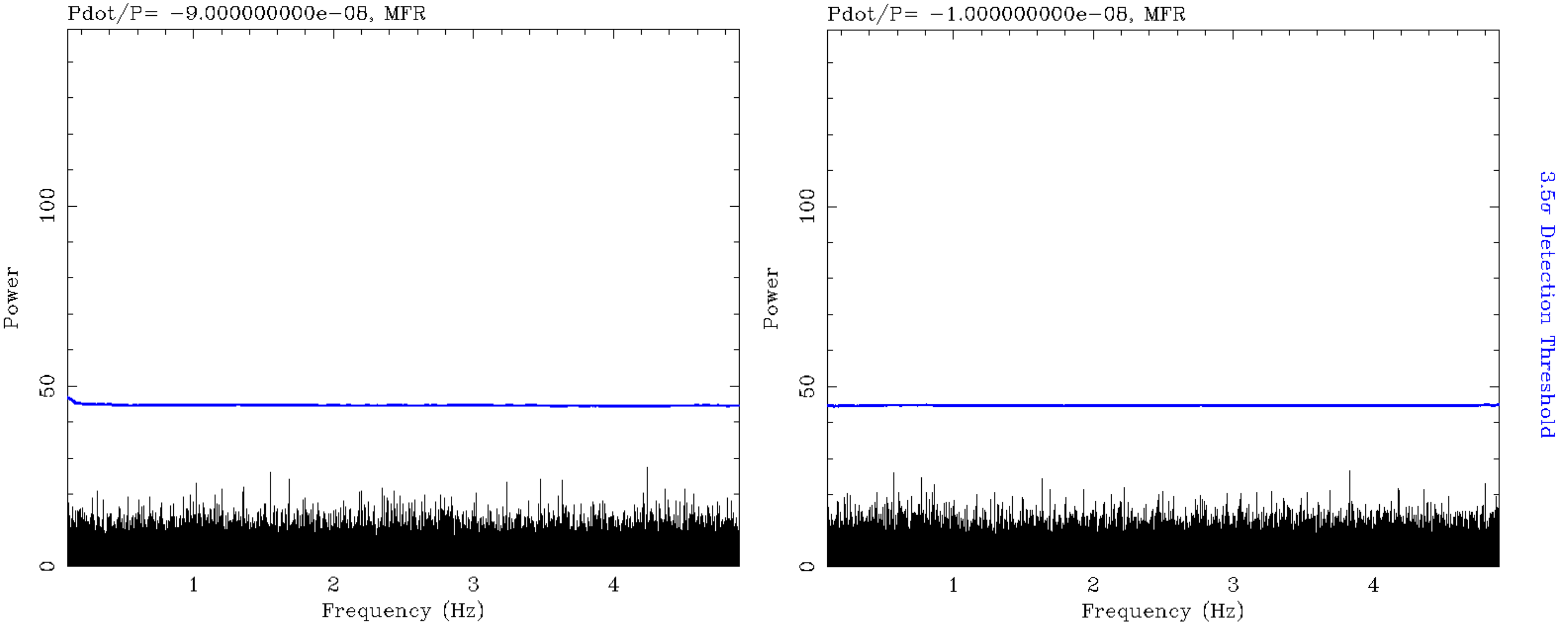
7 XMM pointings (6 source detection)+5 NuSTAR pointings (3 detection)

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

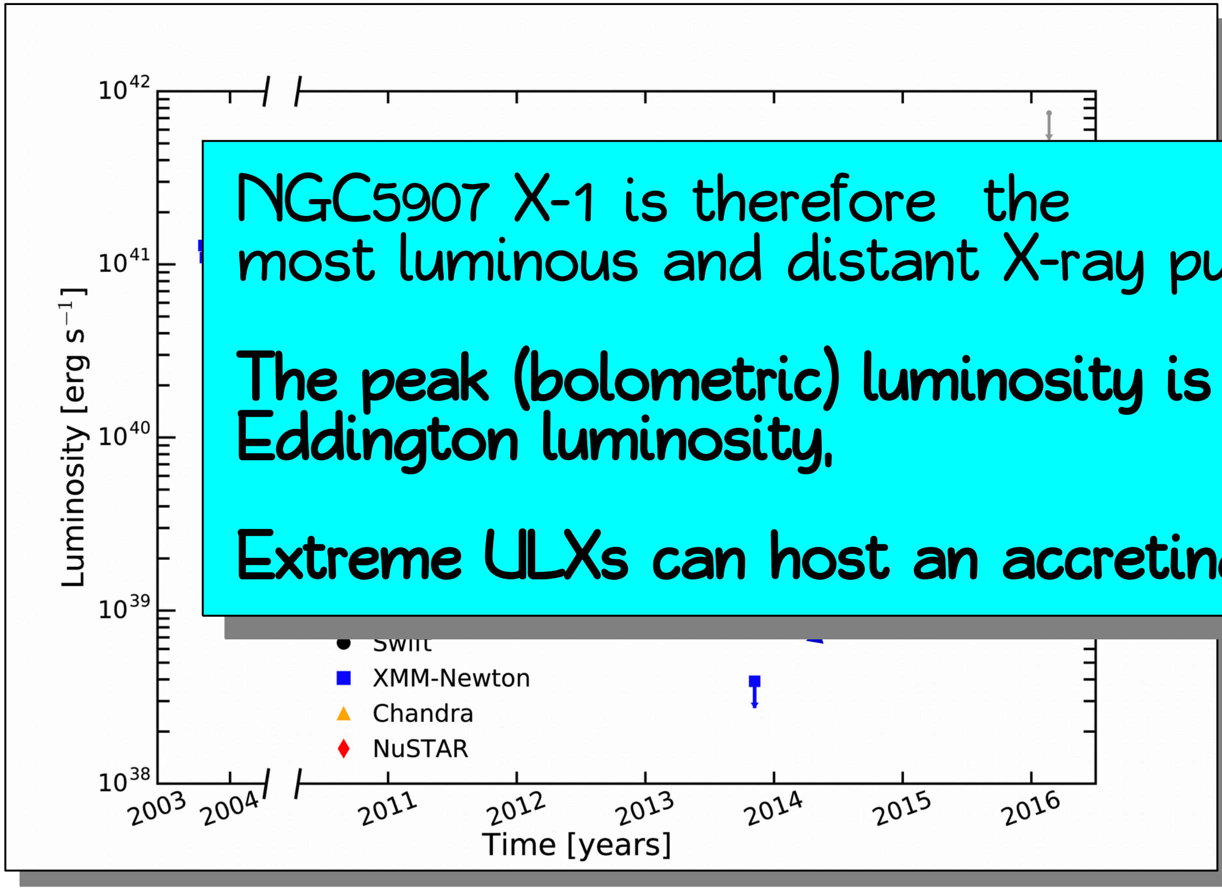


The PULX in NGC5907 ULX

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 × 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

The factor of 10 lower than the local Pdot suggests orbital contribution
Porb=5.3[+2.0,-0.9] days (1σ) and Mc < 20$M_\odot$



NGC5907 X-1 is therefore the
most luminous and distant X-ray pulsar ever detected.

The peak (bolometric) luminosity is ~1000 times the
Eddington luminosity,

Extreme ULXs can host an accreting NS !

For a distance of 17.1Mpc
the (isotropic) luminosity

erg/s

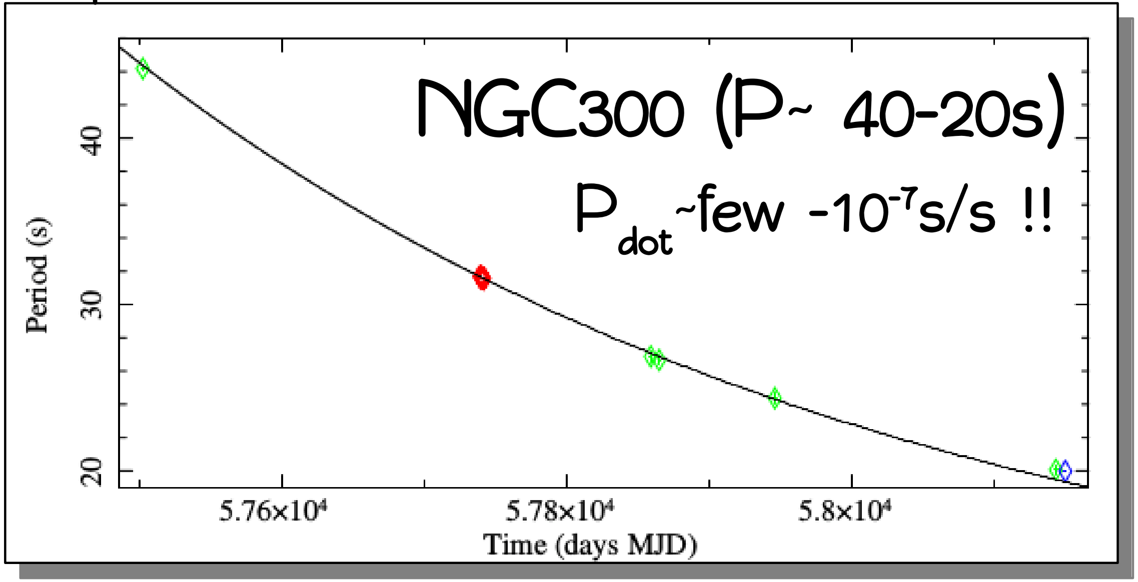
f

ected

(GLI+ 17a, Science)

More PULXs discovered (data mining)

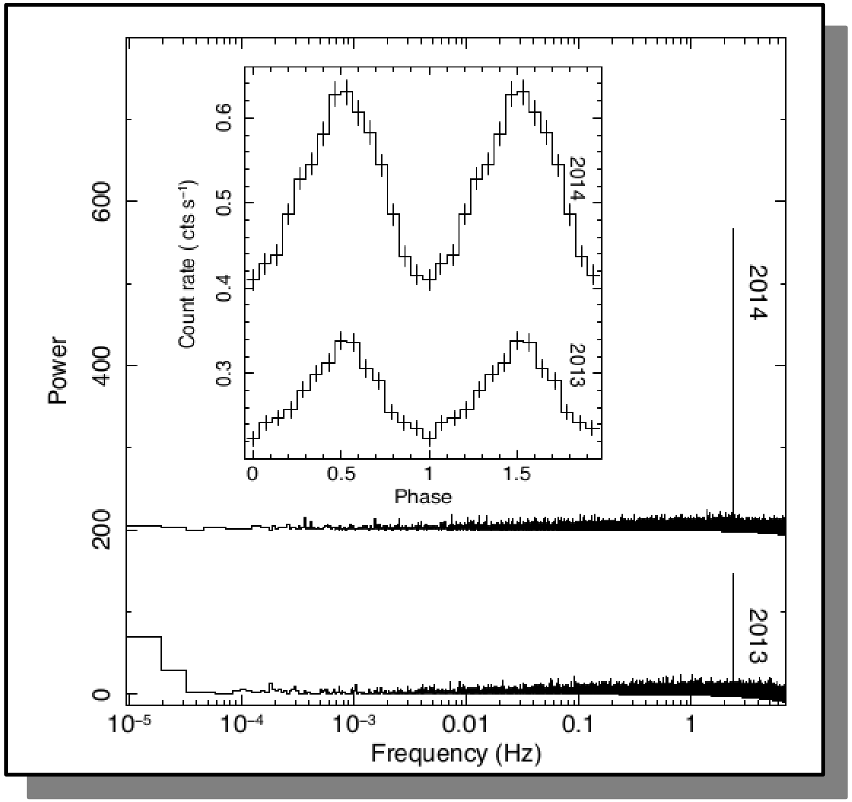
Carpano+18



NGC300 (P~ 40-20s)

P_{dot}~few -10^{-7}s/s !!

(GLI+17b, Fürst+ 16)



NGC7793 P13 (P~0.42s)

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

PULXs overall properties

	M82 X-2	NGC 7793 P13	NGC 5907 ULX1	NGC300 ULX1
Pulse Period	1.37s	0.42s	1.1s	40-20s
Spin-up ($\dot{P}$)	2×10^{-10} s/s	3.5×10^{-11} s/s	8×10^{-10} s/s	6×10^{-7}
Orbital Period	2.5 d	64d	5.3 d	Long or face-on
Superorb. P.	63.8 d	?	78 d	?
Max. Luminosity	2×10^{40} erg/s	6×10^{39} erg/s	$>10^{41}$ erg/s	5×10^{39} erg/s
Min. Luminosity	$<2.5\times10^{38}$ erg/s	$\sim4\times10^{37}$ erg/s	$<4\times10^{38}$ erg/s	transient
Optical Comp.	$M > 5\ M_\odot$	SG B9I	$M \lesssim 30M_\odot$	$M<20M_\odot$
References	Bachetti et al. 2014; Brightman et al. 2017; Dall'Osso et al. 2015	Fürst et al. 2016; Israel et al. 2017a	Israel et al. 2017b; Fürst et al. 2017; Walton et al. 2015	Carpano+ 18

Not easy to identify convincing similarities....

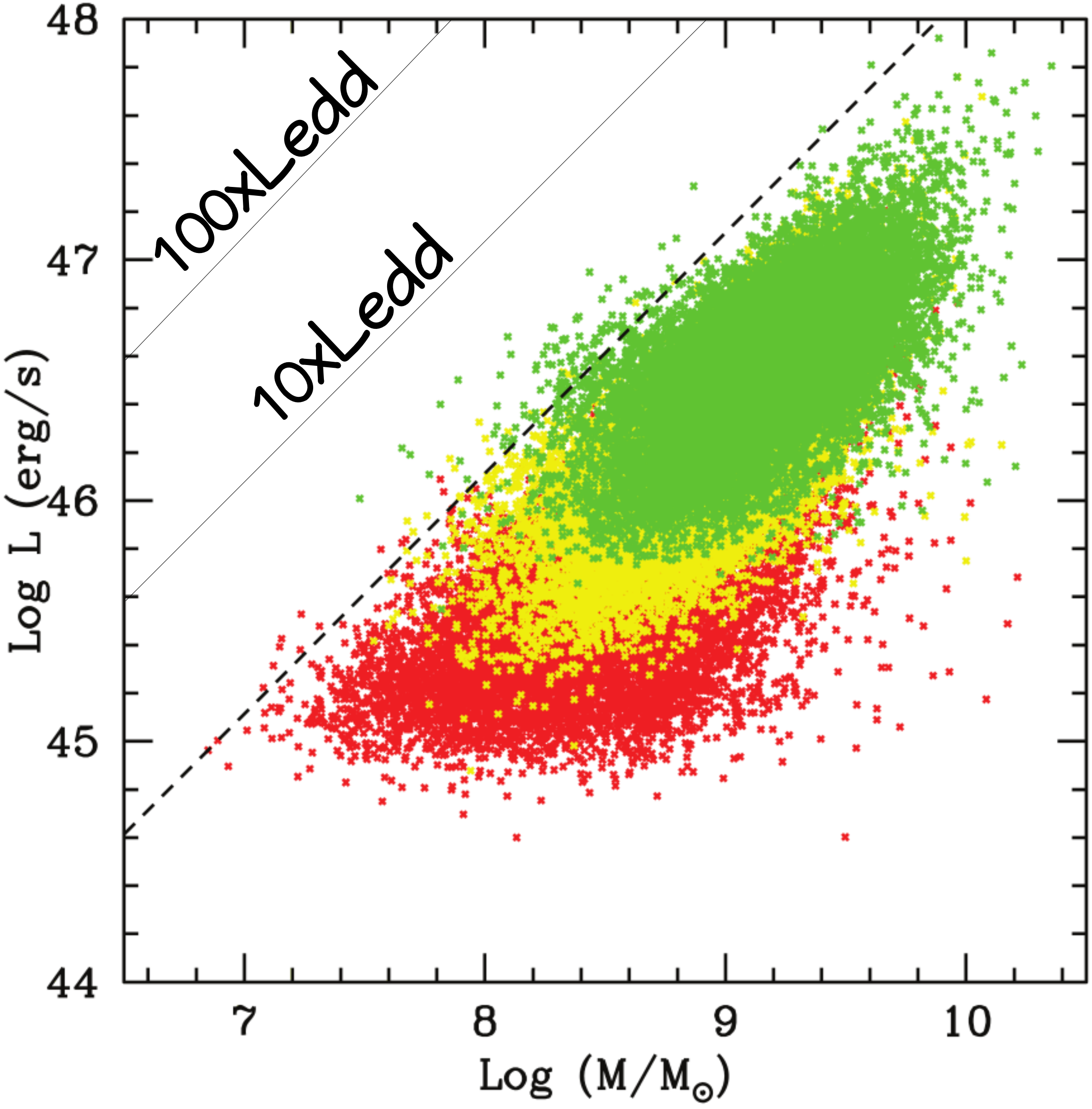
Lx > 10^{39} erg/s and likely massive companions (HMXB or IMXB)

Exceeding Ledd by 30-500 times

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 or 100.

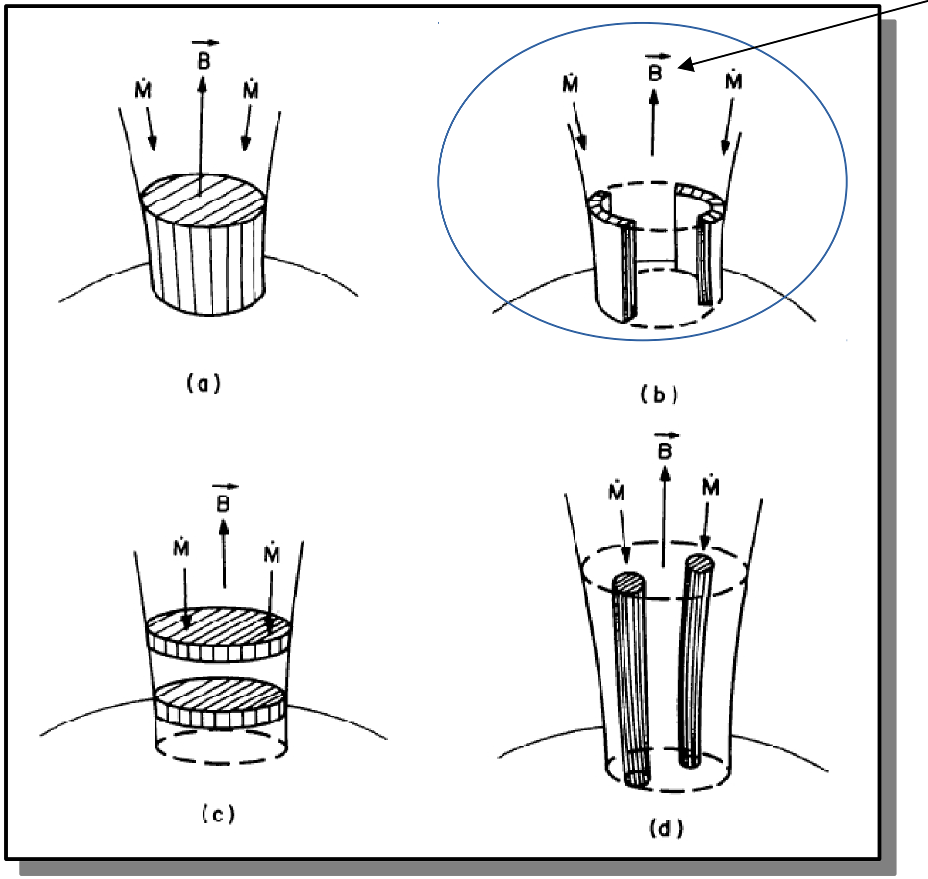
(Steinhardt & Elvis 10)



PULXs accretion

- The maximum X-ray luminosity (L_{Edd}) for a NS depends (at least) from the accretion rate, the magnetic field, the geometry of accretion (highest for a thin hollow funnel) and beaming.

- up to a factor of about 40 higher in L can be reached if B > 10^{13} G assuming a thin hollow funnel



Luminosities

NGC5907 X-1 isotropic peak Lx,bol is **1000** times L_{Edd}
NGC7793 P13 isotropic peak Lx,bol is **500** times L_{Edd}
M82 X-2 isotropic peak Lx,bol is **100** times L_{Edd}
NGC300 X-1 isotropic peak Lx,bol is **50** times L_{Edd}

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

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

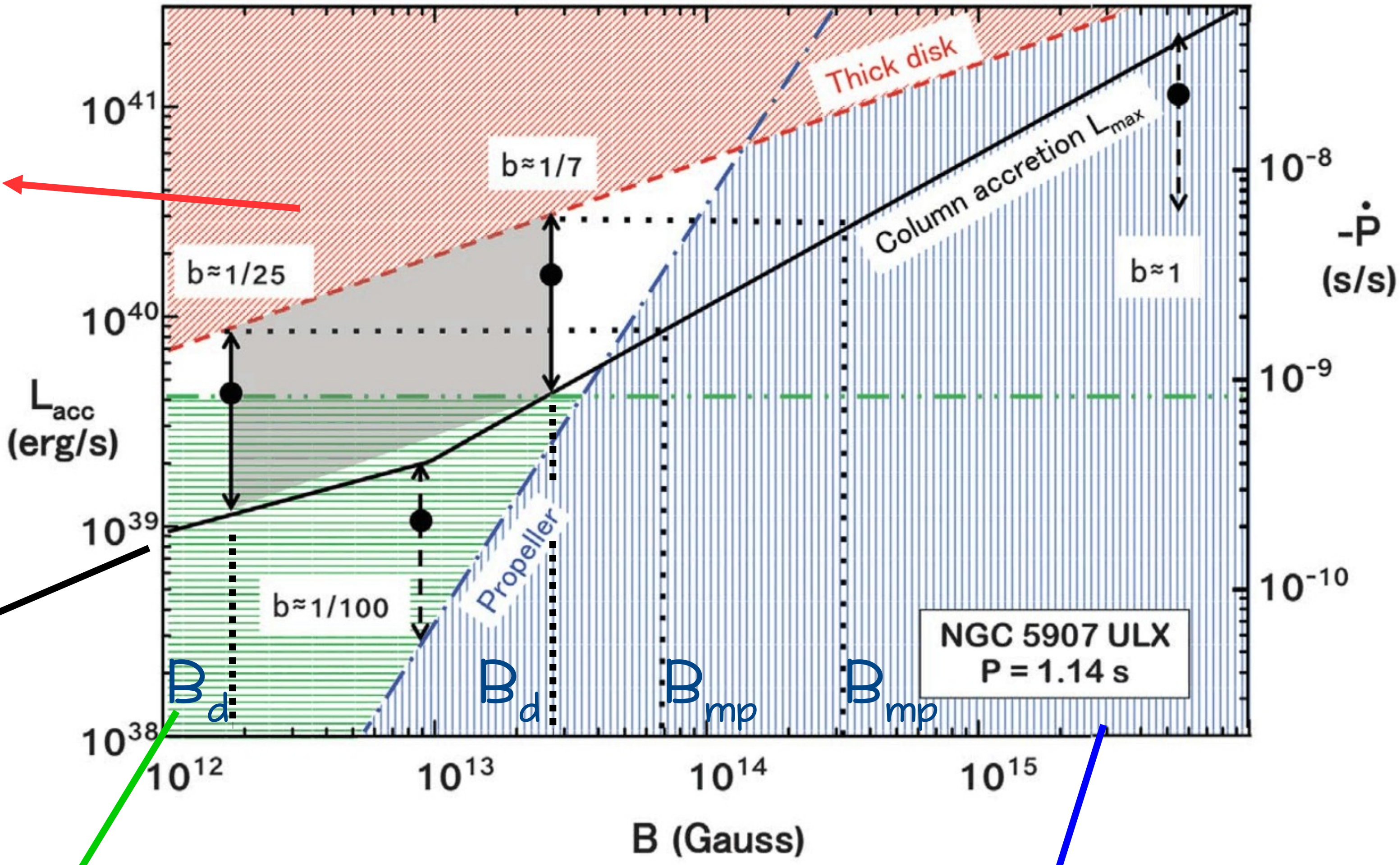
For B = few x10^{15} G up to 10^{41} erg/s can be released on the NS surface …

Moreover, with that B value and 1.13s spin period the NS in NGC5907 ULX should be deeply in the propeller phase ($r_m >> r_c$)!

A moderate beaming factor b<1 (b*Liso=Lacc) is also likely present (at least because we see pulsations) (King+ 2001)

b=1/100 pushes NGC5907 out from the propeller but not able to account for the observed Pdot

Possible scenario for NGC5907 ULX



Super-Eddington emission from the disk; escaping radiation stopped

Maximum Lx atteinable by the accretion column

Minimum Mdot in order to obtain the observed Pdot

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

Possible scenario

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

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

Fiore+19 show that the scenario is possible (numerical calculation)

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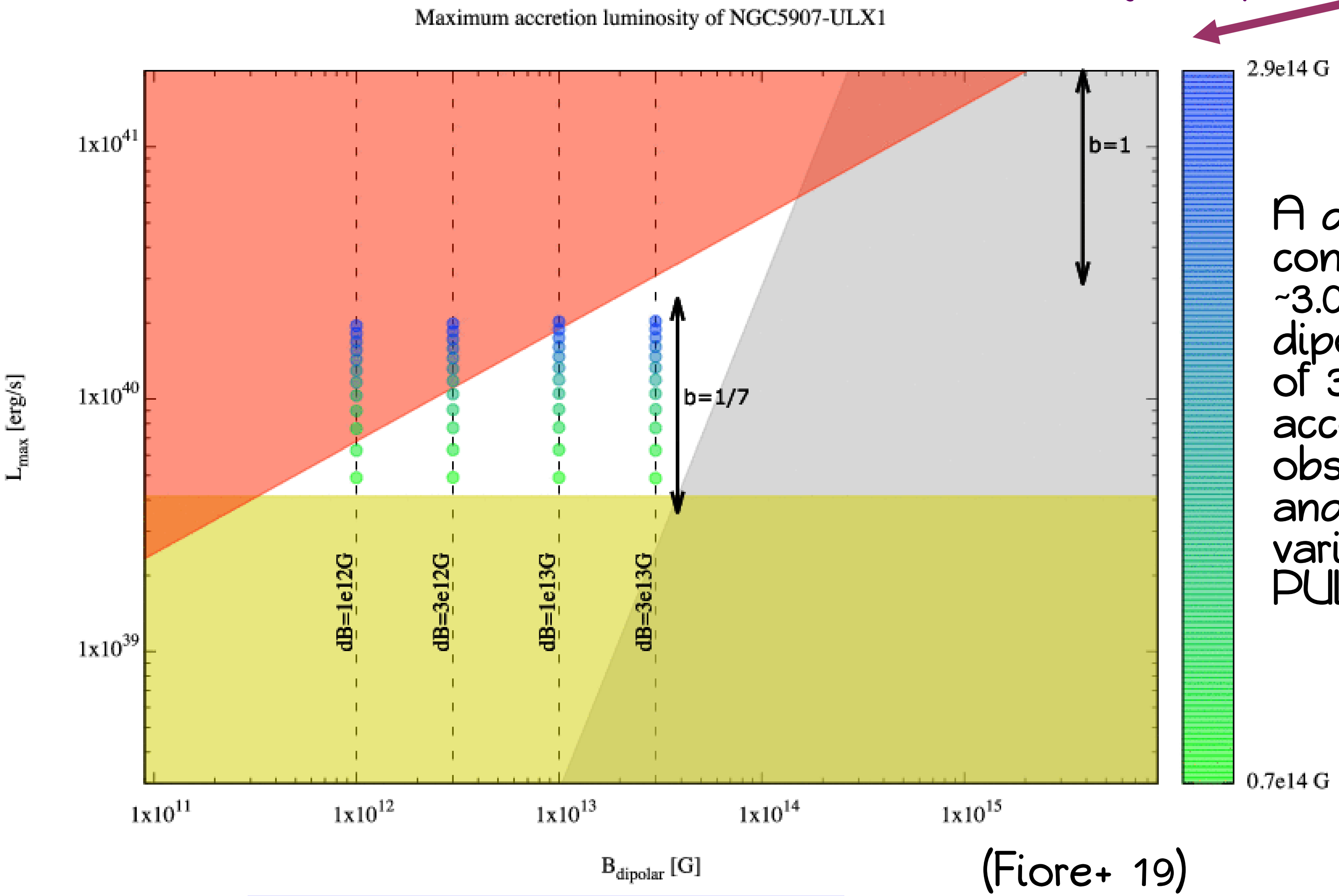
p-CRSFs detected in magnetars → B~1-10x10^{14} G close to the surface, 10 timeslarger then their dipolar component (Tiengo+13).

Super-Eddington outburst of SMC X-3 (Tsygankov+17): Dipolar (1-5x10^{12} G) + Multipolar (2-3x10^{13} G) components

Numerical calculation of the maximum Lx

Intensity of the quadrupolar component



A quadrupolar component of ~3.0e14 G, with a dipolar component of 3.0e13 G, can account for the observed luminosity and luminosity variation of the PULX in NGC5907

(Fiore+ 19)

NGC 5907-ULX1

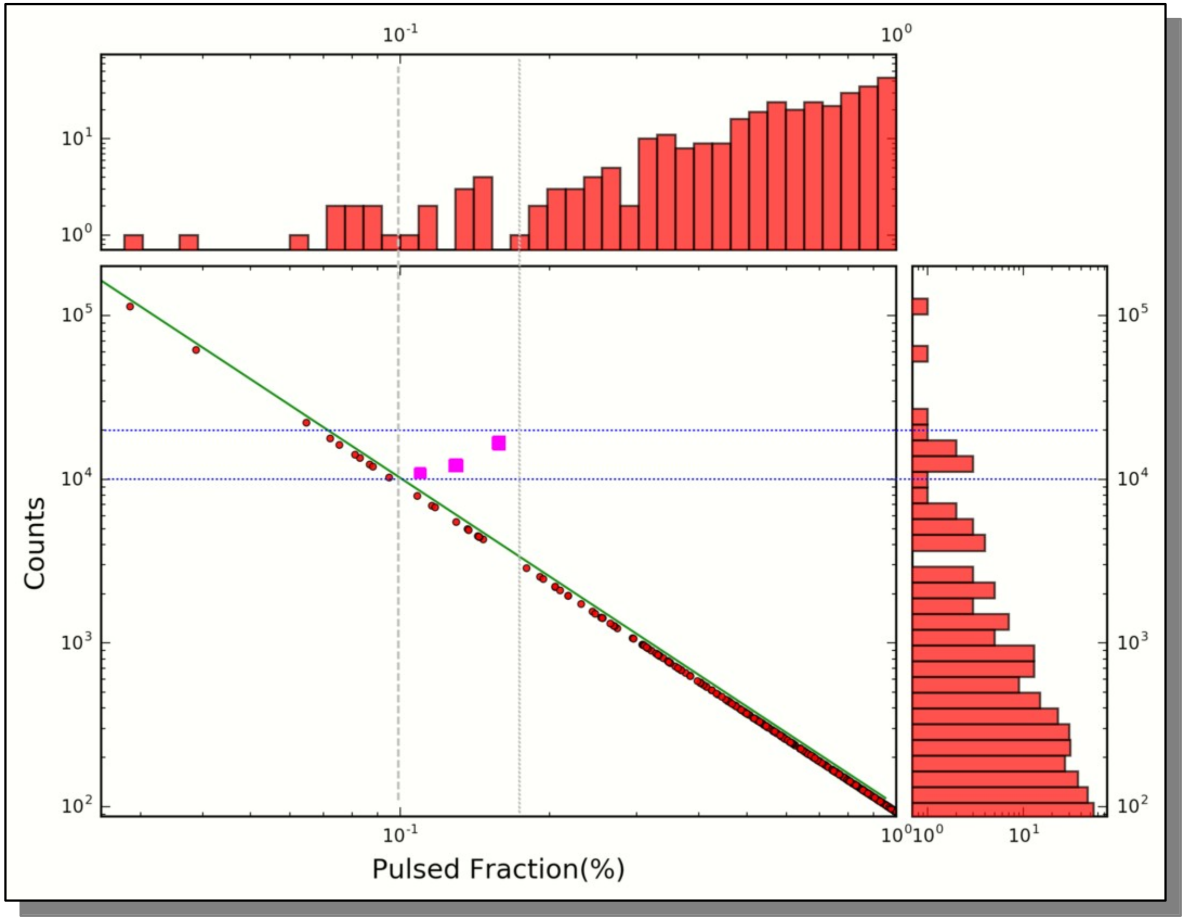
New directions

How many PULXs?
4 out of 300, ~**1%** ?

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?

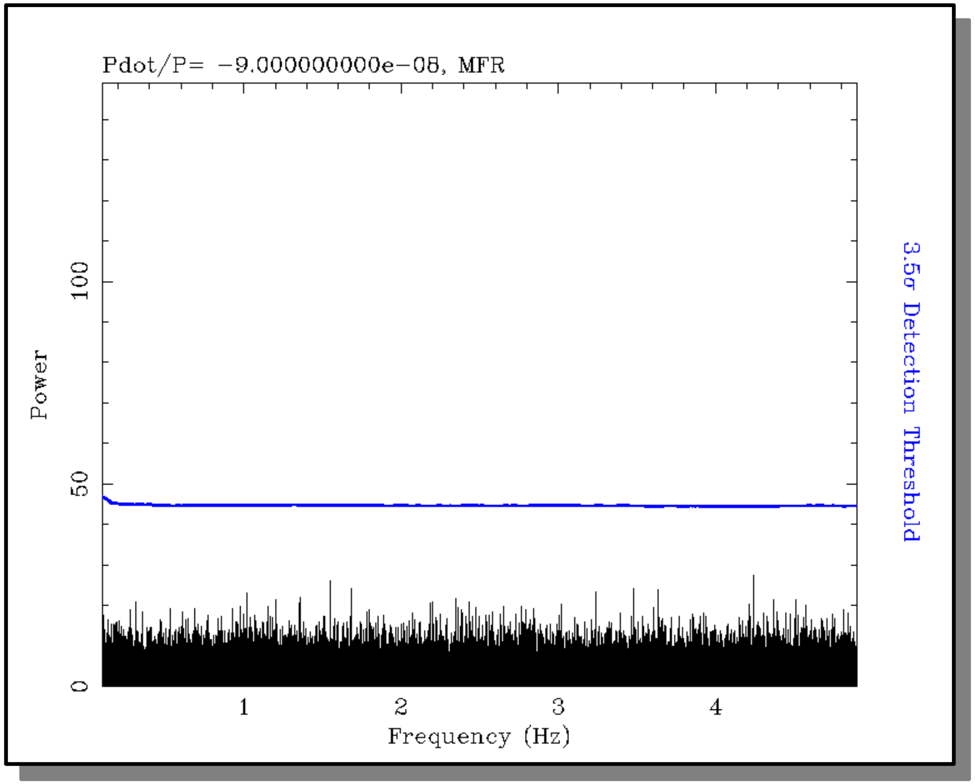
18 ULXs → **21%** are PULXs

Not all pulsars are expected to be beamed towards us.

2-3 ULXs likely BHCs (M>5Msun, Lx>10^{42} erg/s) out of 300 ULXs, ~**1%**

Hybrid Approach: II. More sophisticated tools for analysis and computing

Since in several observations of NGC5907 and M82 the signal went undetected, we concived the ULX Pulsation Accelerated Search for Timing Analysis (PASTA) project, which based on the timing properties of known PULXs carries out an ad hoc timing analysis which also takes into account an eventual (large) Pdot component; correcting the ToA of the events assuming a wide range of Pdot values.



The next step was to correct the ToA for the "UNKNOWN" orbital parameters : We developed a new pipeline, namely Search for Orbital Periods with Acceleration (SOPA and eSOPA) to be applied to all ULXs +candidates. Requieres tens of millions cpu-hours on HPCs/HTCs. We have been awarded with several millions cpu-hours We are first using SOPA with the UNSEEN targets.

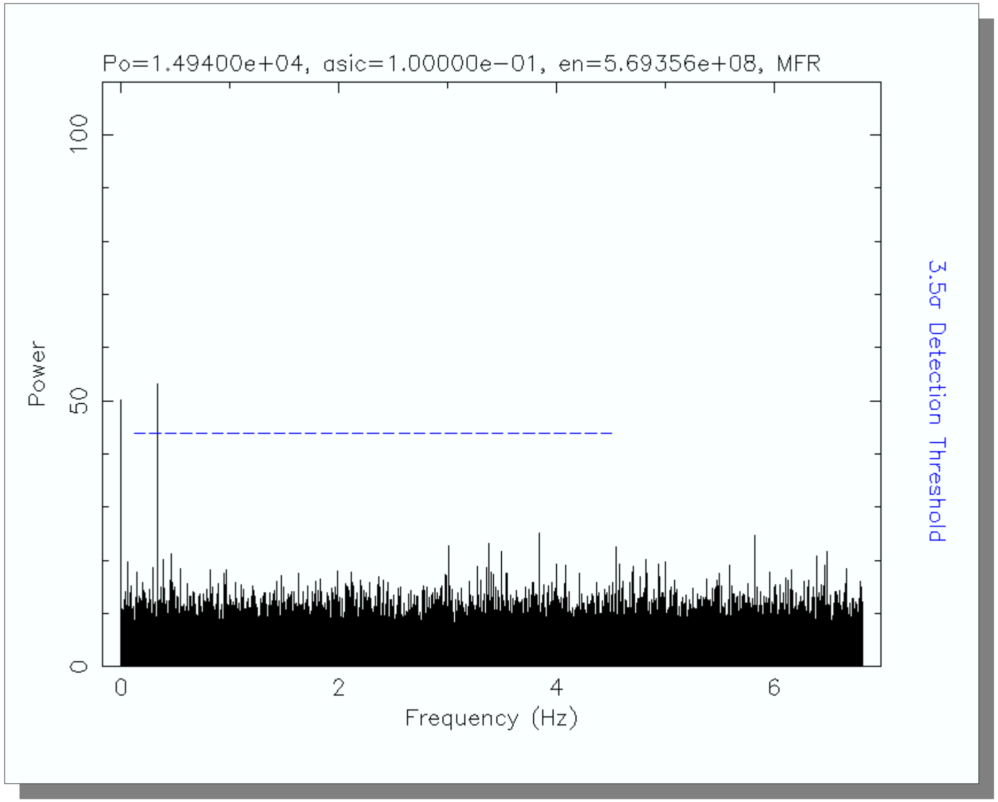
(P_{orb}, $a_x$sin(i), Time of the asc. node, [e, time of periastron])

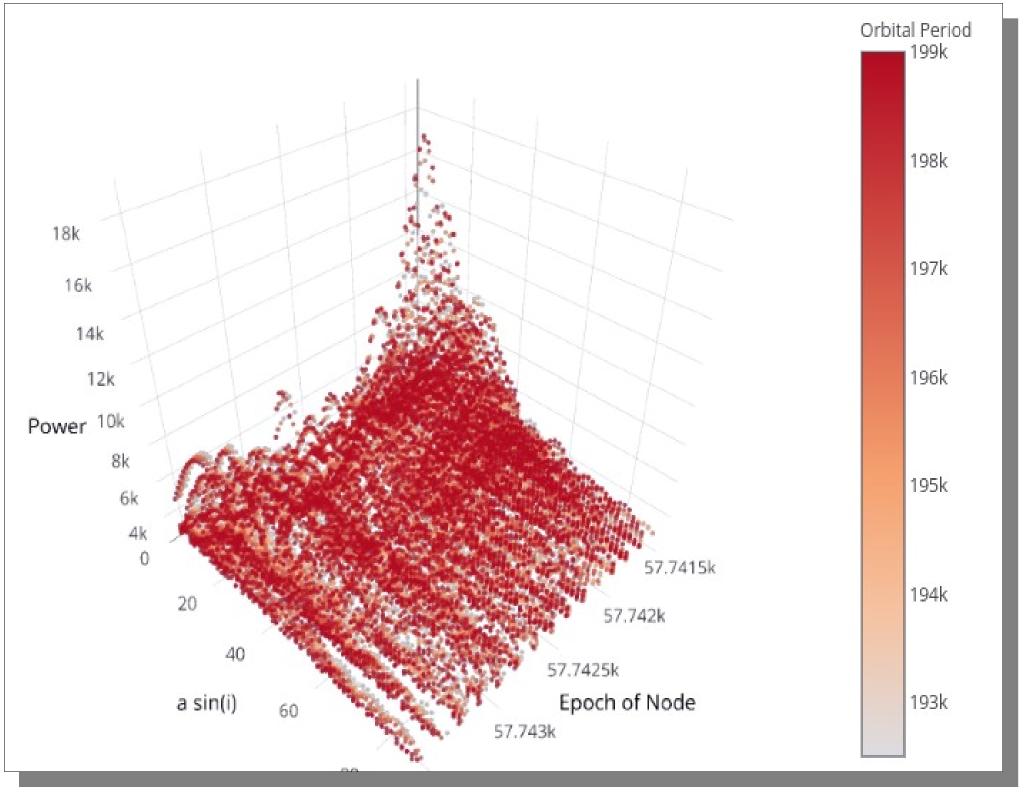
“Big data" and Computing issue

PULX signal detection strongly affected by Pdot and orbital motion:
Events correction in a 3D parameter-space: P_{orb}, $a_X\sin(i)$, T_{node}:

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

For a reasonable grid ~ **10^5** FFTs/periodograms per source →
Need for High Performing Computing (HPC: **INAF-CHIPP, INAF-CINECA**)
and efficient handling of huge amounts of data: tested on M31 →
→ **Second Pulsar discovered in M31! (Rodriguez+ 18 APJL)**





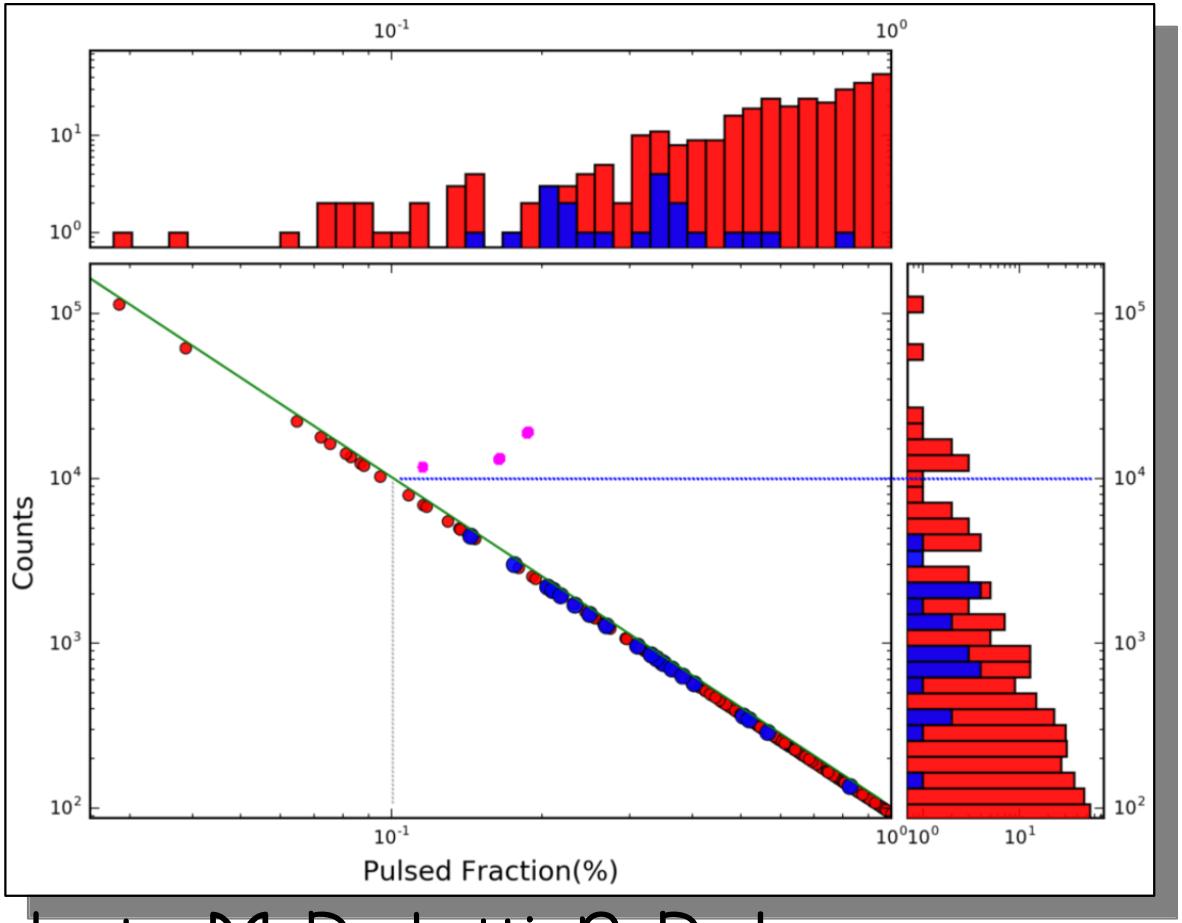
Taking the beat of the UNSEEN

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

Recently accepted as LP in AO17:

8 pointings + **3** DDTs
986.000 seconds
274 hours
~15 ULXs (>10.000 cts)
~30 additional S-Edd sources
1-3 new PULXs expected to be detected!

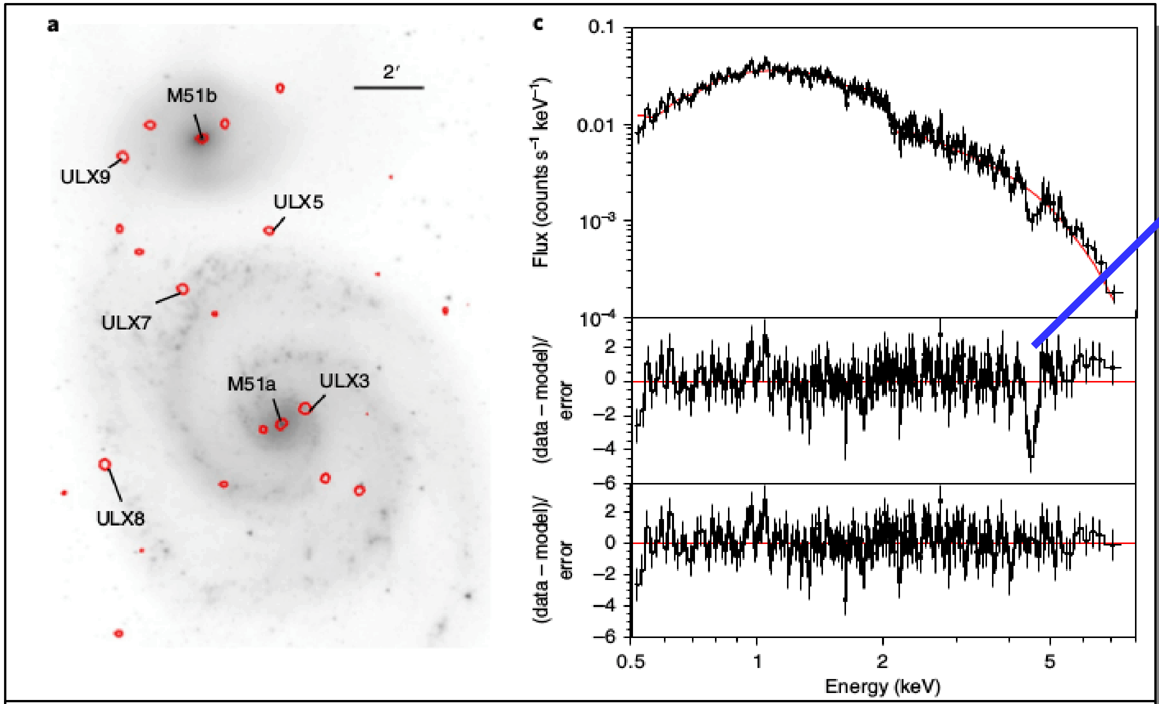
Just completed



The UNSEEN Collaboration:
G.L. Israel, G. Rodriguez,
F. Bernardini, H. Earnshaw, T. Roberts, M. Bachetti, A. De Luca,
A. Tiengo, A. Belfiore, R. Turolla, M. Mapelli, L. Zampieri, F. Pintore,
M. Middleton, P. Esposito, F. Fuerst, D. Walton, P. Casella, S. Dall'Osso,
D. Dagostino, G. Novara, R. Salvaterra, F. Harrison, M. Brightman,
C. Pinto, F. Haberl, M. Marelli, A. Wolter, L. Stella, A. Papitto

Strongy magnetized NSs are unveiled not only through pulsations but owing to **(proton) cyclotron lines**, similar to the case of magnetars……

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

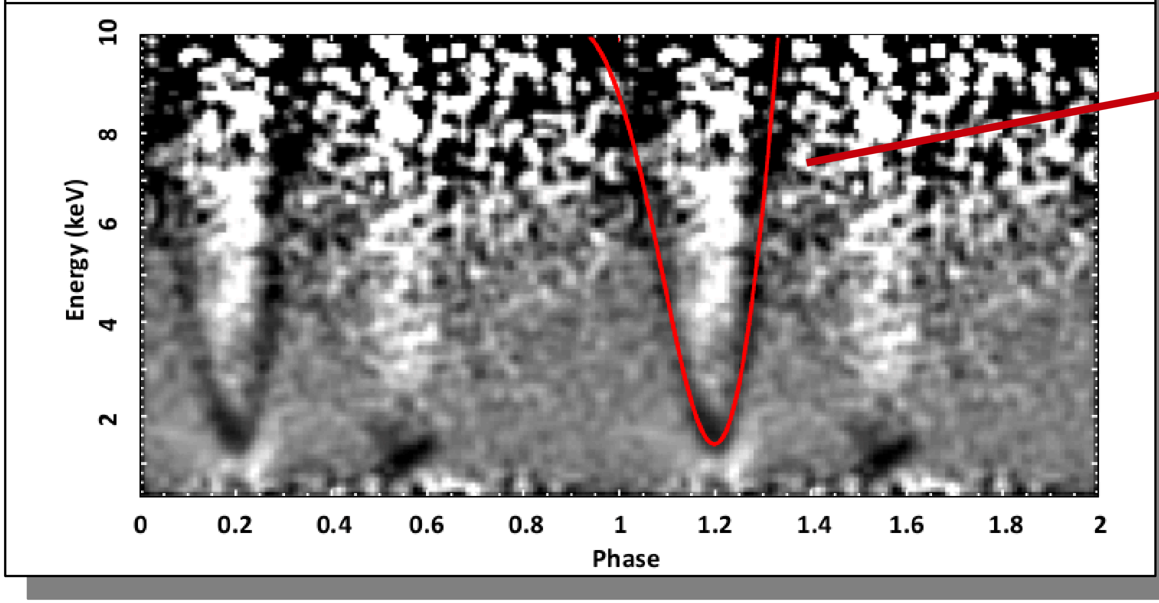


Non pulsating ULX in M51

$$\Delta E = 6.3(1+z)^{-1}(B/10^{15}\,\mathrm{G})\,\mathrm{keV}$$

where z~0.3 for a NS

B~10^{14} G
Chandra spectrum with ~10000 cts
(Brigthman+ 18, Nature Astr.)



Magnetar

B~1-10x10^{14} G (phase-dep.)

Structure (loop?) close to the surface (a factor of 10 larger then their dipolar component)

(Tiengo+ 2013, Nature)

XMM LP

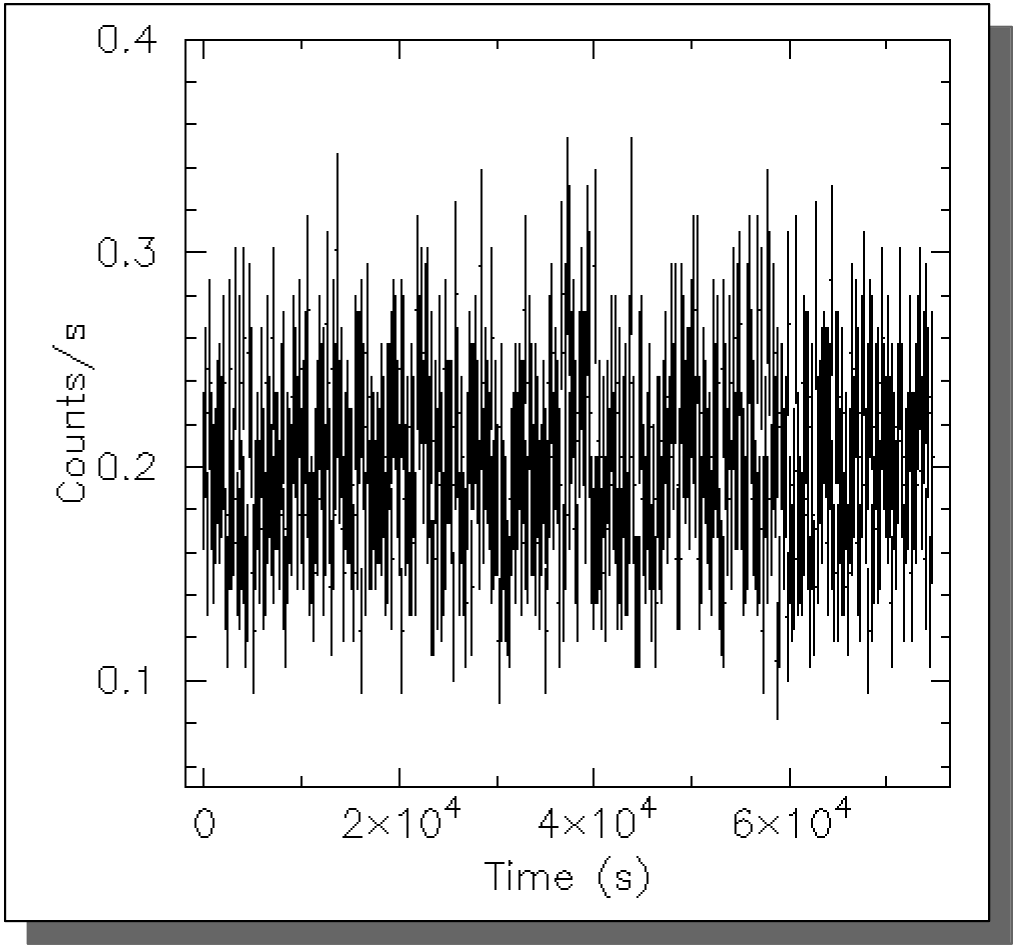
M51 observed in May 2018 for about 75ks

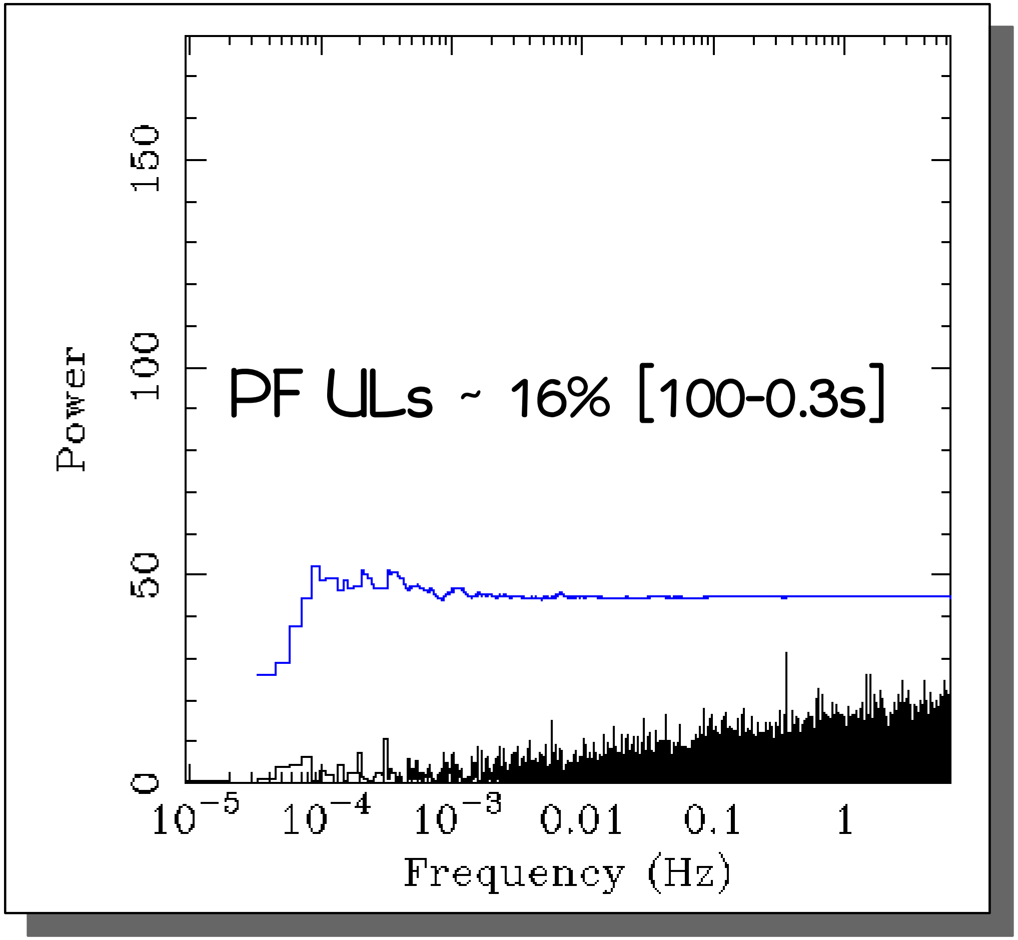
+ 3 DTT (96+63+64ks) requested on in June 2018

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

M51 ULX7

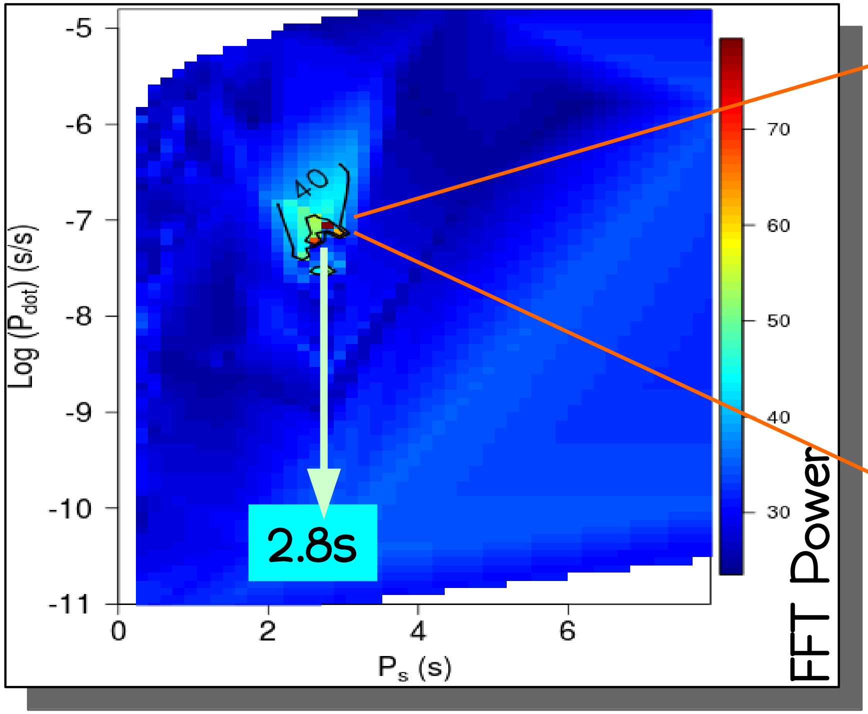
One of the best example of Poissonian process and white noise !



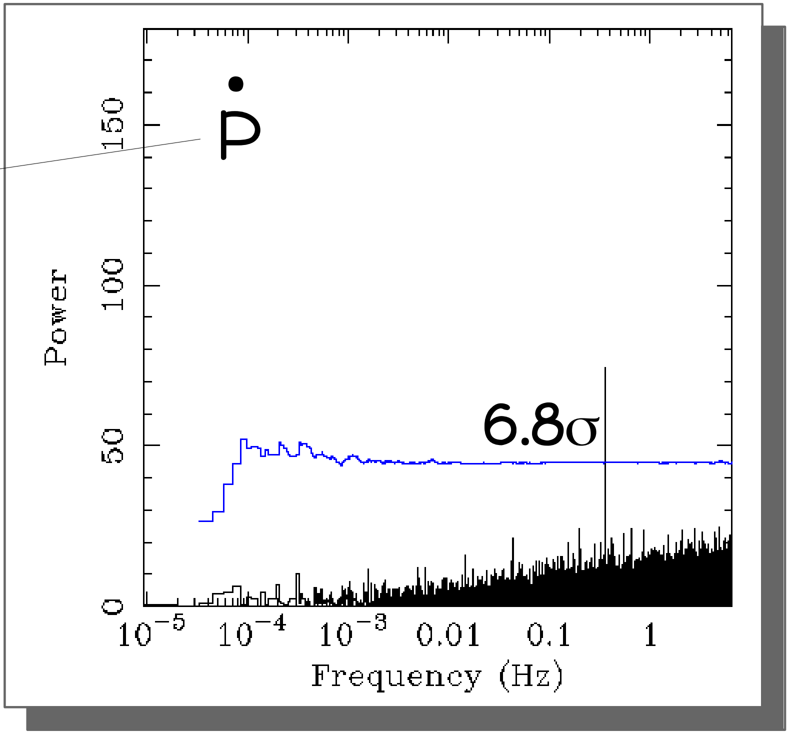


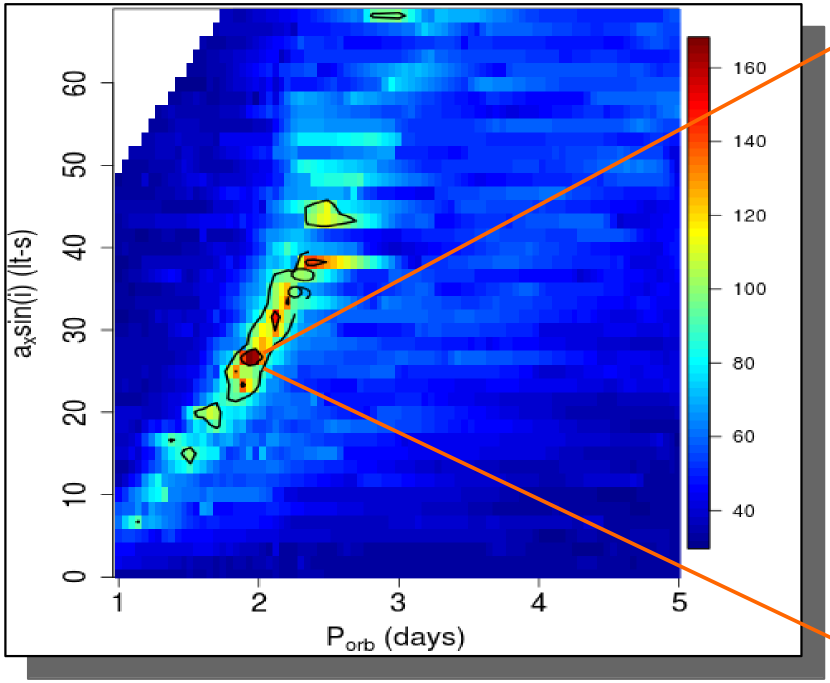
PF ULs ~ 16% [100-0.3s]

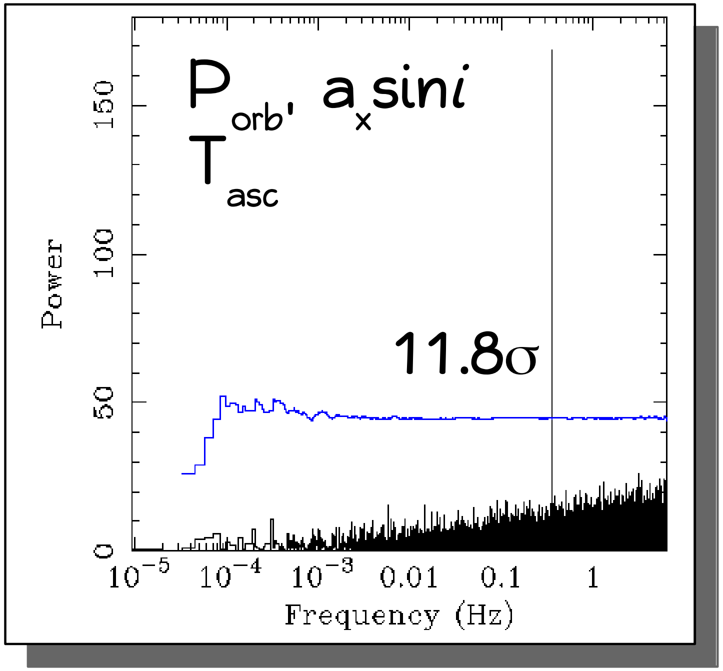
Accelerated search



Dominated by orbital motion





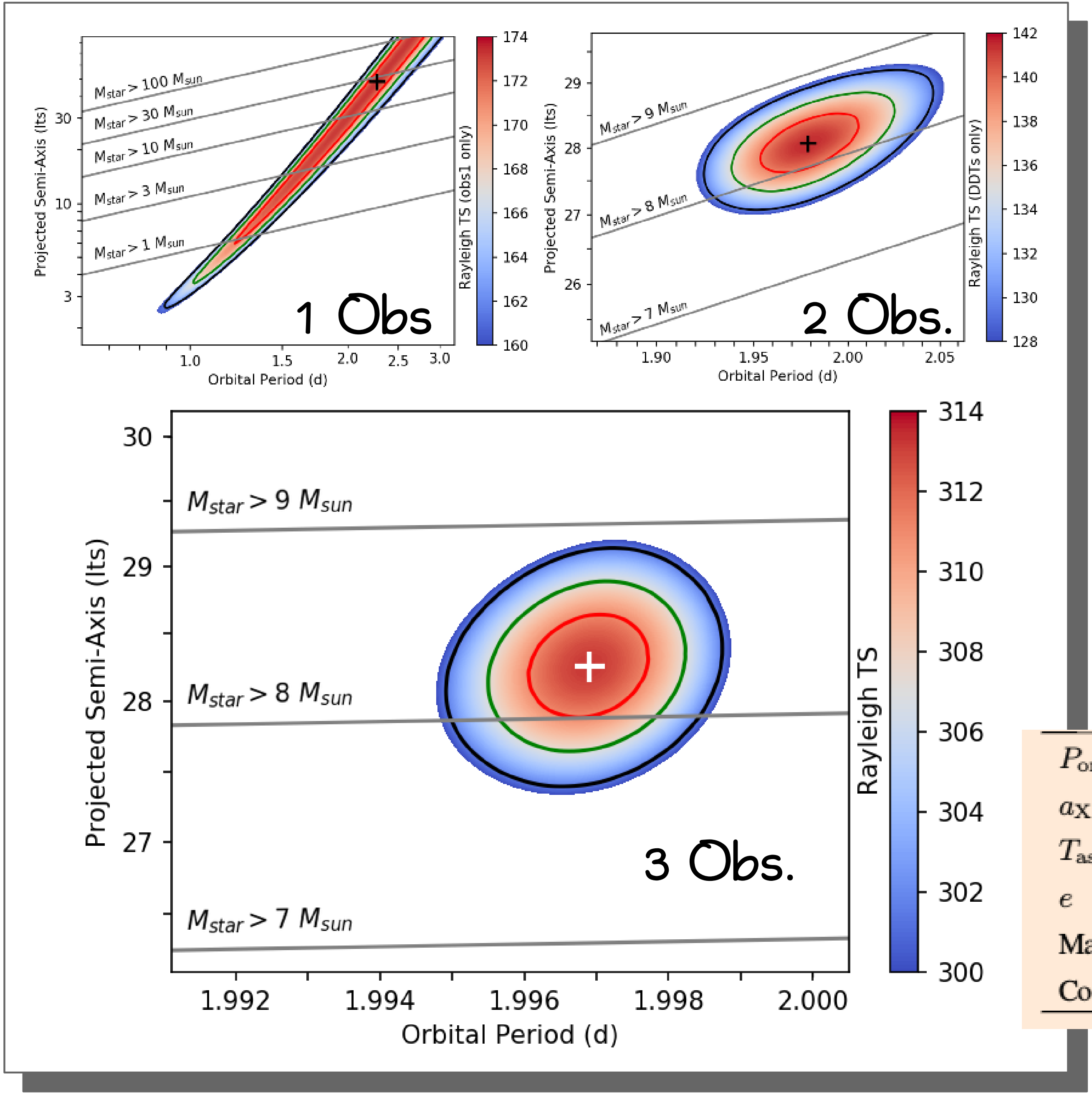


Up to 10^6 FFTs needed to cover the 4D phase space.

Use of HPCs

The binary system hosting M51 ULX7

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

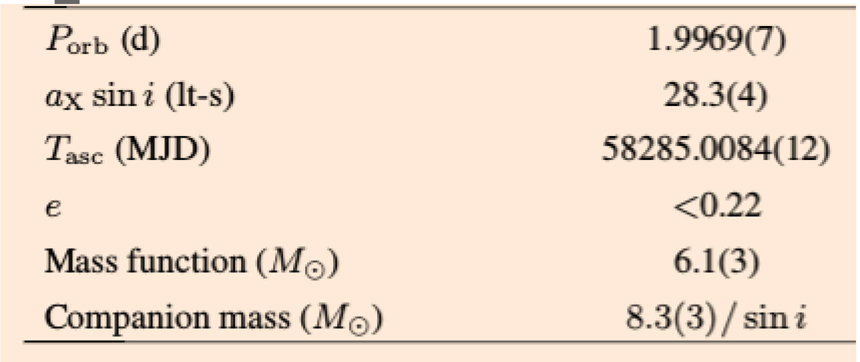


$M_c/M_\odot = 8.3/\sin i$

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

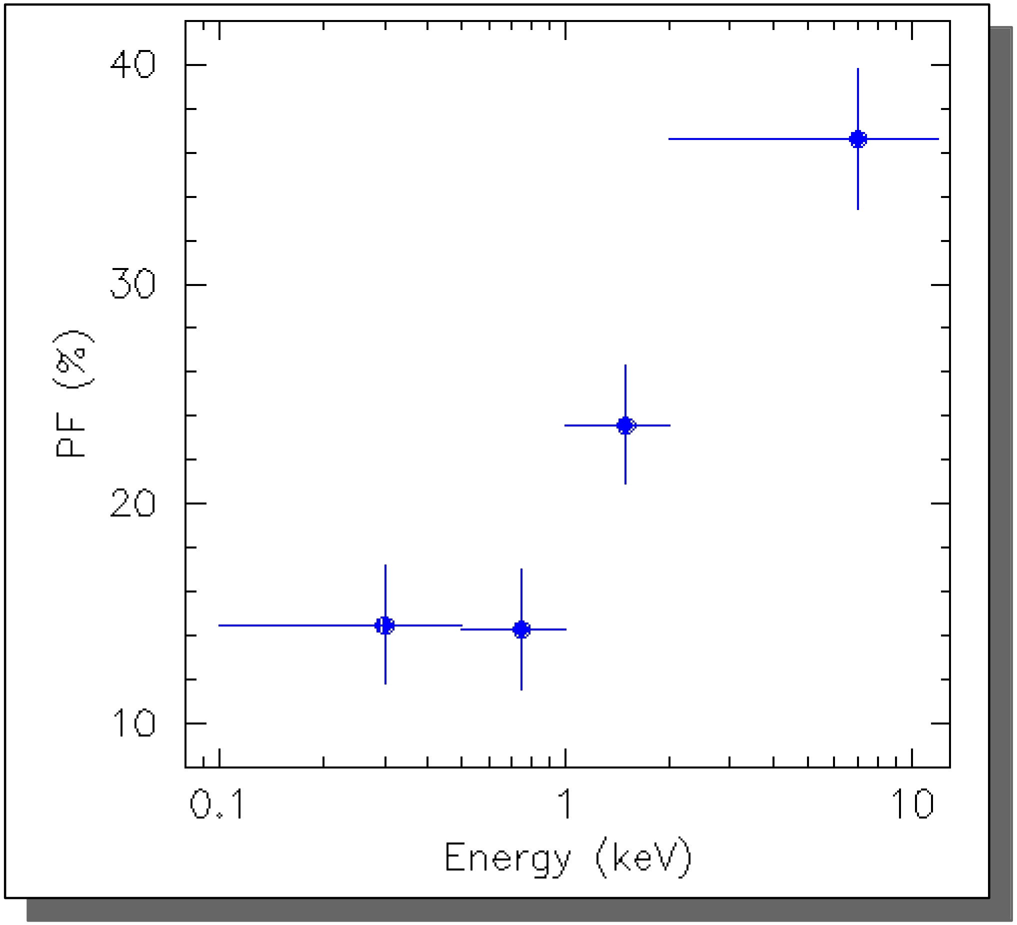
$M_c \simeq 13\ M_\odot$ for average sine values -> HMXB

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

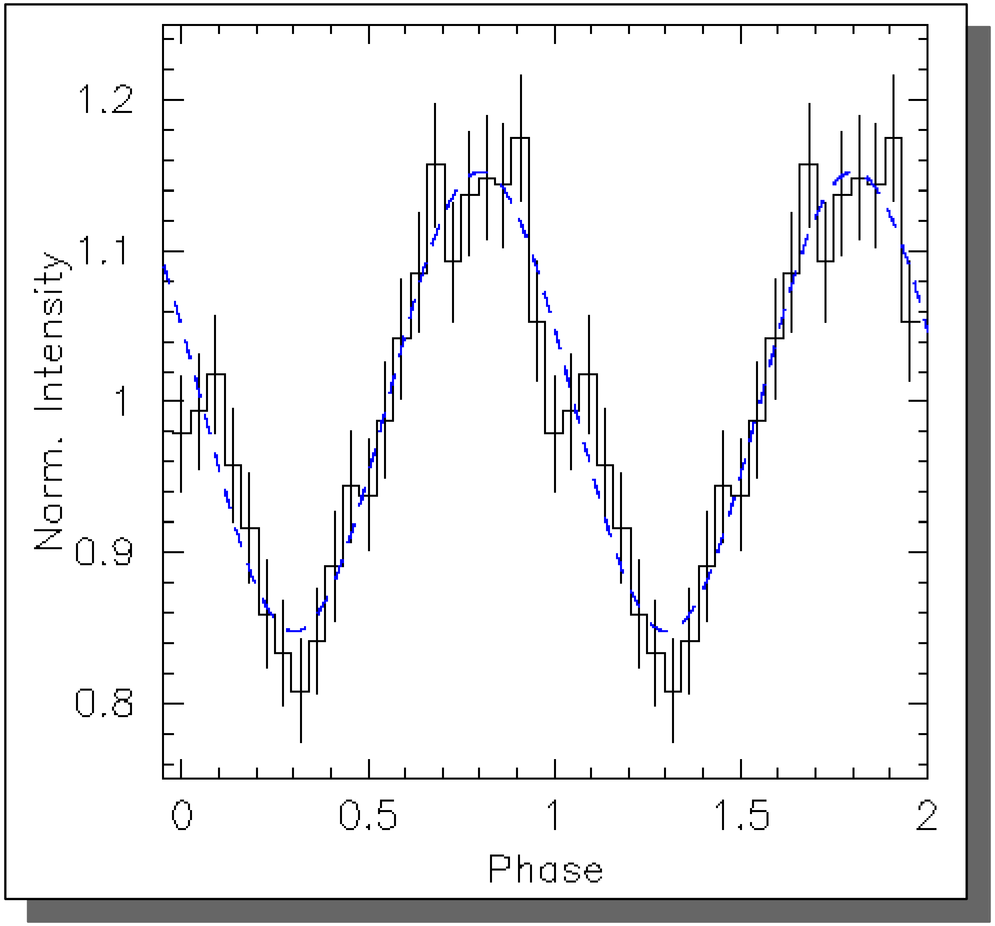


$P_{\rm orb}$ (d)	1.9969(7)
$a_{\rm X} \sin i$ (lt-s)	28.3(4)
$T_{\rm asc}$ (MJD)	58285.0084(12)
e	<0.22
Mass function ($M_\odot$)	6.1(3)
Companion mass ($M_\odot$)	8.3(3) / $\sin i$

M51 ULX7



<PF>=15+\-1%



In terms of P, Pdot, Porb, ax sini, PF and Counts ULX7 is exactely where we expected to find a PULXs

Expectations versus Observations

1 new PULX found so far in the XMM LP

+

1-3 expected based on our statistics

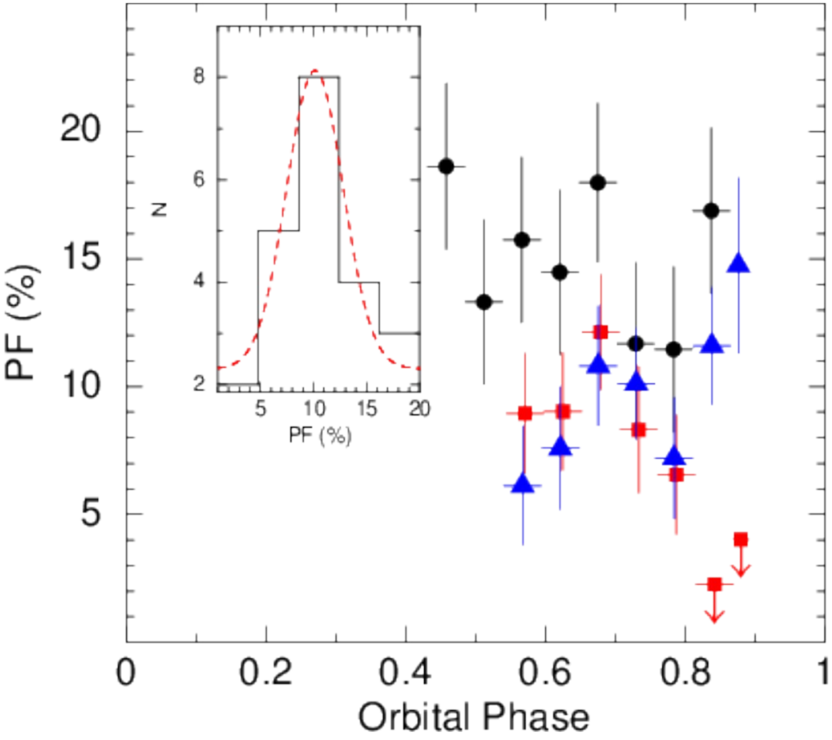
=

marginally consistent results

BUT

1 new PULX discovered in the XMM archive (Carpano+ 18)

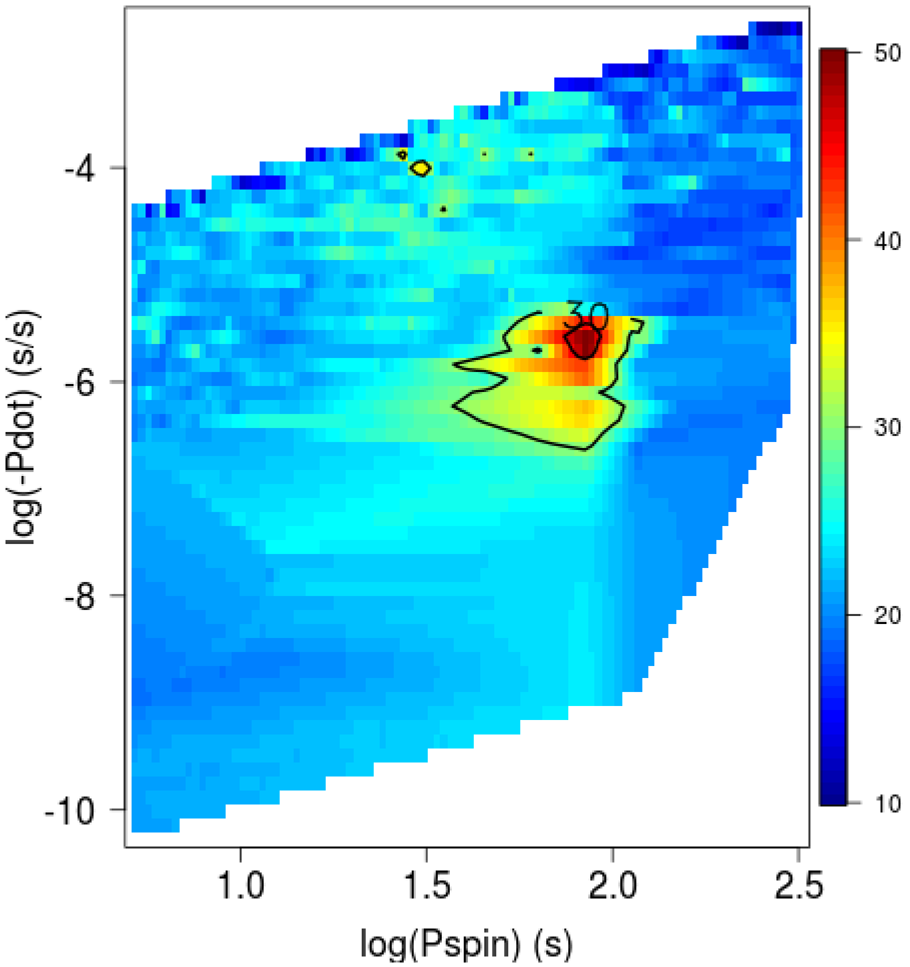
And...



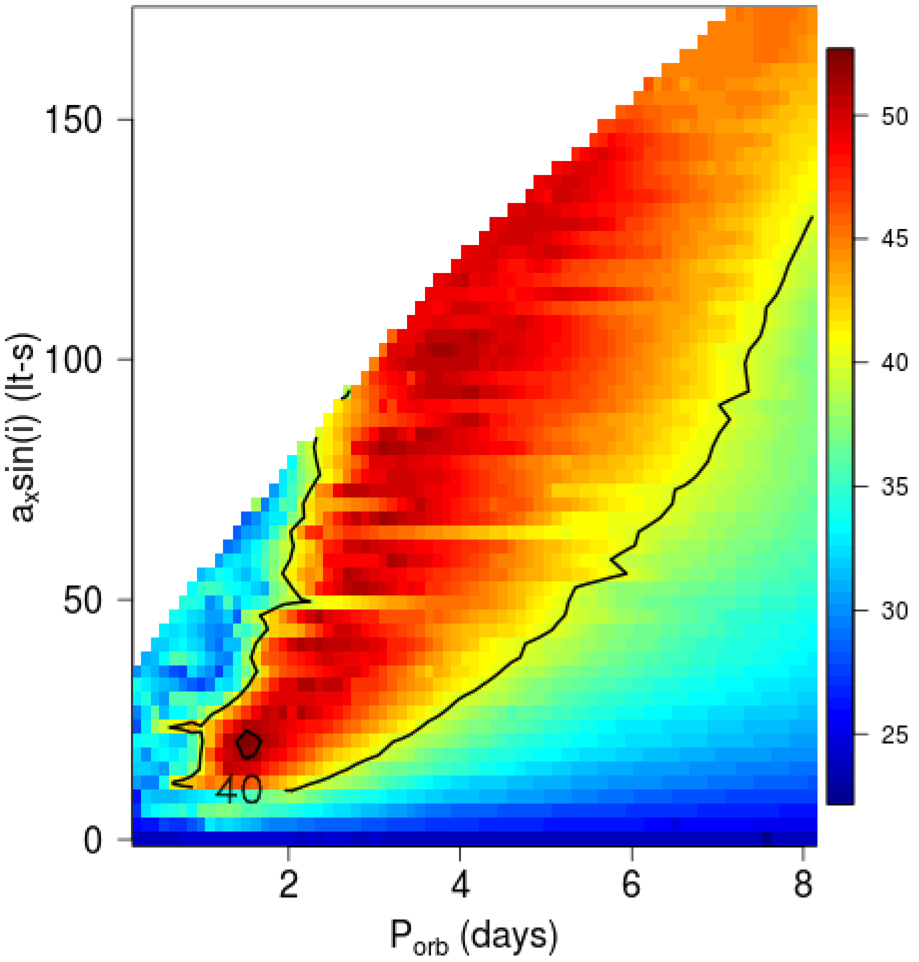
large variability in the signals

undetected for about 3hr

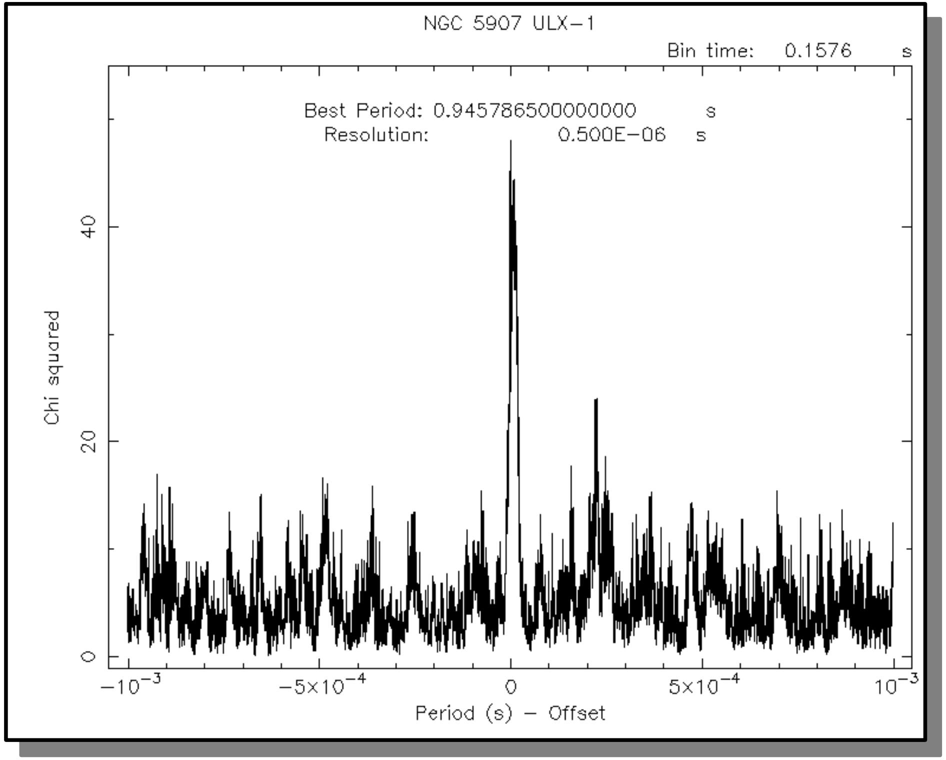
Searching new PULX candidate....



... both in the XMM LP and in the XMM/NuSTAR archive



NGC5907 Follow-up obs

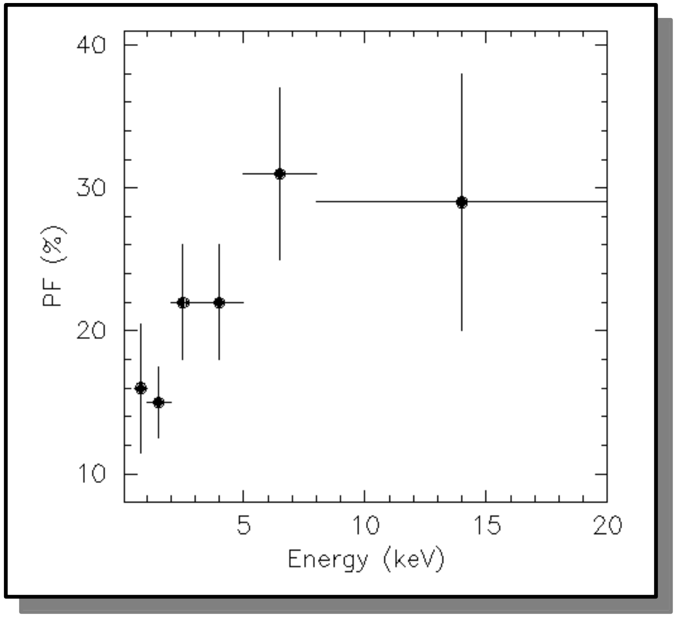


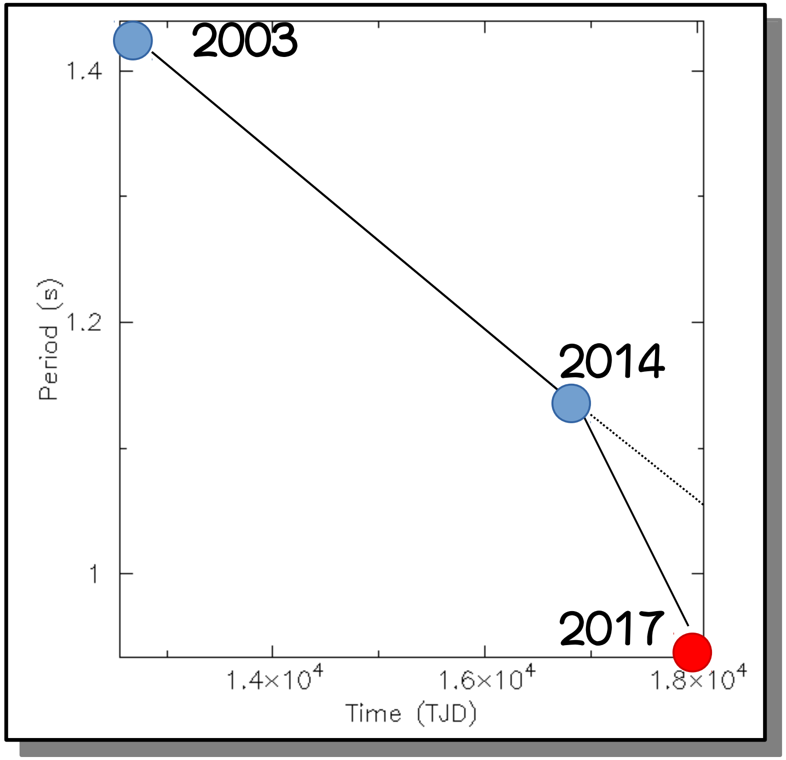
XMM LP AO16 (PI M/A Belfiore)

Faint signal at ~946ms

Pulsed fraction unchanged

Spin-up rate increased





Some implications/Conclusions

- 5 out of 9 know Extragalactic NSs discovered thanks to EXTraS and its heritage. INAF --> strong knowhow in HE data-mining and timing

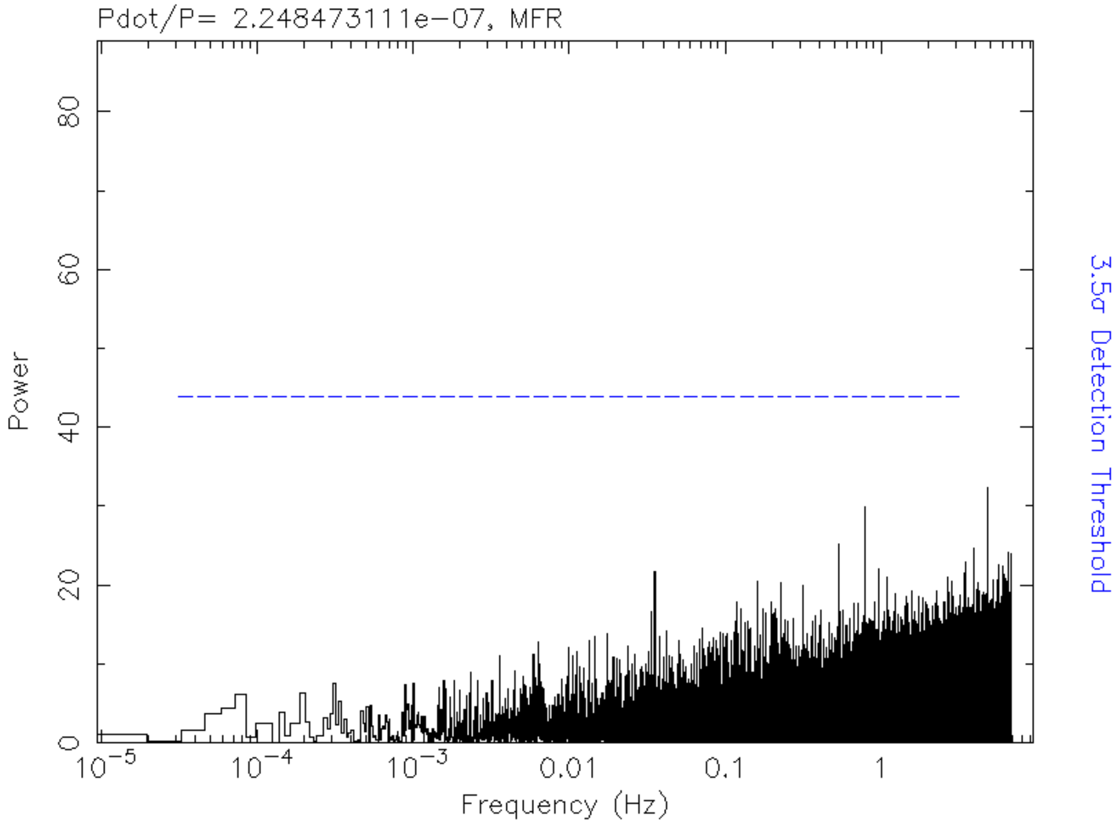
- Even **extreme ULXs** (>1e41 erg/s), like NGC5907 ULX-1, can **hosts accreting NSs**

- **Spectral classification/Lx is not an unambiguous way to classify ULXs:** NGC 5907 ULX, NGC7793 P13 and M51 ULX7 have spectra/Lx not dissimilar from other ULXs (but harder) --> many ULXs might host NSs

- The large “local” Pdot, the orbital effects, the pulse intermittance and small PF make **difficult the detection of these pulsars** with standard tools and current instruments.
  Athena is expected to make a significant contribution for PULXs.

- **PULXs challange the current models of accretion**, even assuming a moderate beaming.
  A multipolar B component close to the surface might account for The PULXs properties (other scenarios are still viable)

- Developed pipelines can be applied straightforwardly to NuSTAR, NICER and Chandra data and, in the future, to eXTP and Athena


Pdot/P= 2.248473111e-07, MFR
Power
0
20
40
60
80
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
1
Frequency (Hz)
3.5σ Detection Threshold

~~U~~NSEEN!