The peculiar variability of A0538-66: a transient ULX in the LMC !

Sandro Mereghetti
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LETTERS TO NATURE

Discovery of 69 ms periodic X-ray pulsations in A0538−66

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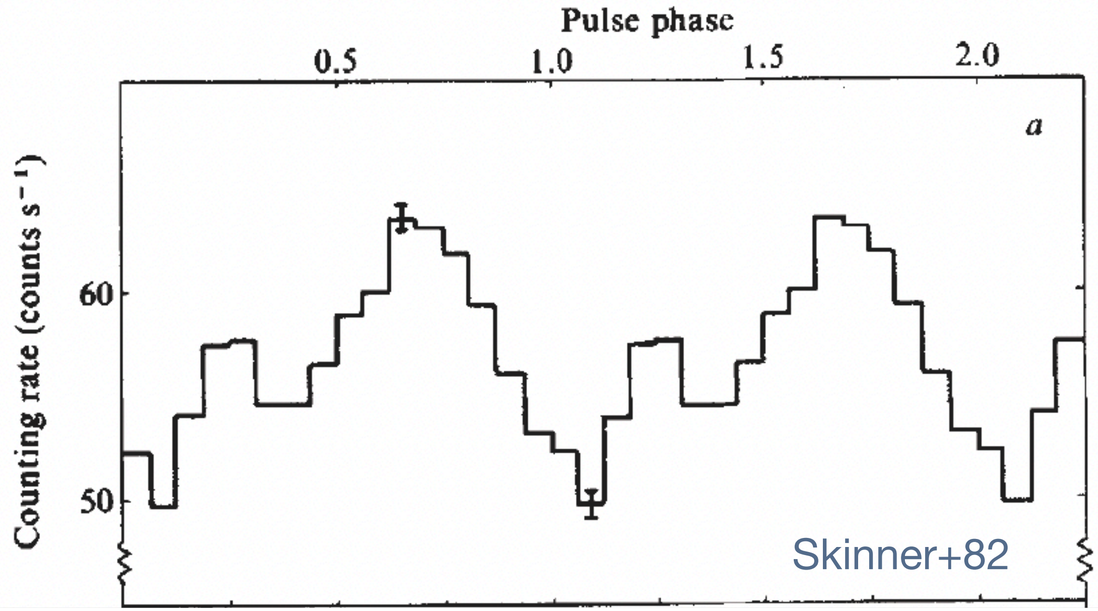
‡ Center for Astrophysics, 60 Garden St, Cambridge, Massachusetts 02138, USA

Both the recurrent X-ray transient A0538−66 and its optical counterpart undergo outbursts at intervals which are multiples of 16.6 days[1–3]. The times of outbursts are subject to appreciable



- Spin Period = 69 ms → $B \lesssim 10^{11}$ G ($R_{mag} < R_{co}$)
- $\dot{P} = 5\ 10^{-10}$ s/s → eccentricity > 0.4

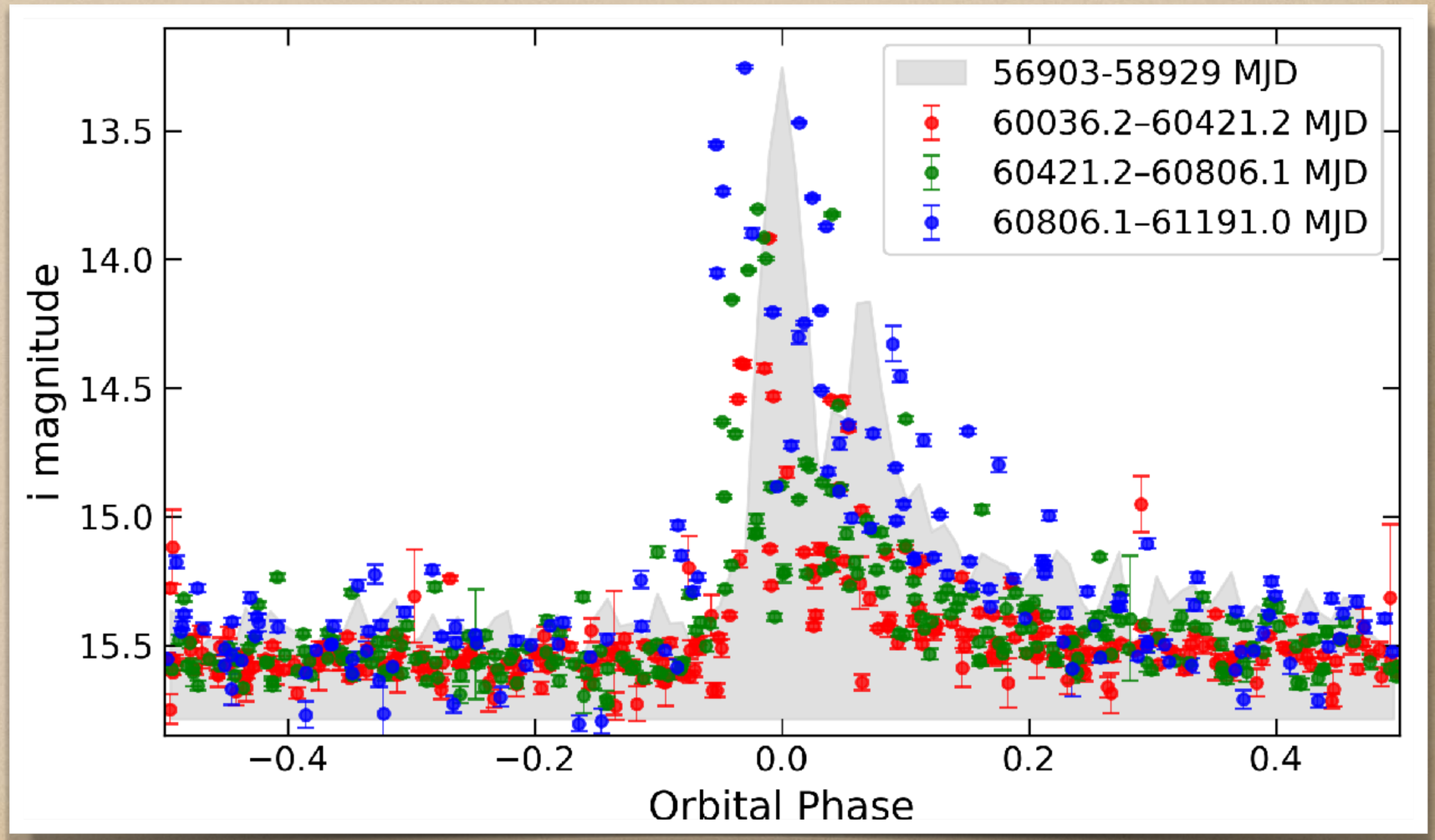
Unique optical behaviour

Strong (Δm ~ 2) periodic (16.6 d) outbursts

—> orbital period

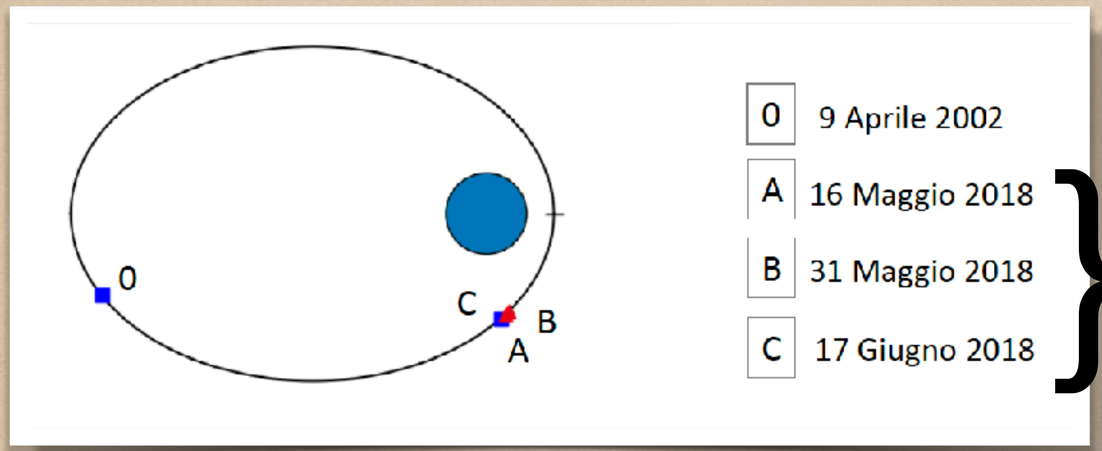
Reprocessing in big cloud surrounding the system

Charles+ 83; Densham+ 83; Maraschi+ 83: Ponman+ 84; Apparao & Tarafdar 88; Ducci, SM +2019

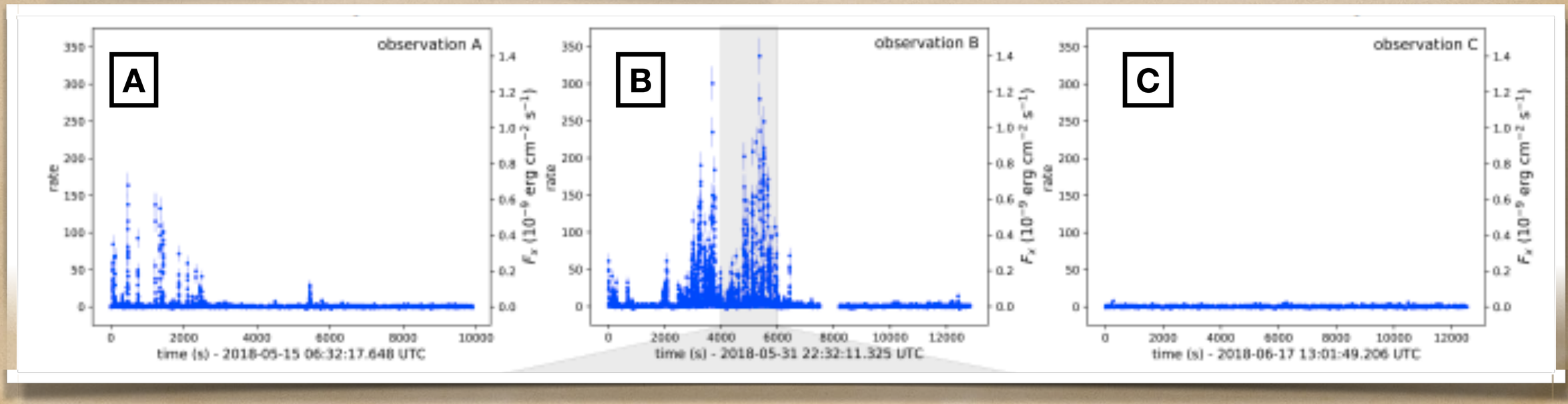


Awakening in 2018 (after decades with low L_x)

Ducci, SM, Santangelo 2019, ApJ

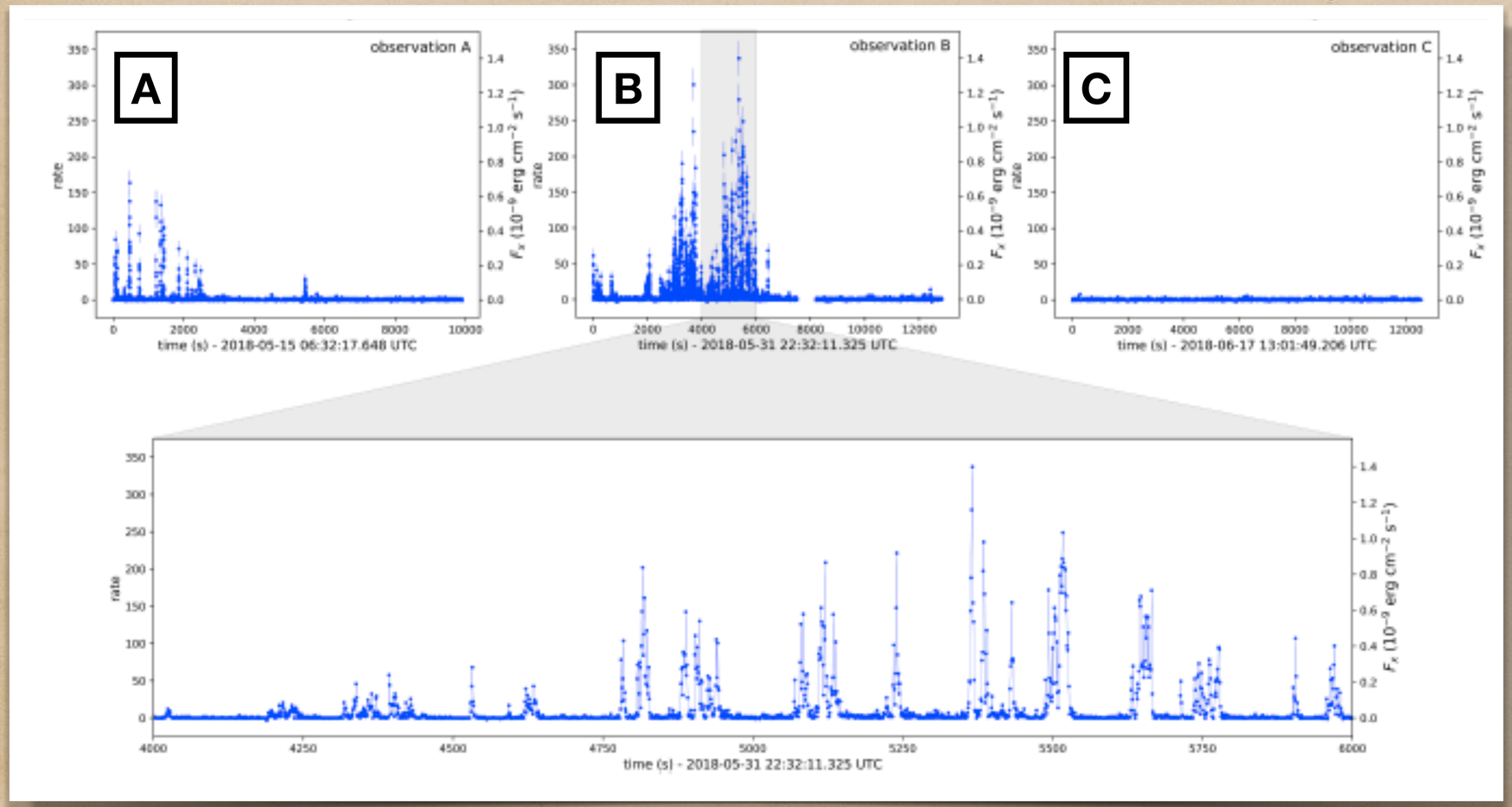


- Three XMM observations at same phase in consecutive orbits

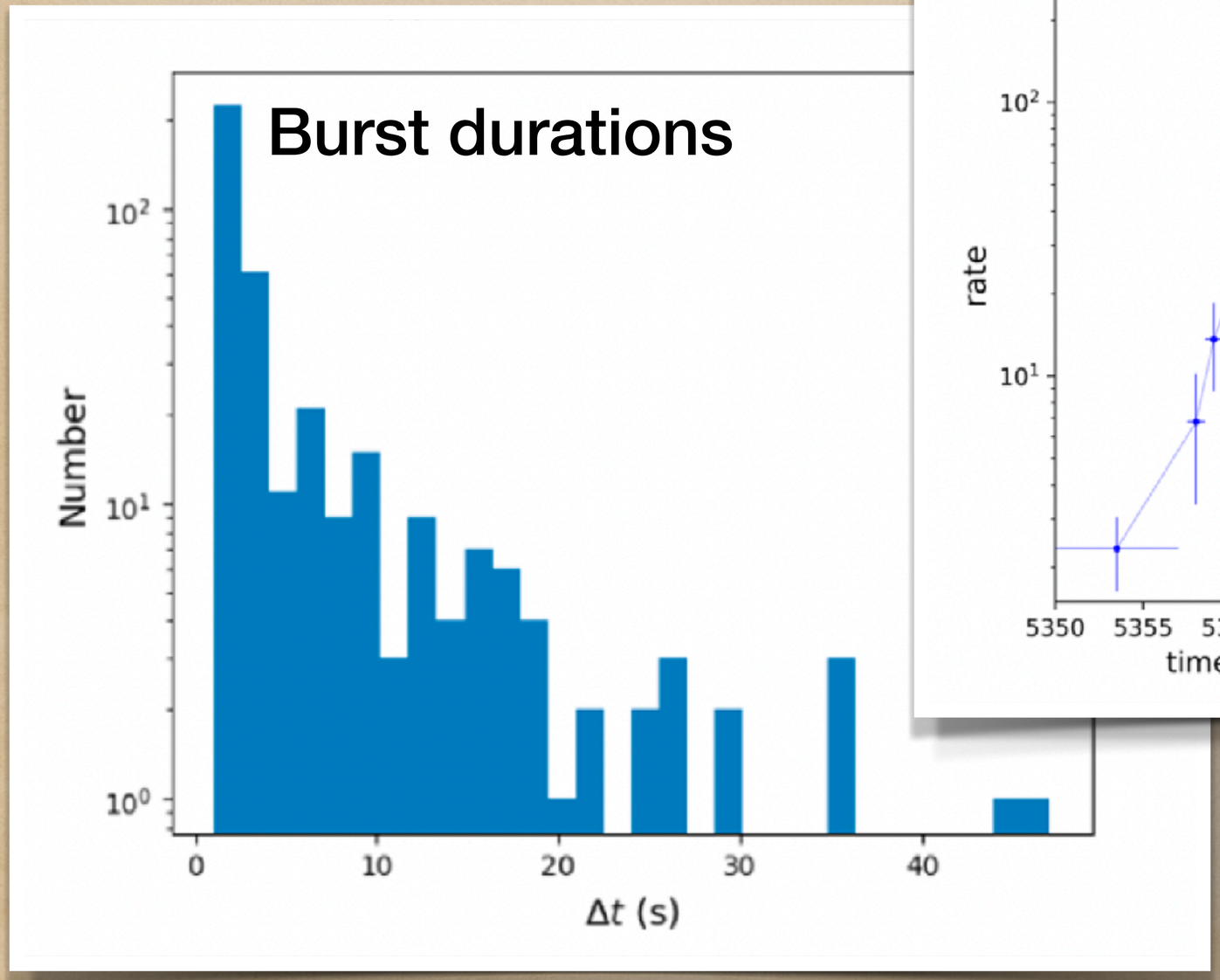


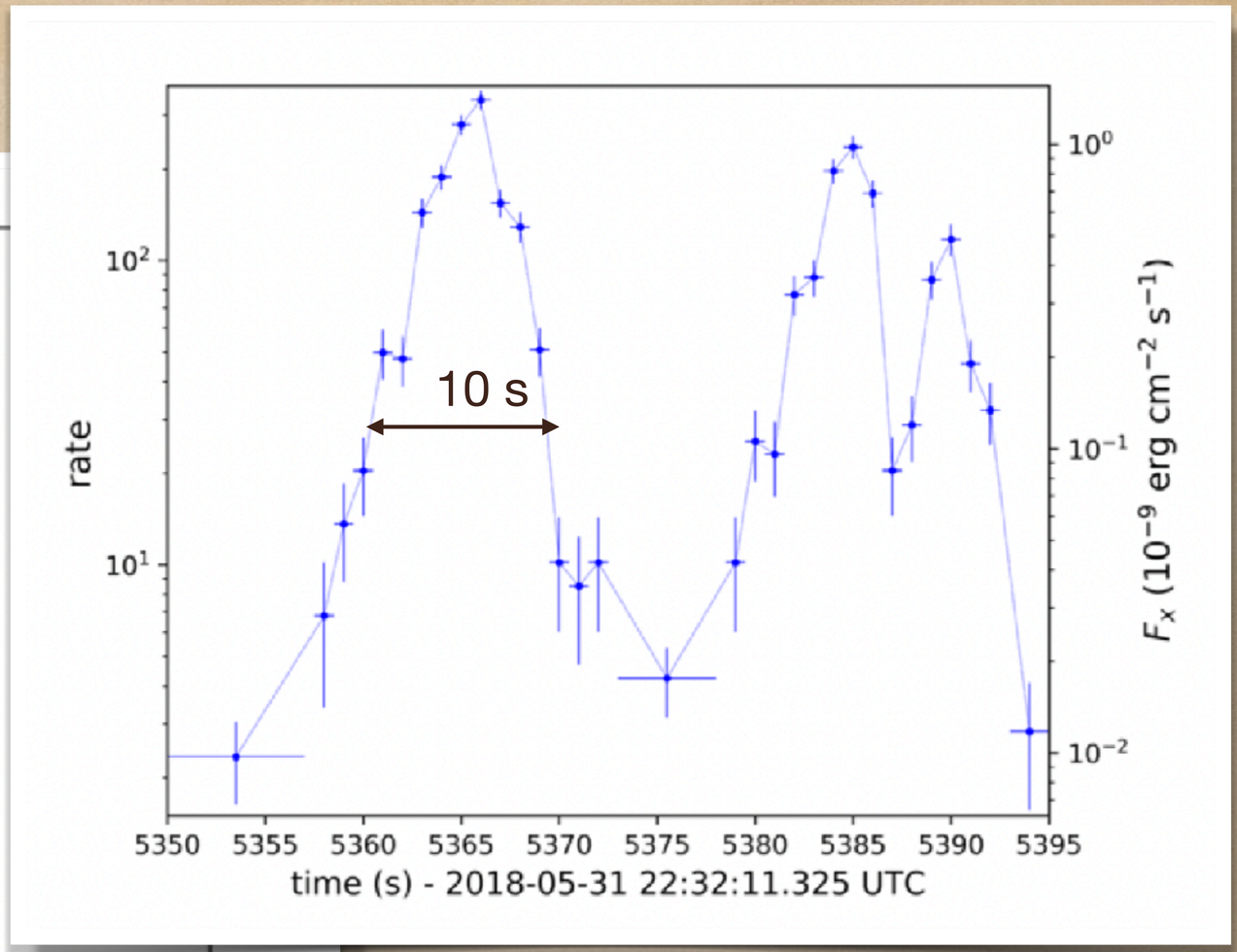
Awakening in 2018 (after decades with low L_x)

$2\ 10^{35} – 2\ 10^{38}$ $2\ 10^{35} – 4\ 10^{38}$ $2\ 10^{34}$ erg/s

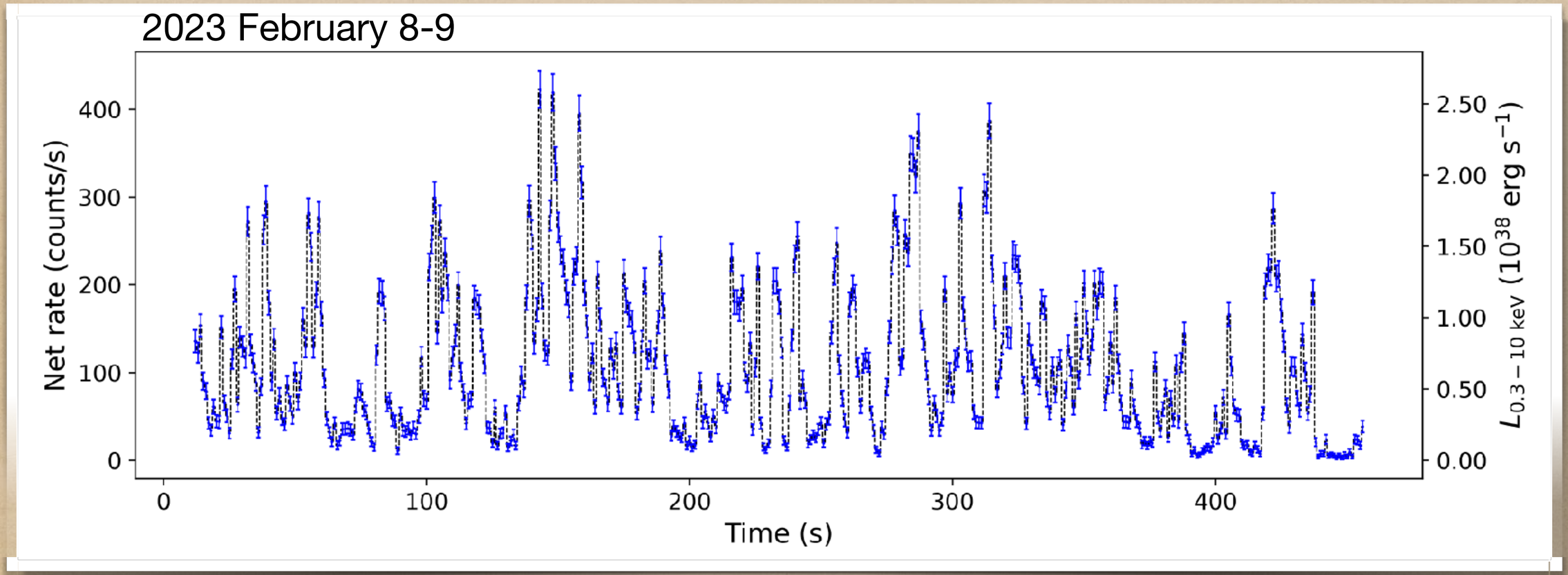


- **Flares in A and B:** variations of factors ~1000 on timescales ≲1 min
- **Quiescent in C:** constant flux 10 x smaller than minimum of flaring state
- **No periodic pulsations**


Burst durations
Number
10^2
10^1
10^0
0
10
20
30
40
Δt (s)

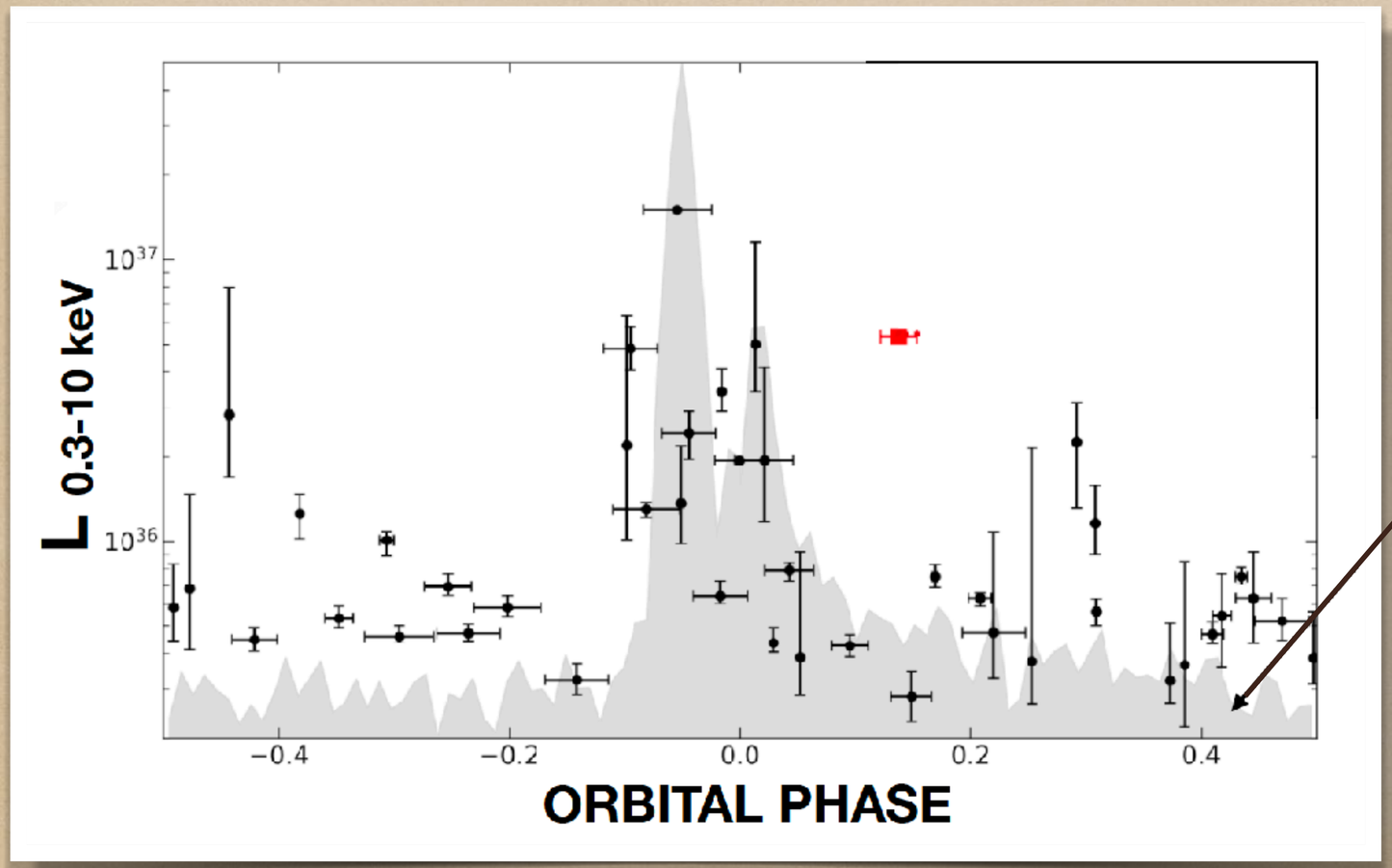

rate
10^2
10^1
10 s
10^0
10^{-1}
10^{-2}
F_x (10^{-9} erg cm^{-2} s^{-1})
5350
5355
5360
5365
5370
5375
5380
5385
5390
5395
time (s) - 2018-05-31 22:32:11.325 UTC

Fast variability seen also in some NICER observations



ΔL too large for magnetic gating effect

NICER X-ray observations



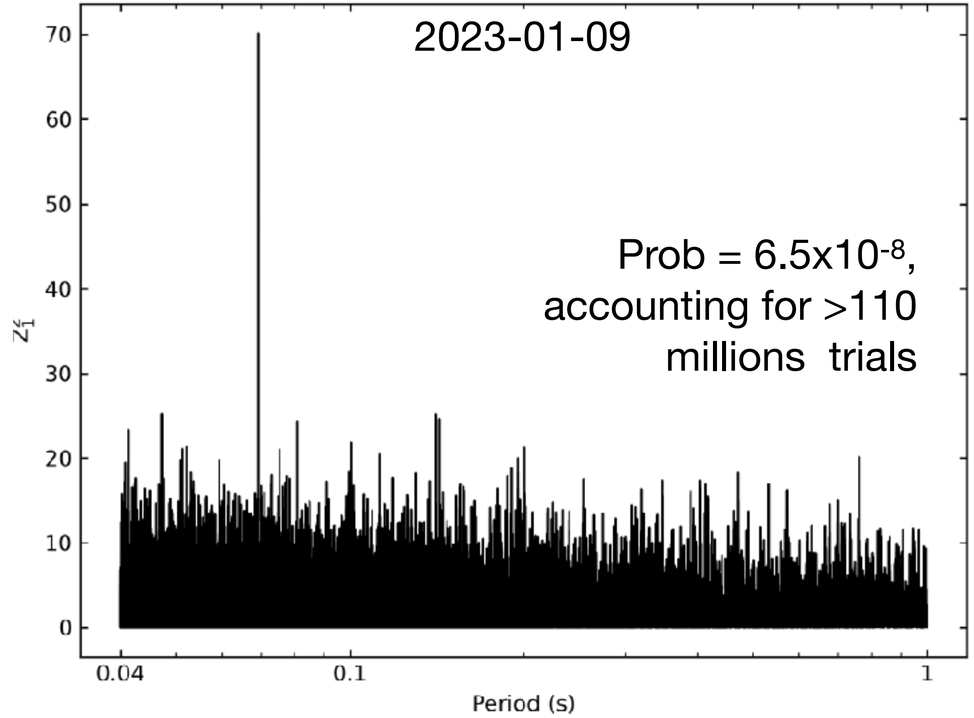
Nov. 2022-April 2025
163 ks in 73 obs

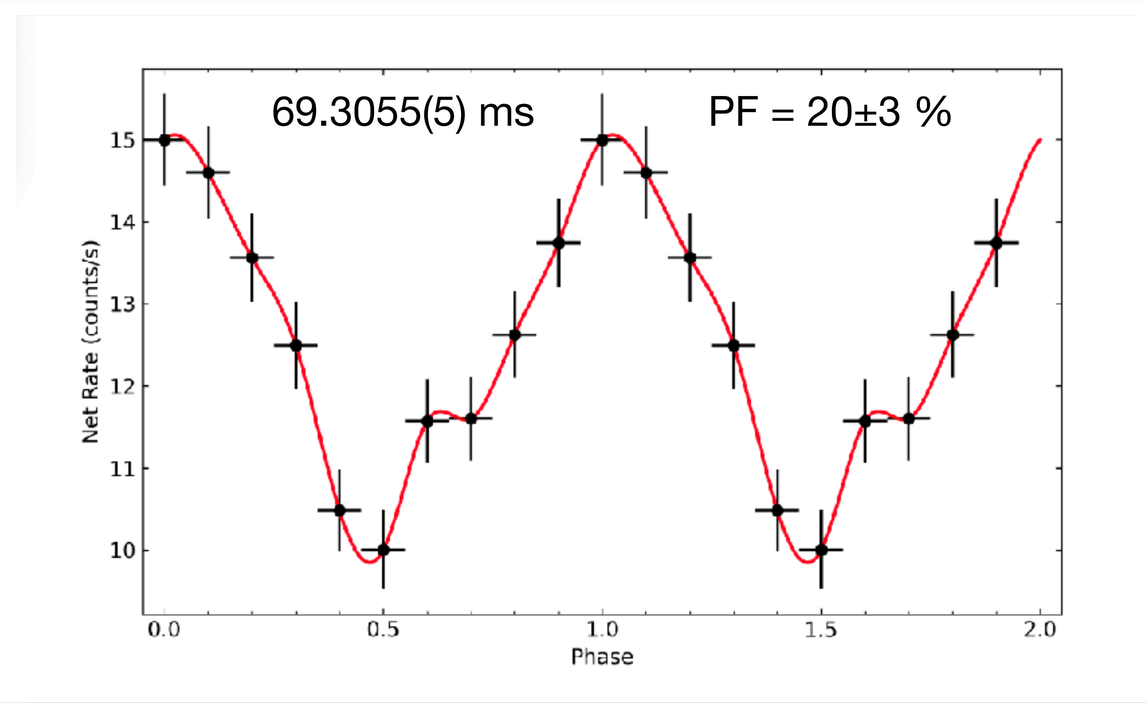
Grey shade is the folded optical light curve

OPEN ACCESS

Sometimes They Come Back: Pulsations in A 0538–66 at 69 ms Rediscovered with NICER

Lorenzo Ducci[1] and Sandro Mereghetti[2]

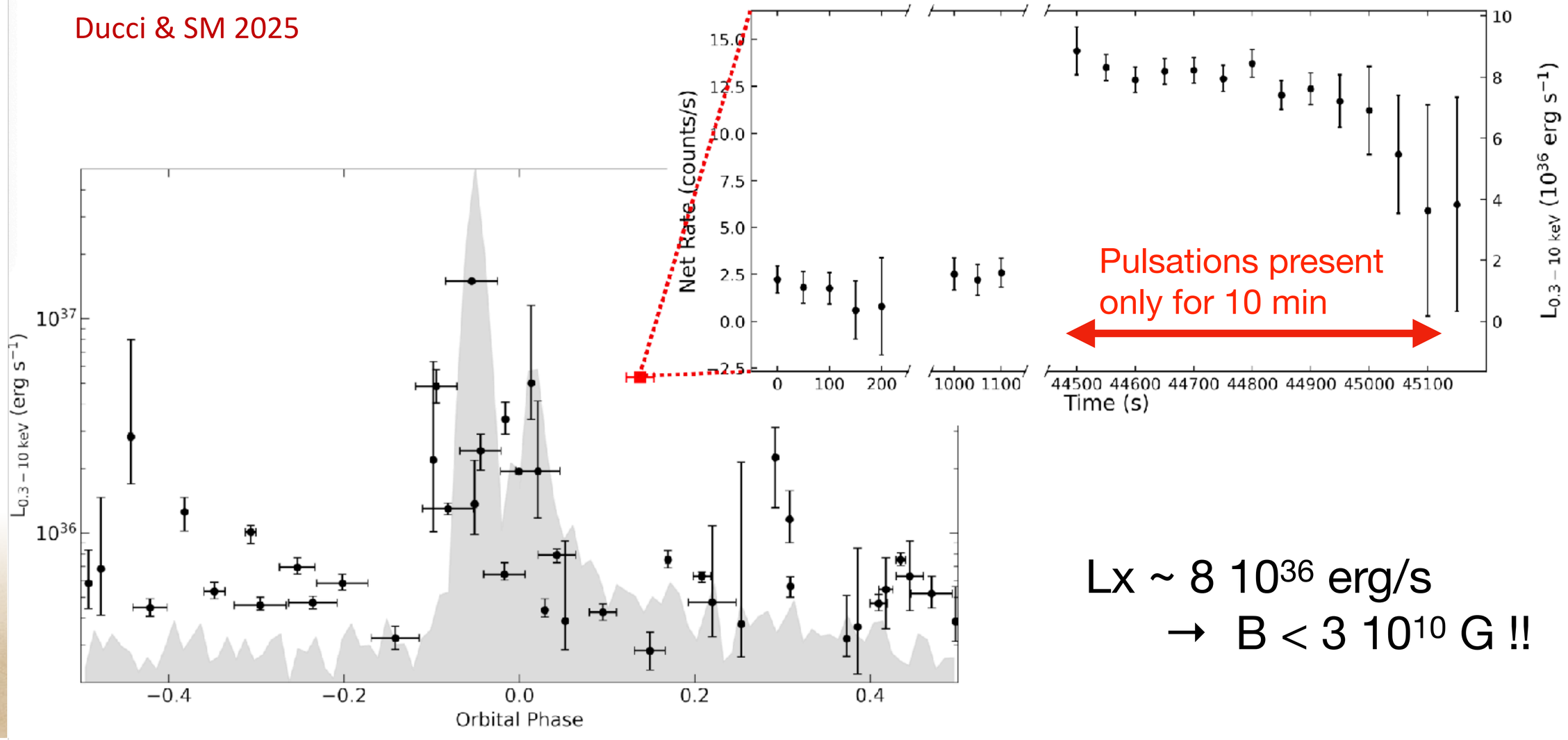




Lx ~ 8 10^{36} erg/s → B < 3 10^{10} G !!

Rediscovery of 69 ms pulsations

Ducci & SM 2025

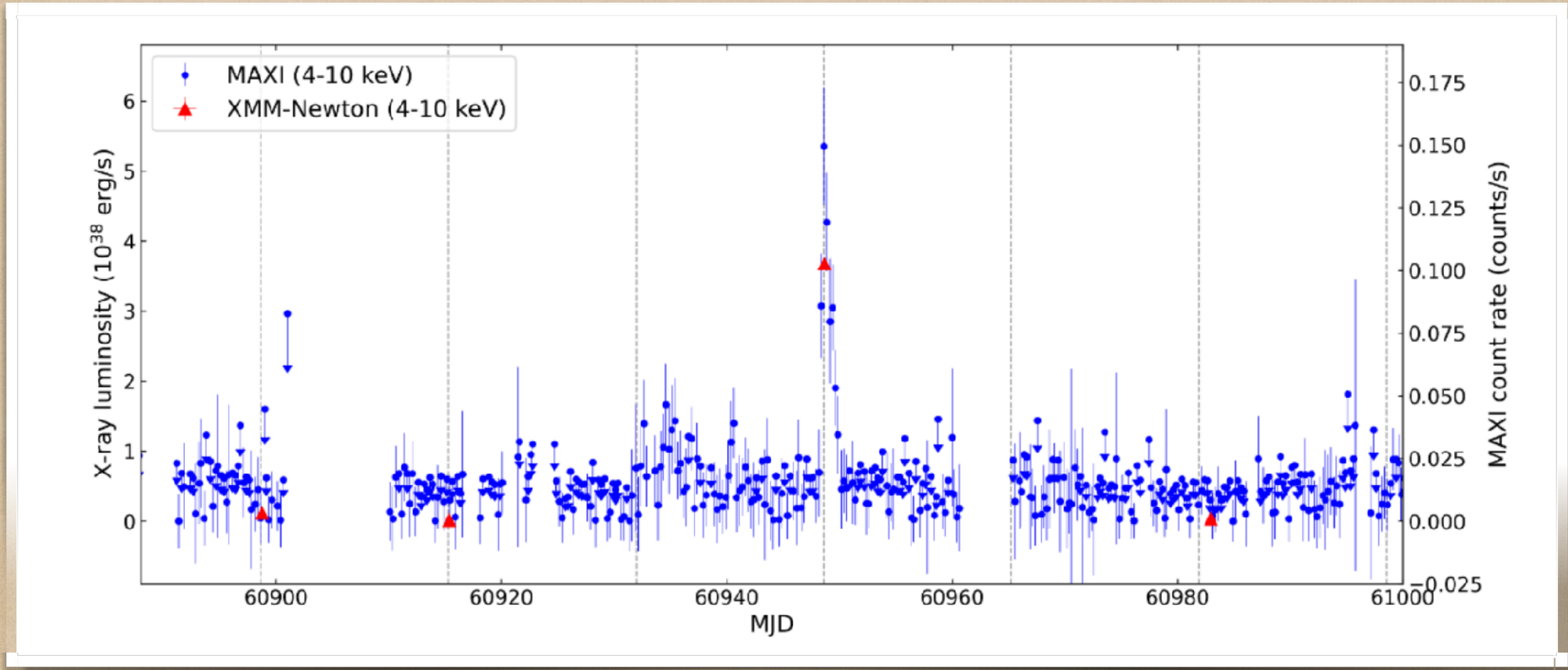


Lx ~ 8 10^{36} erg/s

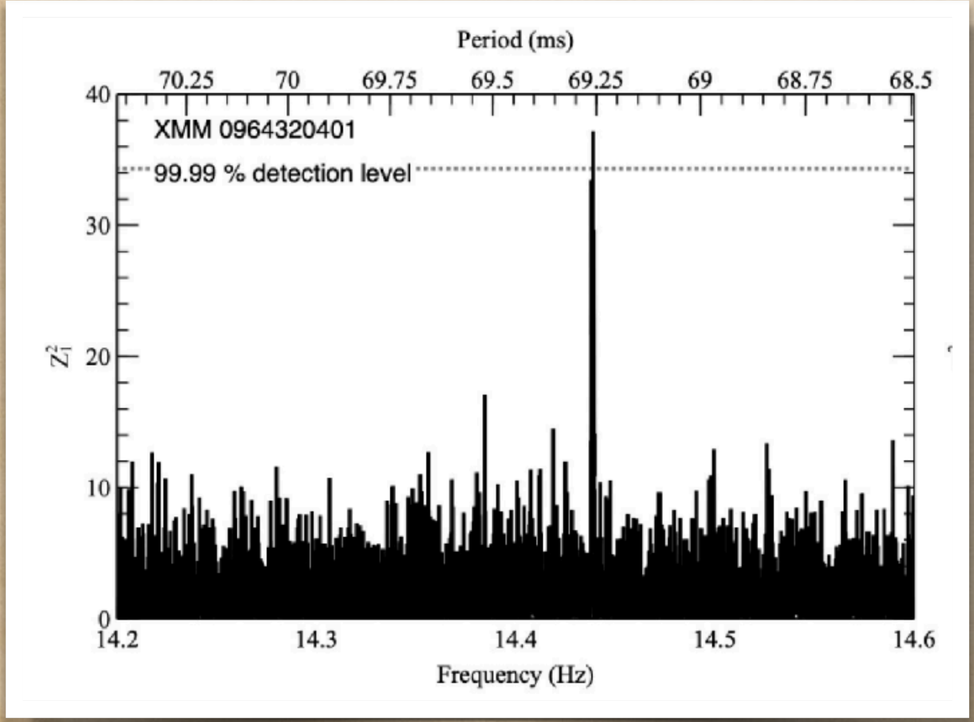
→ B < 3 10^{10} G !!

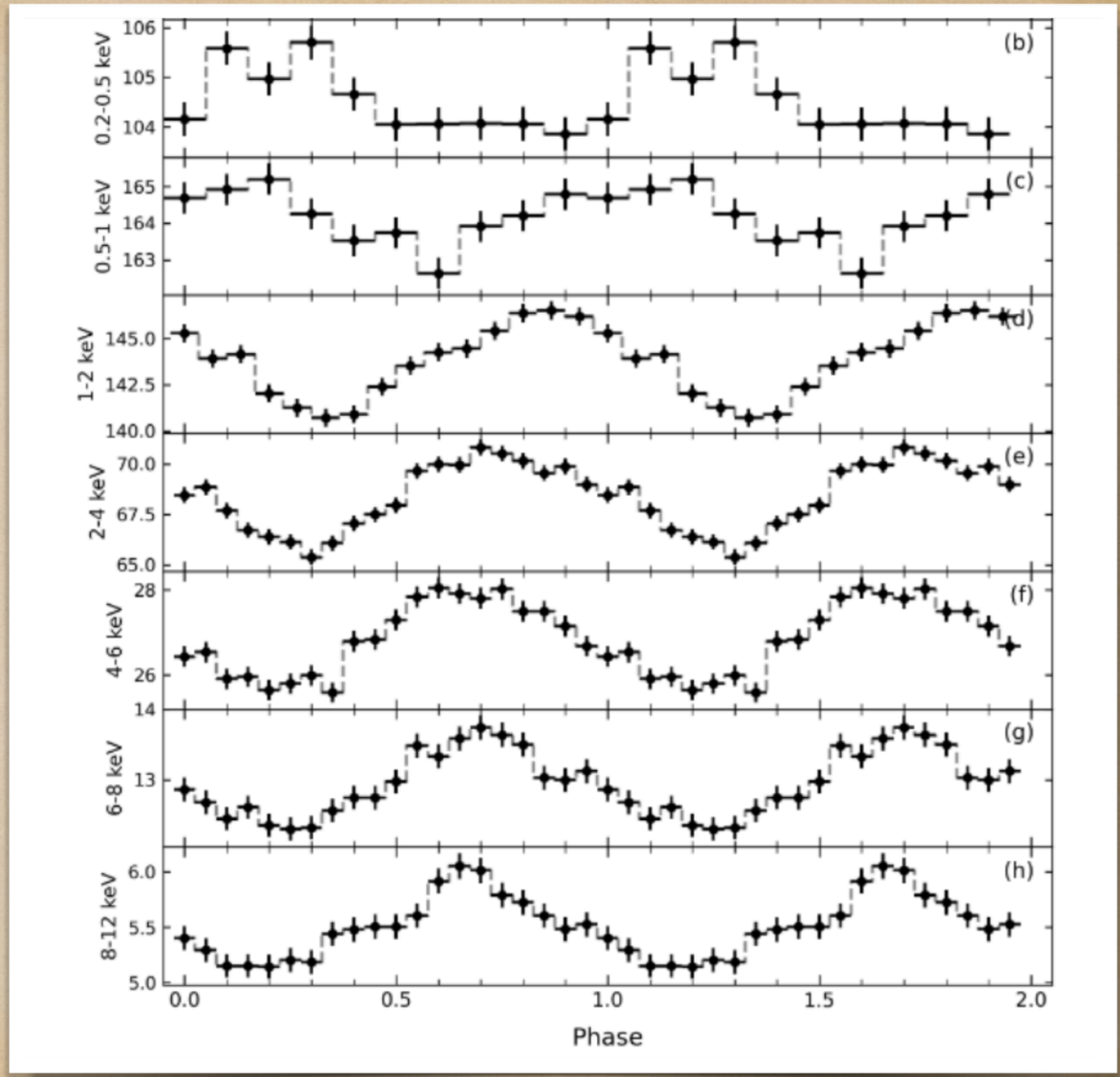
New outburst on 30 Sep 2025: L_X ~ 1.5 10^{39} erg/s

Nakajima+2025; Ducci, SM, Bachetti 2025

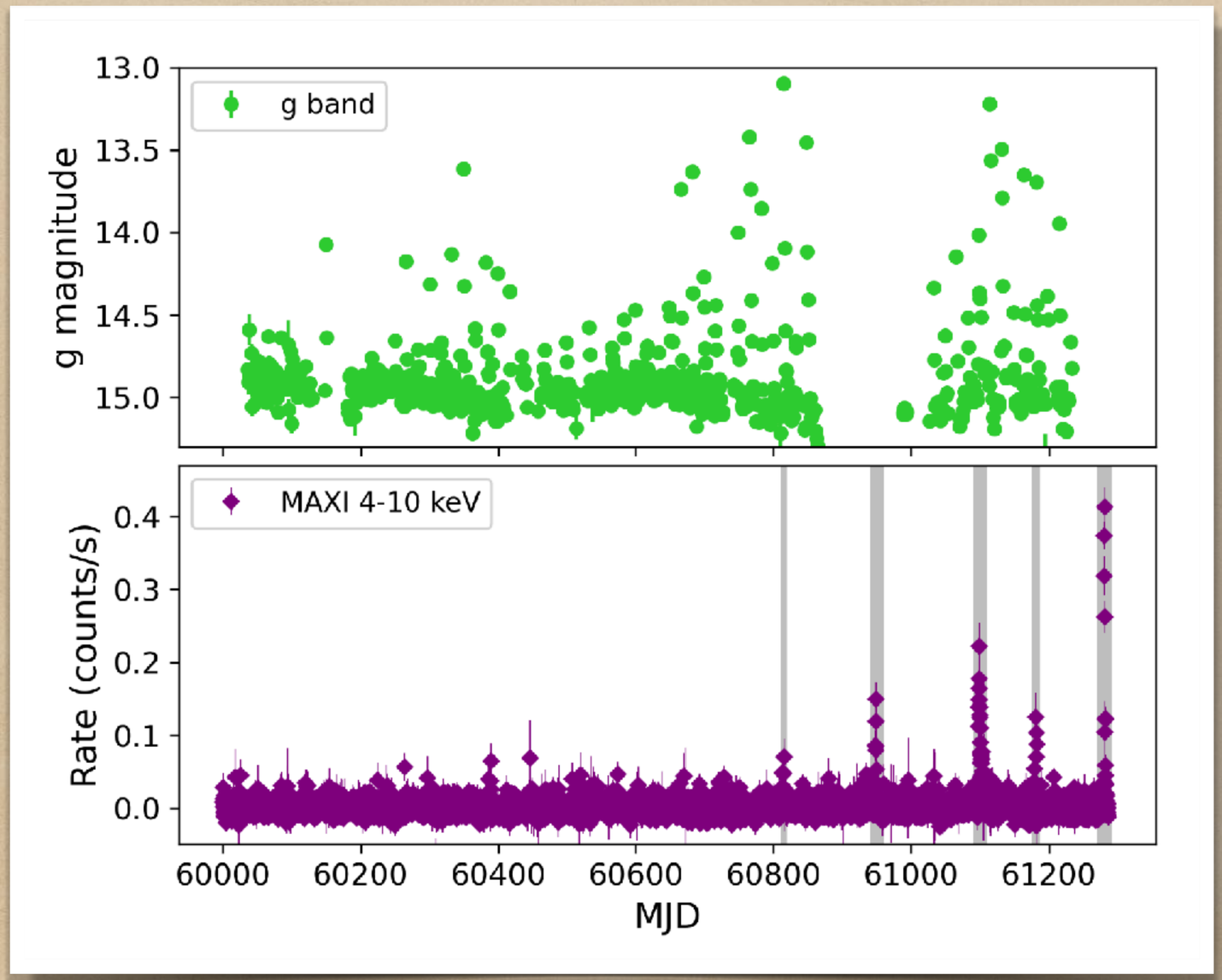


- P = 69.26 ms
- $\dot{P} = 6.6 \times 10^{-10}$
- Phase shift below 1 keV





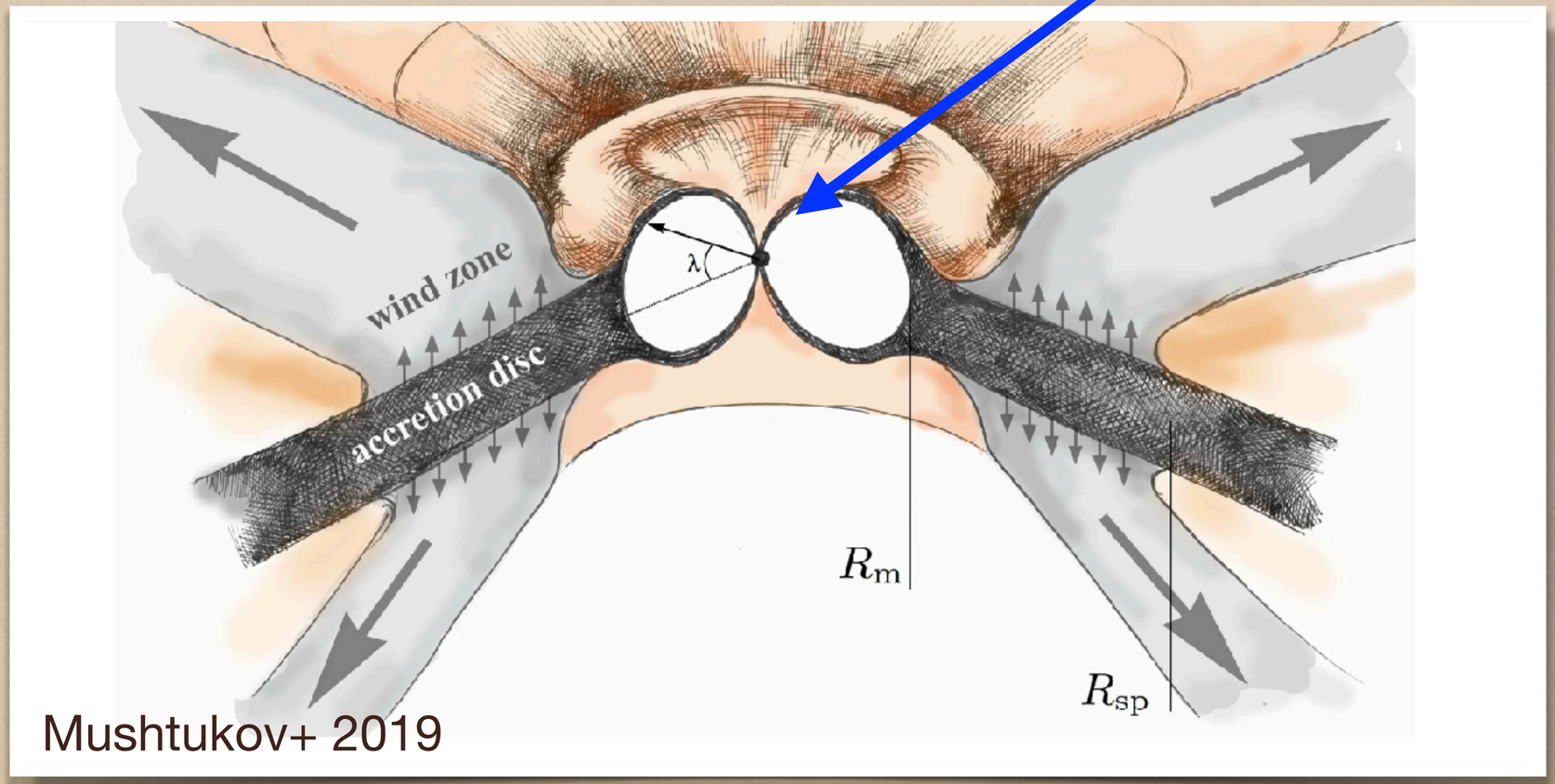
Long term optical (REM) and X-ray (MAXI) monitoring



Several bright optical flares without an associated X-ray flare

Recap

- New outbursts in 2025/26: L_X ~ few 10^{39} erg/s
  → A0538-66 is a PULX in the LMC
- Fast P at 69 ms confirmed with three new detections, but very elusive !!
  (→ large fraction of NS in the ULX population)
- Pulsations detected also at L_X ~ 10^{37} erg/s → B < 3 10^{10} G !?
- Episodes of fast (~10s) strong (x1000) X-ray variability
- Bright optical flares near periastron even when no associated X-rays
- Very luminous radio emission, likely a jet (see Crook-Mansour poster)
- RGS spectra show emission lines from photoionized plasma at rest and blueshifted absorption lines implying outflow at ~0.1c



Mushtukov+ 2019

Conclusions

- Many of the properties of A0538-66 can be explained if the line of sight to the NS is close to the edge of an inflated radiation pressure dominated disk
- The striking differences wrt other Be/NS systems are due to the very fast spin of the NS and the high eccentricity (e~0.7)
- X-ray pulsations are potentially a great diagnostic tool, but a better determination of the orbital parameters is badly needed

BeppoSAX TAC - Brera - April 2000

Bormio - December 2011

Scientific discussions in Cefalù - June 2014

Conclusions

- Many of the properties of A0538-66 can be explained if the line of sight to the NS is close to the edge of an inflated radiation pressure dominated disk
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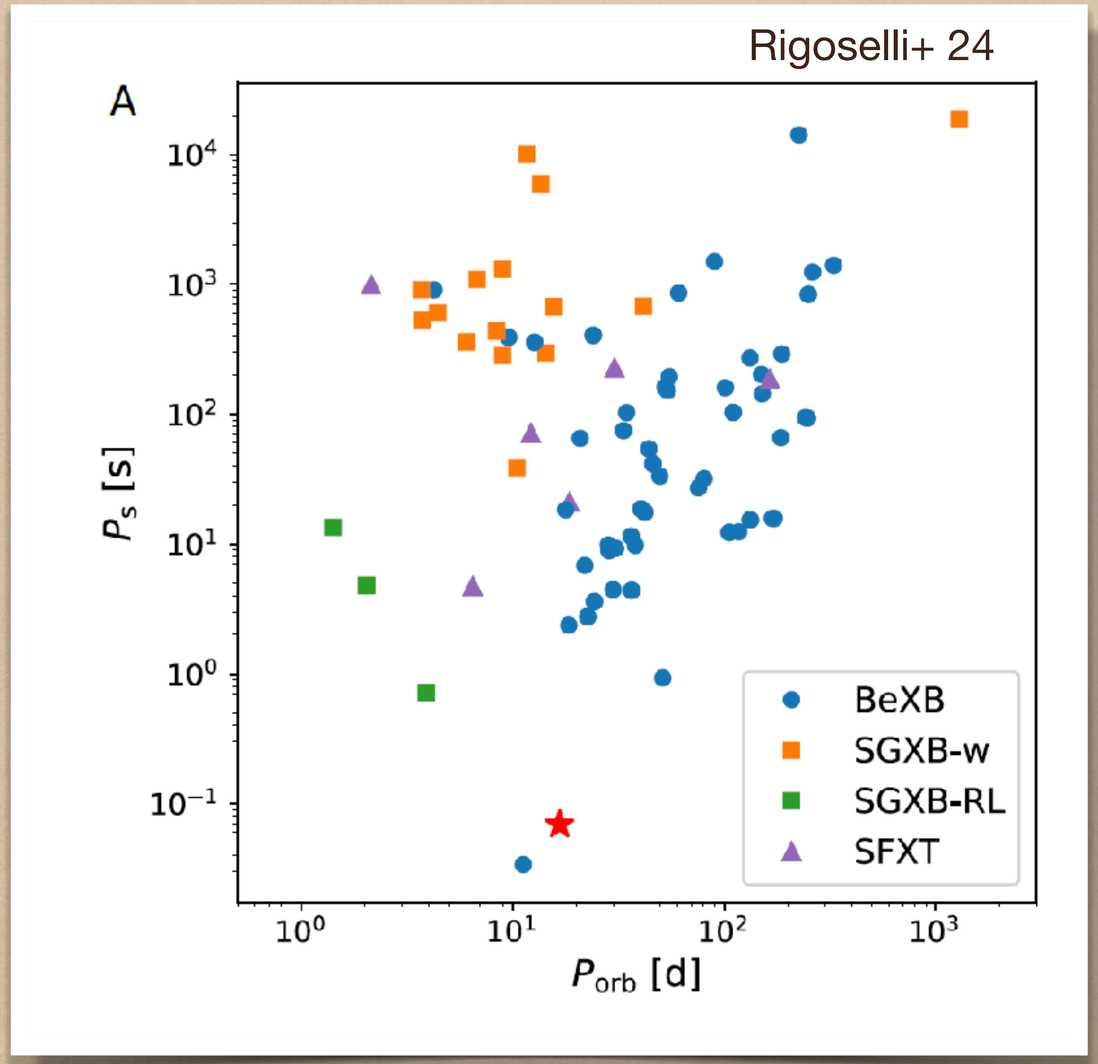
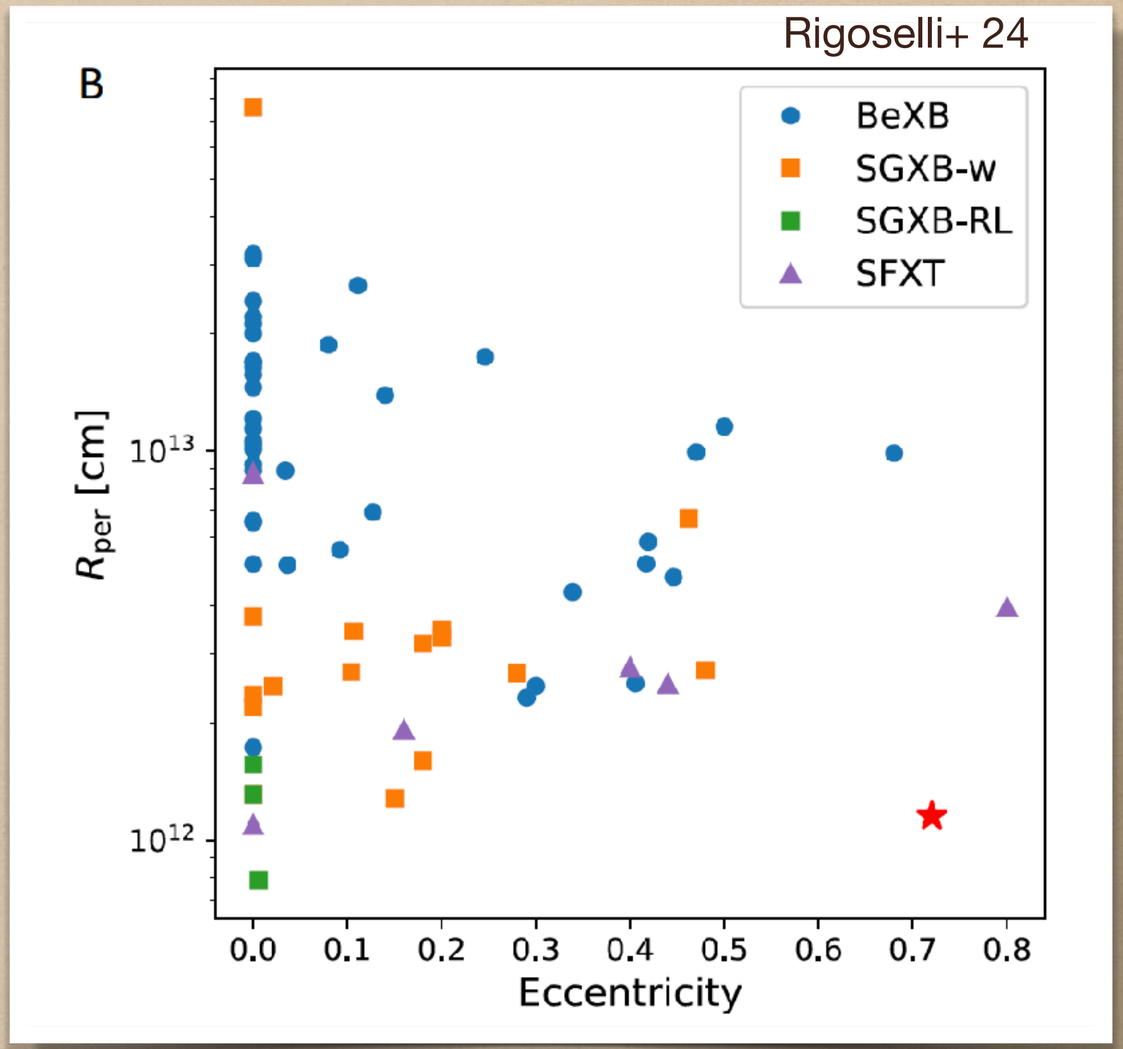
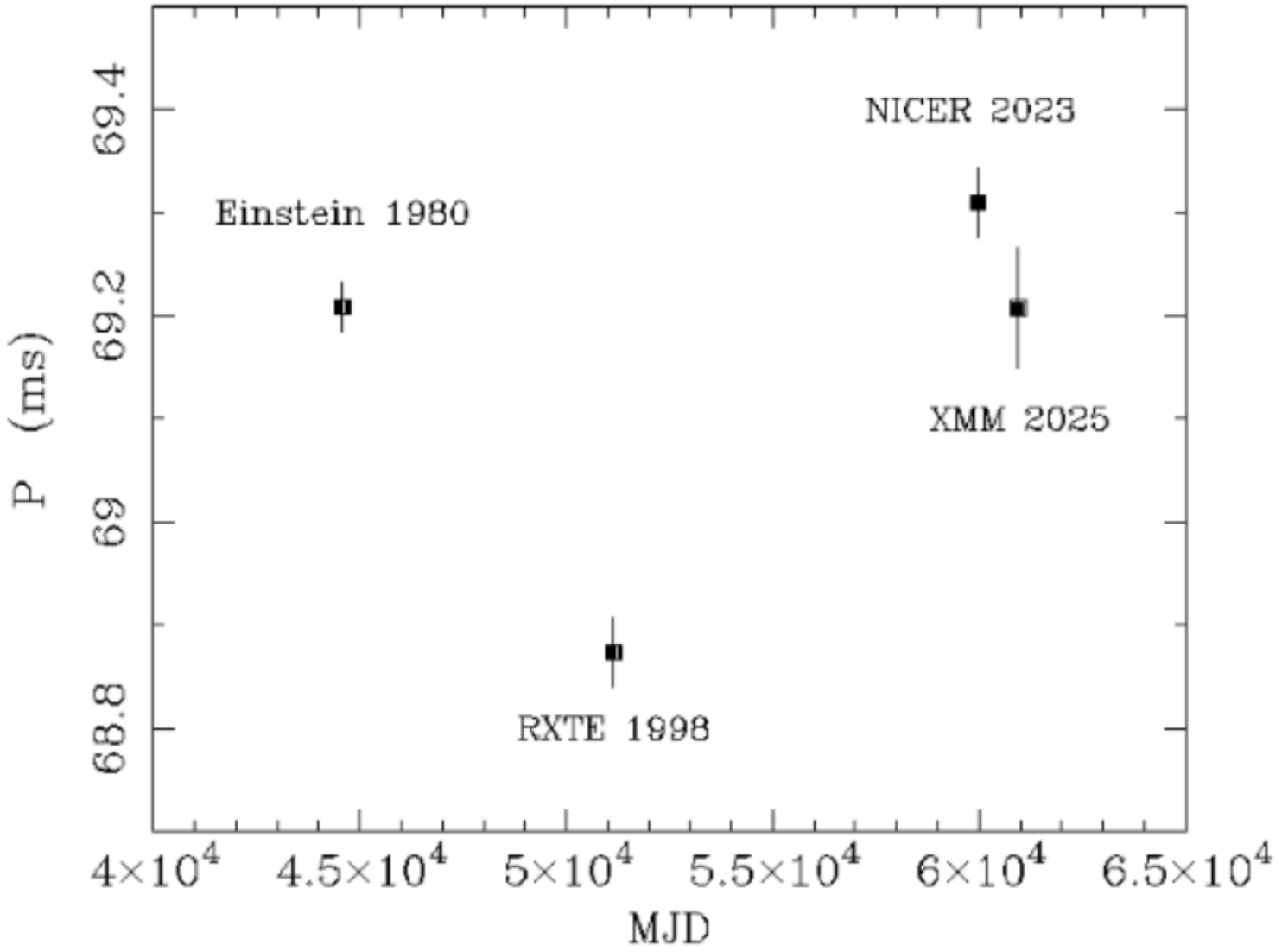
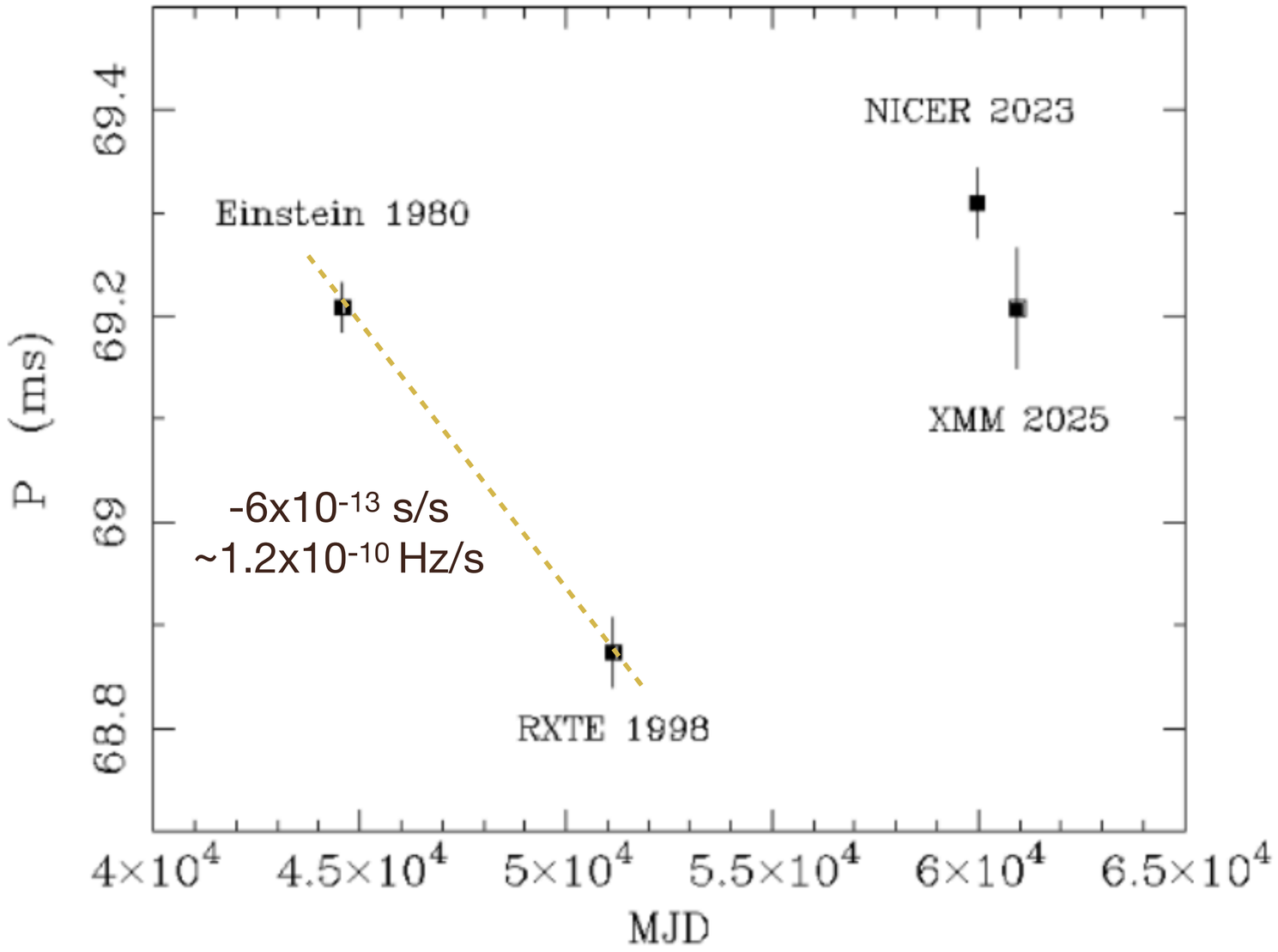
Extra Slides

A0538-66 is an atypical Be/NS binary





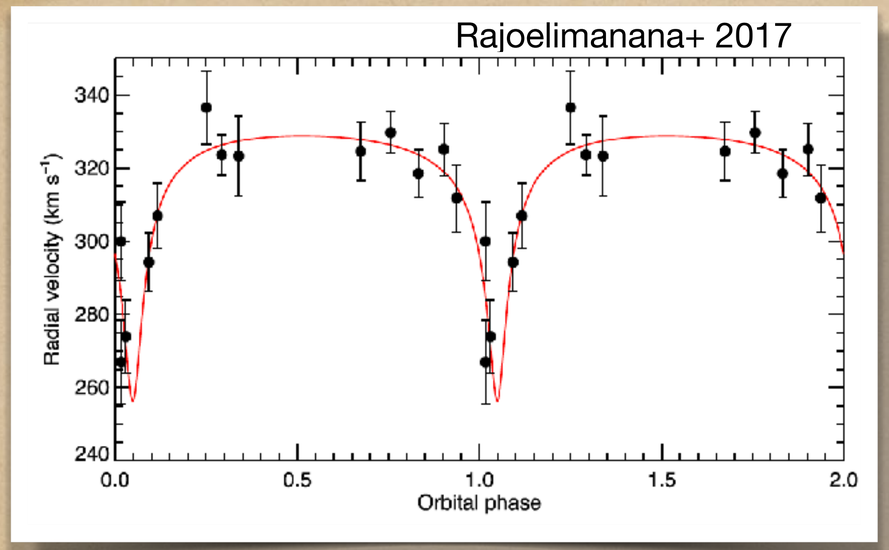

NICER 2023
Einstein 1980
XMM 2025
RXTE 1998
P (ms)
69.4
69.2
69
68.8
4×10^4
4.5×10^4
5×10^4
5.5×10^4
6×10^4
6.5×10^4
MJD

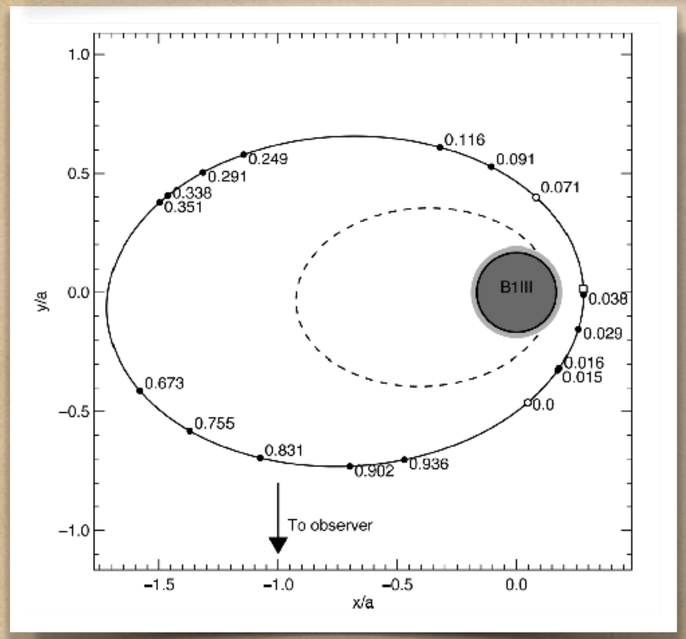


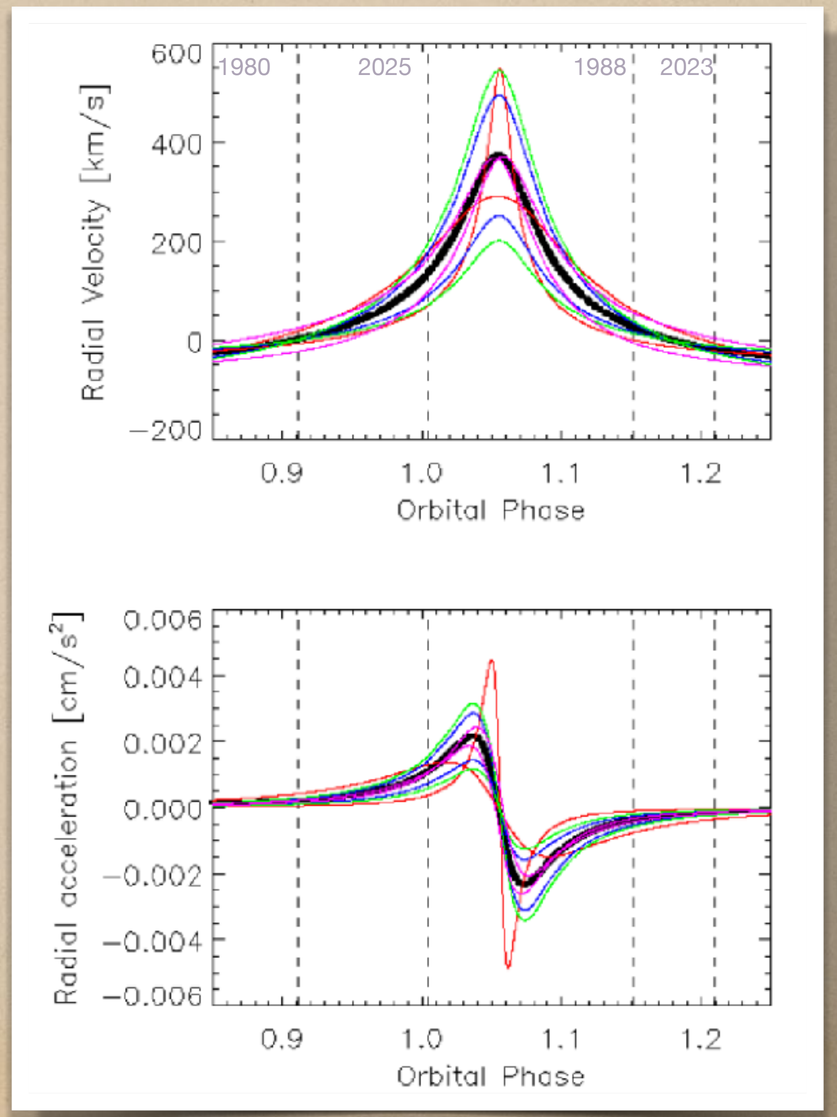
Spin-up by accretion torque requires

$$L_X \sim 1.4 \times 10^{39} \mu_{30}^{-1/3}$$

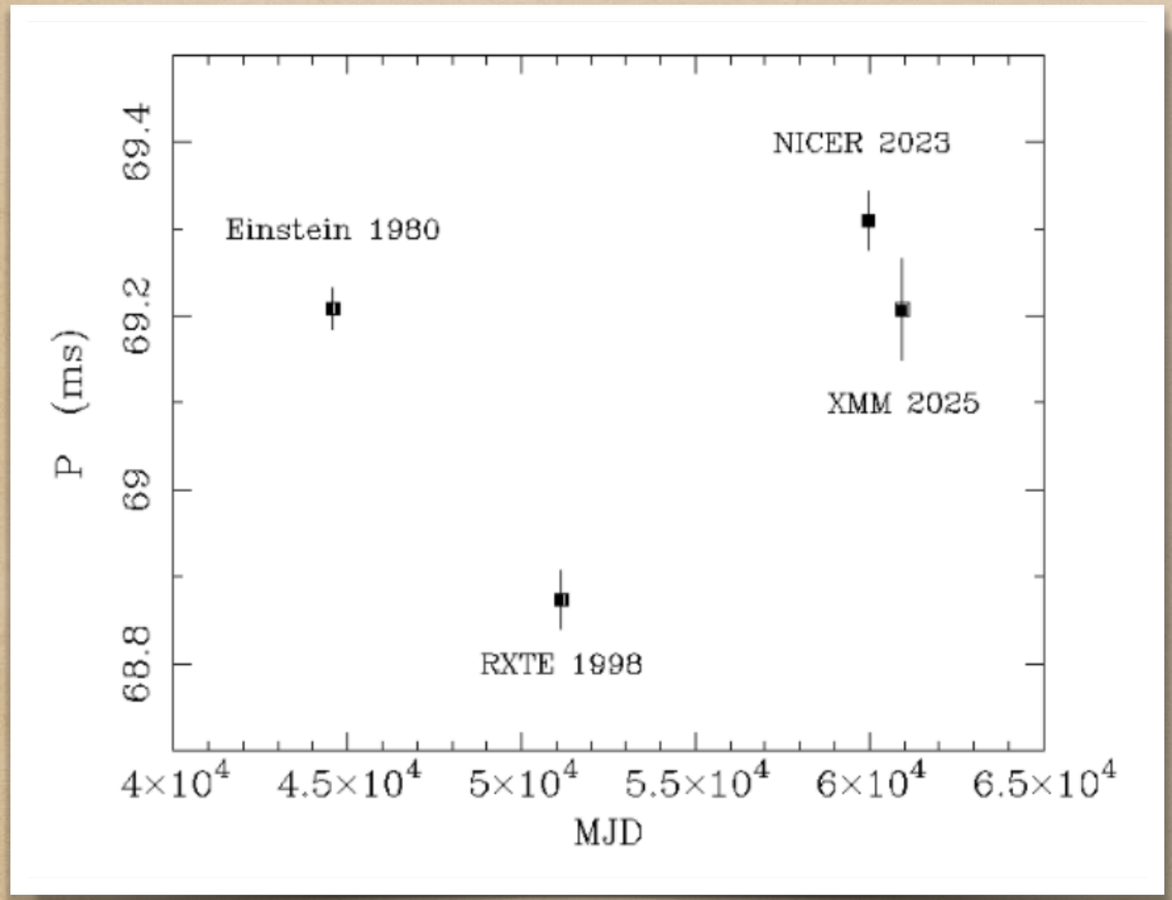
Radial velocity and acceleration of NS

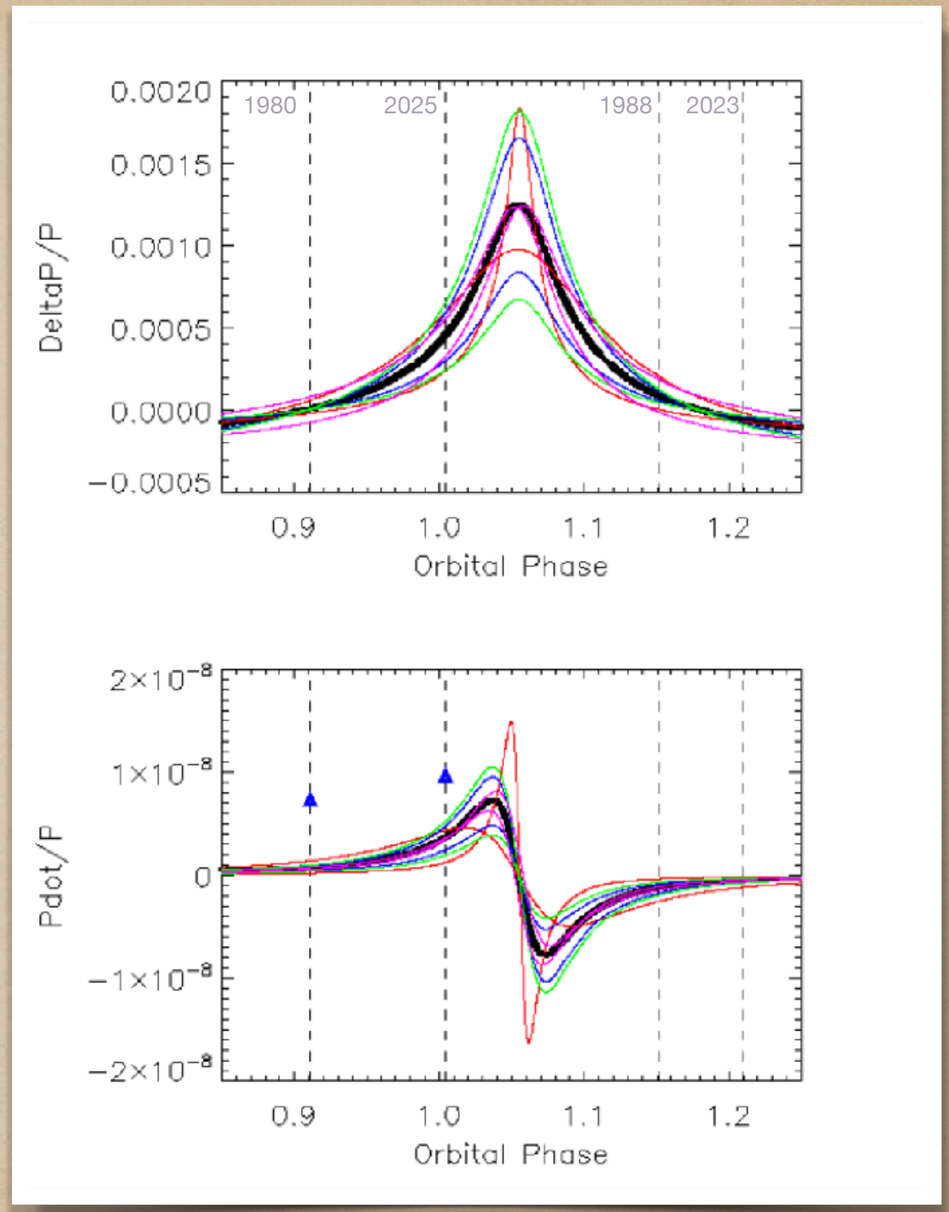




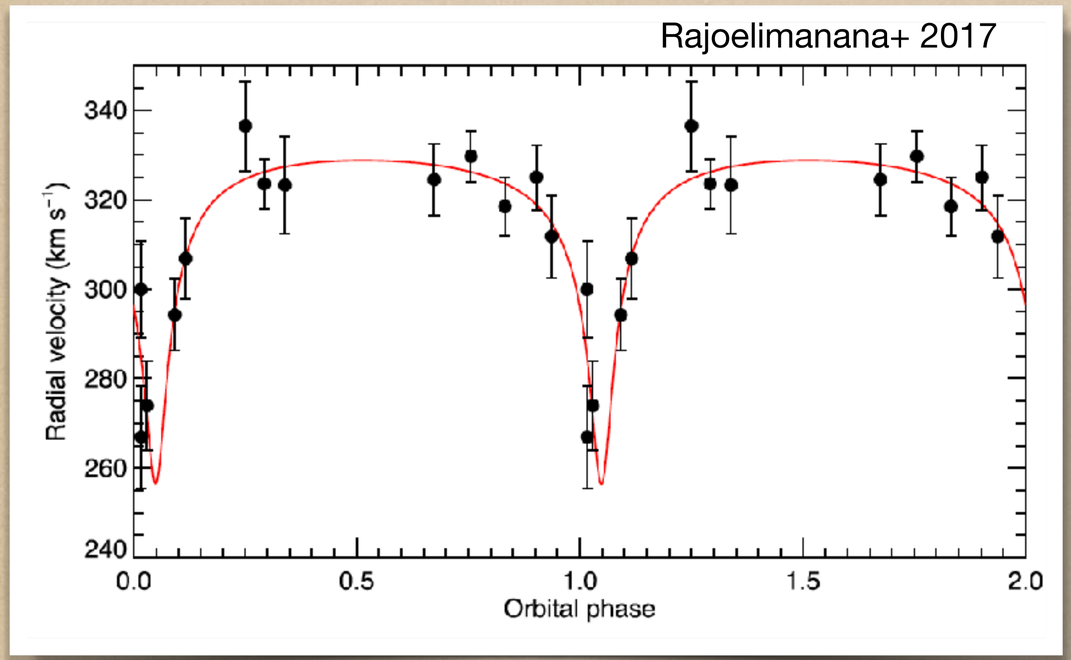


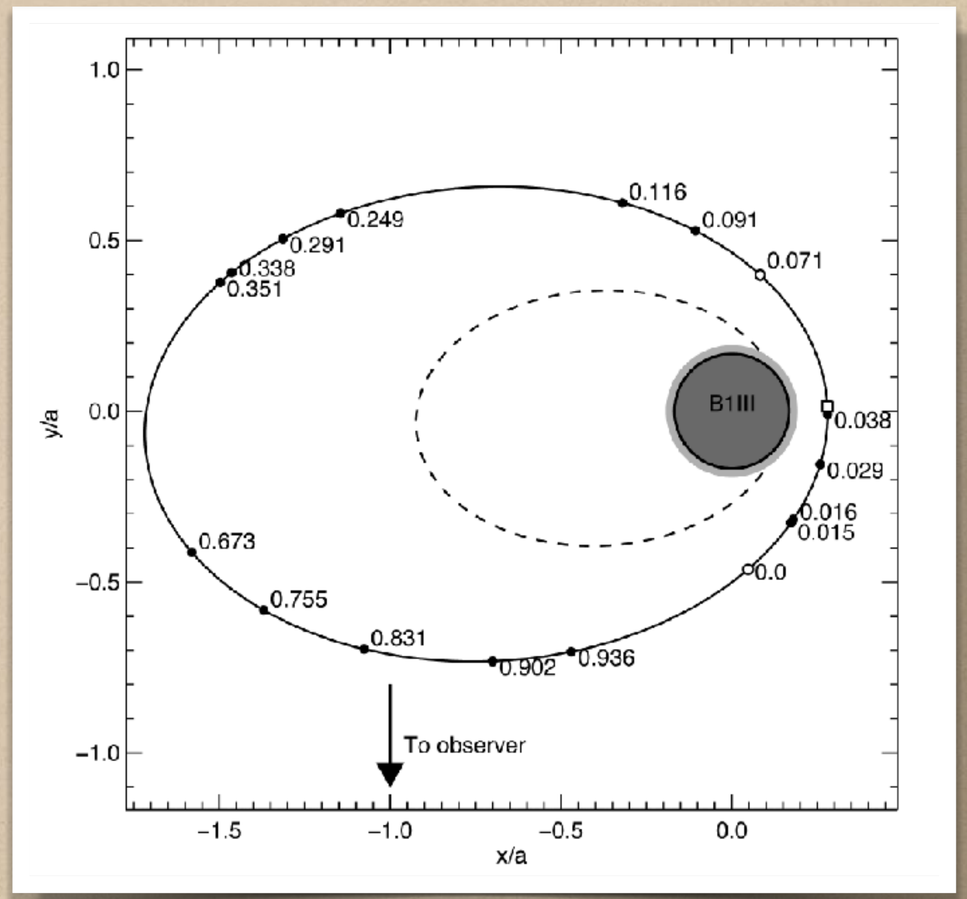
Errors on P are dominated by uncertainties on the orbit





Orbit from optical spectroscopy

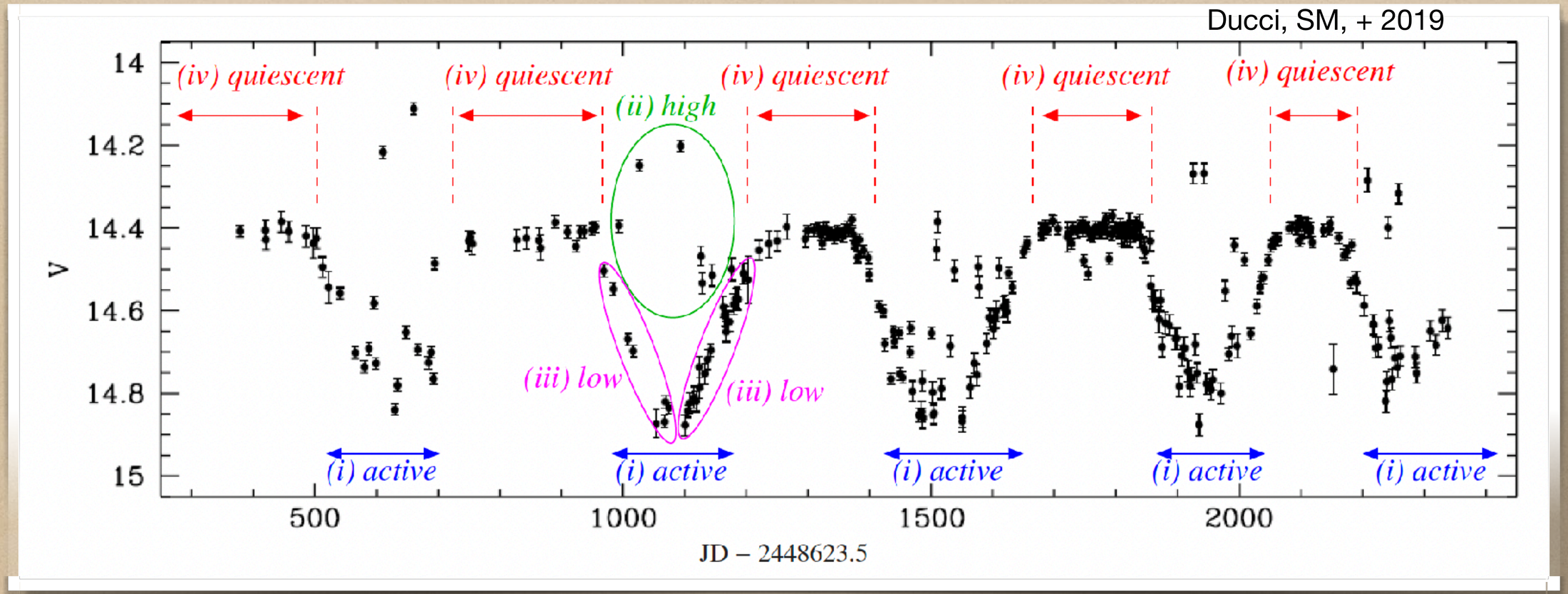




- High eccentricity: e = 0.72±0.14

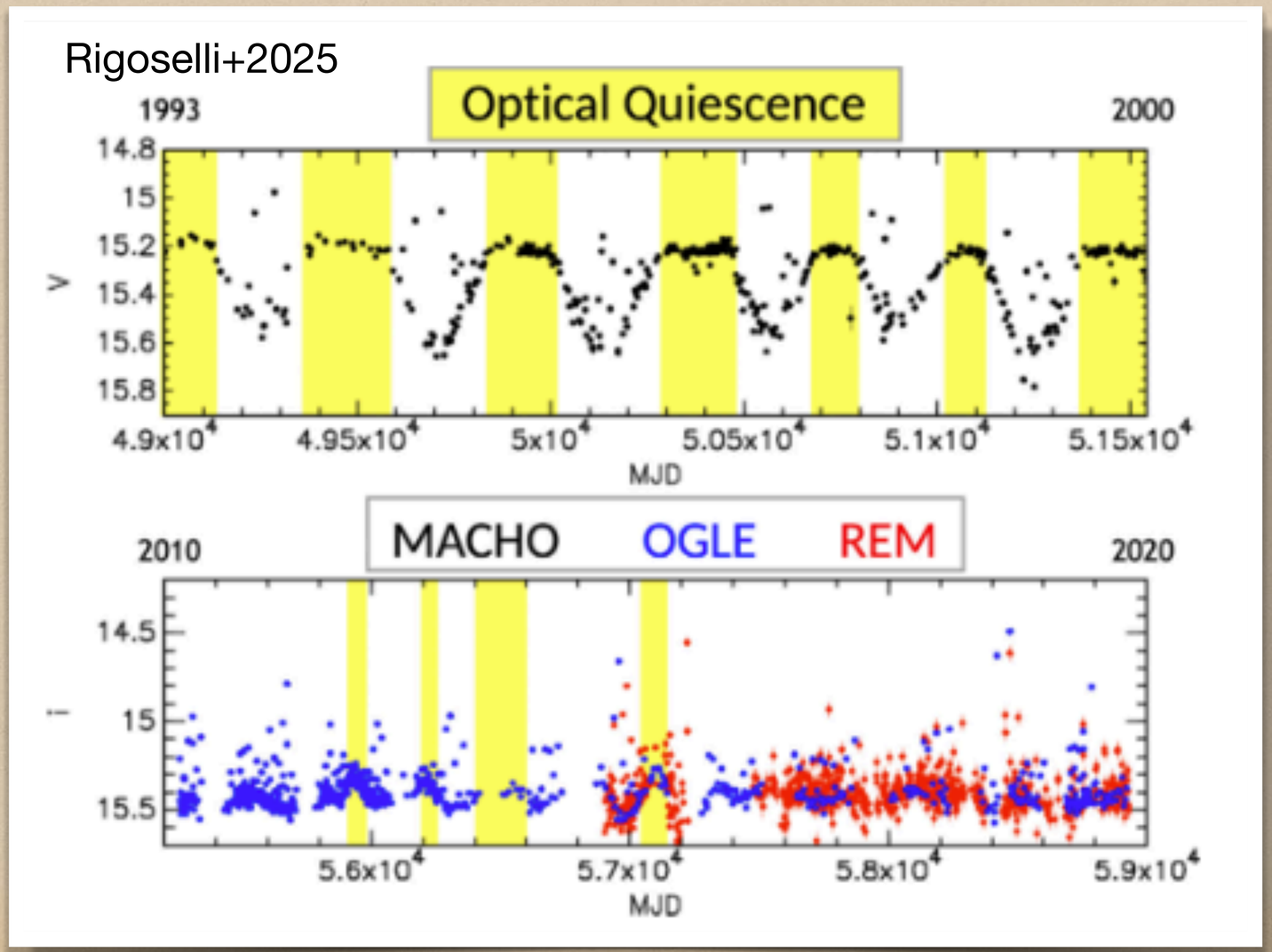
Unique optical behaviour among Be X-ray binaries

super-orbital period ≈ 421 d



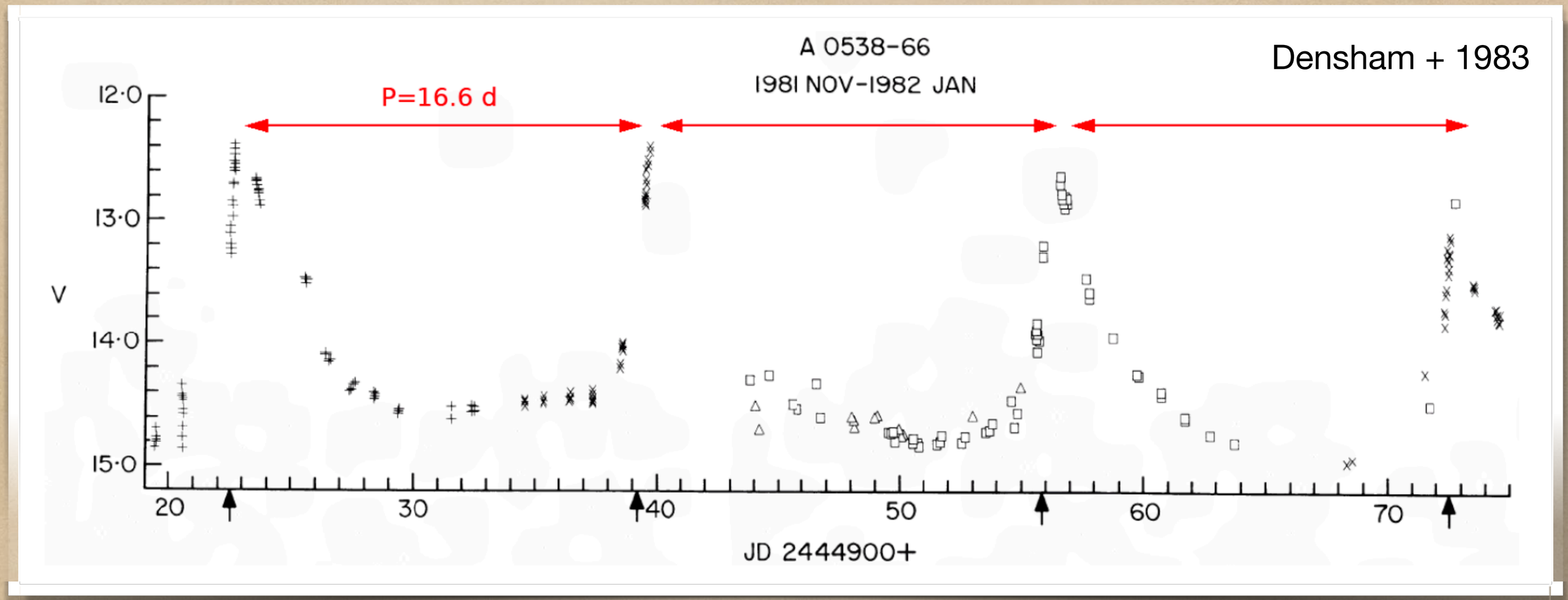
When active: periodic (orbital 16.7 d) outbursts in X-rays and optical

Quiescent periods less frequent after 2019



Circumstellar disk always present

Periodic (orbital) optical outbursts

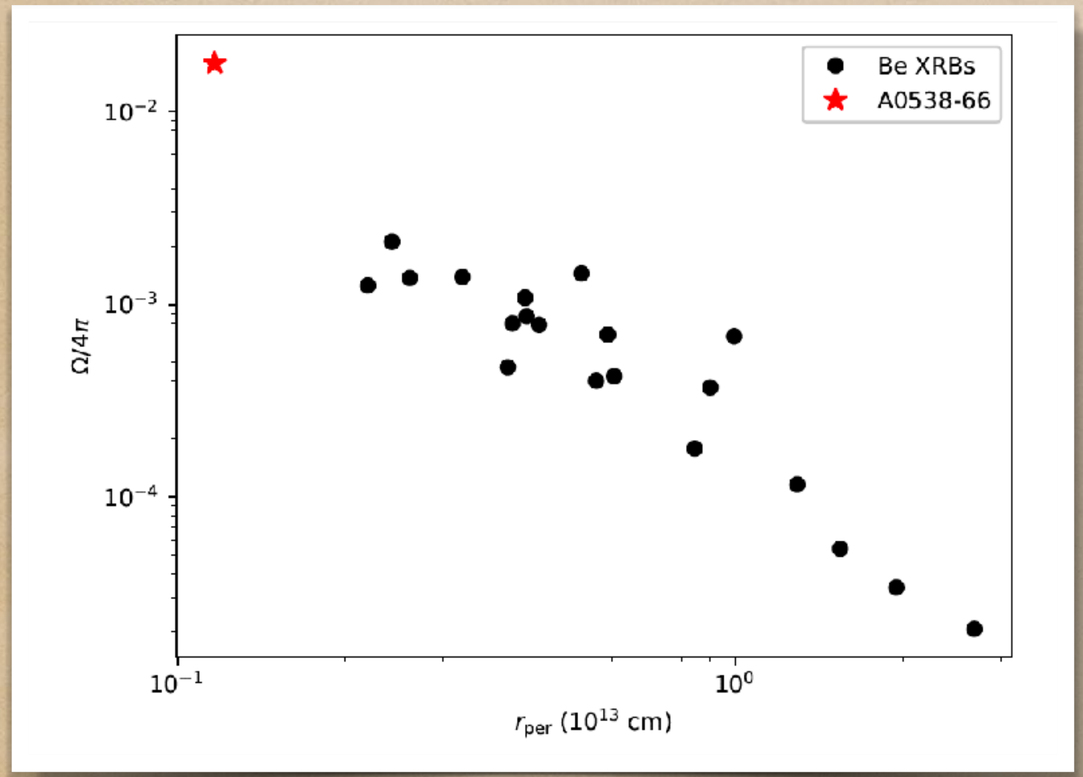


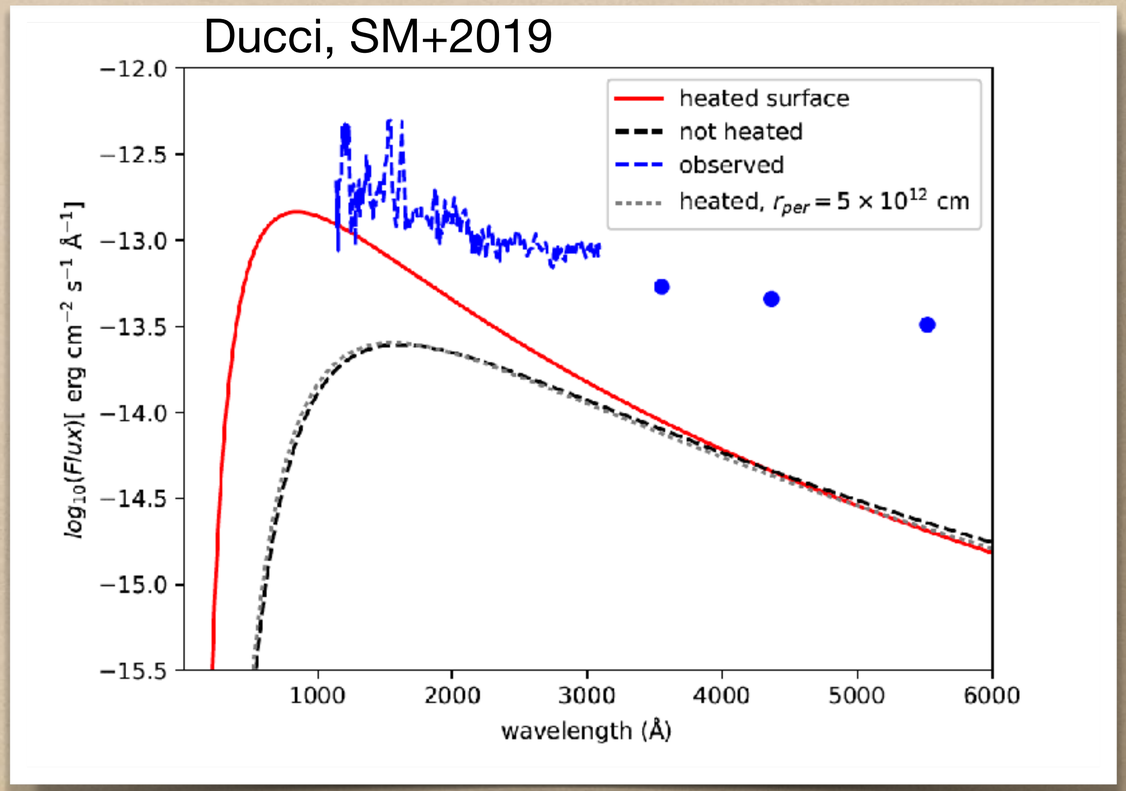
- reprocessing of X-rays in a big dense envelope $n=10^{12}$ cm^{-3}, R_{out}~3 10^{12} cm
  [Densham+83; Maraschi+83; Howarth+84; Apparao & Tarafdar 88; Ducci+19]

- reprocessing on surface of companion star → significant but not enough
  [Charles+83; Ducci, SM+19]

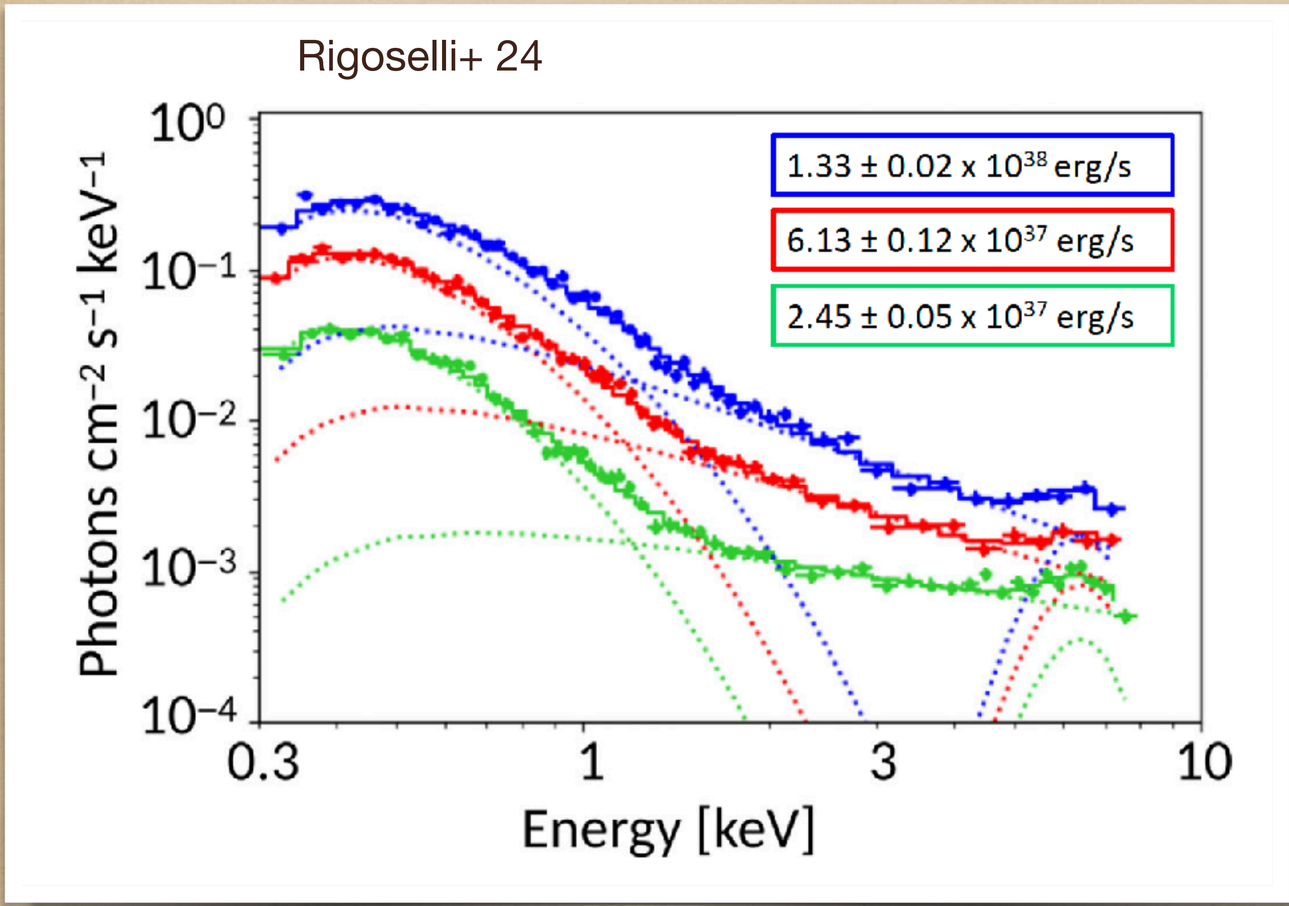
X-ray irradiation of Be star is significant
… but not enough to explain optical flares as reprocessing

Solid angle of mass donor as
seen from the NS at periastron





Bursts spectral-intensity dependence



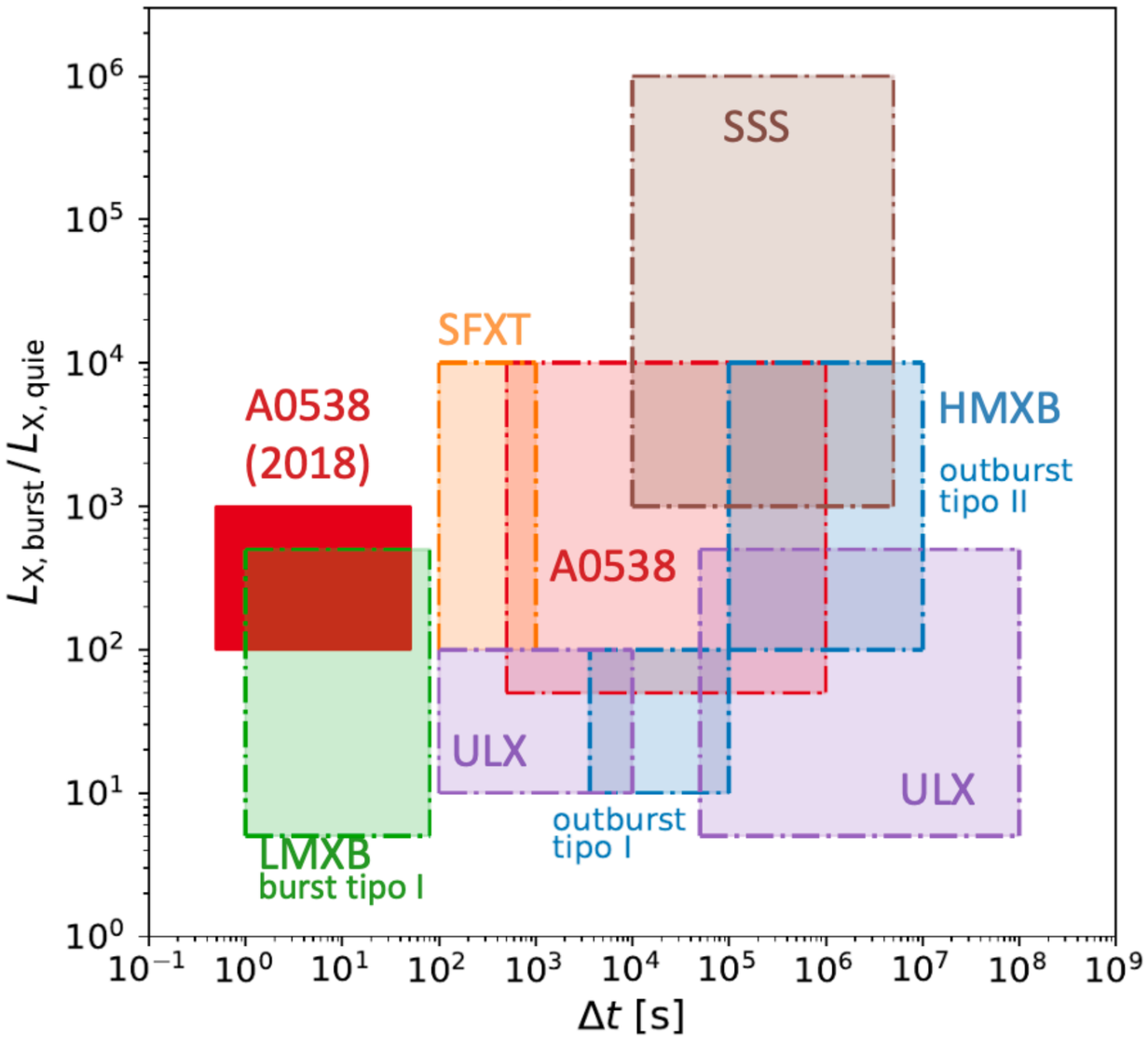
2 components + broad Fe line

As flux increases:

Brems: kT = 0.35 → 0.42 keV

PL: Γ = 0.6 → 1.2

Courtesy Caterina Tresoldi



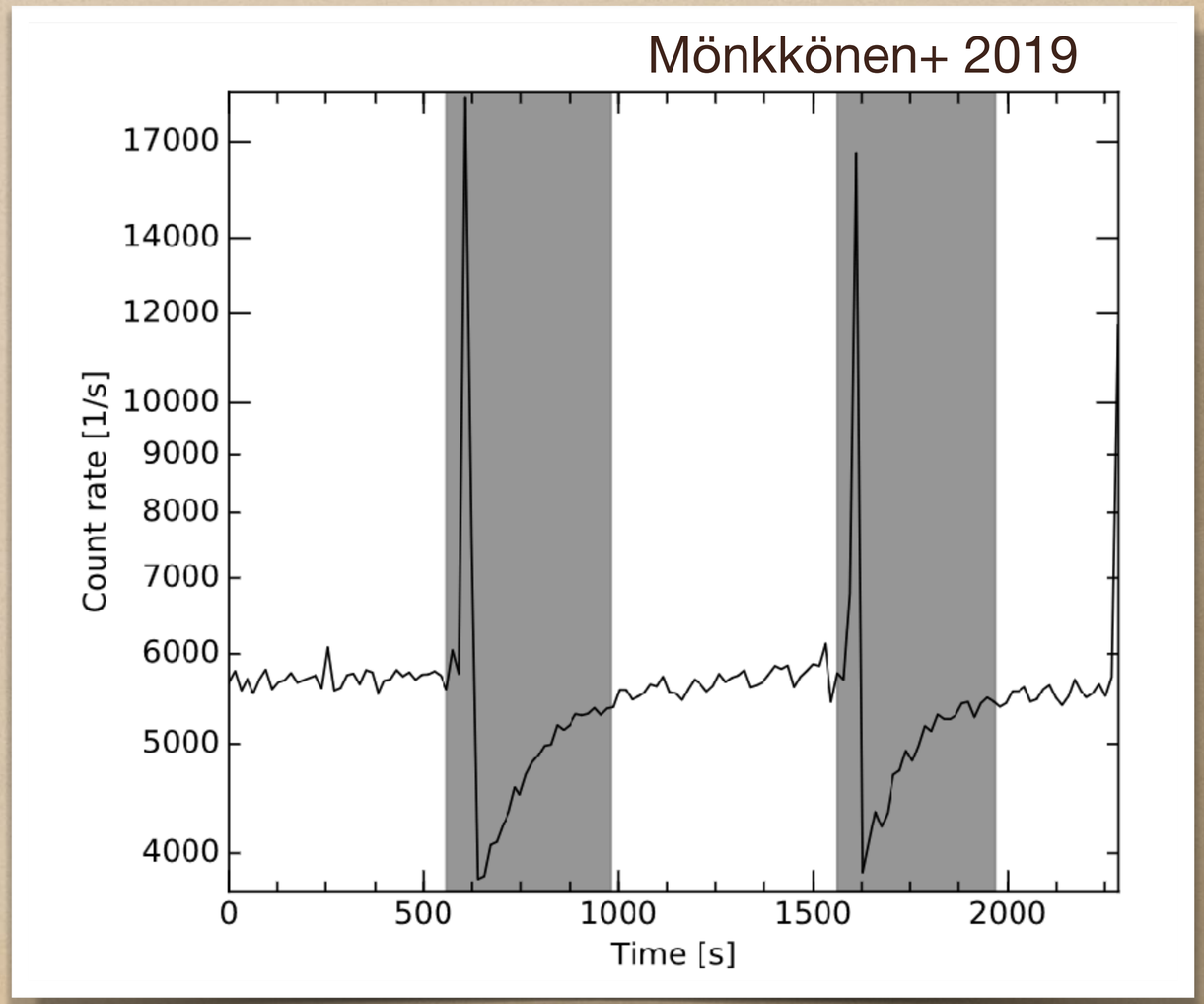
“Bursting pulsar” GRO J1744-28

P = 467 ms
Porb = 12 d

LMXB at 8 kpc ?

B~5 10^{11} G

Short bursts during super-Eddington states caused by instabilities in radiation pressure dominated accretion disk



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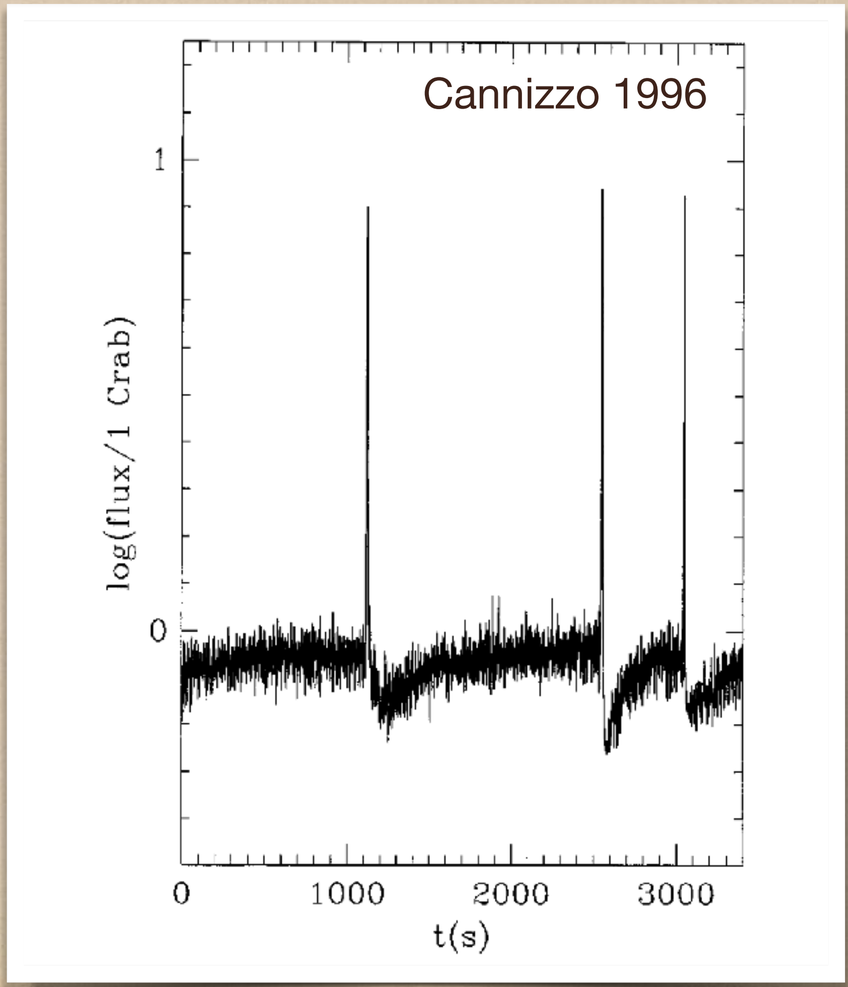
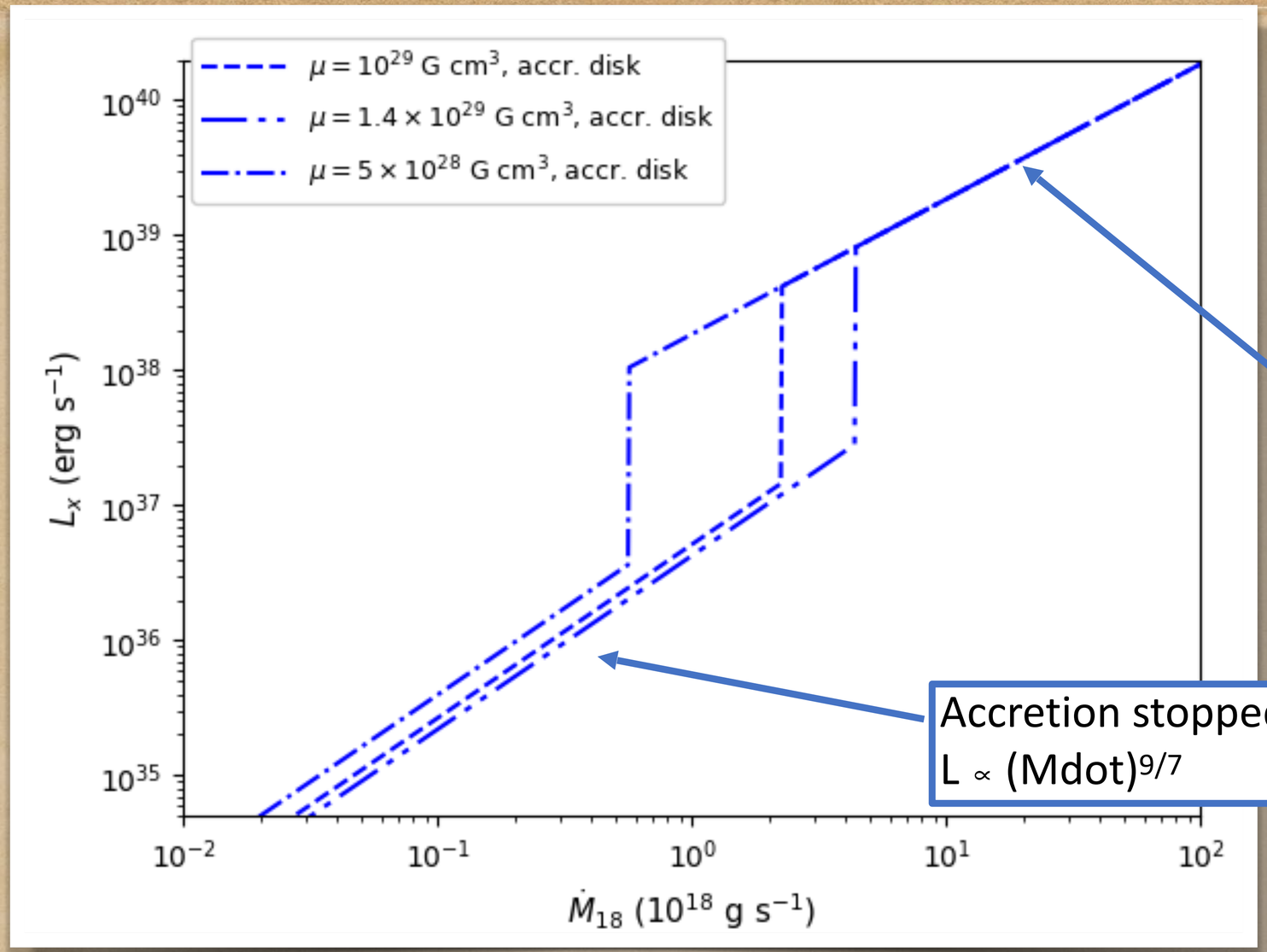


Duration ~ 10s
Recurrence ~ 1000s
Flux increase x 4-5



Centrifugal barrier with B~10^{11} G could explain well previous observations at low luminosity

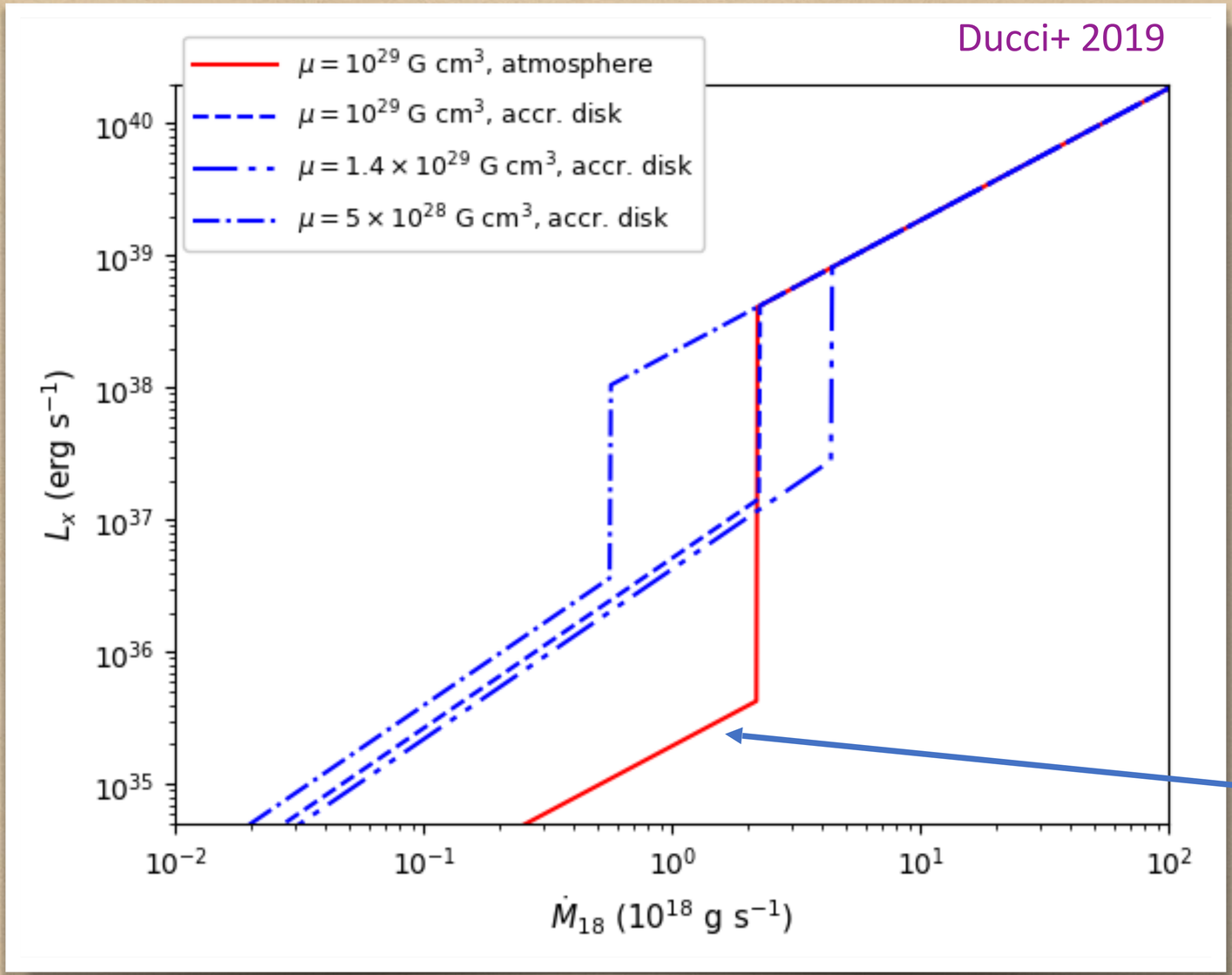
Campana 1997, Corbet+1997, Campana+2002

Accretion onto NS
L ∝ Mdot

Accretion stopped at R_M
L ∝ $(Mdot)^{9/7}$

P=69 ms → Corotation radius ~3 10^7 cm = 30 R_{NS}

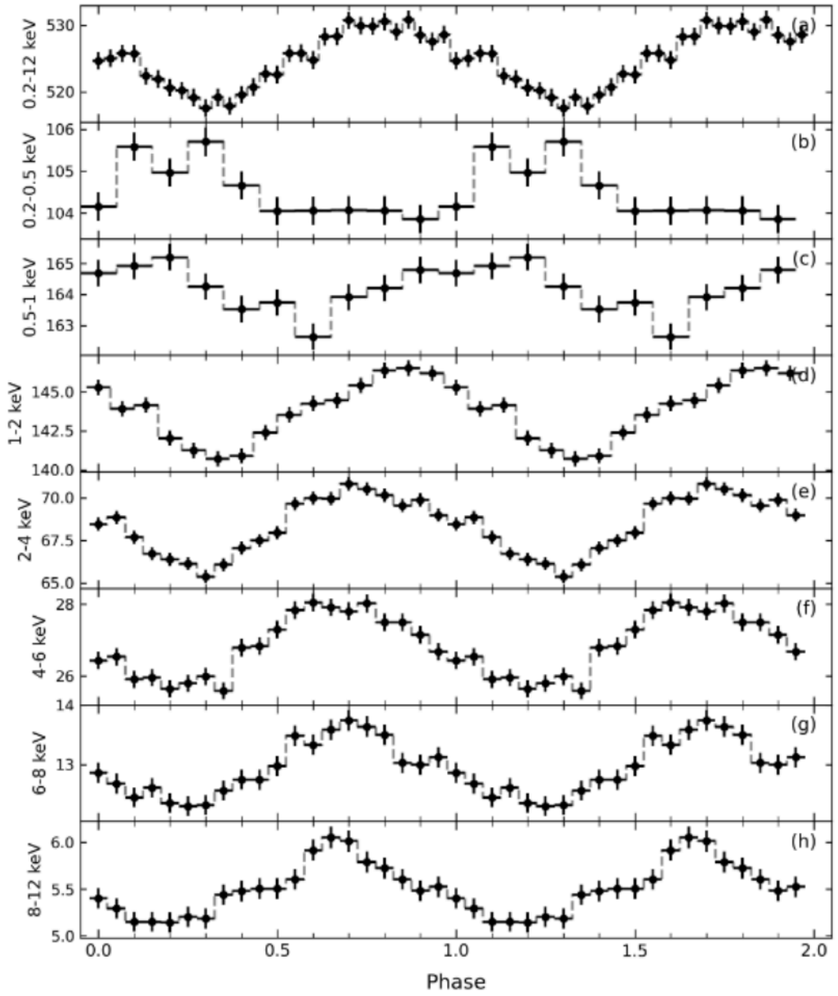
→ luminosity jump for centrifugal barrier is factor ~30 at most

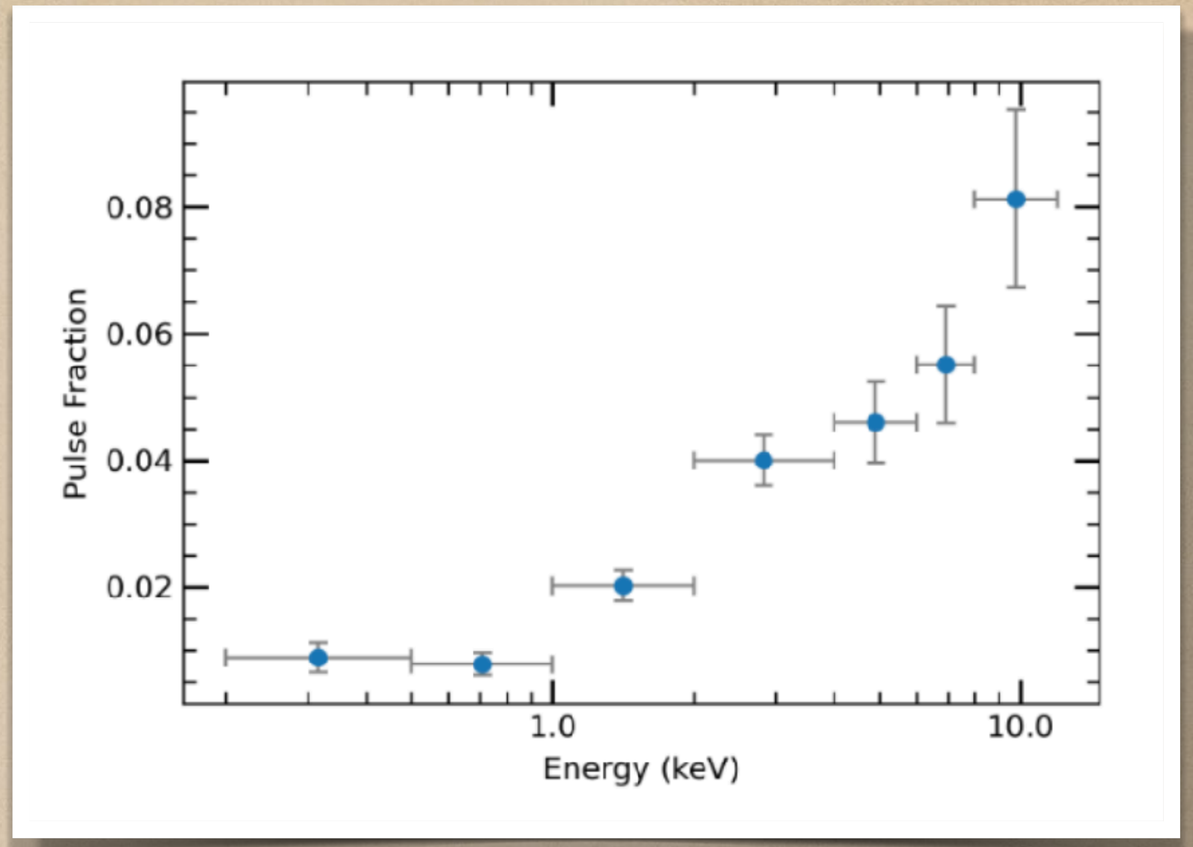


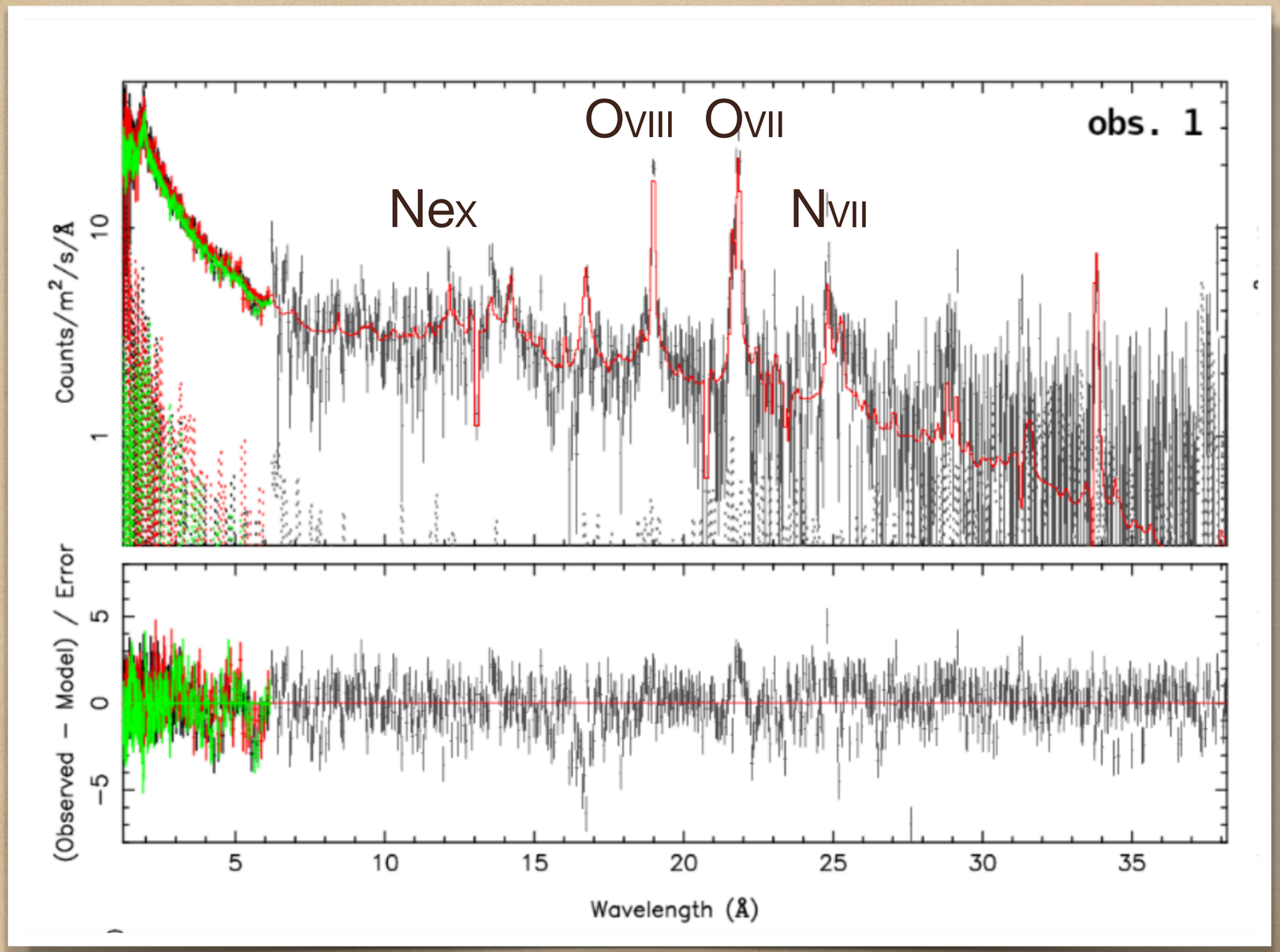
High (ΔL_X~1000) and fast (Δt~100s) variability, possibly due to accretion/ supersonic propeller transitions in a regime of spherical mass inflow, not mediated by an accretion disk

$L_{\text{magnetic reconnection}} + L_{\text{Spin-down}}$ supersonic propeller

Davies & Pringle 1981,
Lipunov 1987,
Ikhsanov 2001,2002
Elsner & Lamb 1984

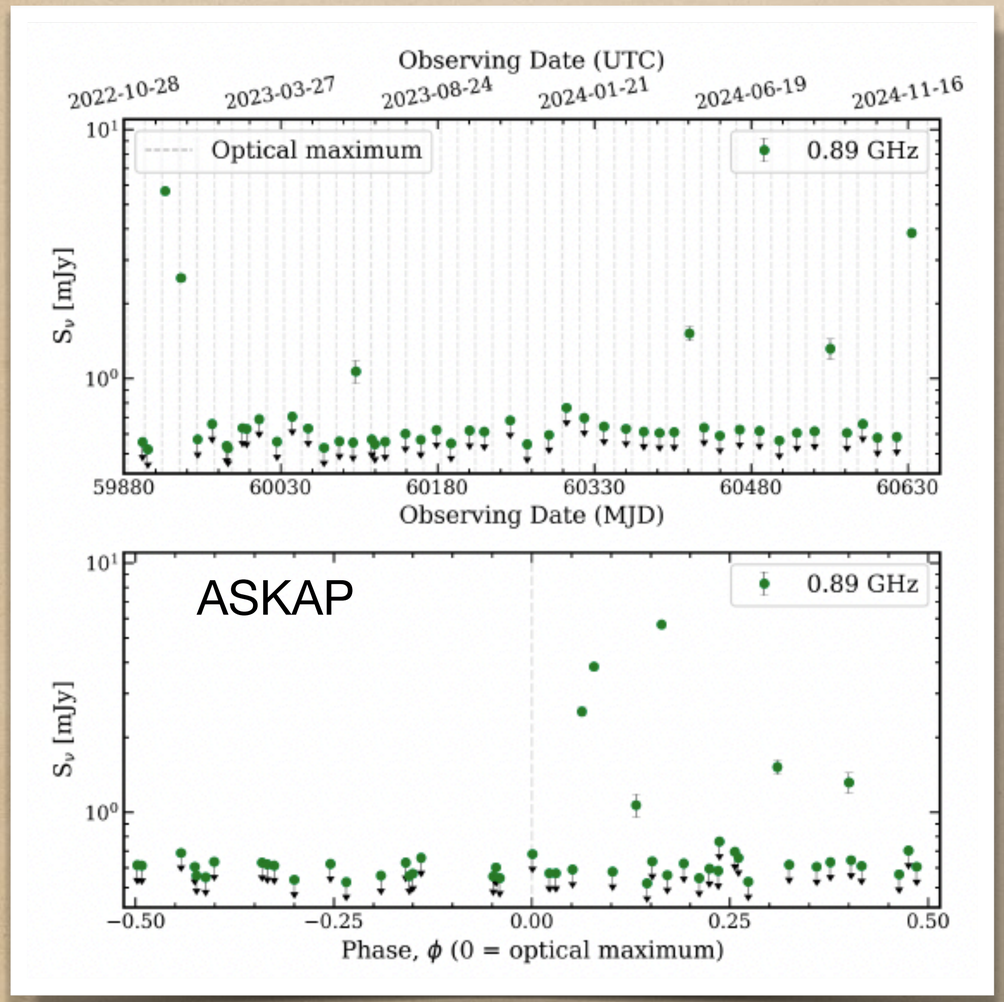

0.2-12 keV
530
520
(a)
0.2-0.5 keV
106
105
104
(b)
0.5-1 keV
165
164
163
(c)
1-2 keV
145.0
142.5
140.0
(d)
2-4 keV
70.0
67.5
65.0
(e)
4-6 keV
28
26
(f)
6-8 keV
14
13
(g)
8-12 keV
6.0
5.5
5.0
(h)
0.0
0.5
1.0
1.5
2.0
Phase

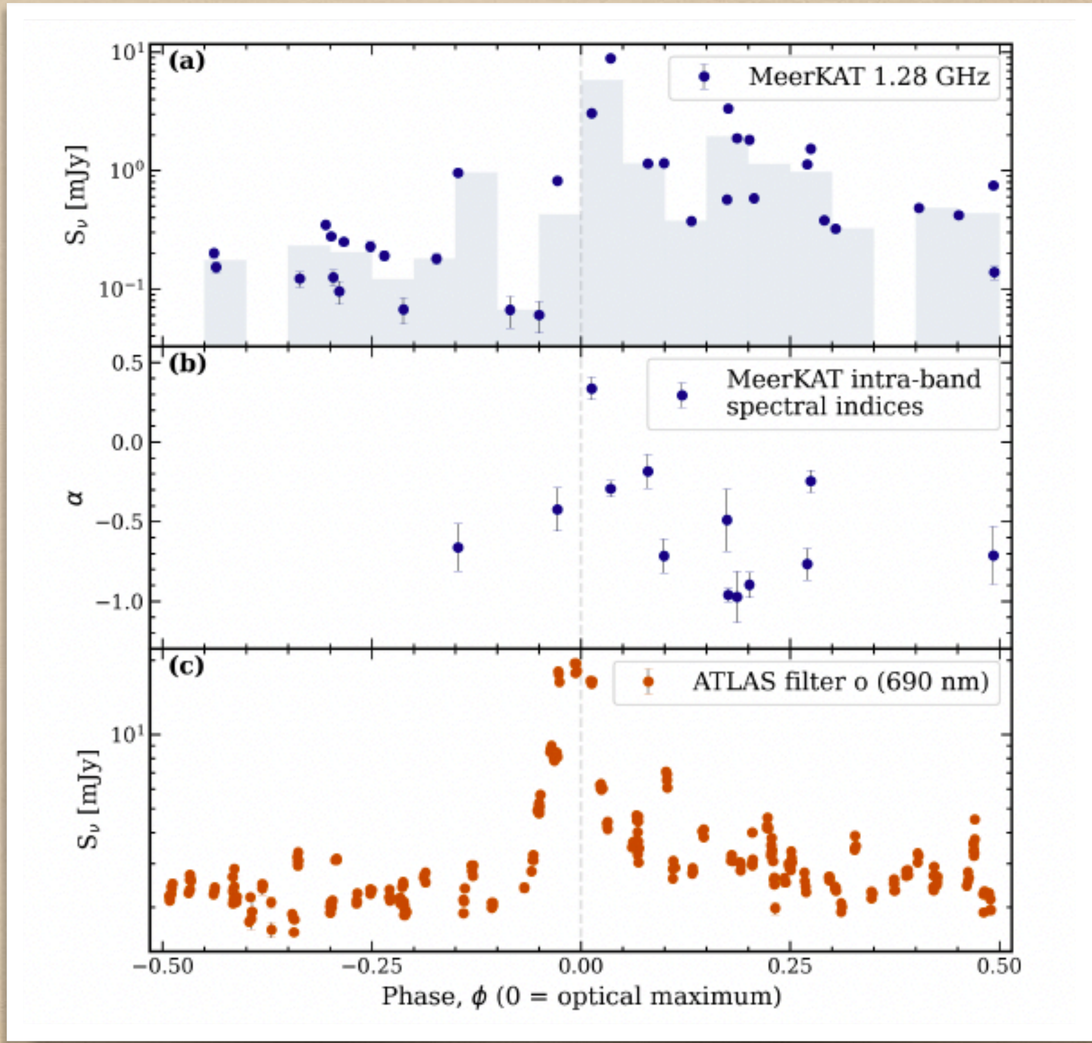

Pulse Fraction
0.08
0.06
0.04
0.02
1.0
10.0
Energy (keV)


OVIII
OVII
obs. 1
NeX
NVII
Counts/m²/s/Å
10
1
(Observed − Model) / Error
5
0
−5
5
10
15
20
25
30
35
Wavelength (Å)

Discovery of radio emission from A0538-66

[Crook-Mansour+ 2026]





Properties of radio emission [Crook-Mansour+ 2026]

- Variable F ~ 0.1-10 mJy @ 1.3 GHz
- Orbitally modulated
- Variable spectrum
  α = -1 to +0.5
- Not polarised

- Thermal emission from wind unlikely (α, mass loss too low)

- Likely synchrotron in relativistic jet/ ejecta or shock with Be wind as in gamma-binaries