What can we learn from the variability of the M82 ULXs?

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+ Hamza El Byad, the NuSTAR ULX WG, the Italian PULX group, and many others

SpecTem Polar
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TULIP

The many tones of accretion, Cefalù, MJD 61293

Video Credits: Tiziana di Salvo

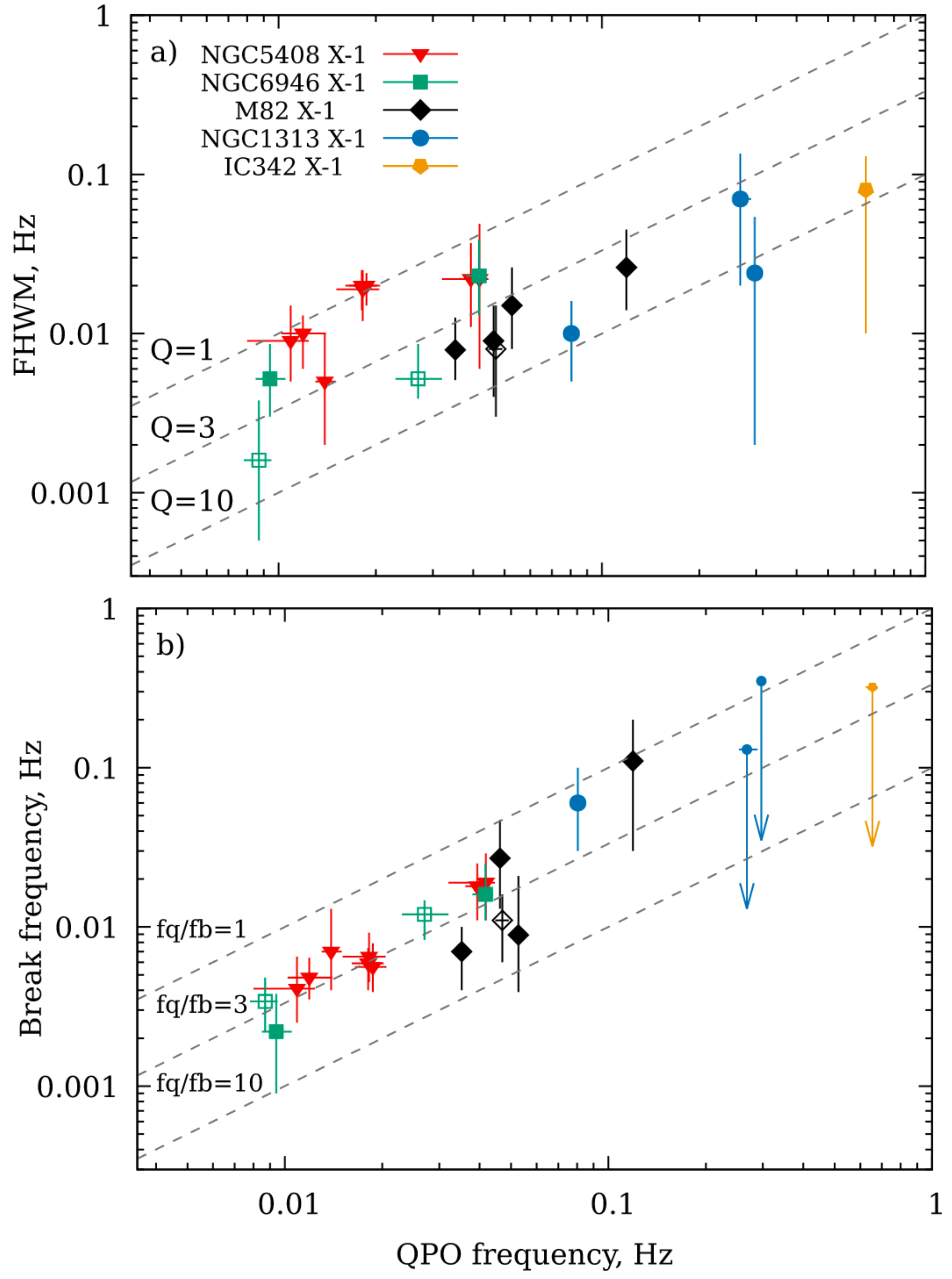
“How we wish you were here”

ULX power spectra

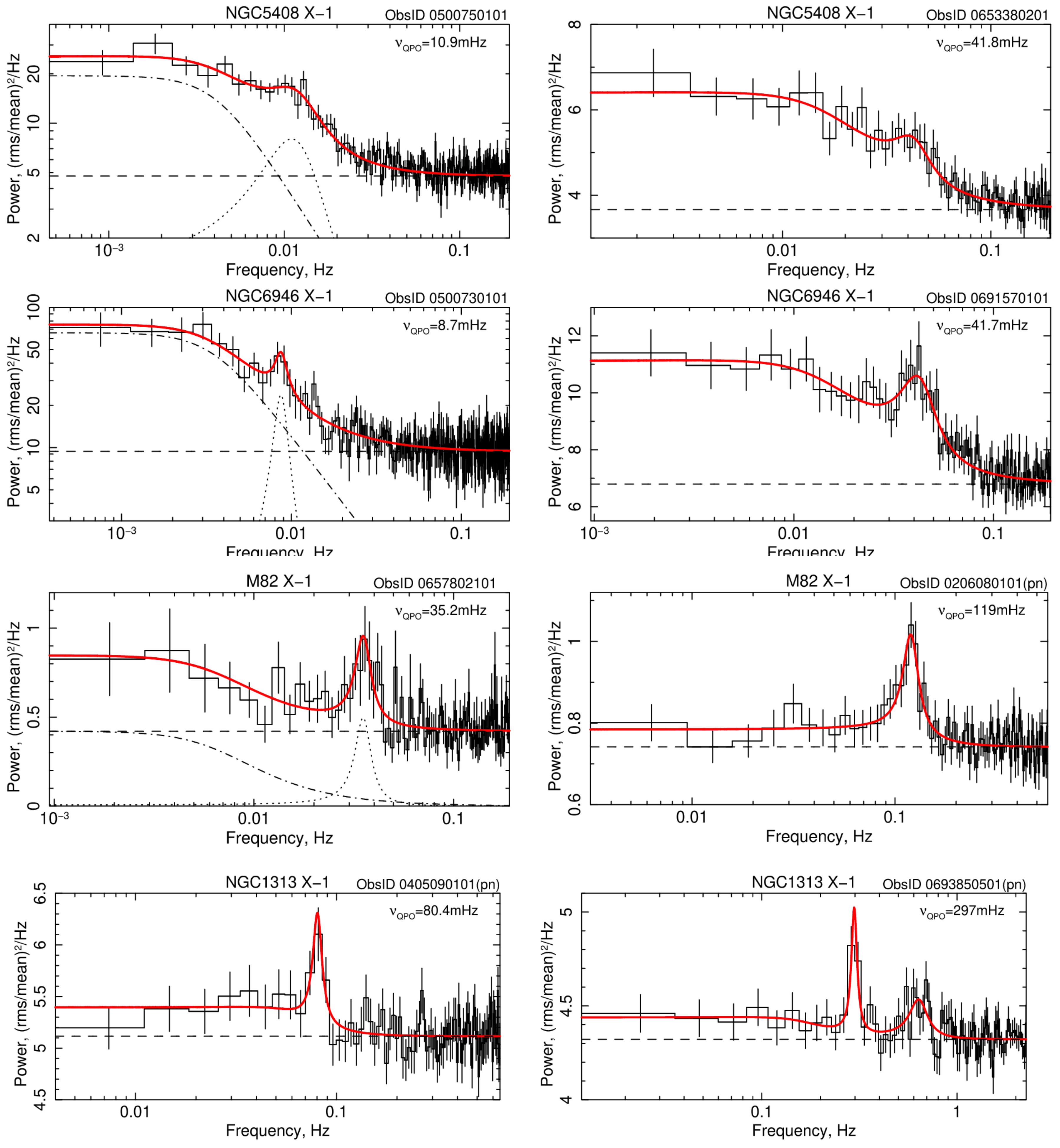
Aperiodic variability and QPOs 1-500 mHz, lags, and more

Tomaso-coauthored

Mucciarelli+06 MNRAS **365**, 1123
Caballero-Garcia+13, MNRAS **436**, 4
De Marco+13, MNRAS **436**, 3782, 2013
Casella+08, MNRAS, **387**, 1707
Feng, Rao & Kaaret, ApJL **710**, L137, 2010
(…)



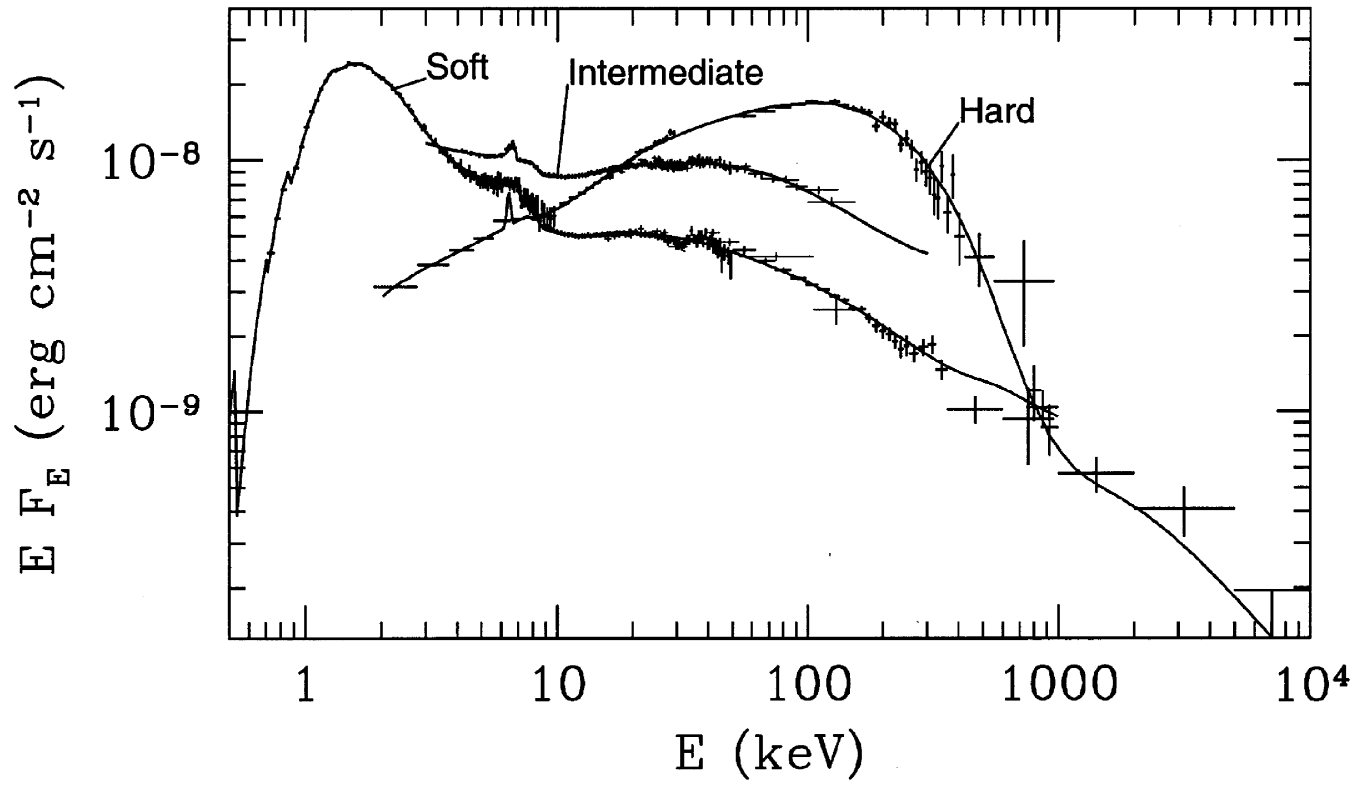
Atapin+19, MNRAS 486, 2766



See review by Pinto, Leone's poster for new work on lags

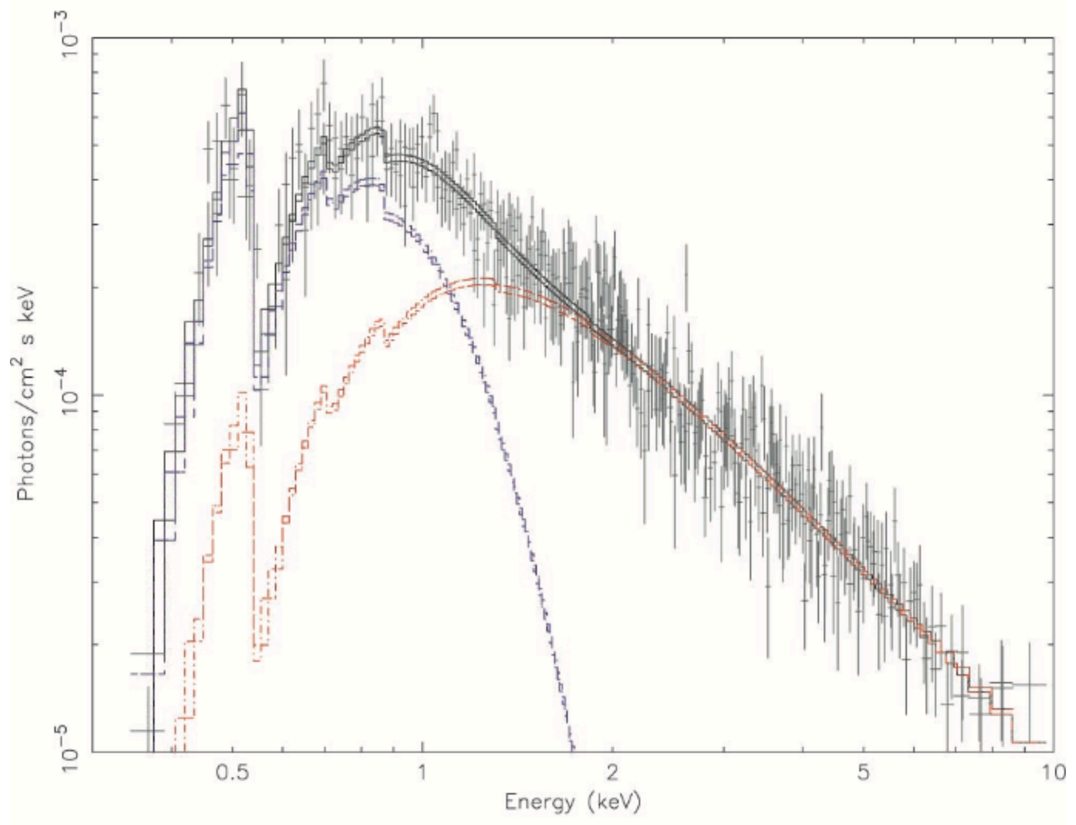
Scaling

ULX spectra have low disk temperature. ULX *power* spectra have low characteristic *frequencies*.
And so it's easy: very massive black holes?



disk @
1 keV

Gierliński+99,
MNRAS **309**, 496

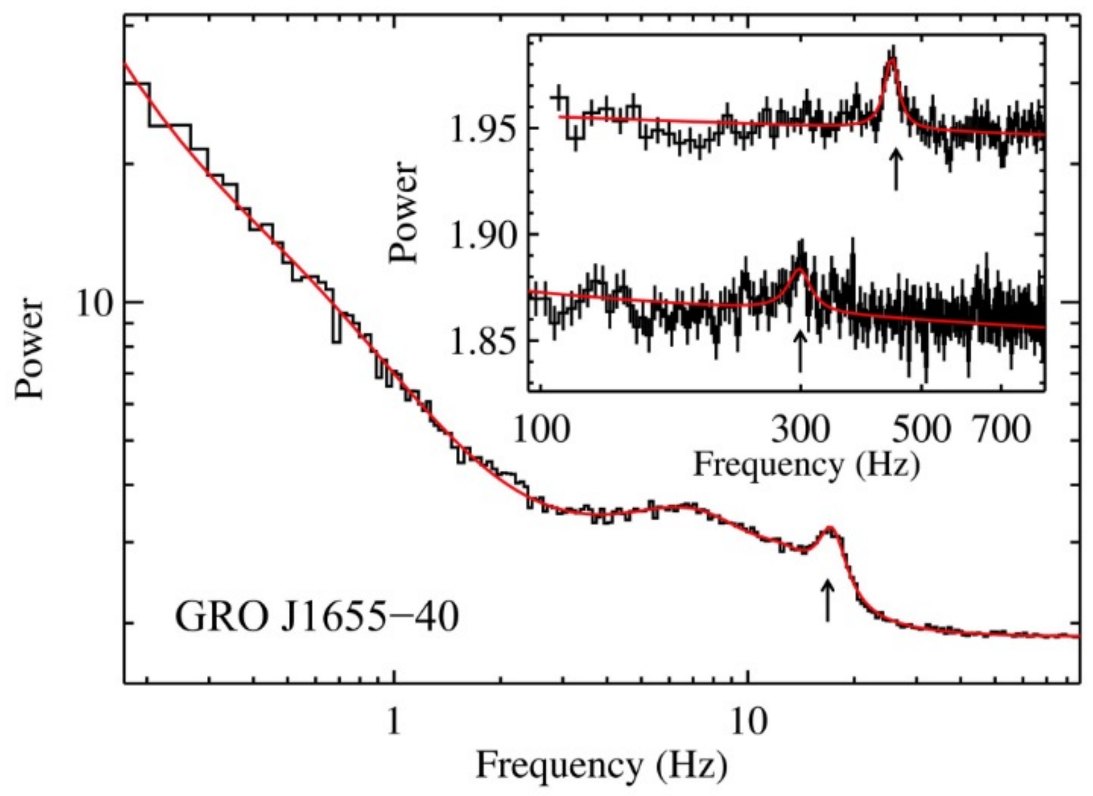


disk @
0.2 keV

Miller+03,
ApJ **585**, L37

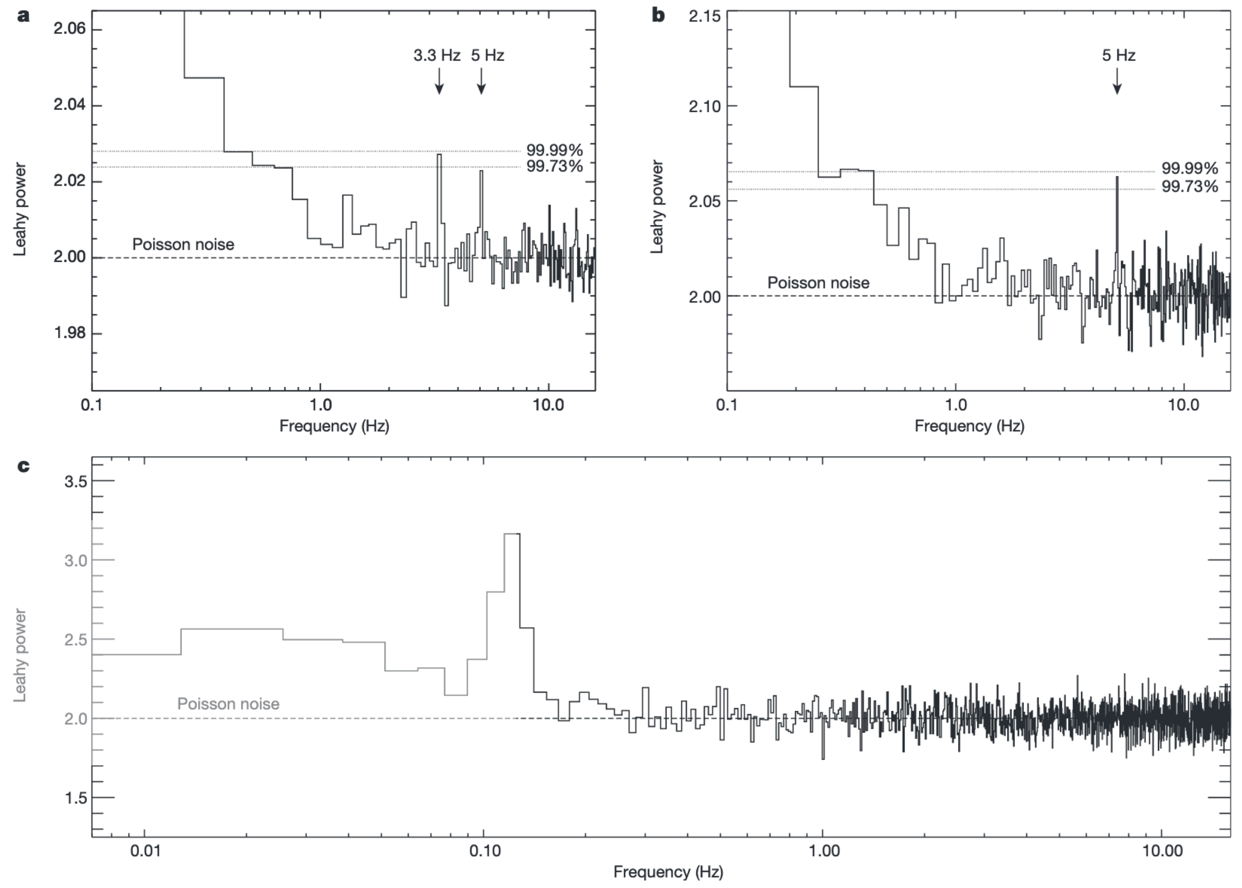
QPOs @
1-400 Hz

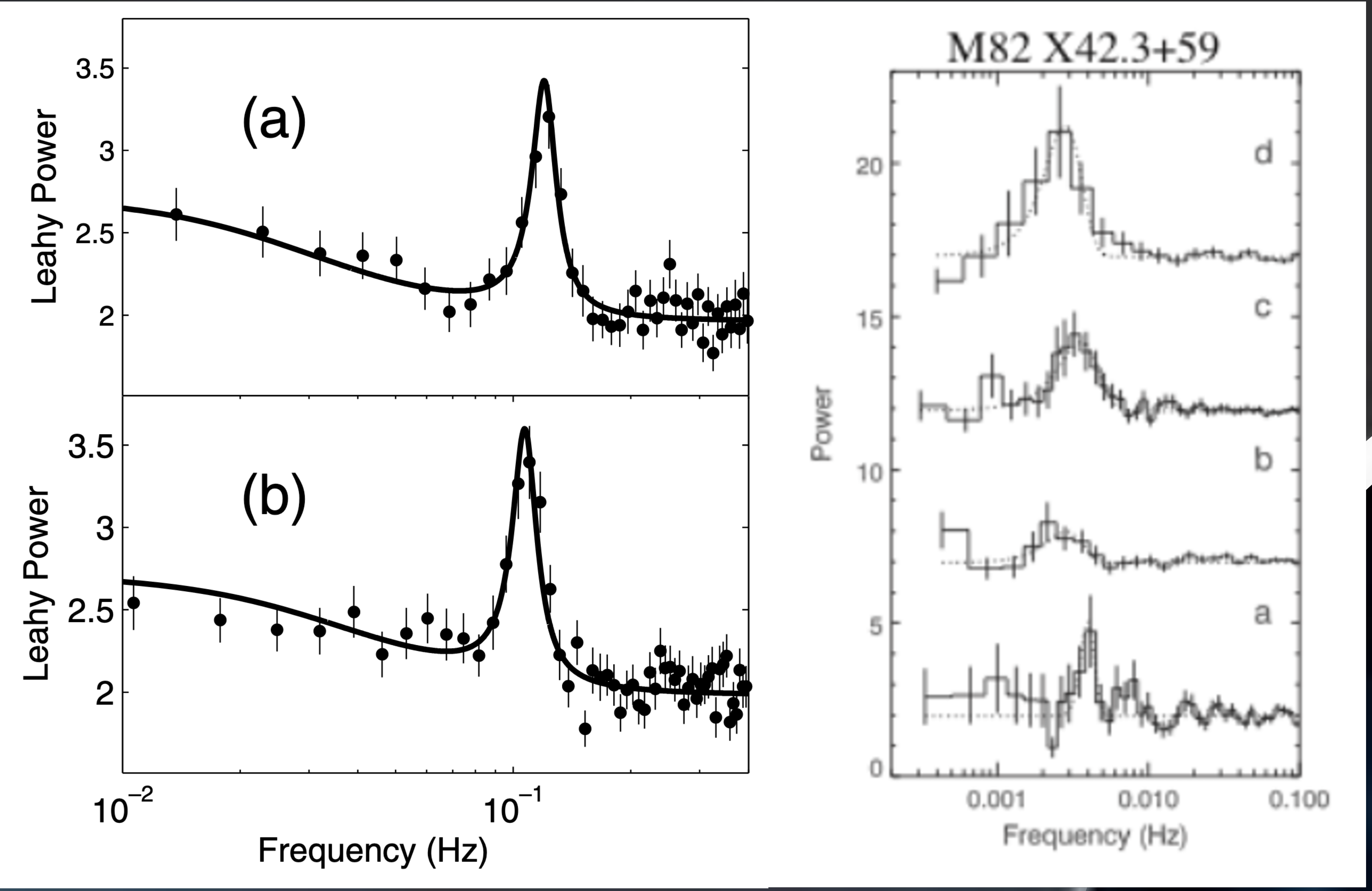
Motta+14,
MNRAS **437**, 2554



QPOs @
0.03-5 Hz

Pasham et al.
Nat. 2014



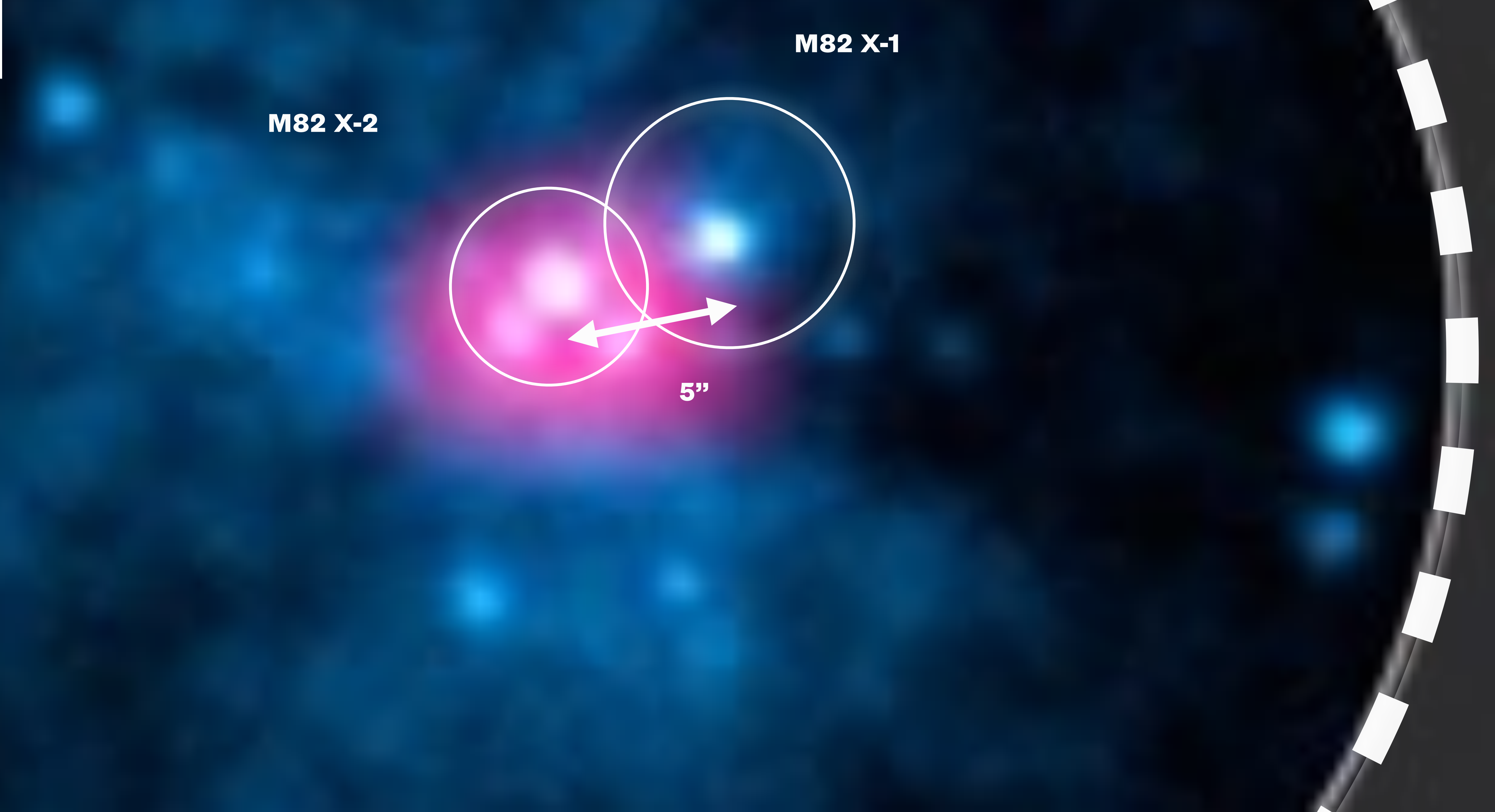


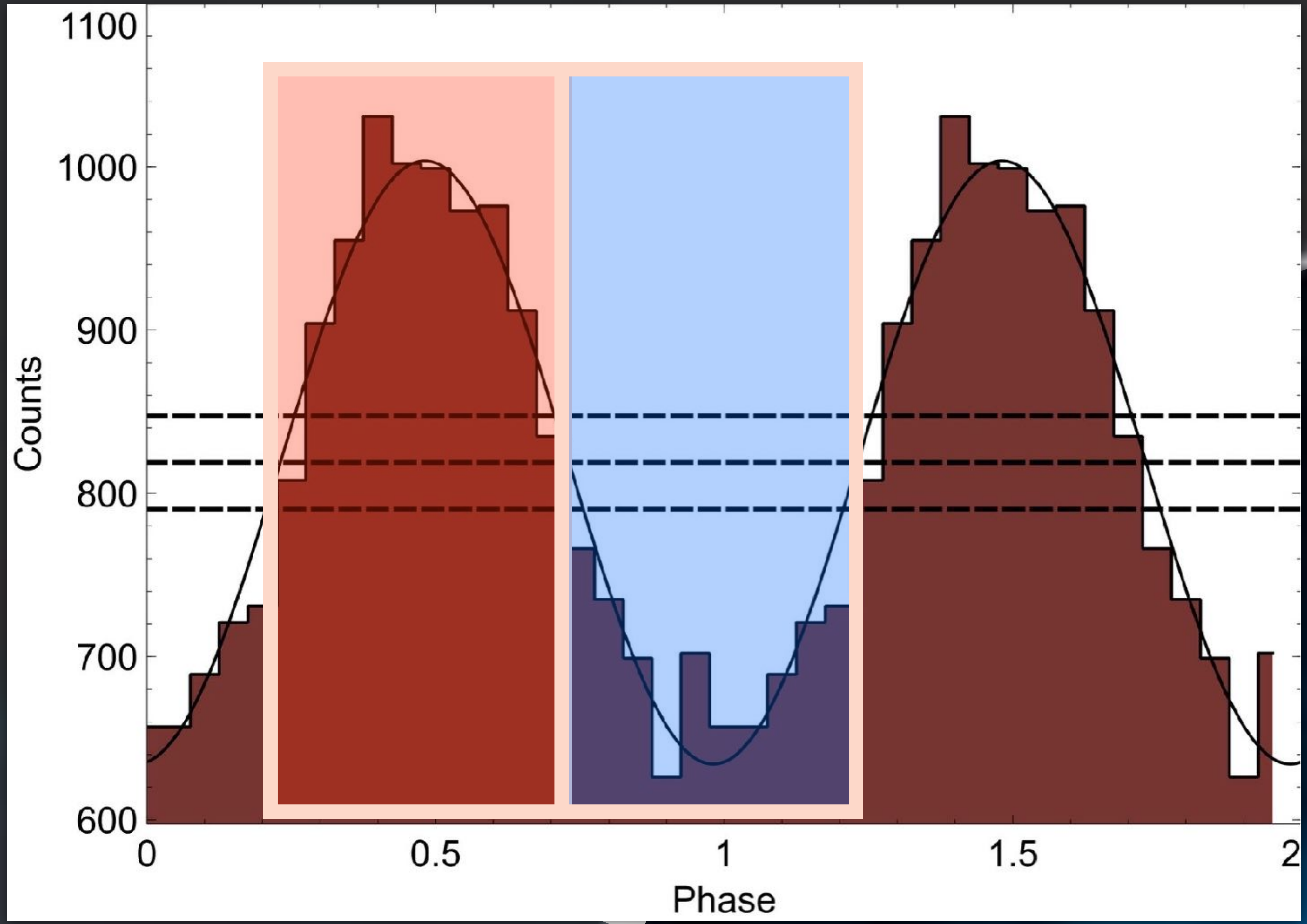
Mucciarelli+03

“Scaling the frequency inversely to the BH mass, the observed QPO frequency range (from 50 to 166 mHz) would yield a BH mass anywhere in the interval few tens to 1000 Msolar.”
Mucciarelli+06

“With this identification, the mass of the black hole in X42.3+59 can be inferred as in the range of 12,000-43,000 solar masses by scaling the QPO frequency to that of the type A/B QPOs in stellar mass black holes”

Feng+10



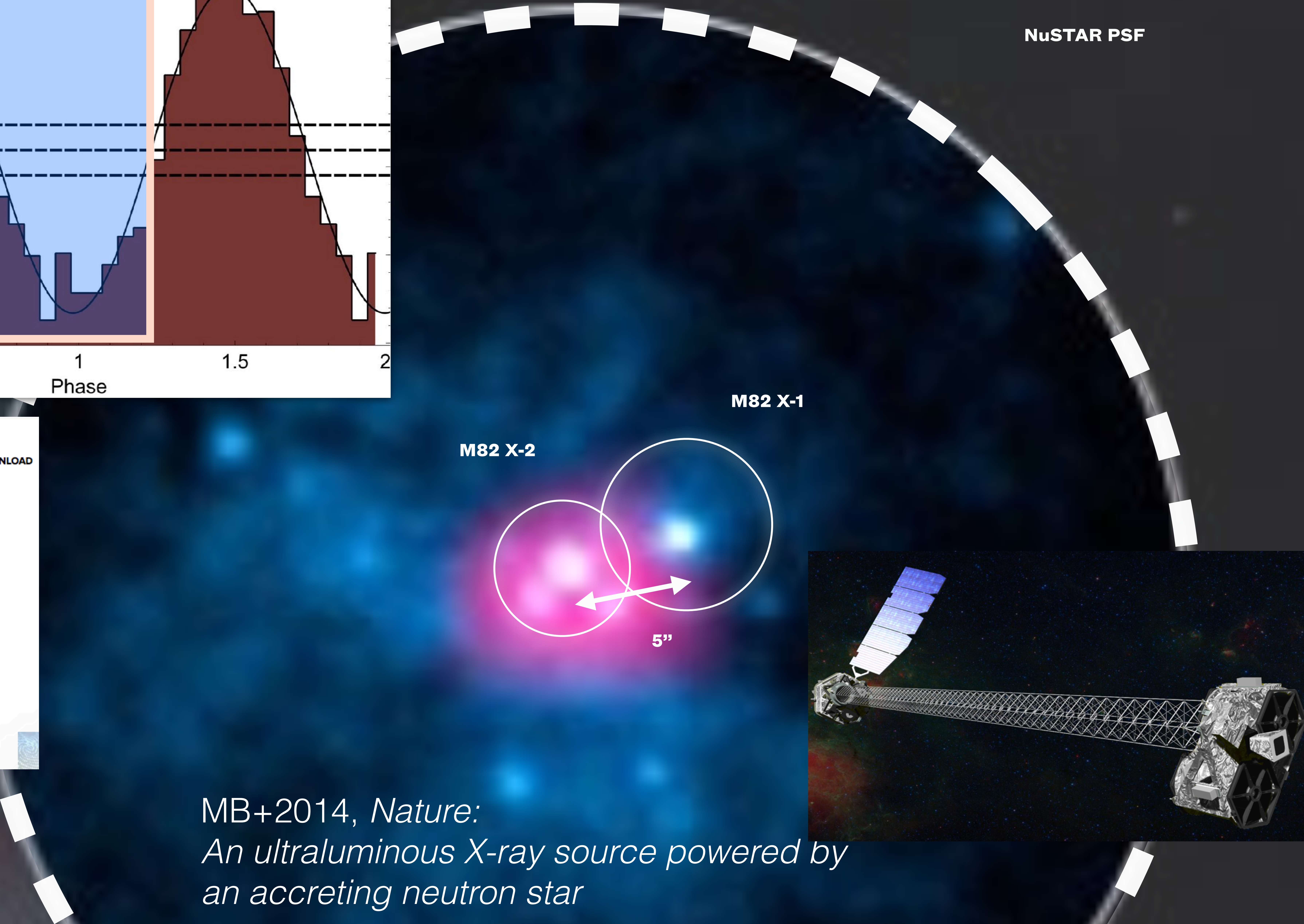


SCI-TECH

NASA finds 'Mighty Mouse' pulsar brighter than 10 million suns

The discovery of a new unusually bright dead star leads astronomers to question assumptions about a type of cosmic radiation -- and pulsars themselves.

BY MICHAEL FRANCO / OCTOBER 8, 2014 4:13 PM PDT



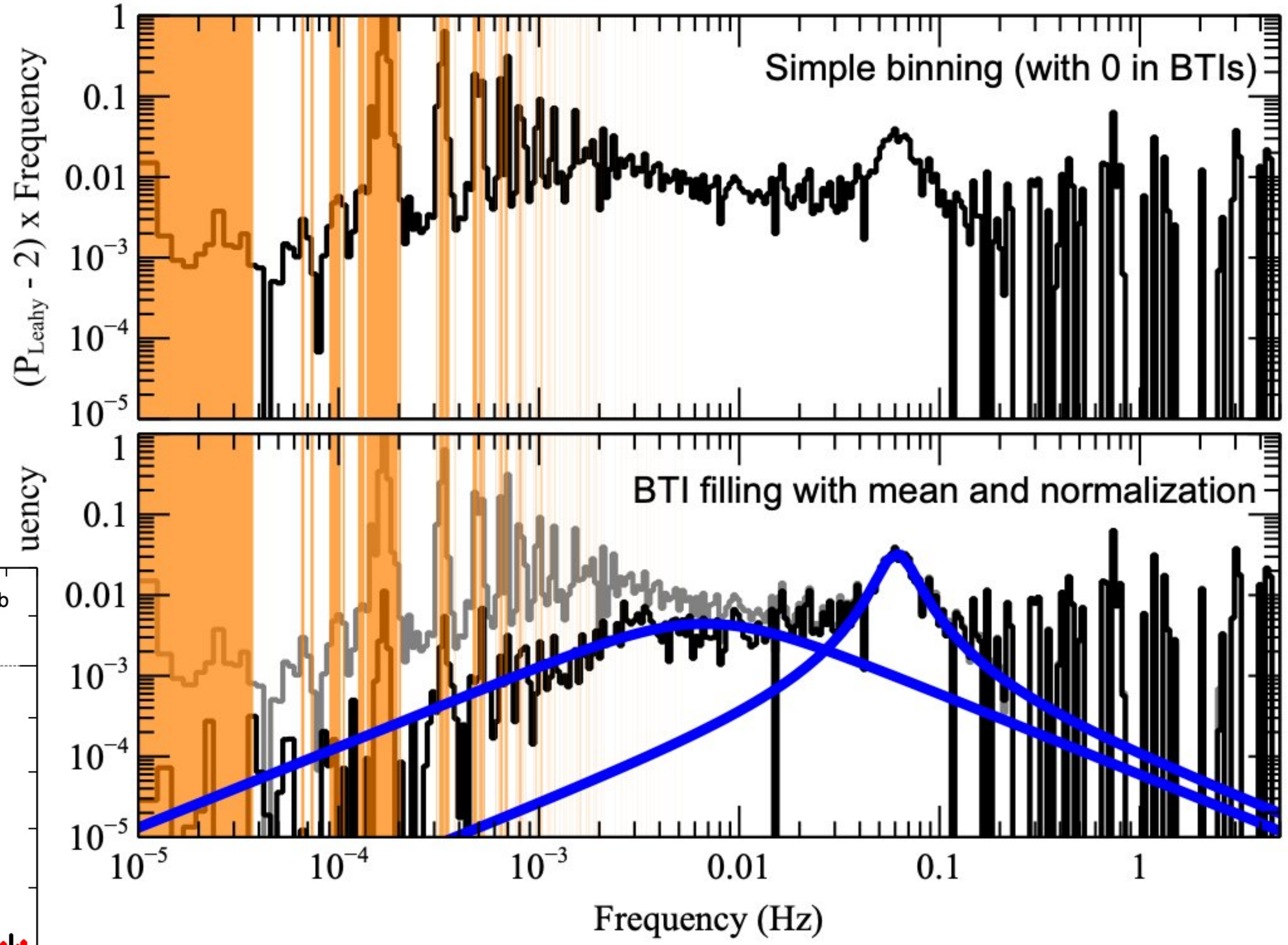
MB+2014, *Nature:*
An ultraluminous X-ray source powered by an accreting neutron star

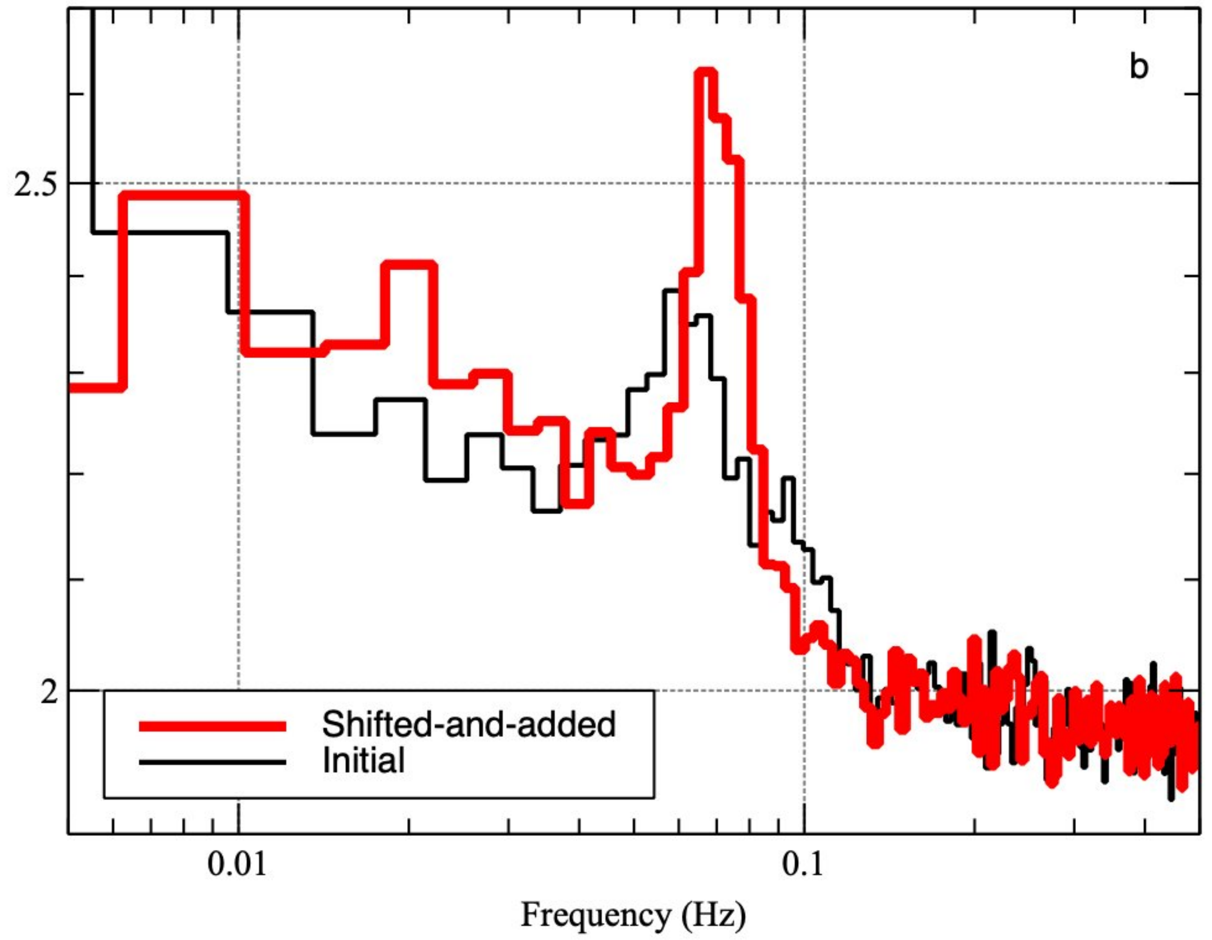
But those QPOs are still interesting!

~~PhD student~~

Doctor! Hamza El Byad

- PDS Modeled with likelihood from Barret & Vaughan 2012.
- New technique for modeling gappy PDSs
- Model: 1-2 Lorentzians depending on AIC
- Classified as QPOs when Q>2, RN below.
- Applied to all NuSTAR data of M82 (10 years, ~3 Ms total exposure), plus simultaneous Chandra data when available.
- New technique for model-driven shift-and-add of QPOs (to look for additional frequencies)





El Byad, MB et al. 2025, ApJ **989**, 202

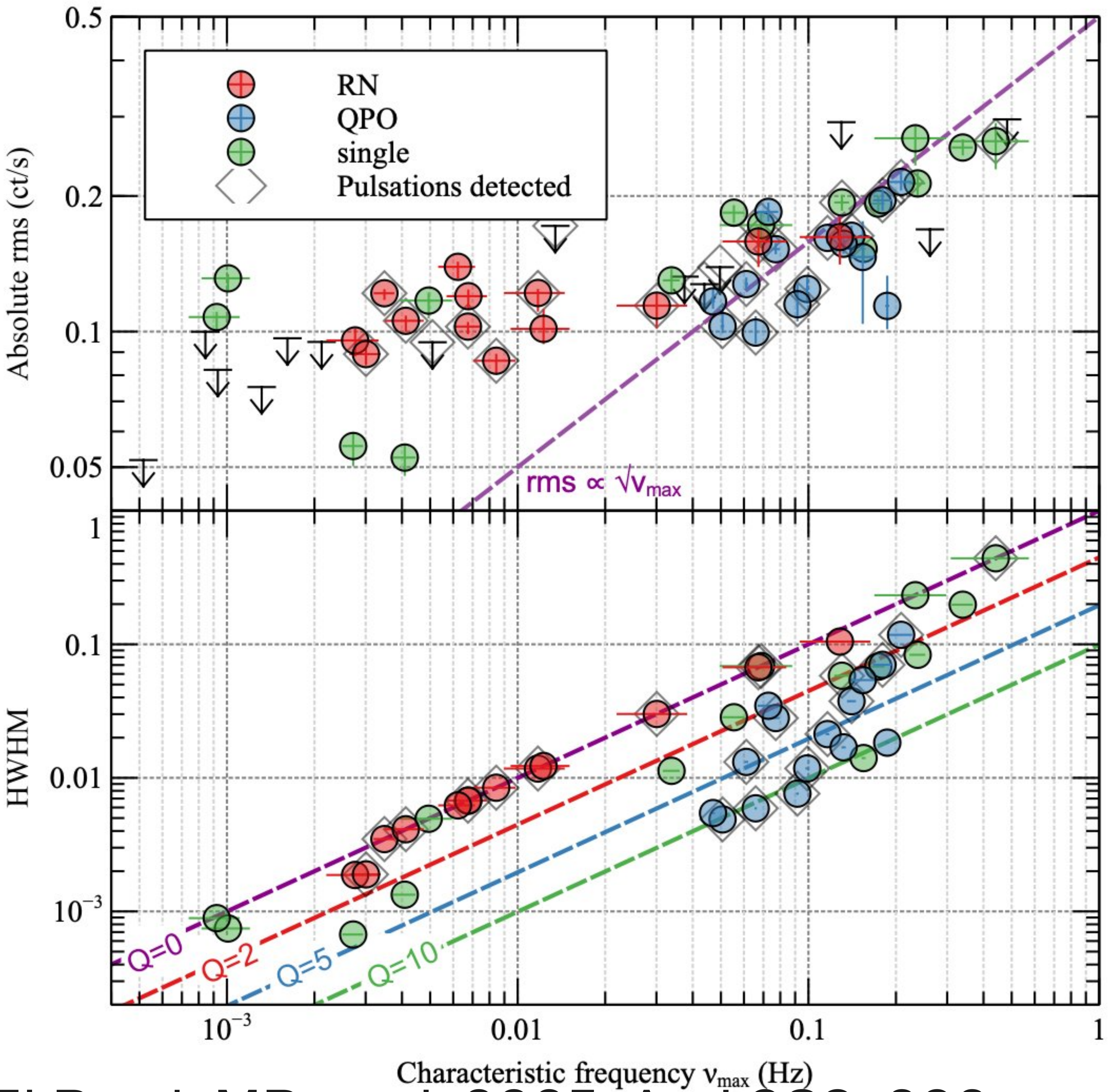
QPO Results

The QPOs from M82 X-1

- The rms increases with frequency
- The Q factor tends to *decrease* with frequency (-> similar to HMXBs)

The QPOs from M82 X-2

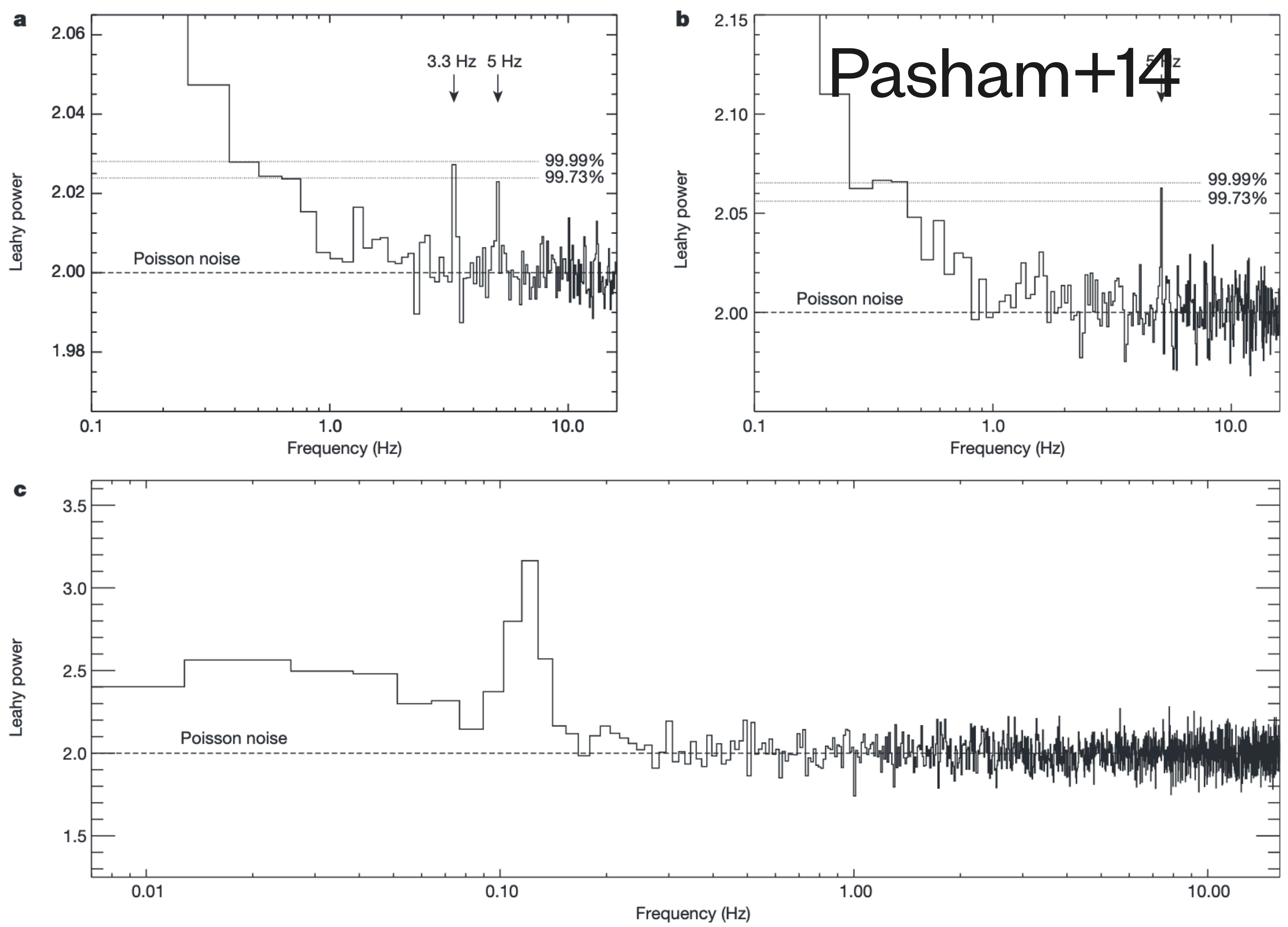
RN and QPO frequency not clearly correlated. How to tell a mHz QPO from RN? A matter of definitions.

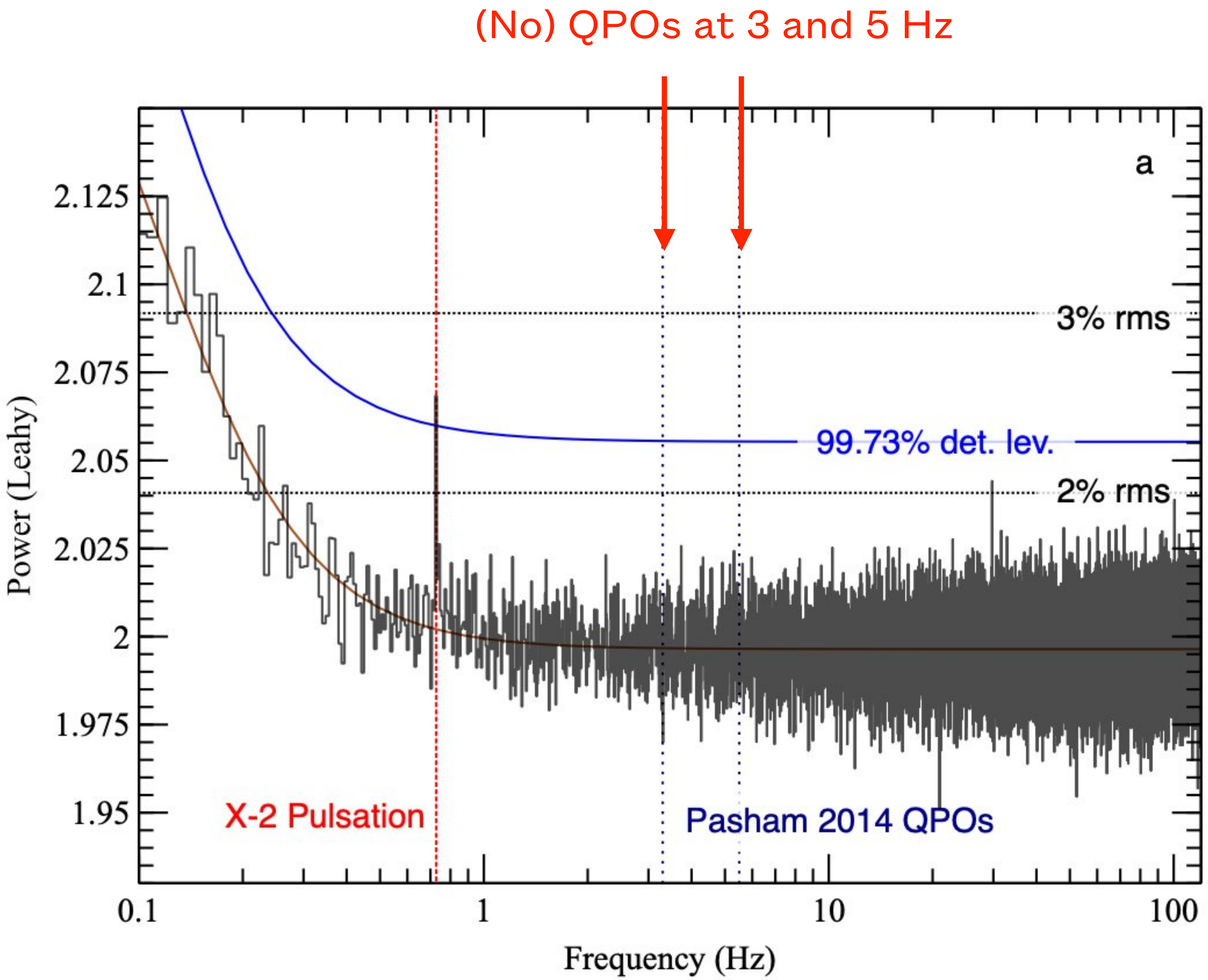


El Byad, MB et al. 2025, ApJ **989**, 202

QPO Results - II

- We do not find the 3 - 5 Hz QPO pair from Pasham+14.
- LF QPO too variable to be seen in integrated PDS
- Pulsations can be seen





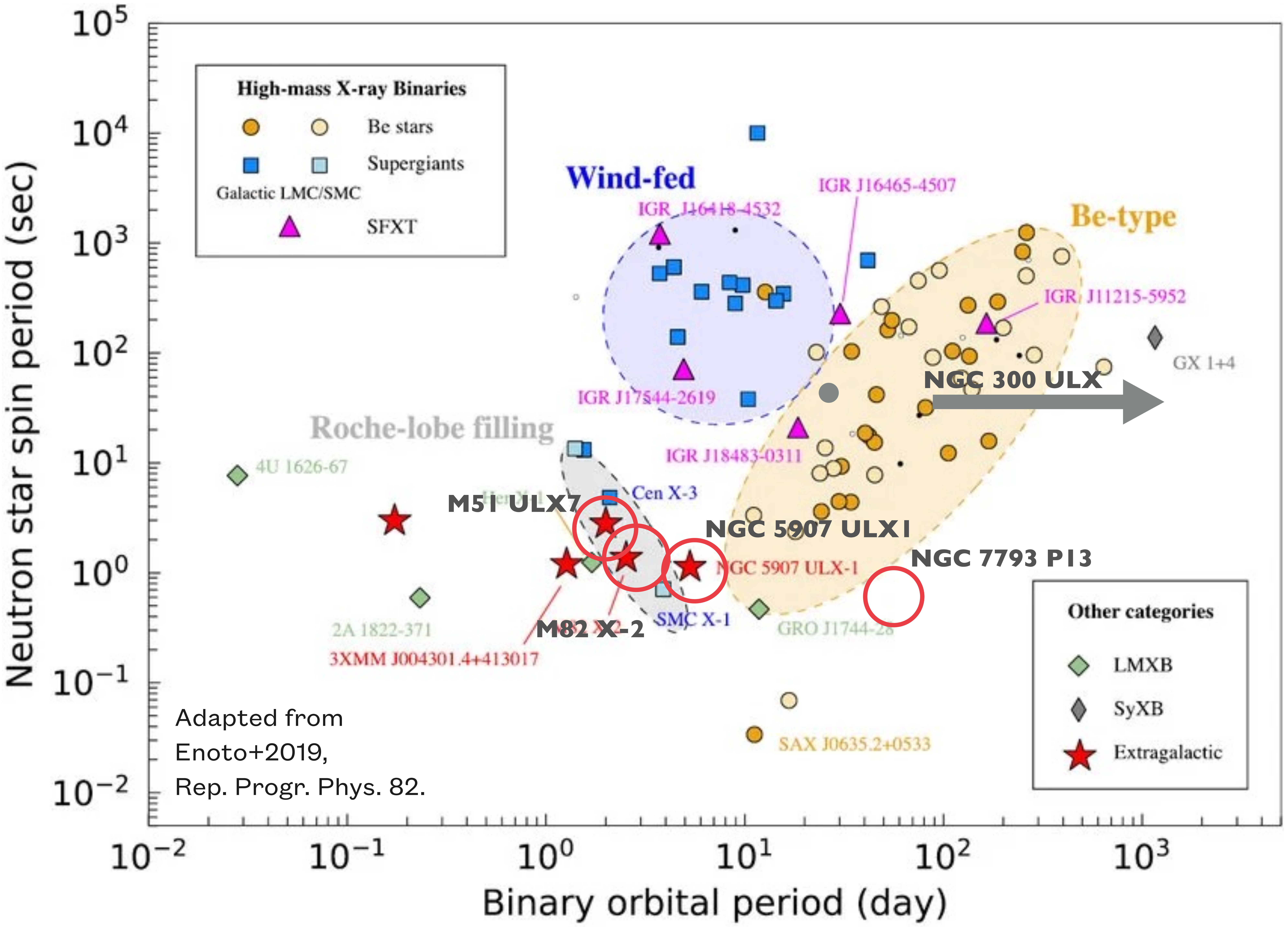
El Byad, MB et al. 2025, ApJ **989**, 202

Source	P_{spin}	$L_{X,peak}$ (10^{39} erg/s)	Discovery Reference(s)
NGC 5907 ULX1	1.1	100	Israel+17b
M82 X-2	1.4	20	Bachetti+14
NGC 7793 P13	0.4	15	Furst+16, Israel+17a
NGC 1313 X-2	1.5	10	Sathyaprakash+19
M51 ULX-7	2.8	10	Rodriguez-Castillo+21
NGC 300 ULX1	126—20	4	Carpano+18
NGC 4631 X-8	9.7	3	Ducci+25
Swift J0243.6+6124	9.8	2	Kennea+17

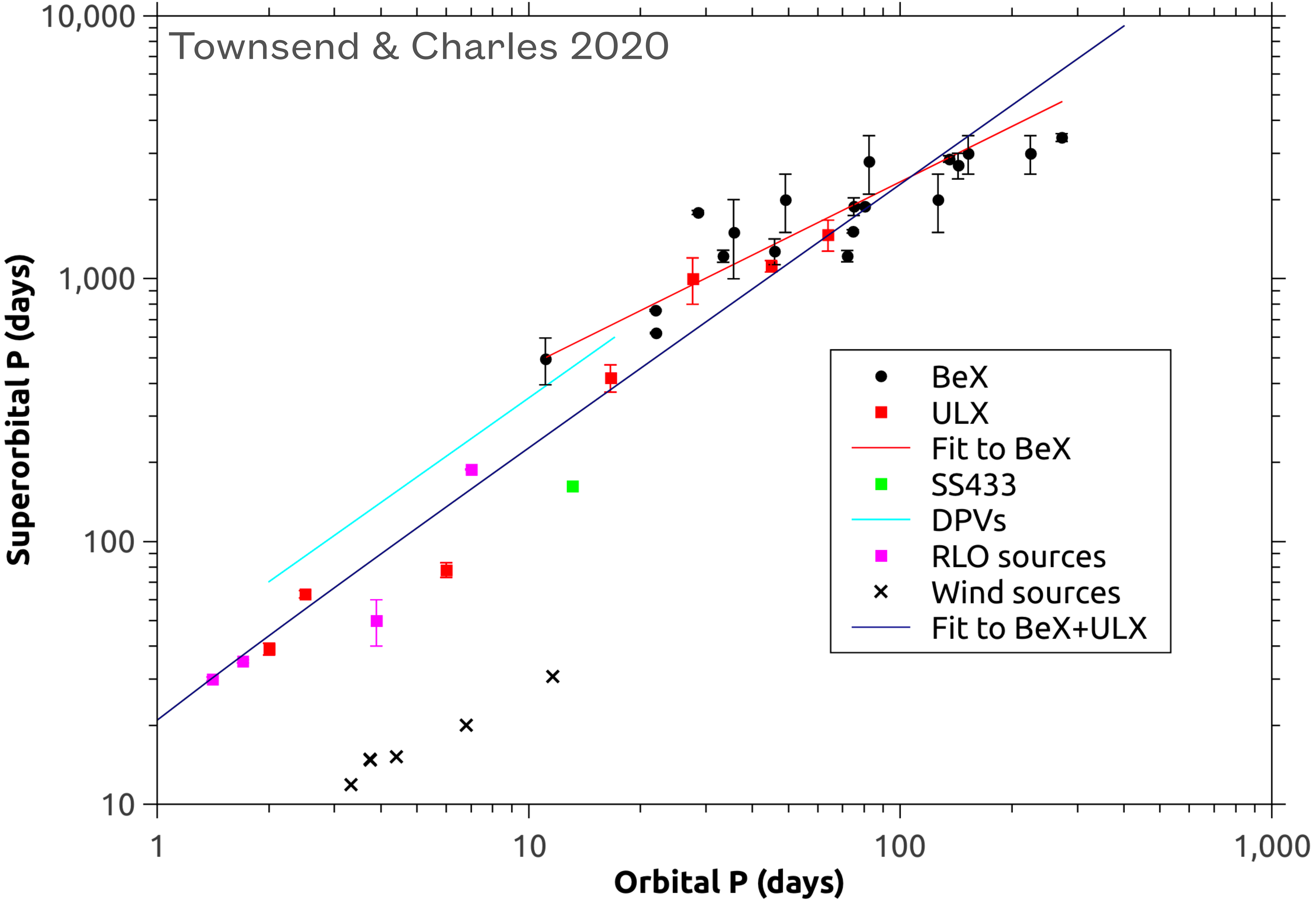
See also S. Mereghetti's talk, and A. Knight's poster

Source	P.F. (%)	f (Hz)	$\dot{f}$ (10^{-10} Hz/s)	Porb (d)	Donor	Notes
NGC 5907 ULX1	~15	0.7 – 0.9	**-20 — +60**	5?		
M82 X-2	>20	0.725	-0.5 — +1	2.52	O/B? >5 Mo	
NGC 7793 P13	~20	**2.4**	~2	64	BSG?	
NGC 1313 X-2	5	0.68	6—20?	?		Only detected in two <30 ks intervals
M51 ULX-7	5-20	0.36	0.2 — 1.2	2	MS?	
NGC 300 ULX1	**~90**	0.008—0.05	9	many?	RSG?	
NGC 4631 X-8	30	0.103	10 (orbit?)	?		
Swift J0243.6+6124	50	0.1	~2	27	Be	

HMXBs on steroids?



Adapted from Enoto+2019, Rep. Progr. Phys. 82.



Townsend & Charles 2020
Superorbital P (days)
Orbital P (days)
10,000
1,000
100
10
1
10
100
1,000
BeX
ULX
Fit to BeX
SS433
DPVs
RLO sources
Wind sources
Fit to BeX+ULX


$R_{\rm M} \propto B^{4/7}\dot{m}^{-2/7}$
$R_{\rm co} = \left(\frac{GMp^2}{4\pi^2}\right)^{1/3}$
$R_M > R_{co}$: “propeller"
$R_M < R_{co}$: “slow rotator”
$R_M = R_{co}$: “spin equilibrium”
R_M
R_{co}

$$R_{\mathrm{M}} \propto B^{4/7}\dot{m}^{-2/7}$$

$$R_{\mathrm{co}} = \left(\frac{GMp^2}{4\pi^2}\right)^{1/3}$$

$R_M > R_{co}$: "propeller"

$R_M < R_{co}$: "slow rotator"

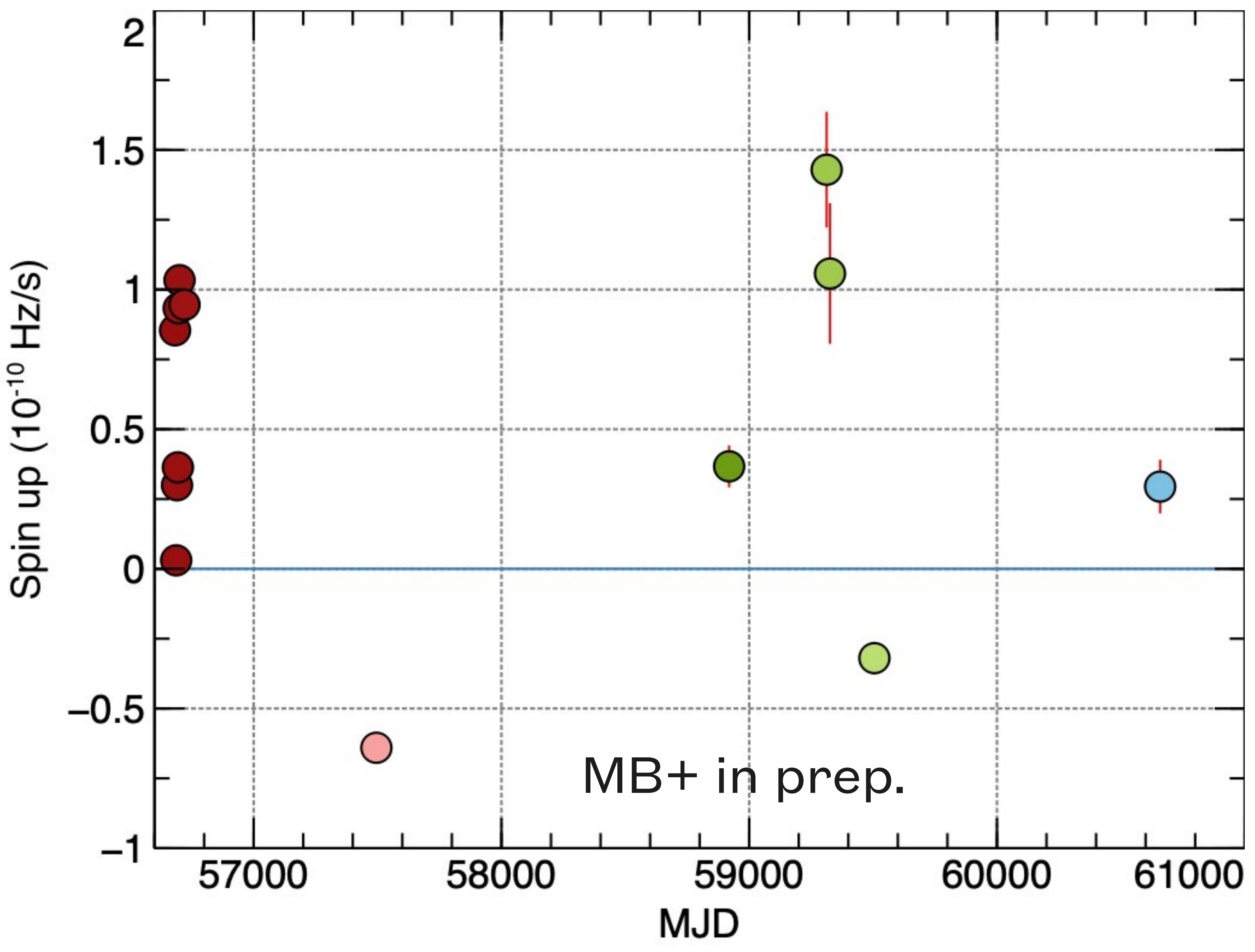
$R_M = R_{co}$: "spin equilibrium"

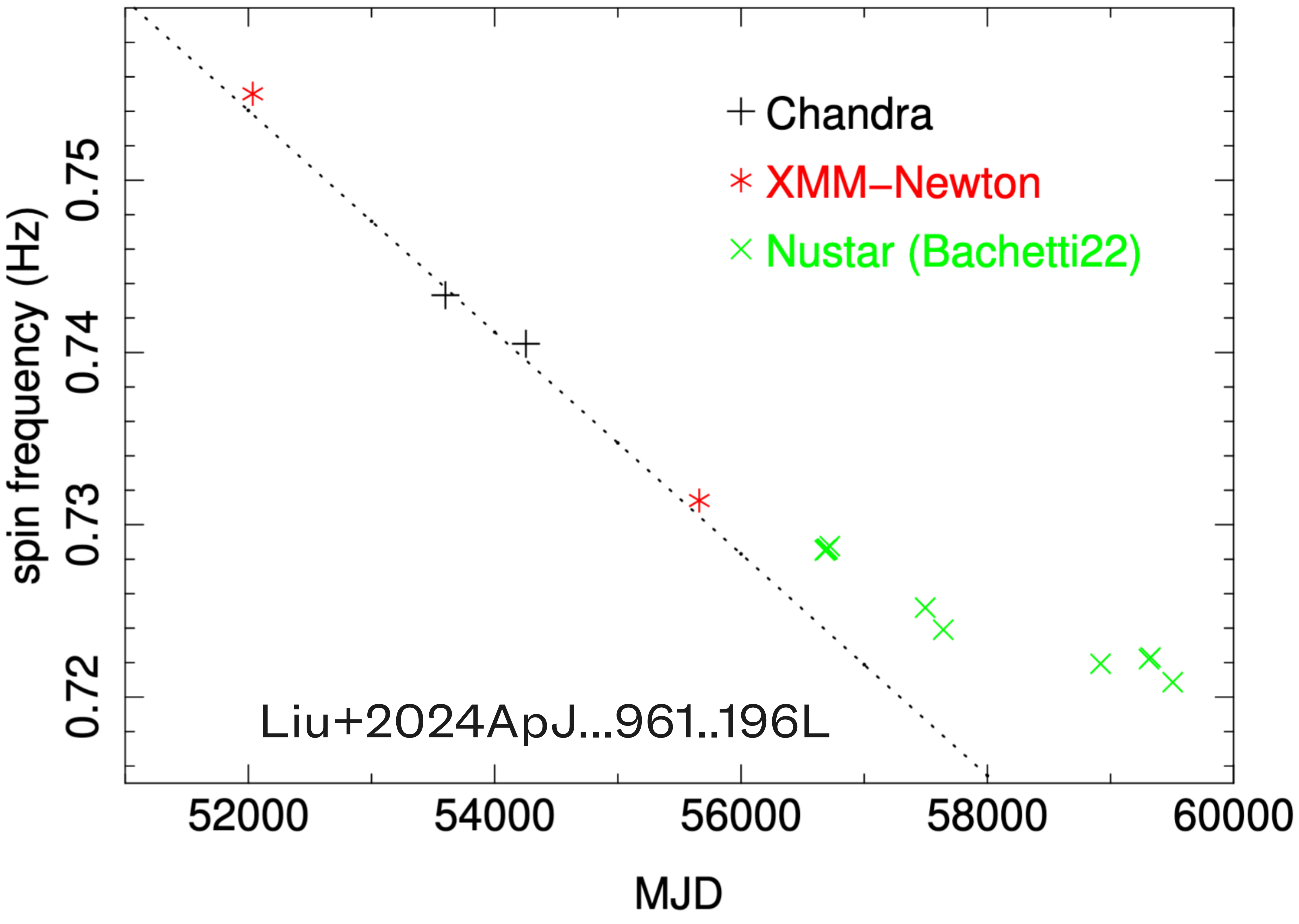
See A. Alpar talk for a more in-depth discussion

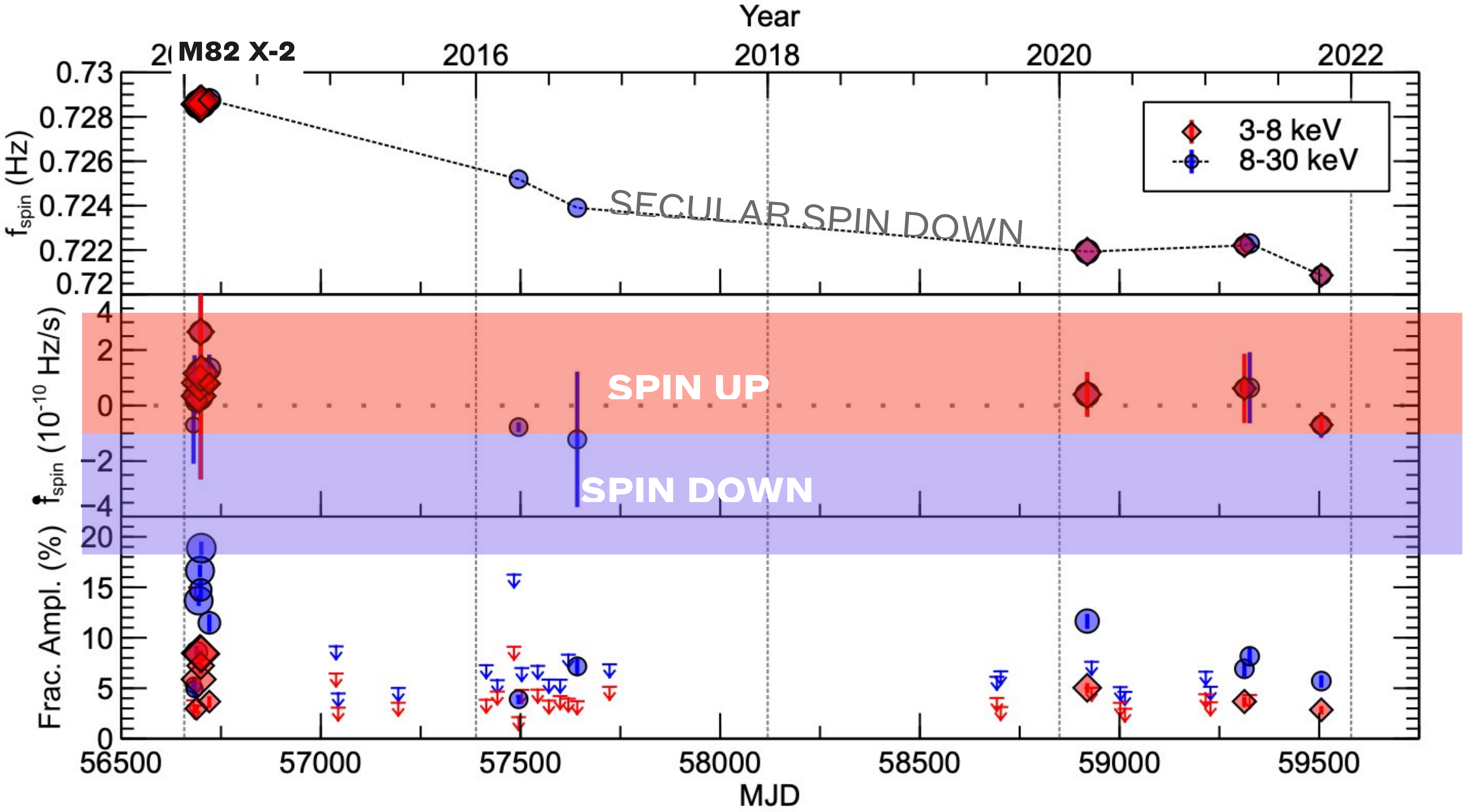
Spin up and down, up and down

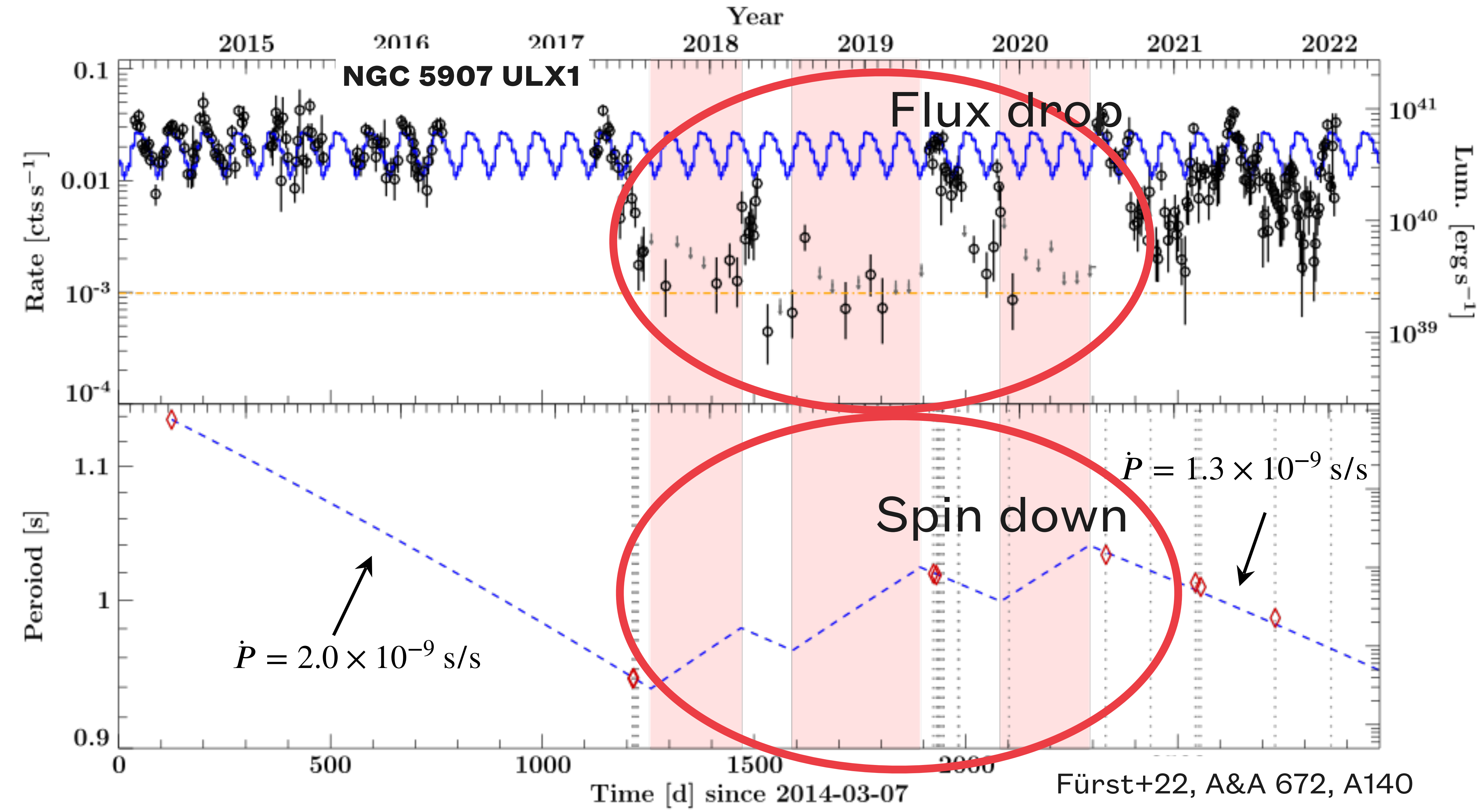
M82 X-2: Highly variable spin up, spin down while accreting.

Spin equilibrium?

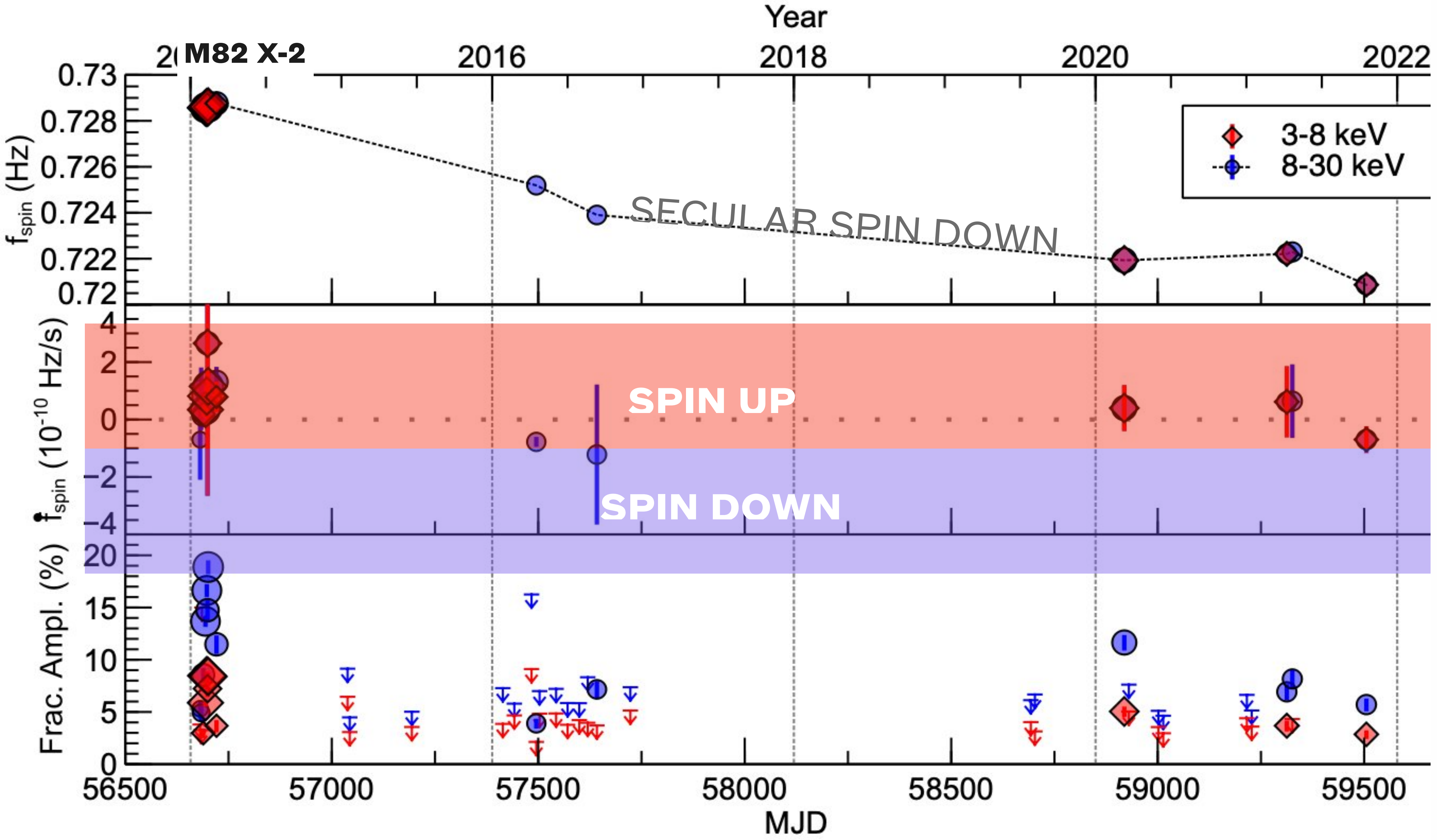


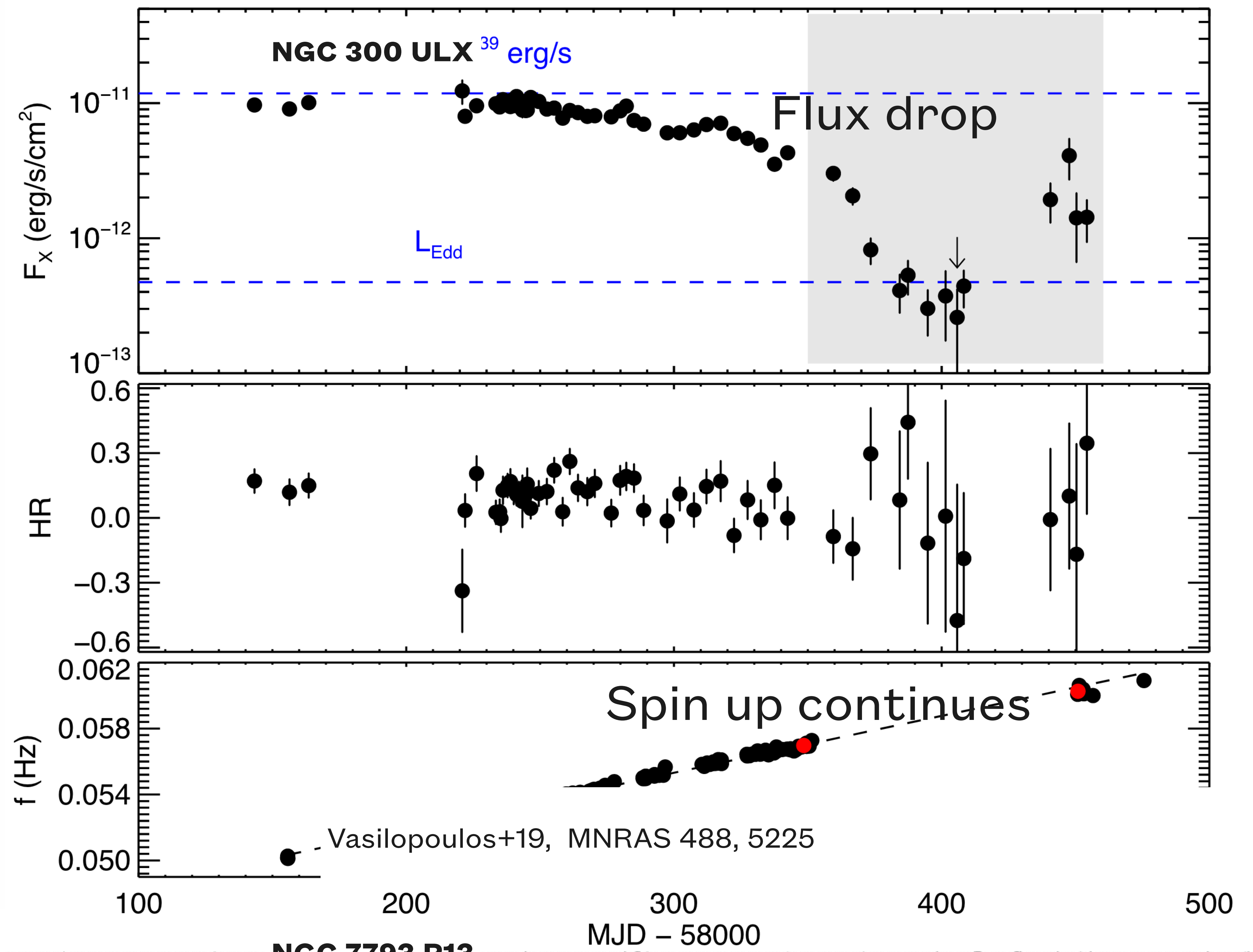


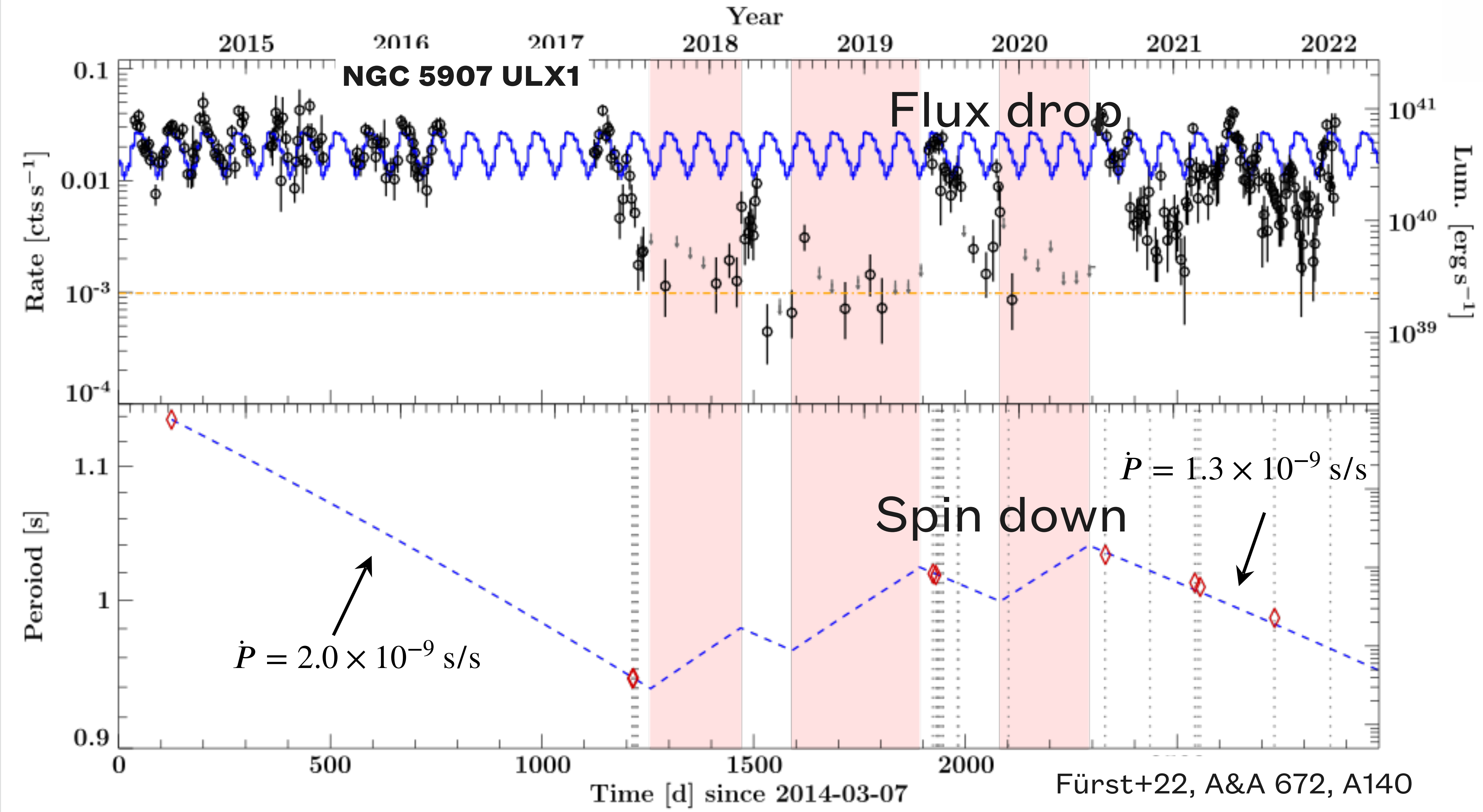




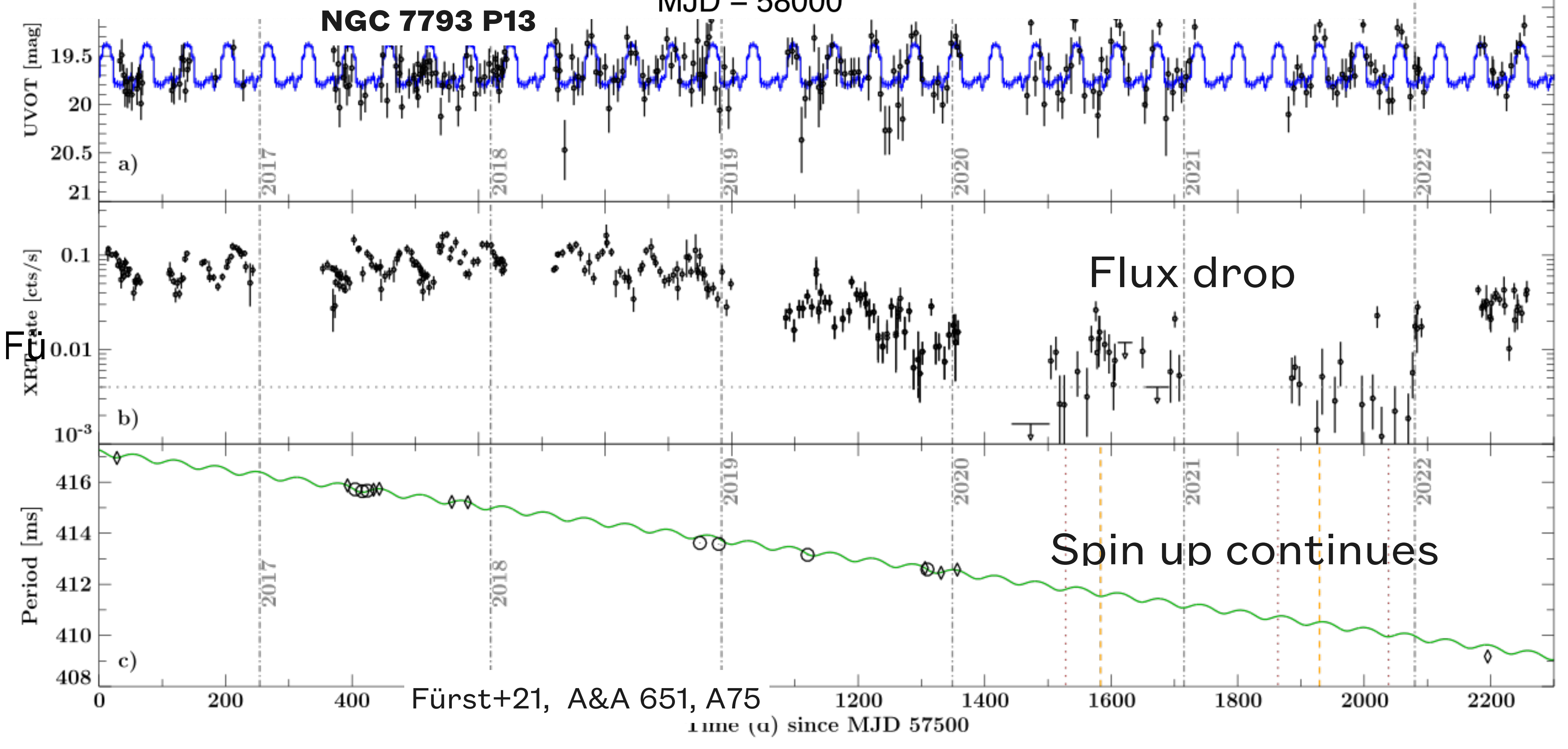
Fürst+22, A&A 672, A140



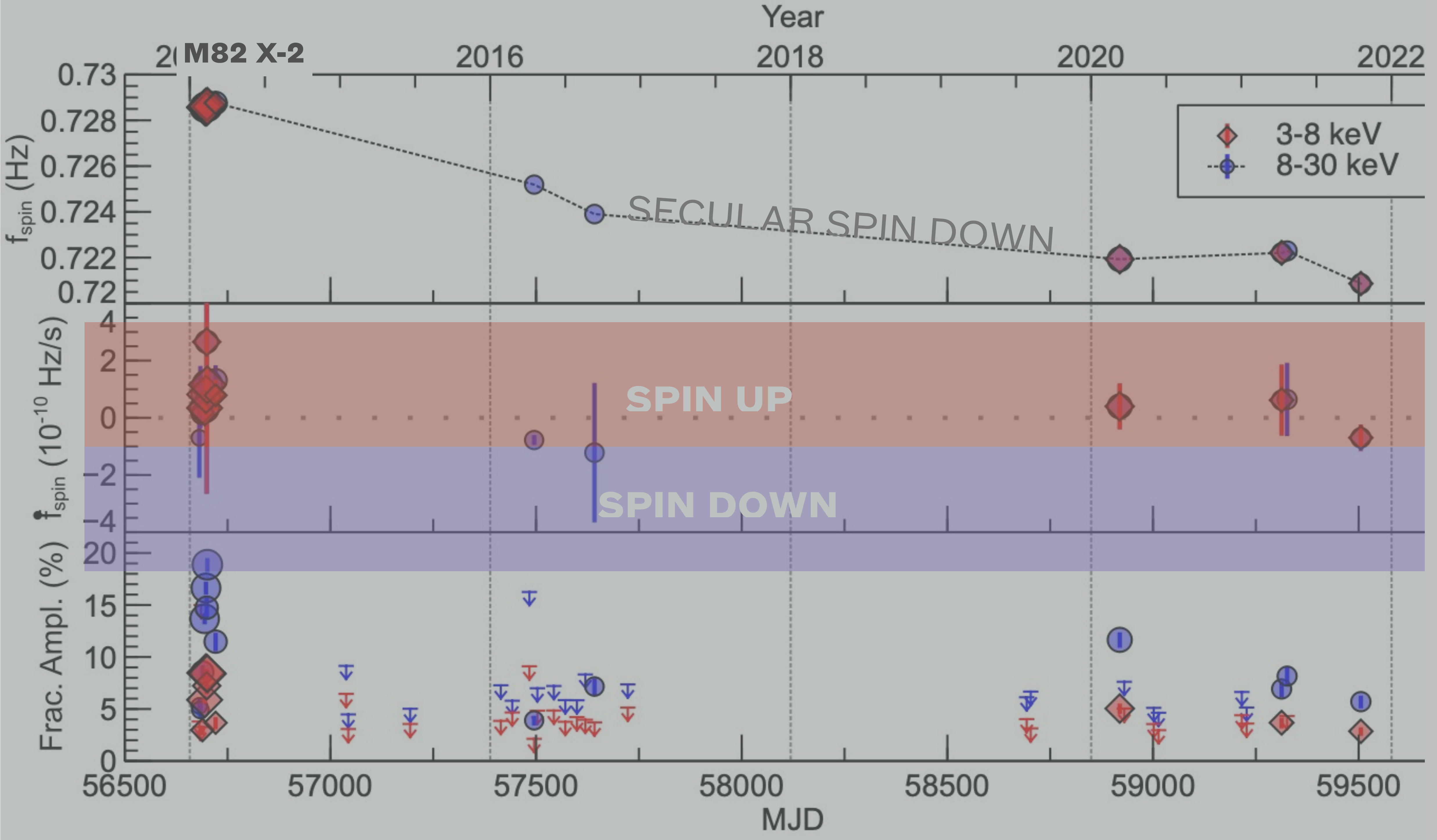


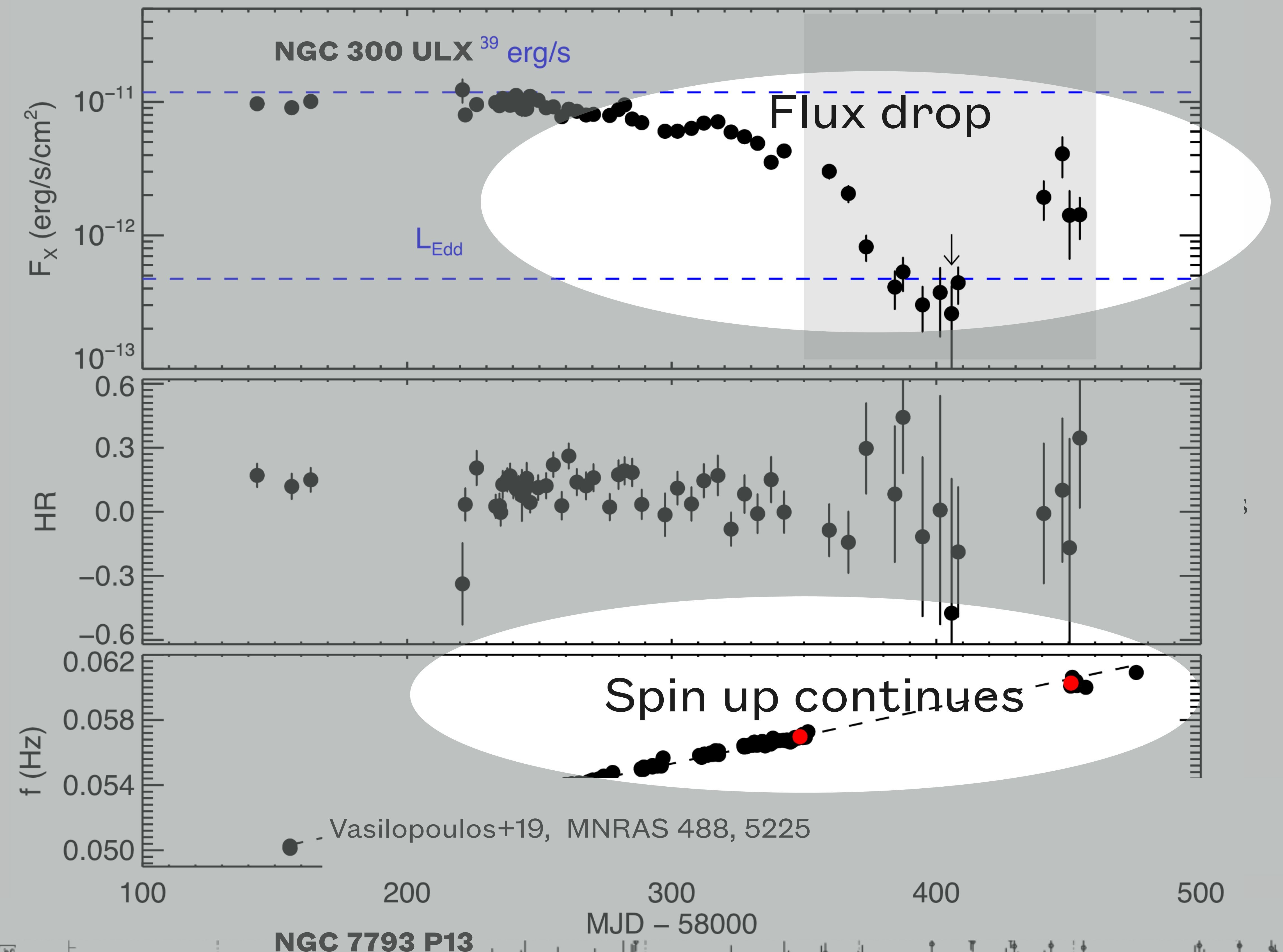


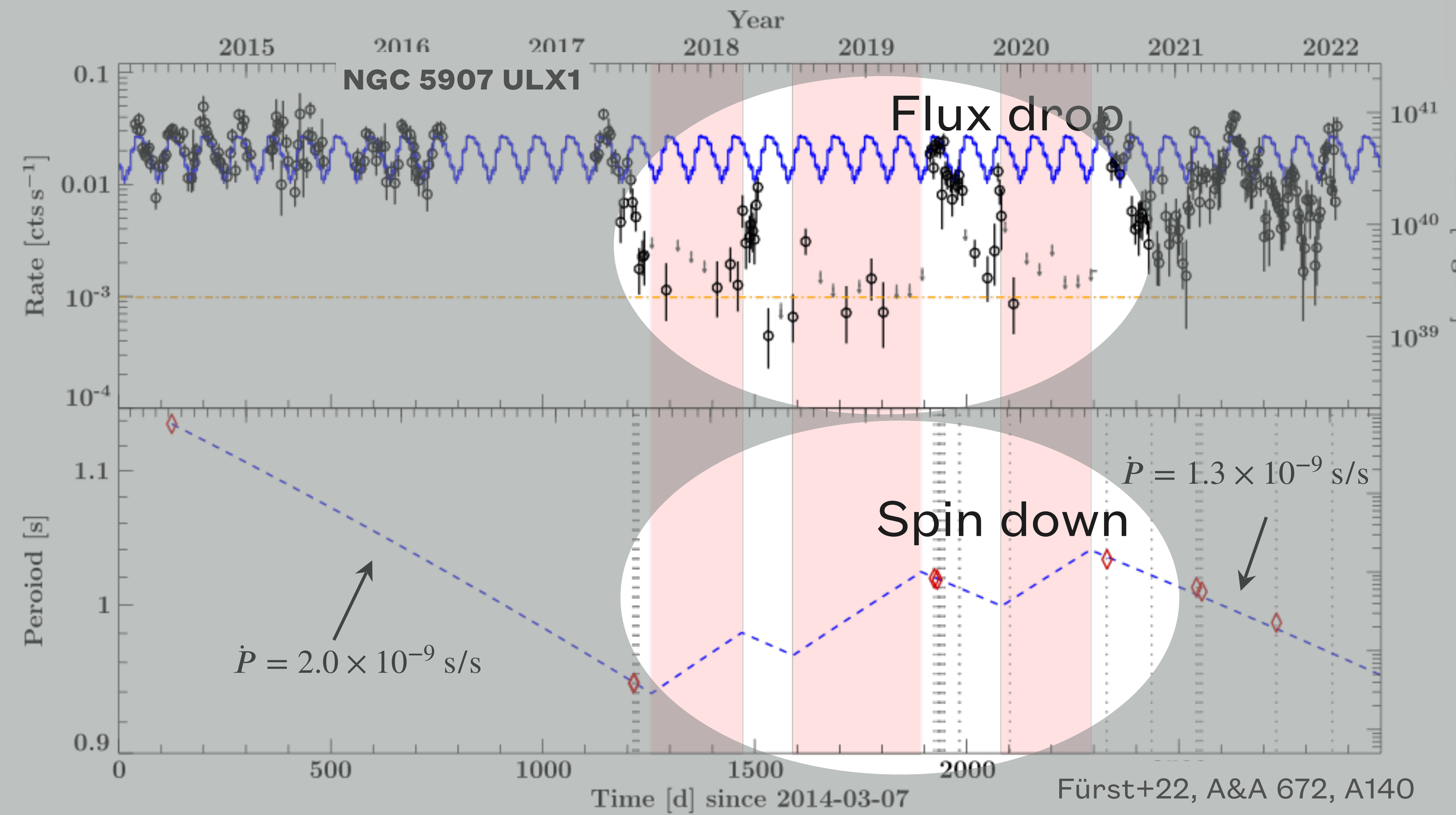
Fürst+22, A&A 672, A140



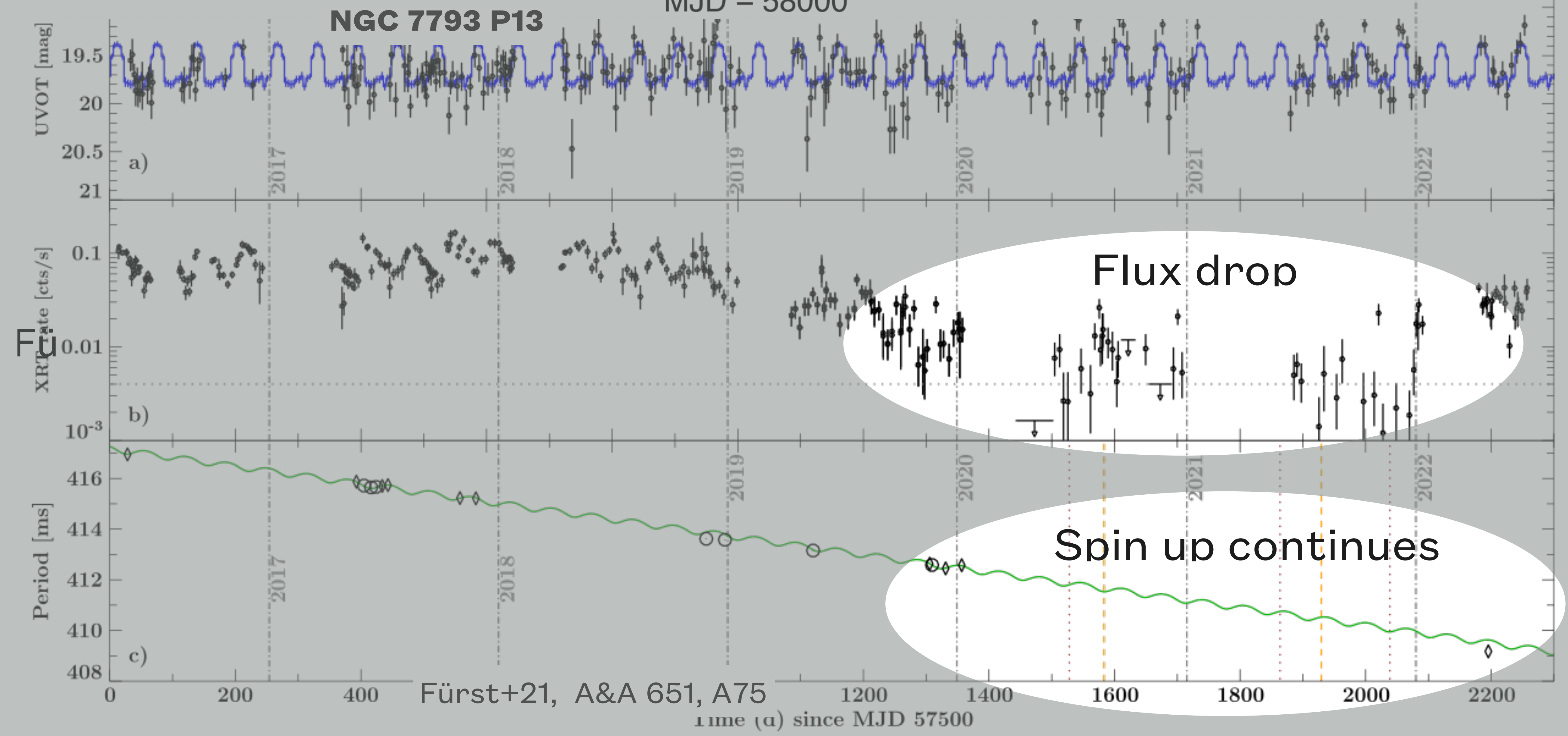
Fürst+21, A&A 651, A75







Fürst+22, A&A 672, A140



Fürst+21, A&A 651, A75

Two sub-populations emerge?

1. **Long orbit PULXs**
   (NGC 300 ULX1, NGC 7793 P13)
   - ~tens of days orbits. Supergiant companions
   - Monotonic Spin up
   - $\dot{\nu}$ independent of observed flux (including flux drops)
   - Lower average luminosity?
2. **Short orbit PULXs**
   (M82 X-2, M51 ULX-7, NGC 5907 X-1?)
   - ~few days orbits. (Late) main sequence donors?
   - Spin up alternate with spin down (not in M51, up to now)
   - $\dot{\nu}$ changes with observed flux
   - Higher average luminosity?
   - But: only in M51: pulsations / QPO dychotomy (Imbrogno+24).

If spin equilibrium...

Standard assumption: $\dot{M} \propto L_x$.

Equating $R_{\rm co} = R_{\rm M}$, we get $B \approx 10^{14}\,{\rm G}$

But can we simply do that?

If spin equilibrium...

Standard assumption: $\dot{M} \propto L_x$.

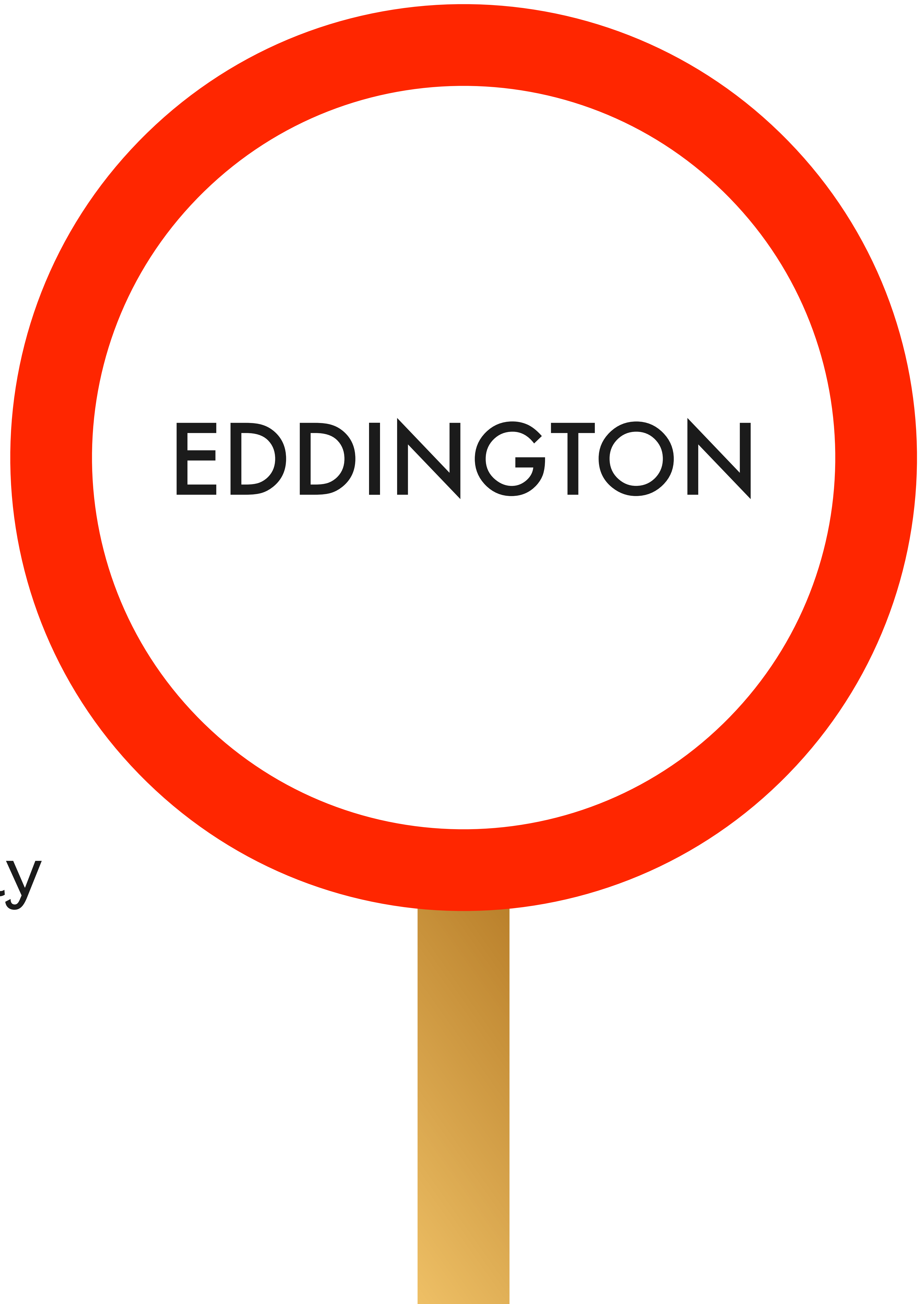
Equating $R_{\rm co} = R_{\rm M}$, we get $B \approx 10^{14}\,{\rm G}$

But can we simply do that?

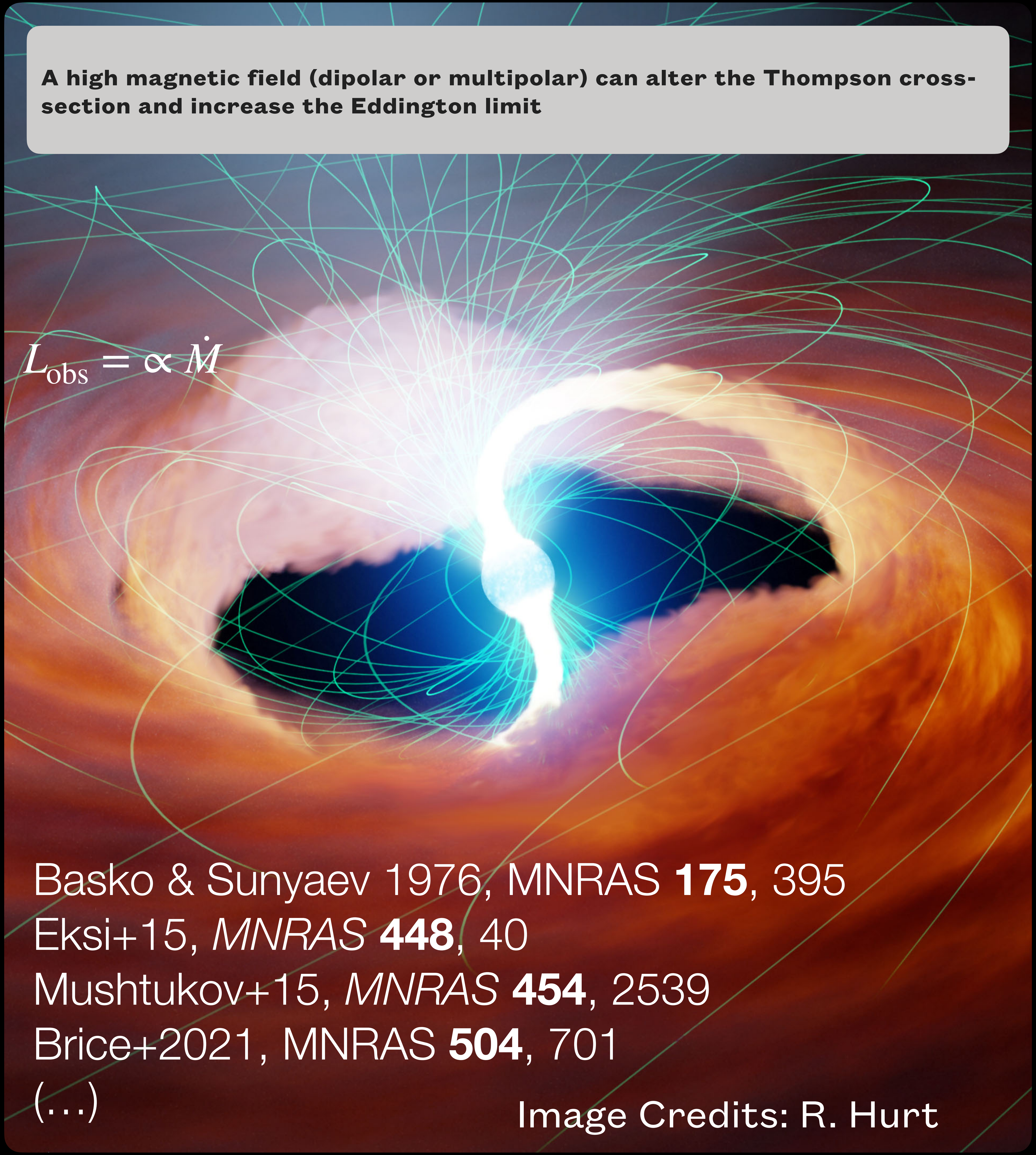
Of course not. Because... Eddington limit.

We still need to accrete without swiping away the infalling matter.

Or... say that L_x is amplified



A high magnetic field (dipolar or multipolar) can alter the Thompson cross-section and increase the Eddington limit

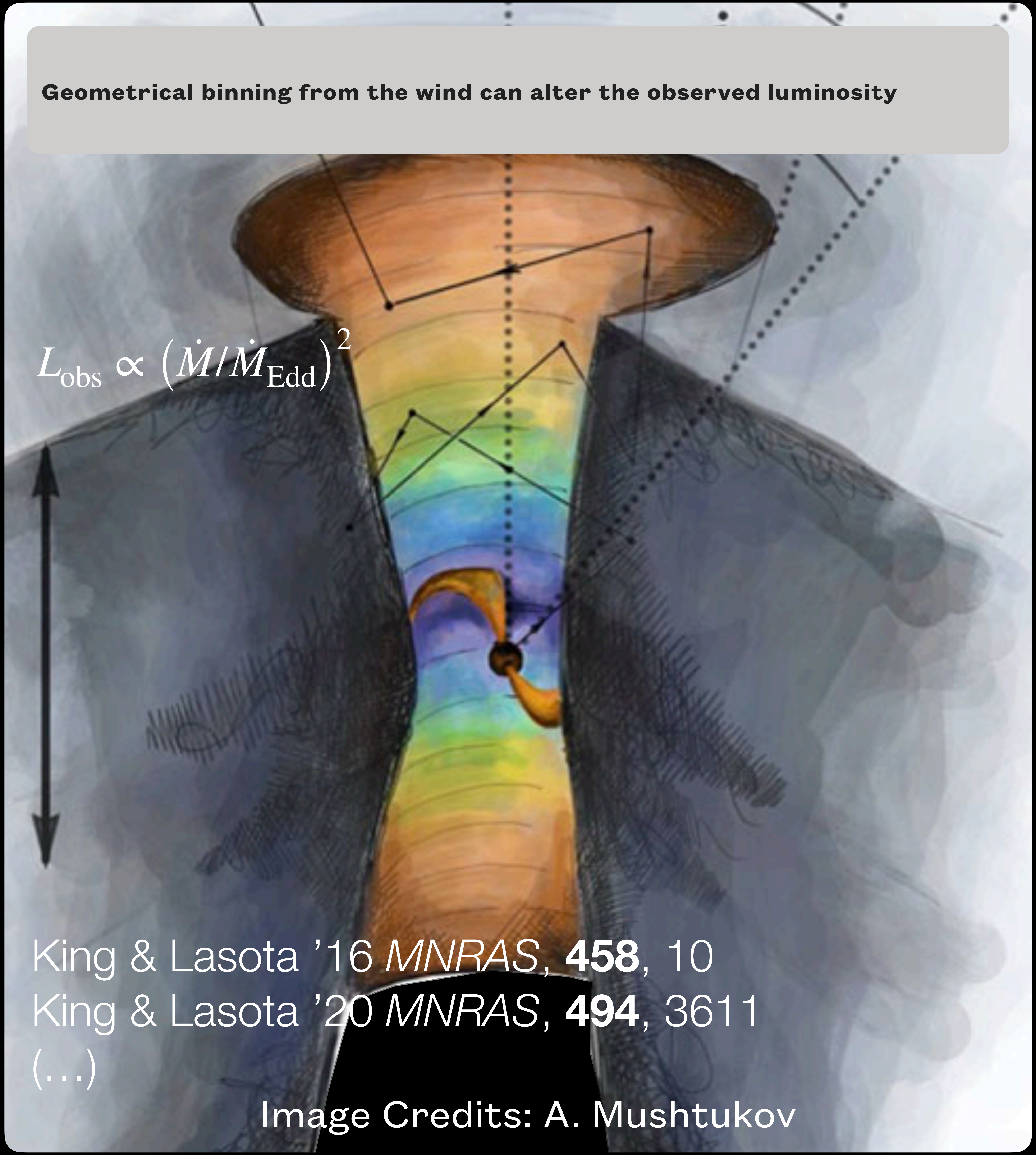


$$L_{\rm obs} = \propto \dot{M}$$

Basko & Sunyaev 1976, MNRAS **175**, 395
Eksi+15, *MNRAS* **448**, 40
Mushtukov+15, *MNRAS* **454**, 2539
Brice+2021, MNRAS **504**, 701
(...)

Image Credits: R. Hurt

Geometrical binning from the wind can alter the observed luminosity



$$L_{\rm obs} \propto \left(\dot{M}/\dot{M}_{\rm Edd}\right)^2$$

King & Lasota '16 *MNRAS*, **458**, 10
King & Lasota '20 *MNRAS*, **494**, 3611
(...)

Image Credits: A. Mushtukov

How do we measure the *real* mass accretion rate?

Constraints from orbital decay

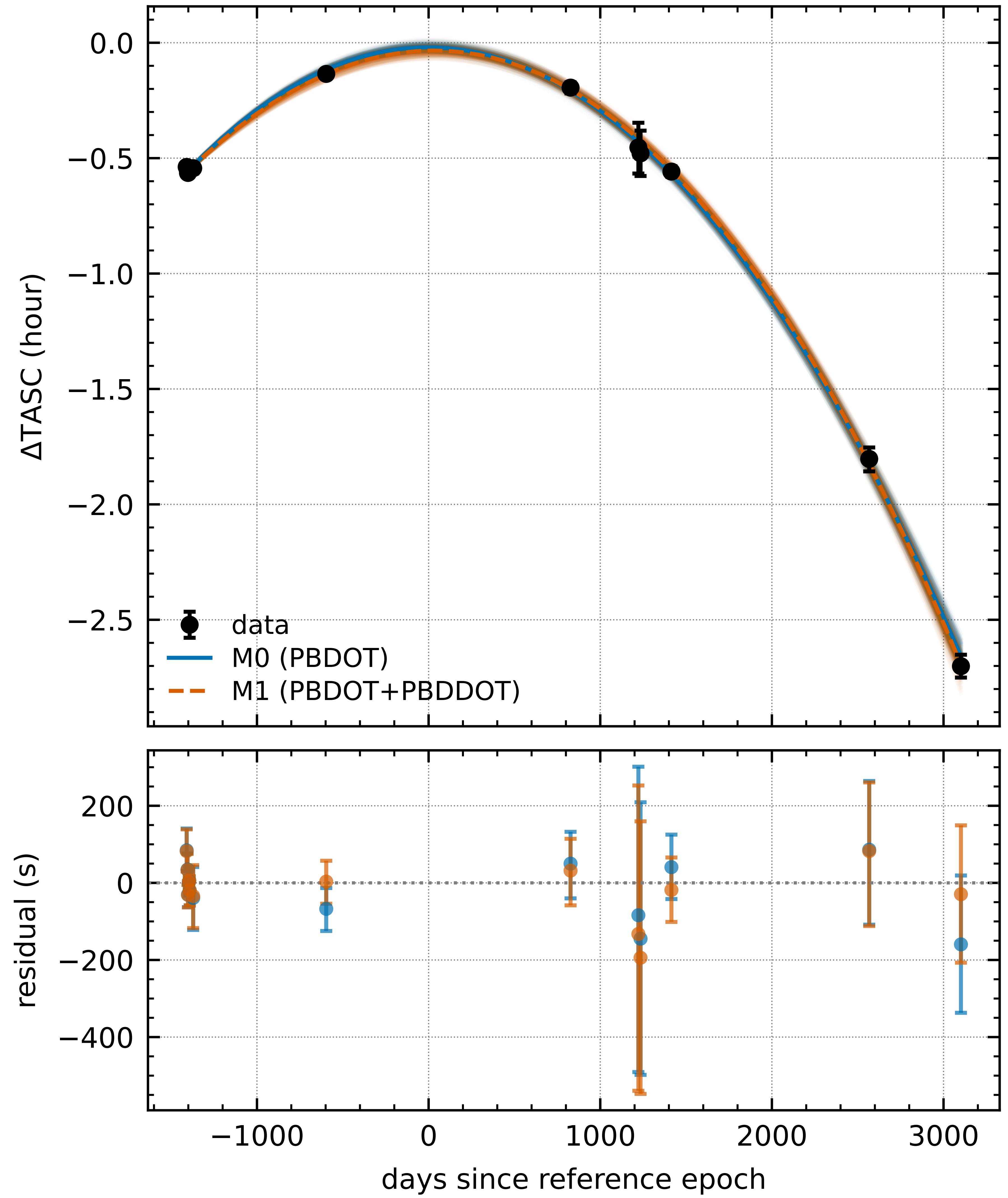
MB+22: Orbital decay in M82 X-2, by $\dot{P}_{\rm orb} \approx -6 \cdot 10^{-8}$

If conservative, mass transfer at $\dot{M} \approx 200\dot{M}_{\rm Edd}$ in M82 X-2

But:

1. How much of it actually *accretes*? How much is lost in winds?
2. Is it mass transfer? Or anomalous magnetic braking (Chen+24, ApJ 973 38)? A circumbinary disk? Or something else?

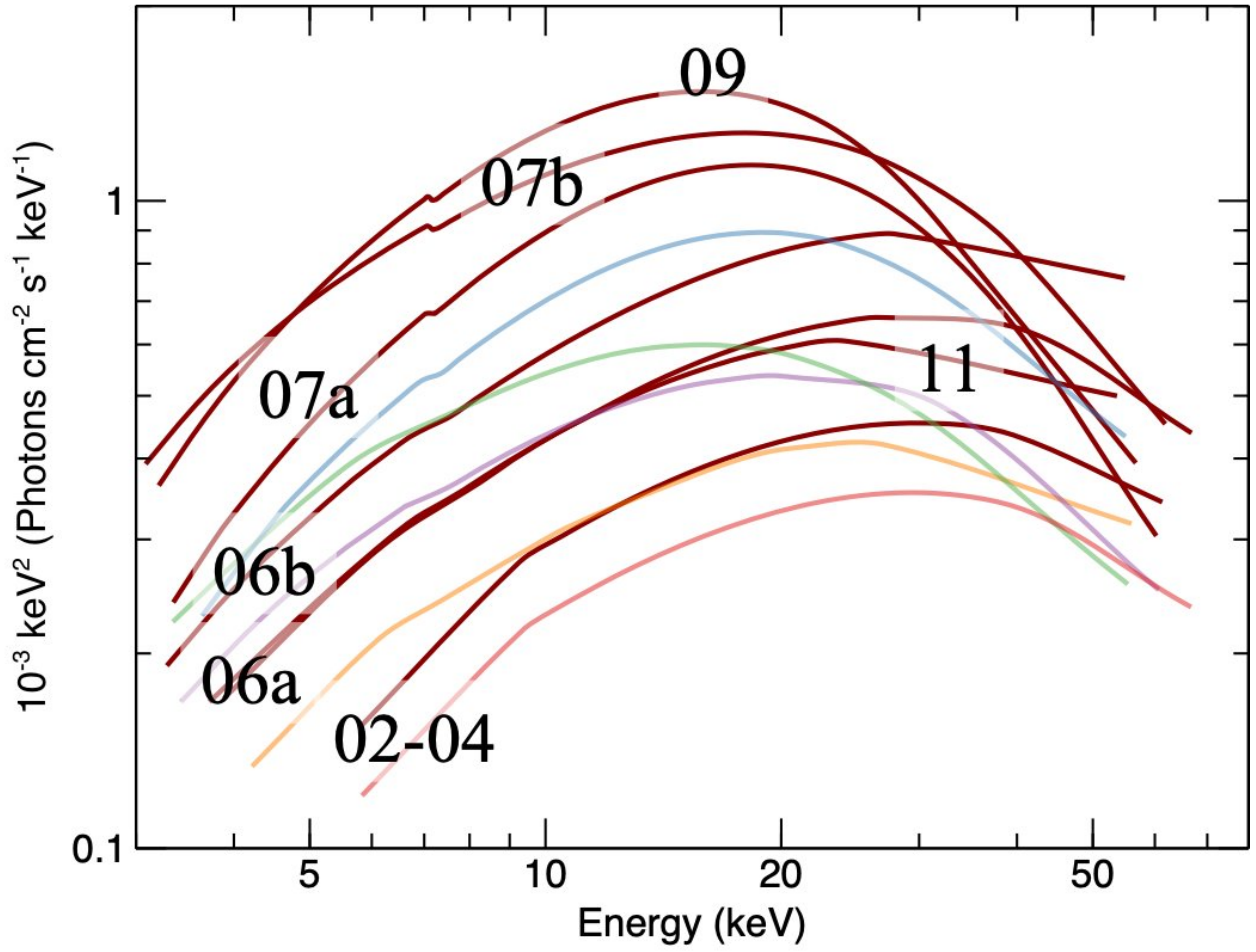
In the meantime: track decay. Second derivative excluded at level $|\ddot{P}| < 10^{-9}\,{\rm yr}^{-1}$ (MB+ in prep)

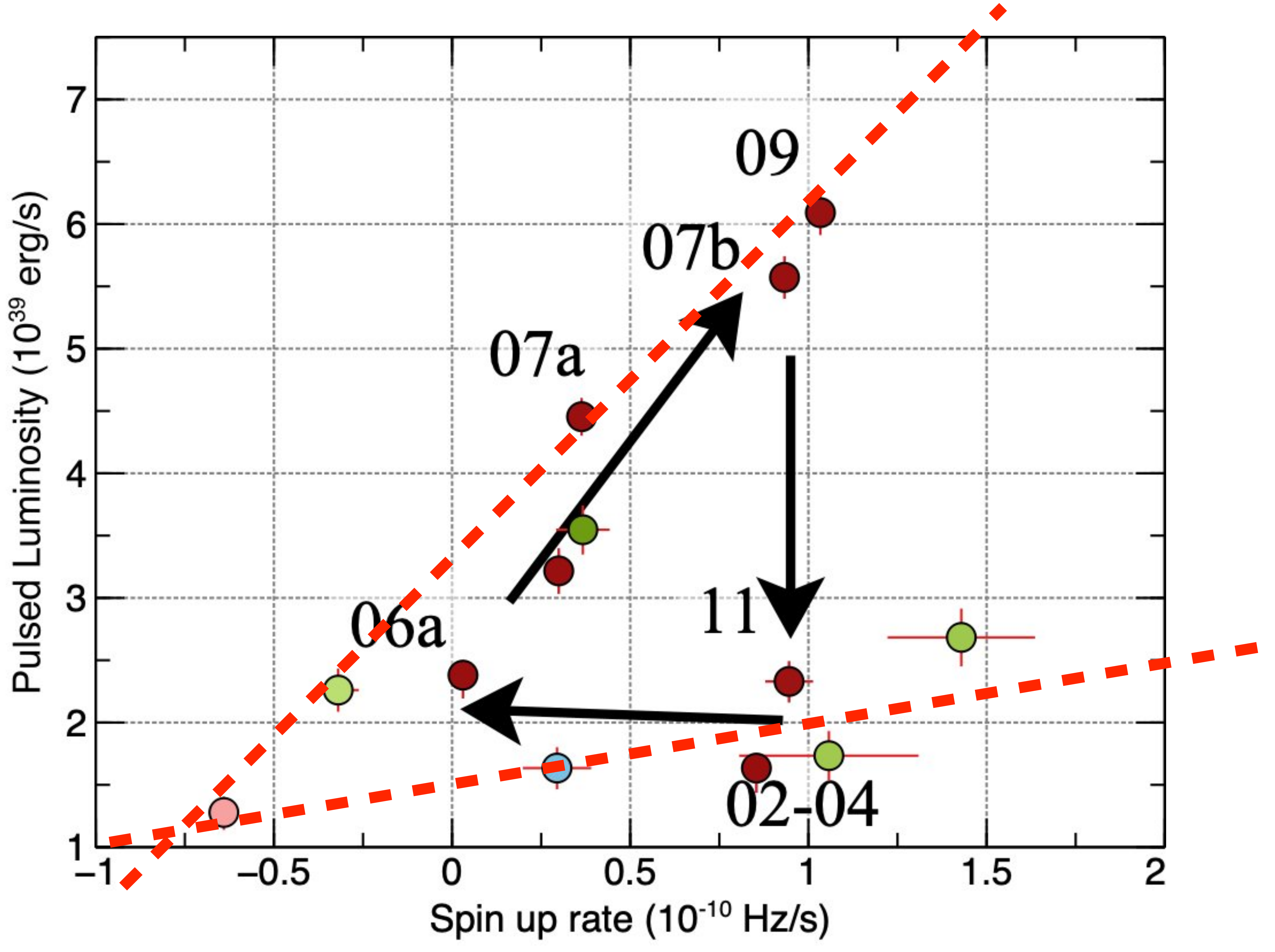


Pulsed spectra

MB+ in prep: new algorithm for precise pulsed spectra modeling.

Pulsed luminosity vs spin up rate: two tracks?





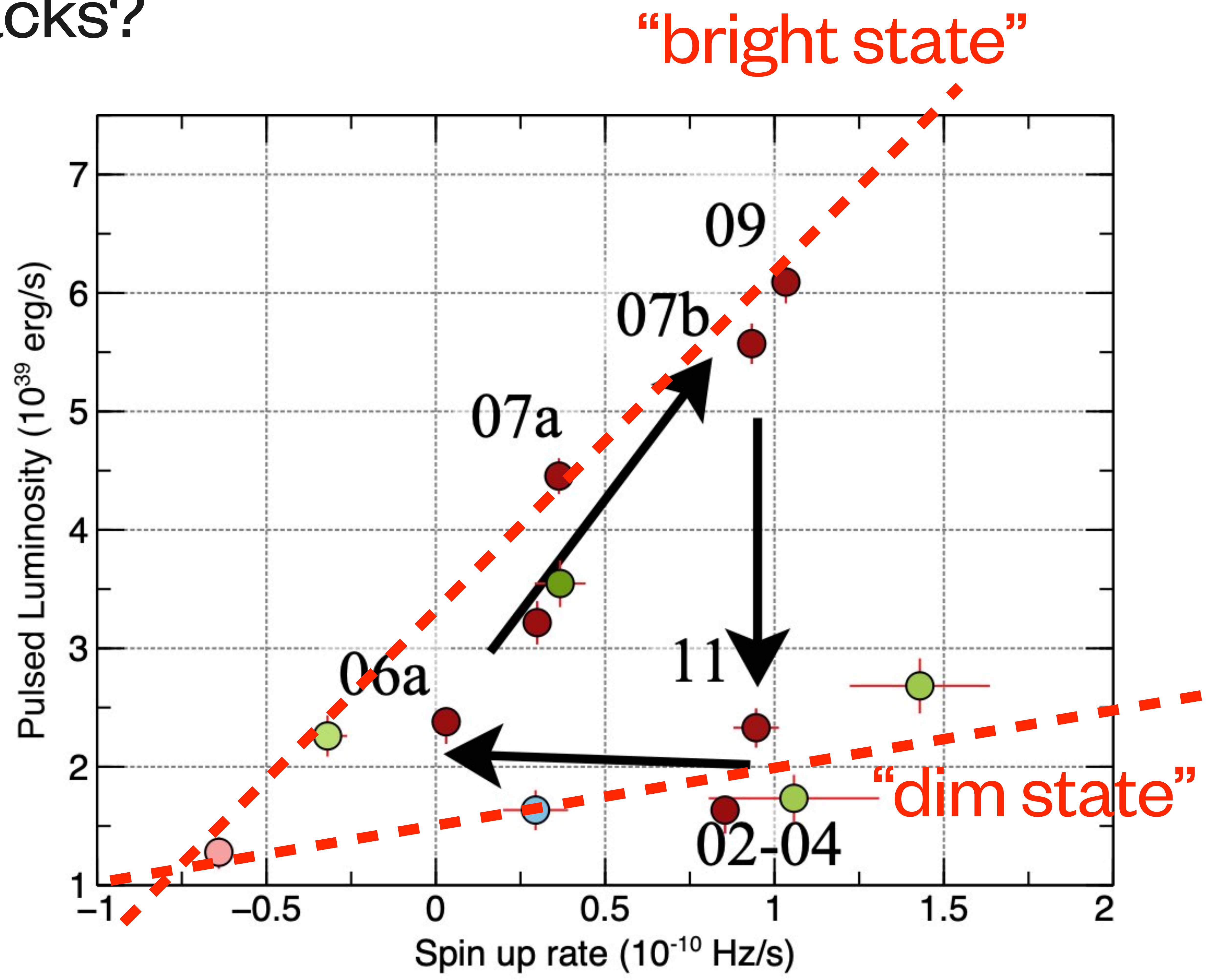
See Ferrigno's poster for an alternative method to study pulsed spectra.

Pulsed spectra

MB+ in prep: new algorithm for pulsed spectra calculation.

Pulsed luminosity vs spin up rate: two tracks?

- Pulsed spectra are highly variable, the luminosity changes by a factor~6 (up to 40xEddington in the pulsation alone)
- Two tracks:
  - Occultation when dim?
  - Beaming when bright? (difficult)
  - Changes in the disk or B configuration?



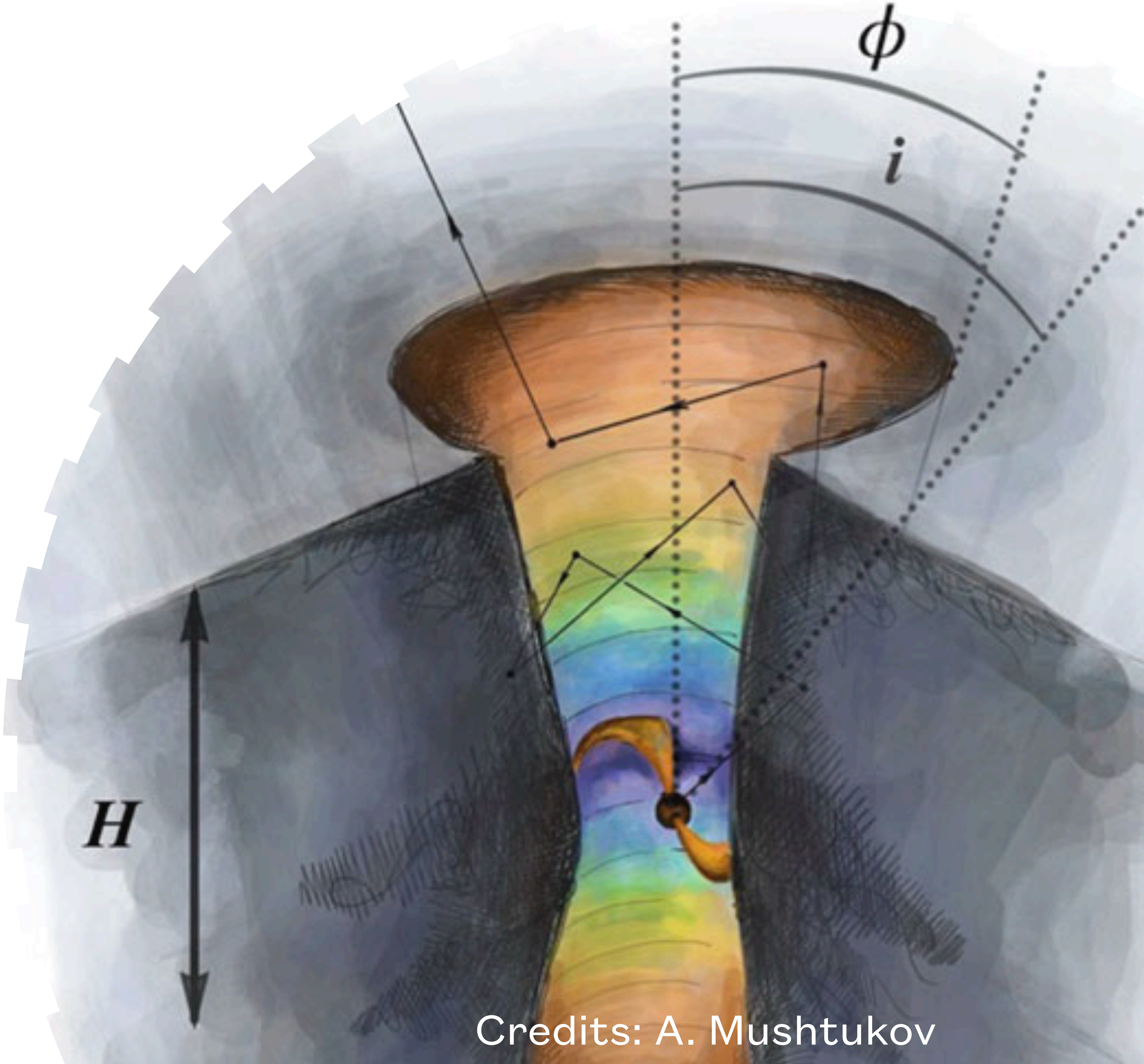
Conclusions

ULX pulsators: **glitches**, accretion-driven and secular **spin up/down**, **orbital decay**. Phenomenology reminiscent of various classes of HMXBs (but more extreme).
Difficult to detect!

M82 X-2: luminosity / spin up relation with two tracks. Extreme orbital decay. A lot of available mass, still unclear how much of it accretes.

Timing gives us precise measurements when images and spectra are too contaminated. Do more timing!

QPOs from M82 X-1: Q vs freq of LF QPO similar to HMXBs. Cannot confirm 3:2 "HF QPOs".



Credits: A. Mushtukov