Matteo Bachetti
(INAF-OA Cagliari)

Ultraluminous X-ray Sources - I

Broadband and timing properties

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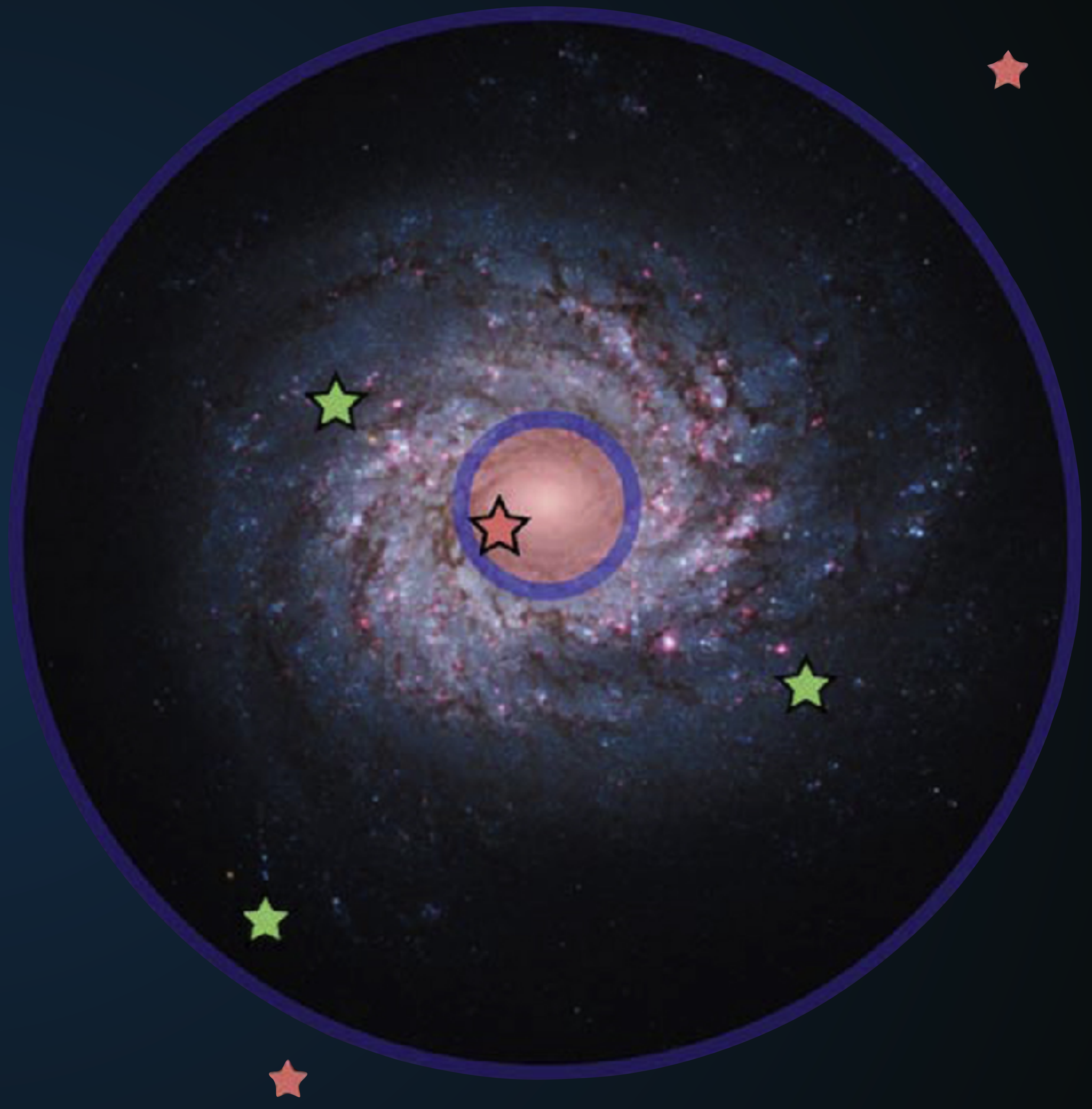
GENERAL PROPERTIES

DEFINITION

Ultraluminous X-ray sources are *off-nuclear, point-like* X-ray sources exceeding the (isotropic) Eddington limit for a stellar-mass Black Hole (StBH)

$L_{ULX} > 3 \times 10^{39}$ erg/s



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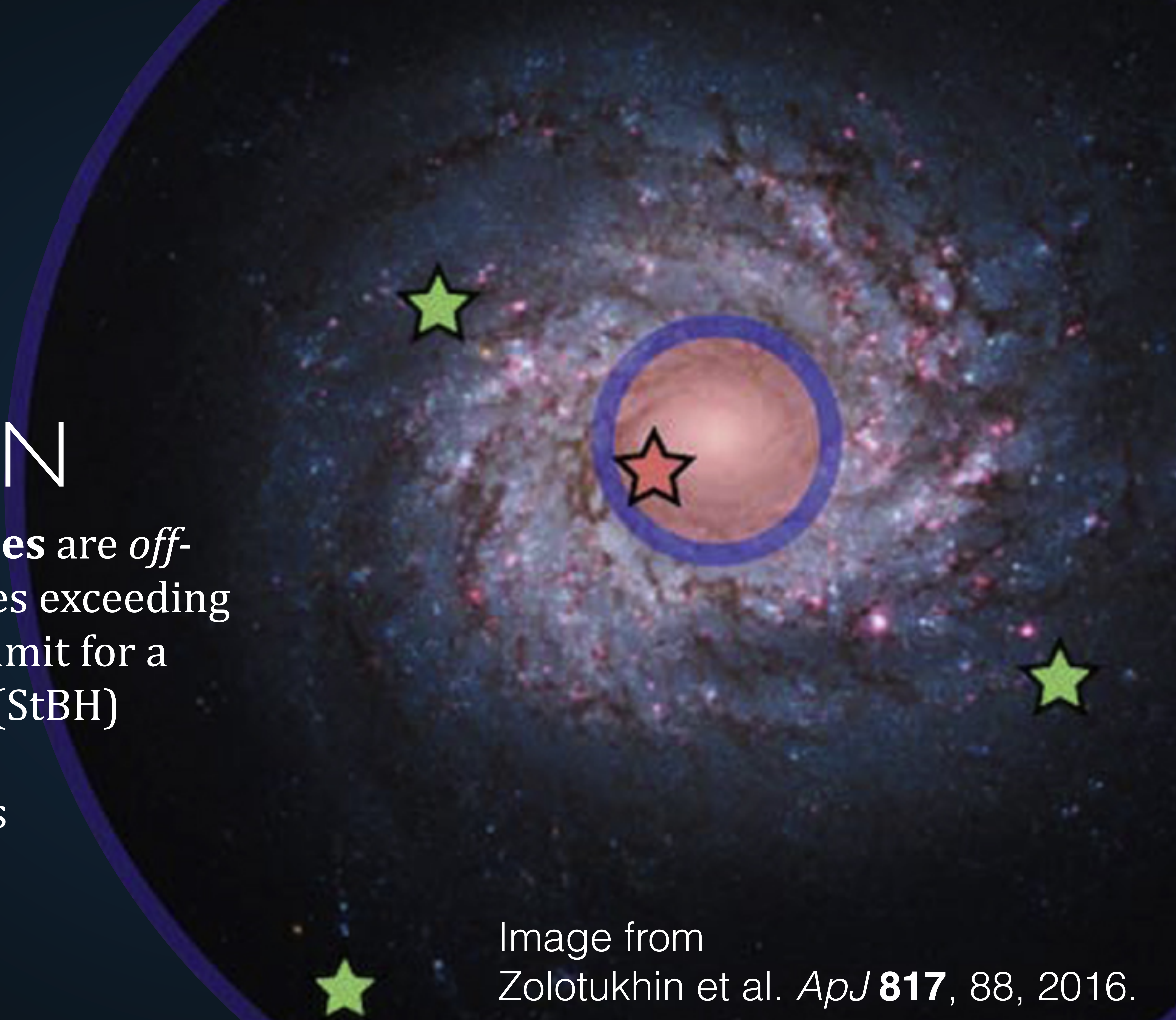


Image from
Zolotukhin et al. *ApJ* **817**, 88, 2016.

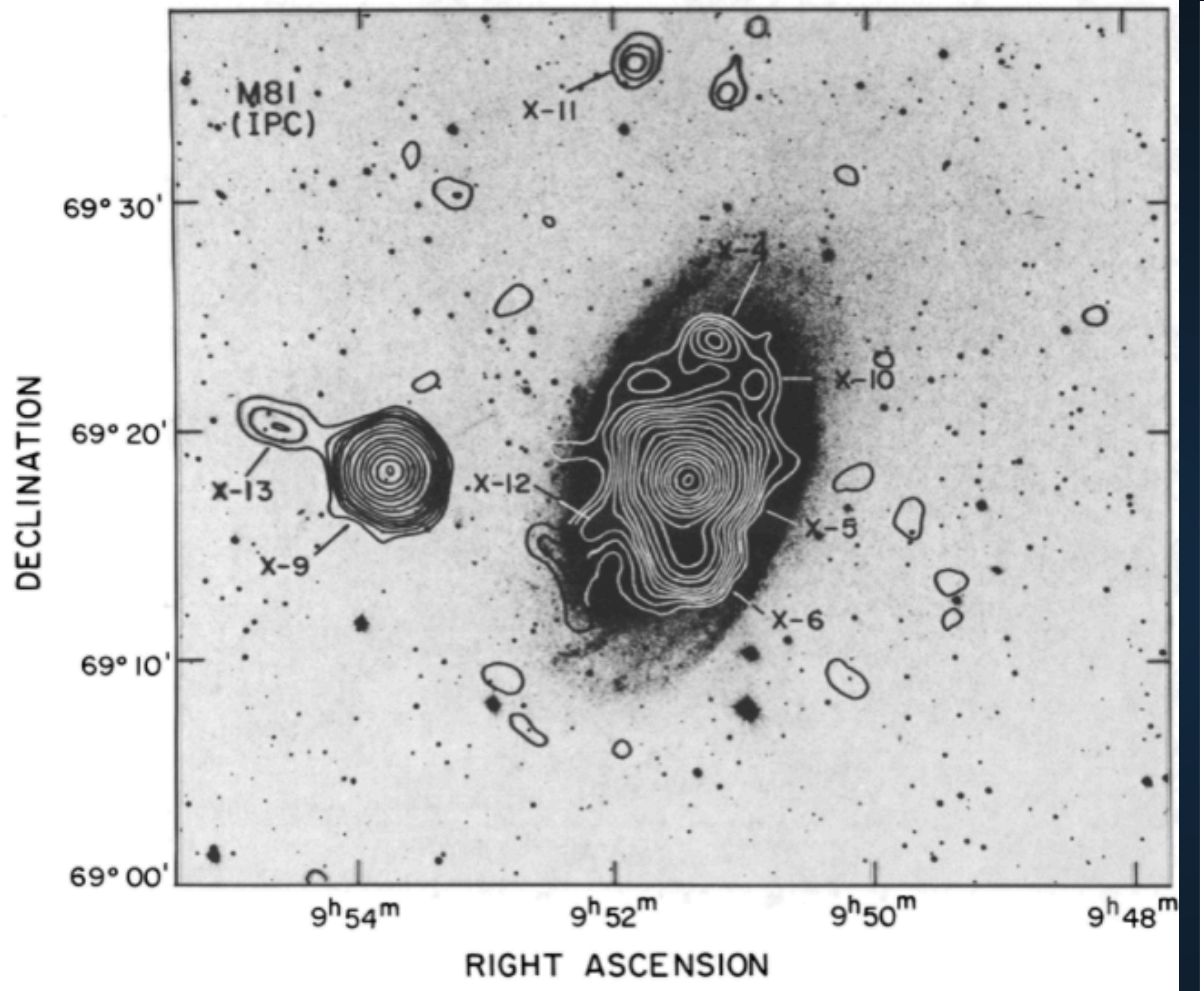


FIG. 2.—IPC contour map of M81 overlaid on the POSS O plate. The first contour is at 2 σ above the field background. Discrete sources detected in the IPC image are indicated by an X followed by a number. Data were smoothed with a Gaussian with $\sigma_G = 35''$. The equivalent Gaussian sigma of a point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

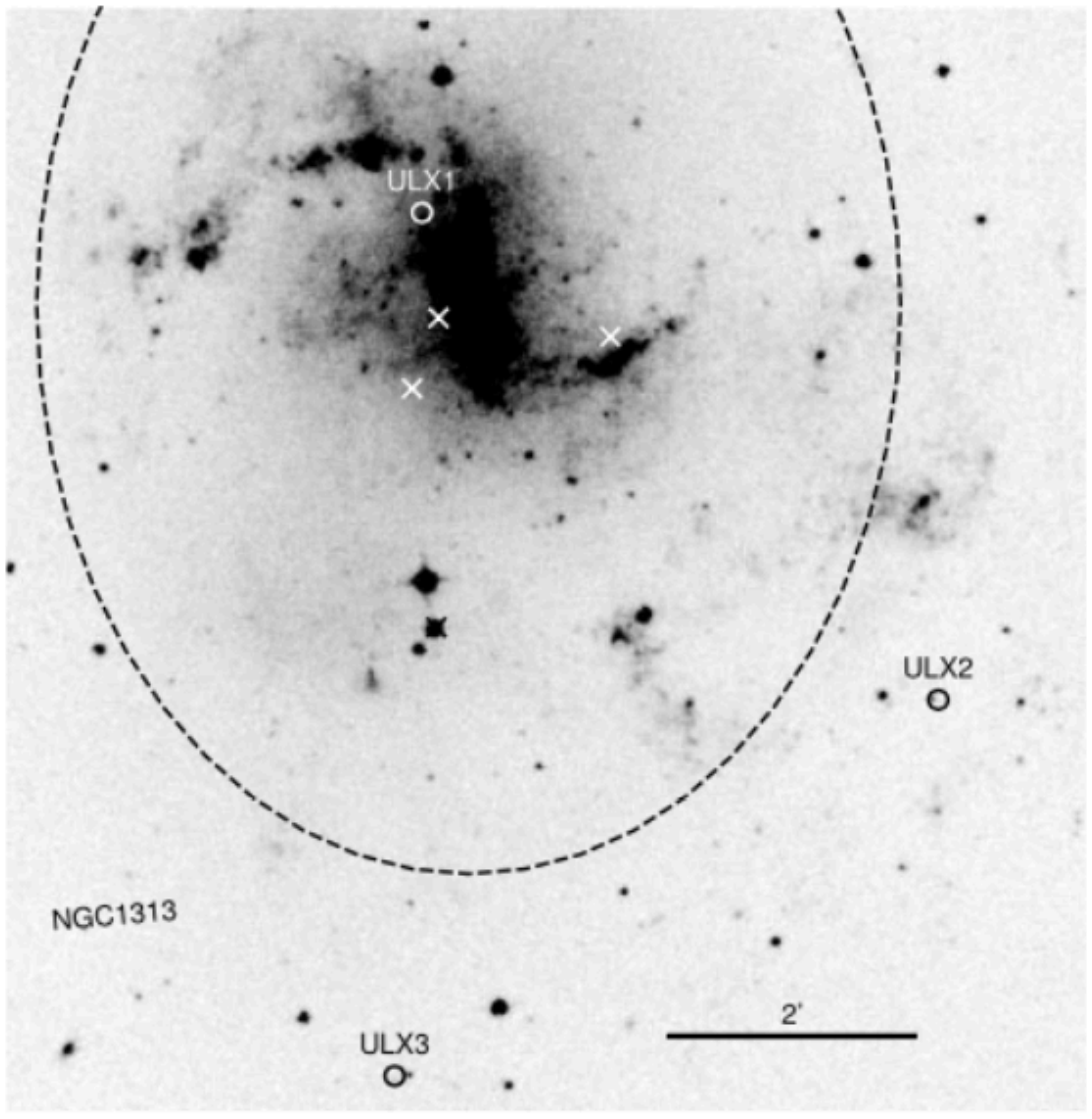


FIG. 23.—Finding chart for the ULXs in NGC 1313.

EINSTEIN -
Fabbiano, *ApJ*, 325, 544–562, 1988.

ROSAT -
Liu & Bregman, *ApJ*, 642 171–187, 2006.

ULTRALUMINOUS X-RAY SOURCES IN EXTERNAL GALAXIES

A. R. King,[1] M. B. Davies,[1] M. J. Ward,[1] G. Fabbiano,[2] and M. Elvis[2]

Received 2001 February 22; accepted 2001 April 4; published 2001 April 30

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

SUPER-EDDINGTON FLUXES FROM THIN ACCRETION DISKS?

Mitchell C. Begelman[1]
JILA, University of Colorado, 440 UCB, Boulder, CO 80309-0440; mitch@jila.colorado.edu

Received 2002 January 22; accepted 2002 February 28; published 2002 March 6

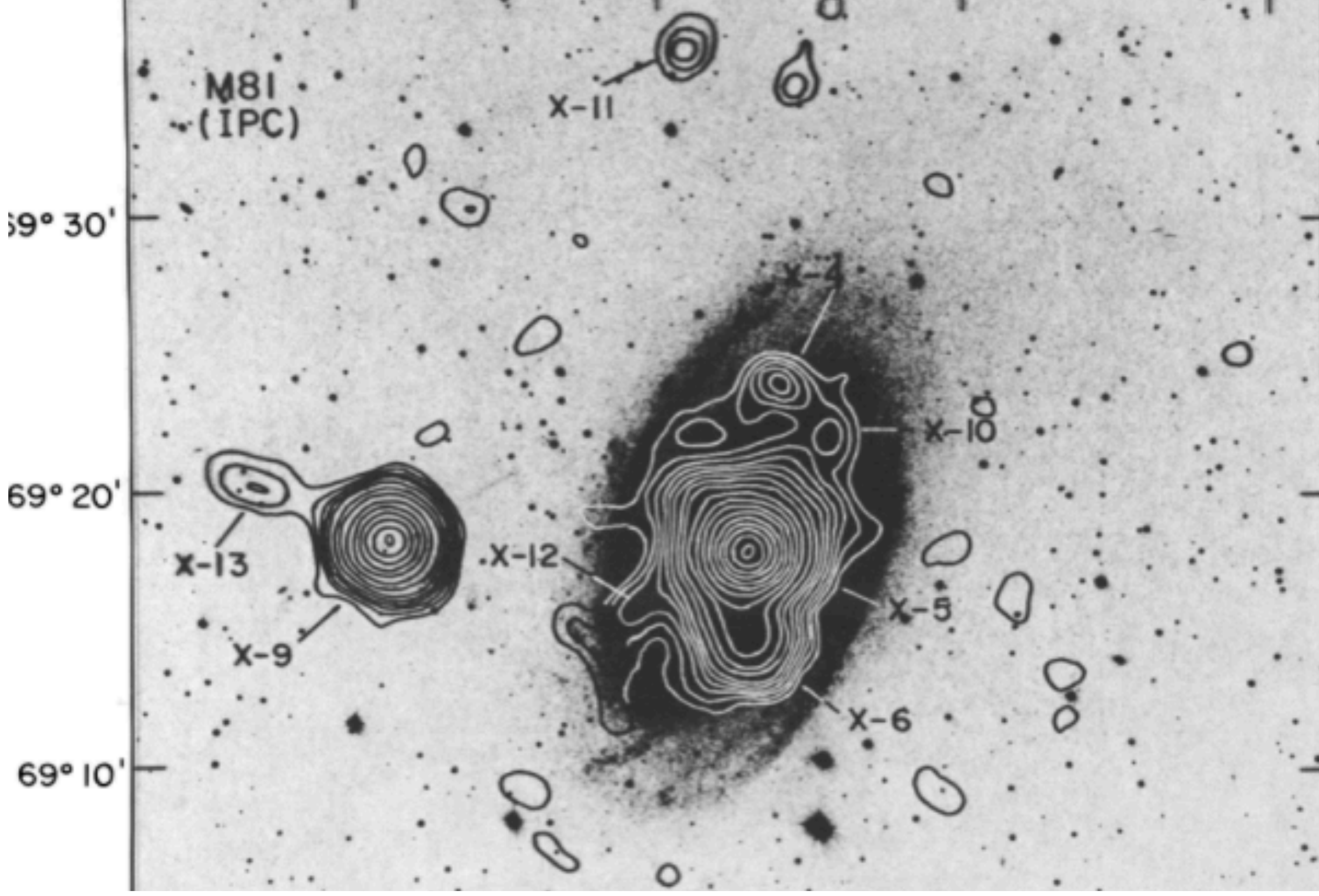
ABSTRACT

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

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

P. Kaaret,[1★] A. H. Prestwich,[1] A. Zezas,[1] S. S. Murray,[1] D.-W. Kim,[1] R. E. Kilgard,[1] E. M. Schlegel[1] and M. J. Ward[2]

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.



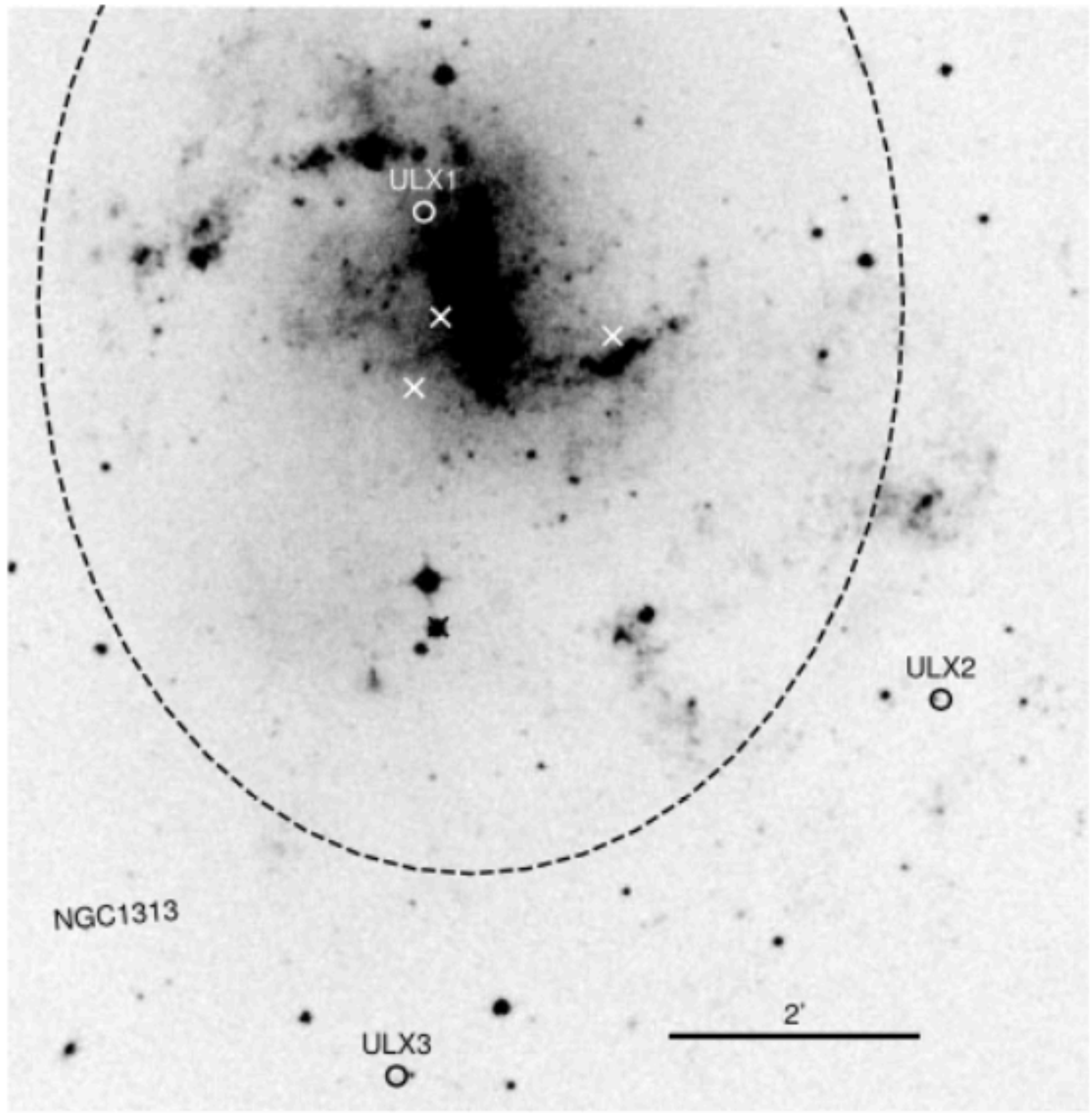
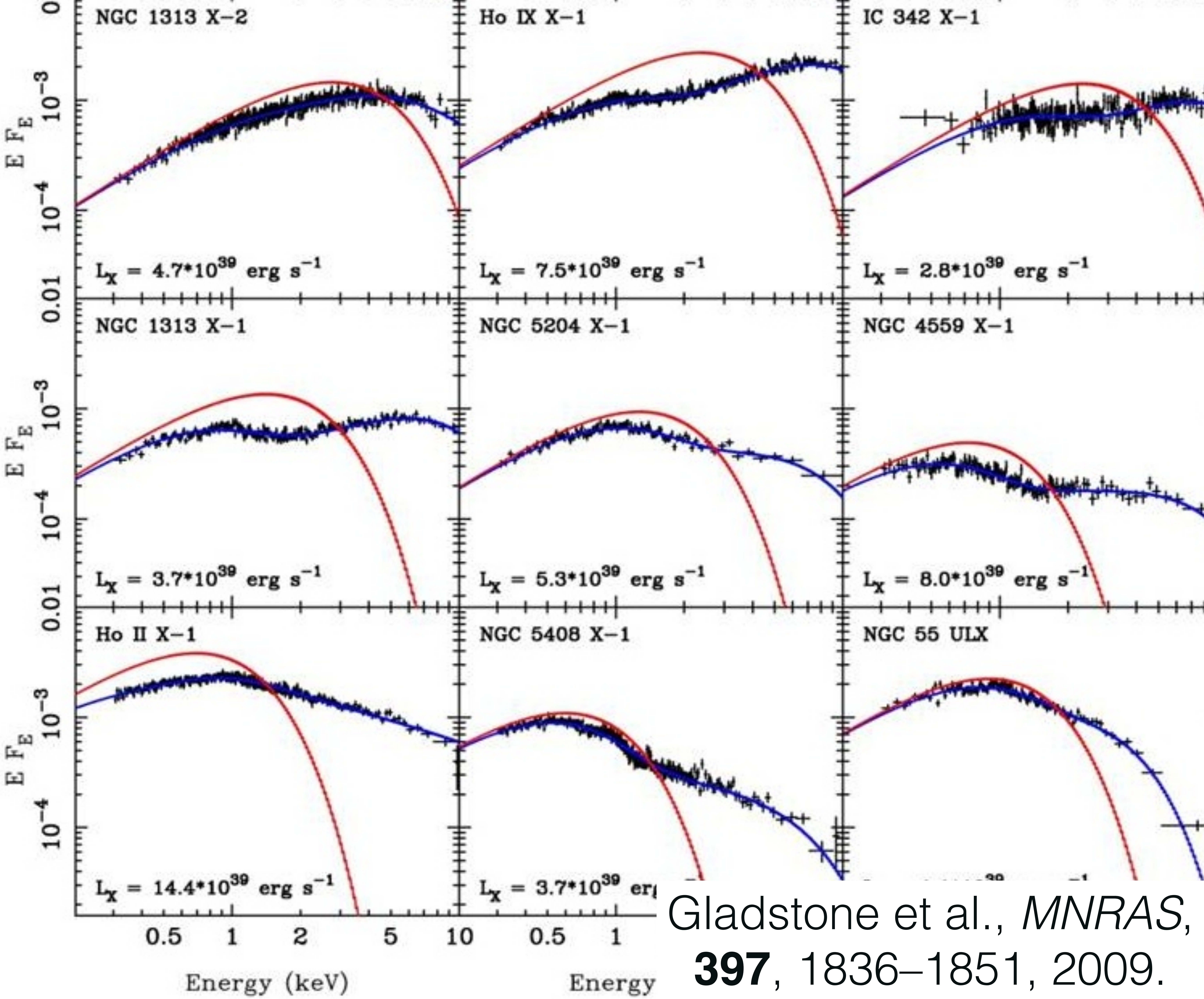
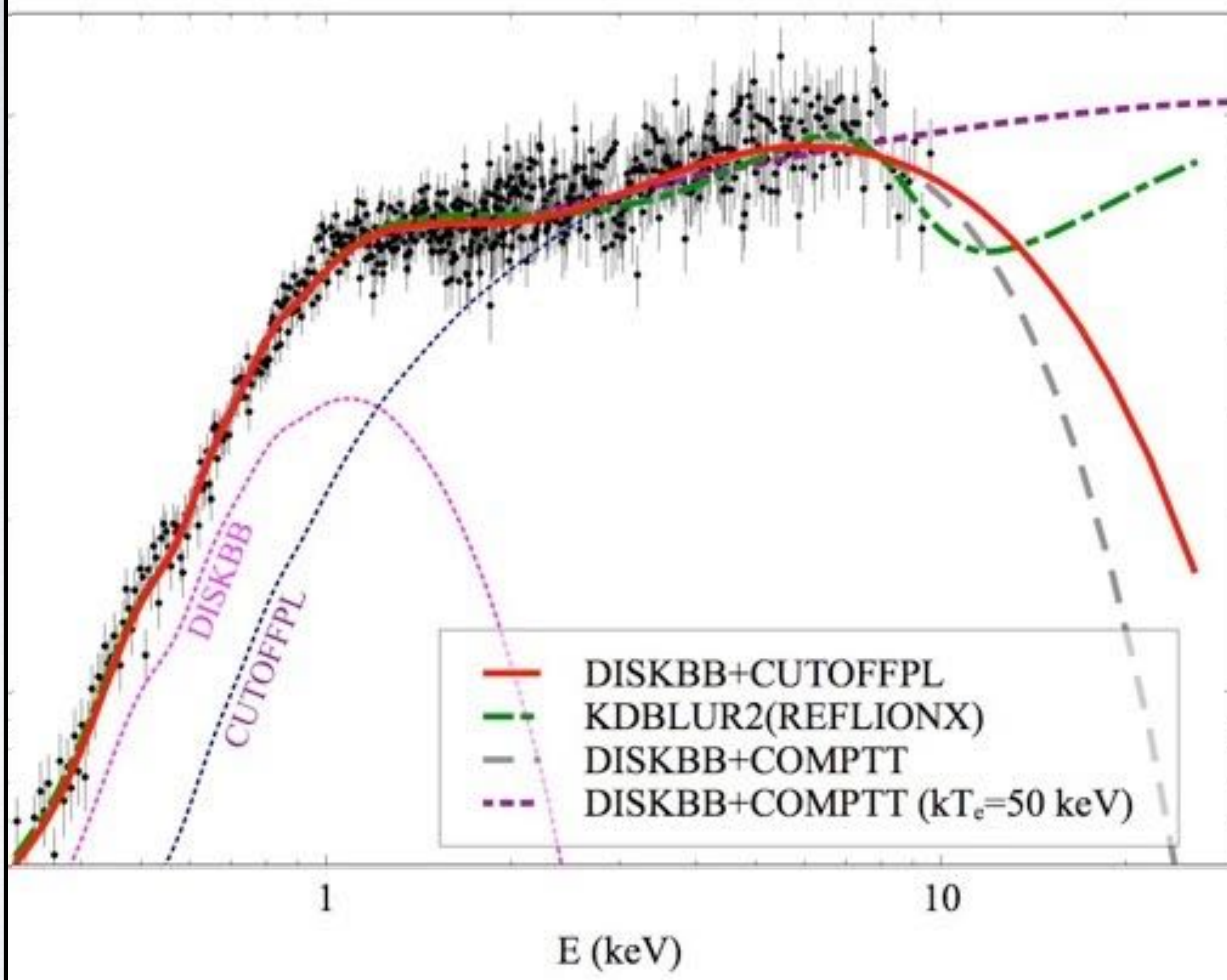


Fig. 23.—Finding chart for the ULXs in NGC 1313.

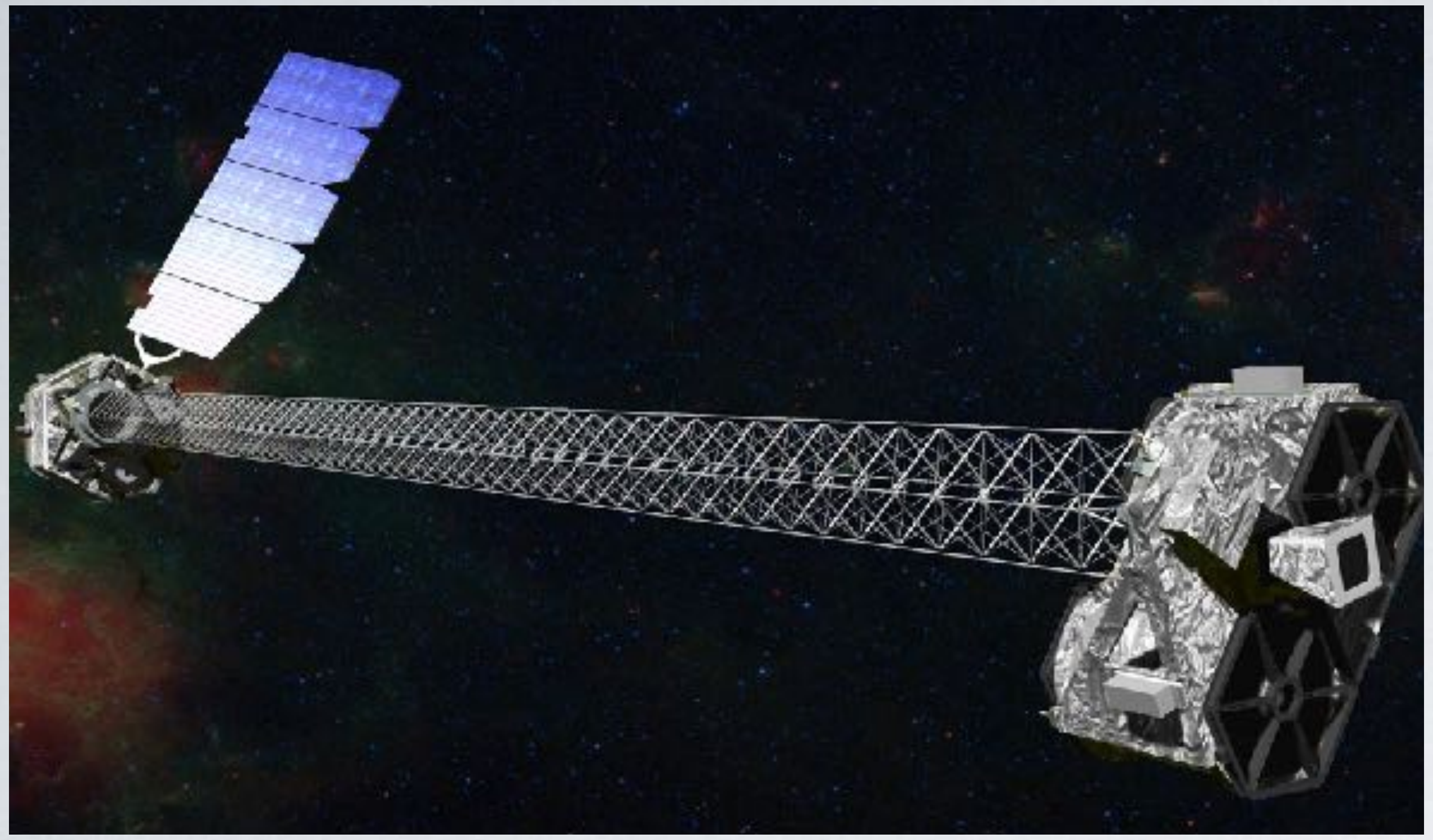
Curvature above ~10 keV?



Gladstone et al., *MNRAS*, **397**, 1836–1851, 2009.

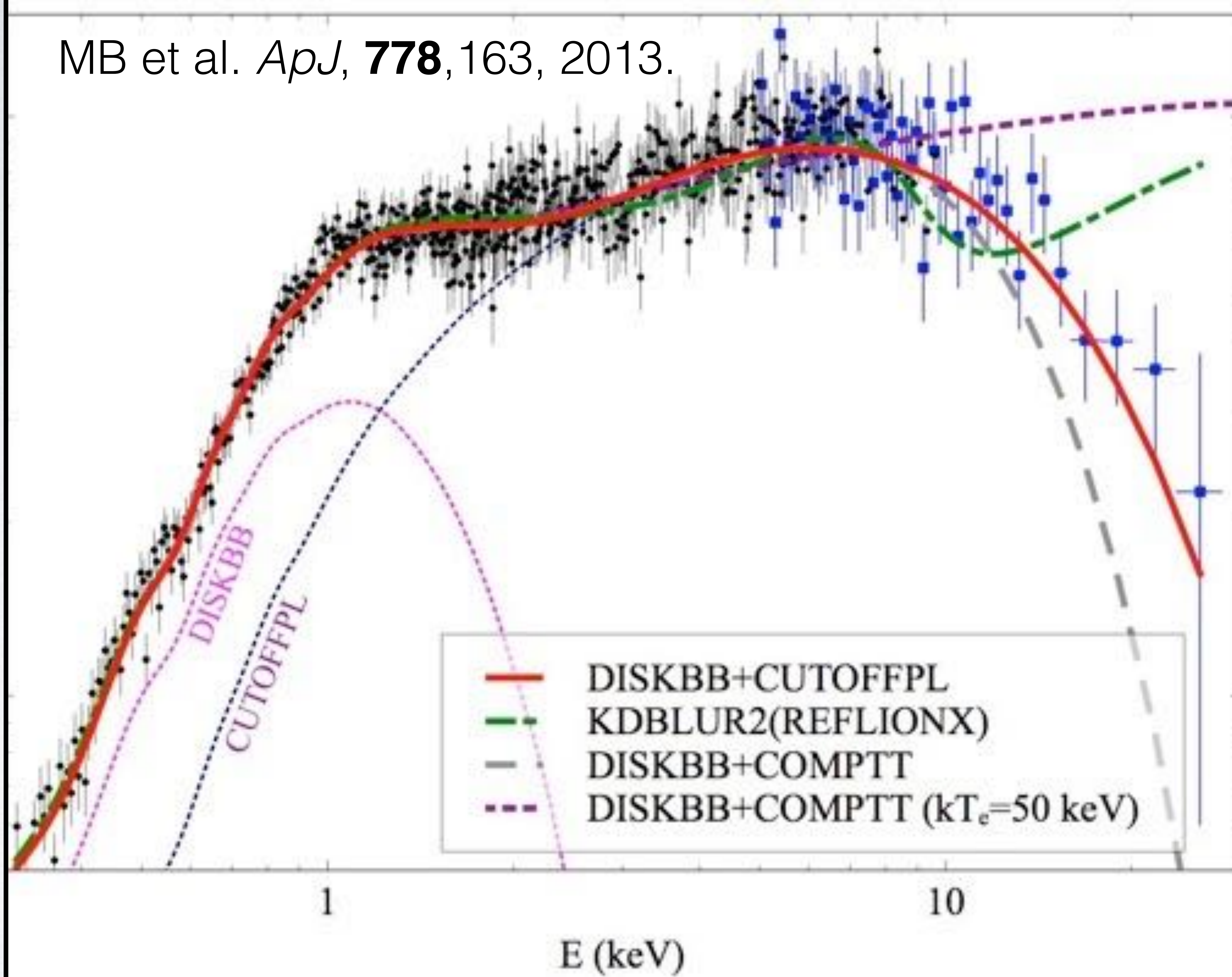


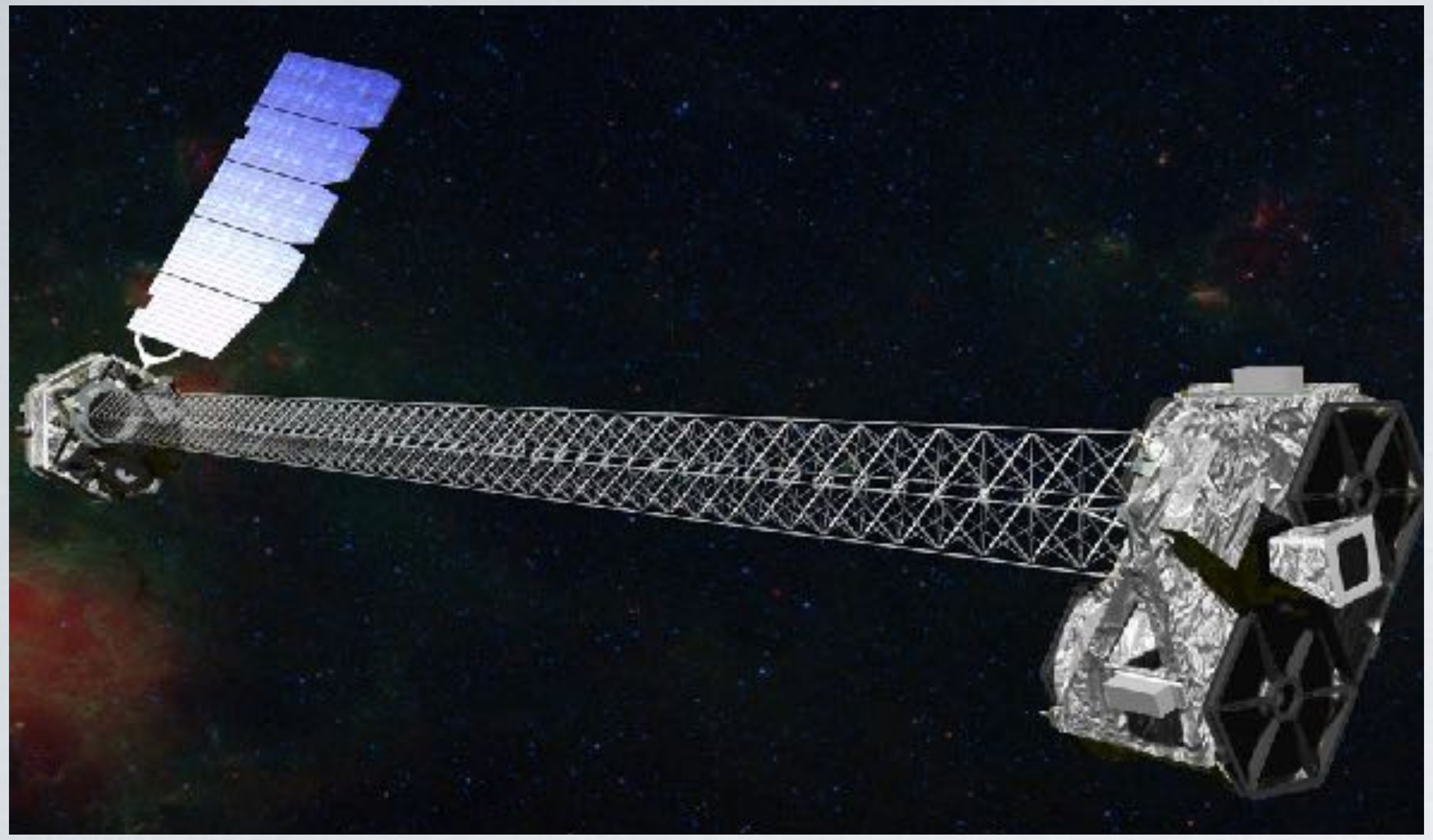
DISKBB
CUTOFFPL
DISKBB+CUTOFFPL
KDBLUR2(REFLIONX)
DISKBB+COMPTT
DISKBB+COMPTT (kT$_e$=50 keV)
1
10
E (keV)



NuSTAR: above 10 keV, ULX spectra are curved

MB et al. *ApJ*, **778**,163, 2013.

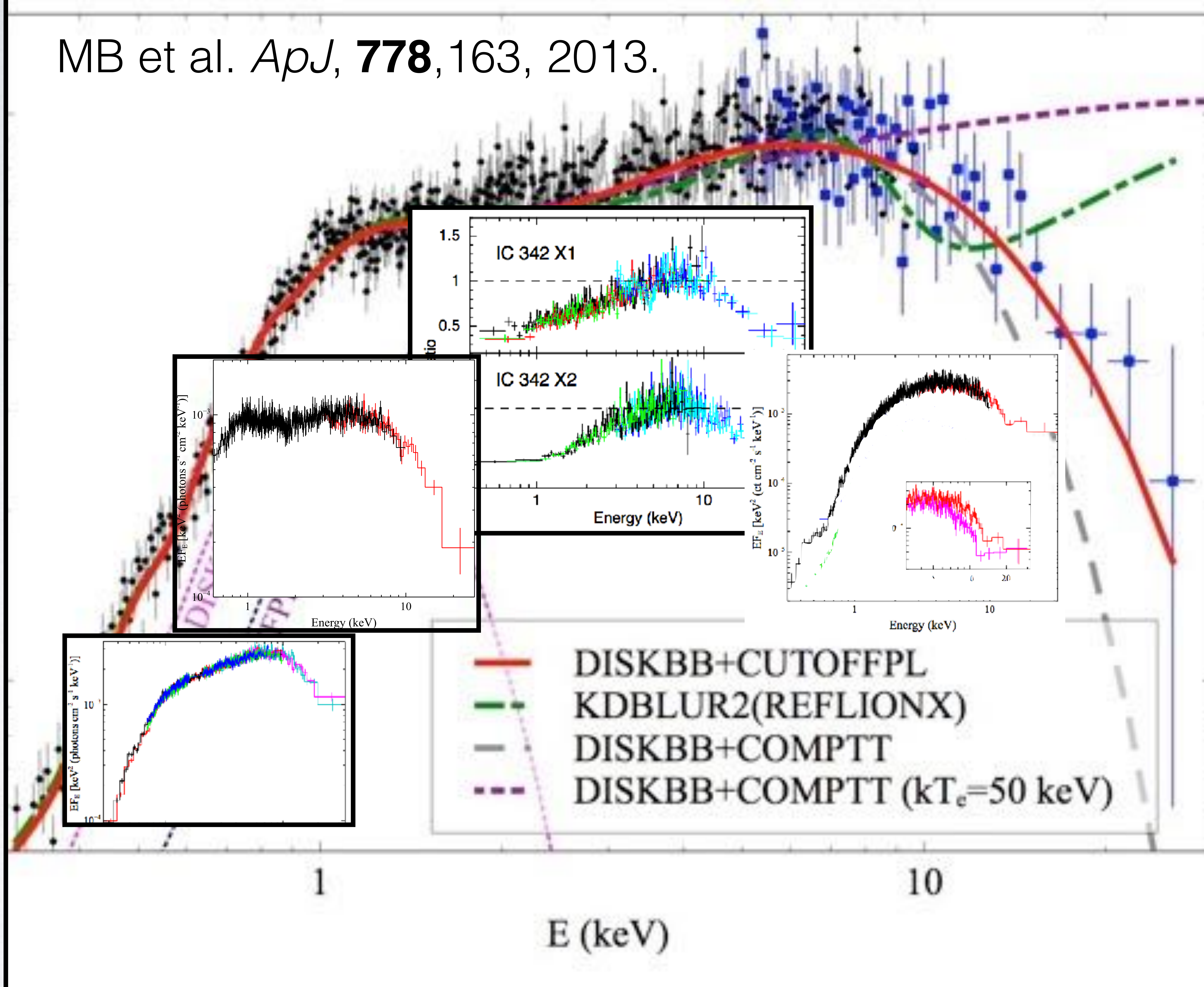


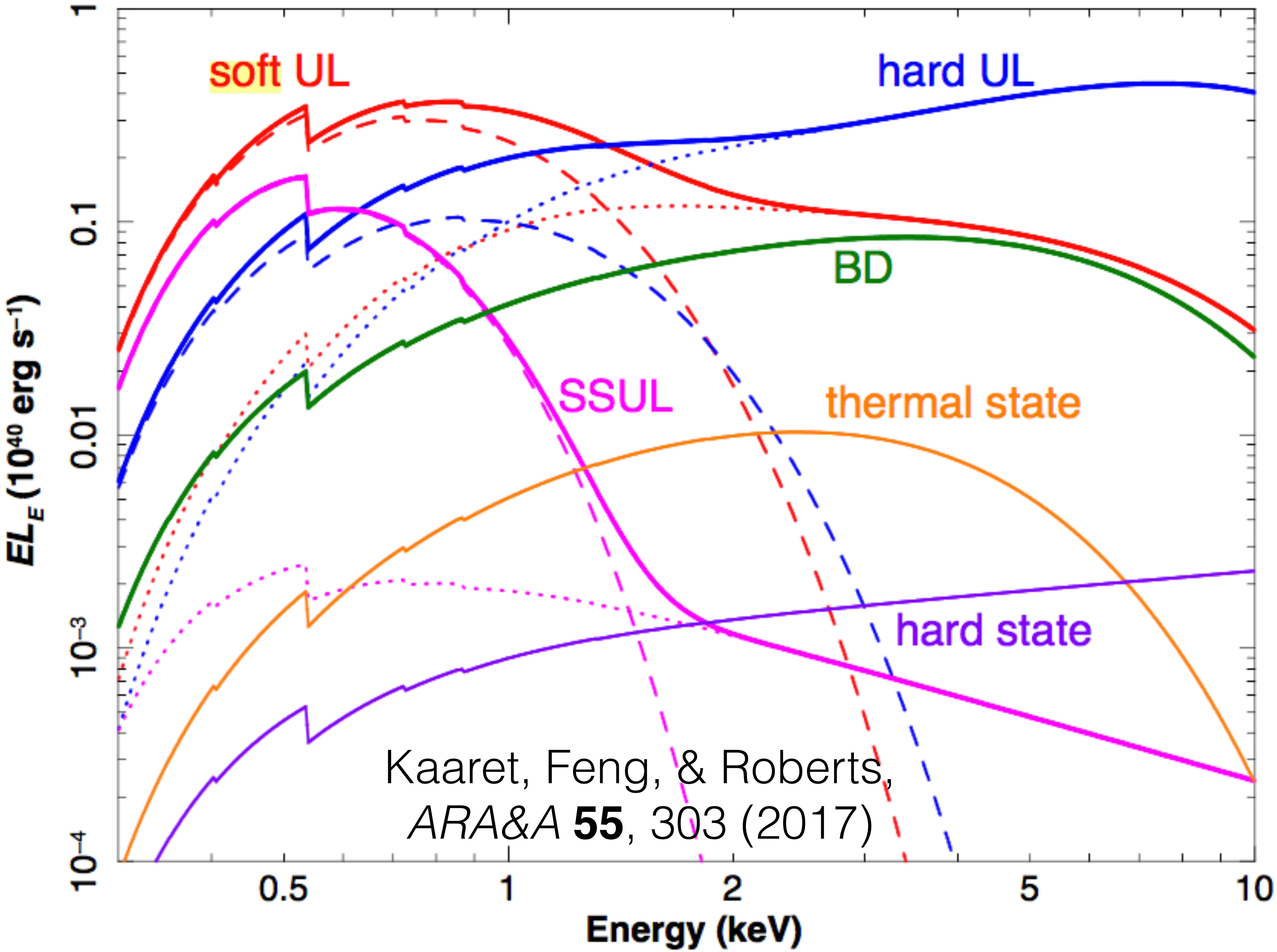


NuSTAR: above 10 keV, ULX spectra are curved

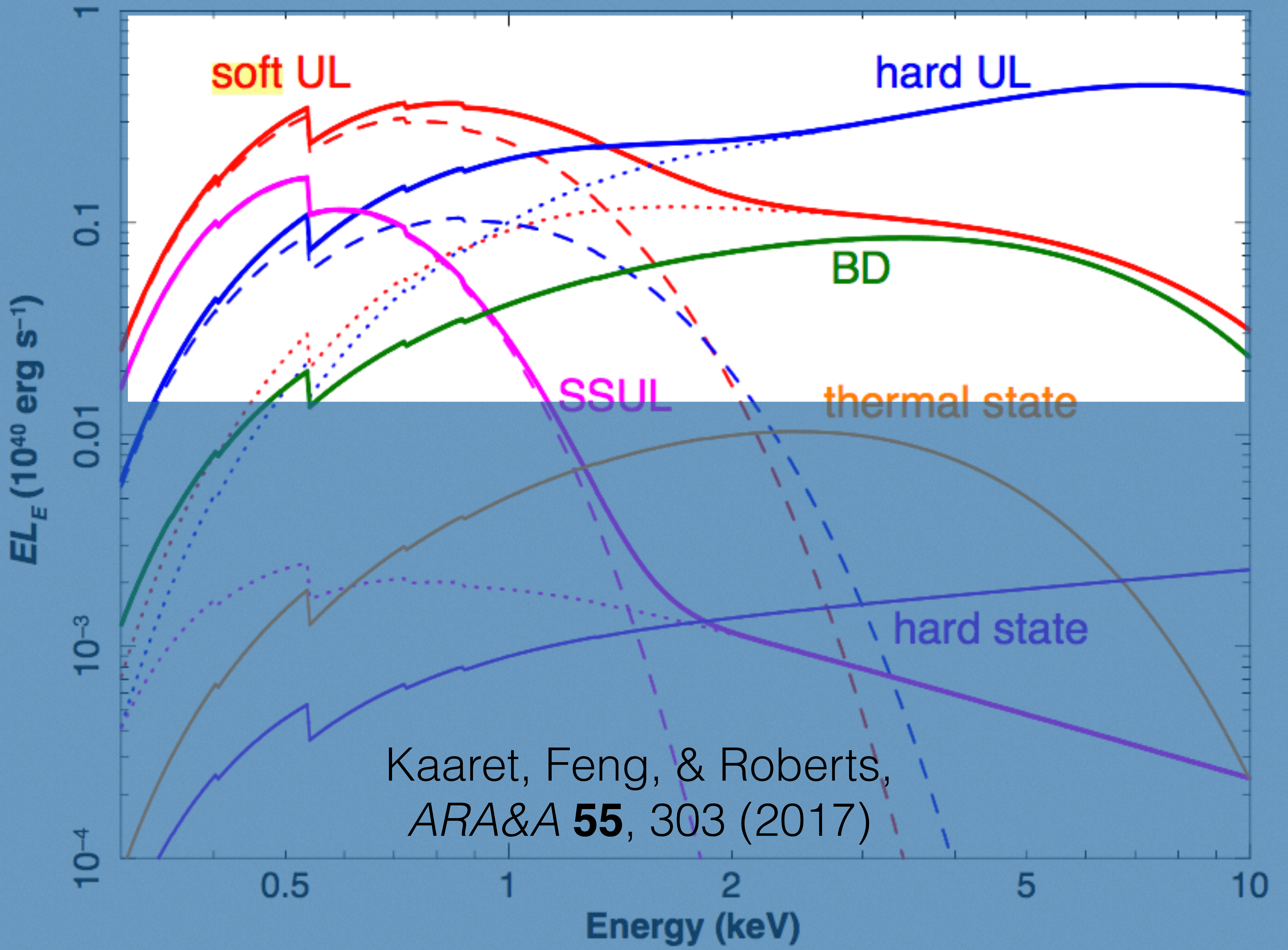
MB+ *ApJ* **778**, 163 (2013).
Walton+ *ApJ* **779**, 148 (2013).
Walton+ *ApJ* **793**, 21 (2014).
Rana+ *ApJ* **799**, 121 (2015).
Walton+ *ApJ* **799**, 122 (2015).
Walton+ *ApJ* **806,** 65 (2015)
(…)

MB et al. *ApJ*, **778**, 163, 2013.



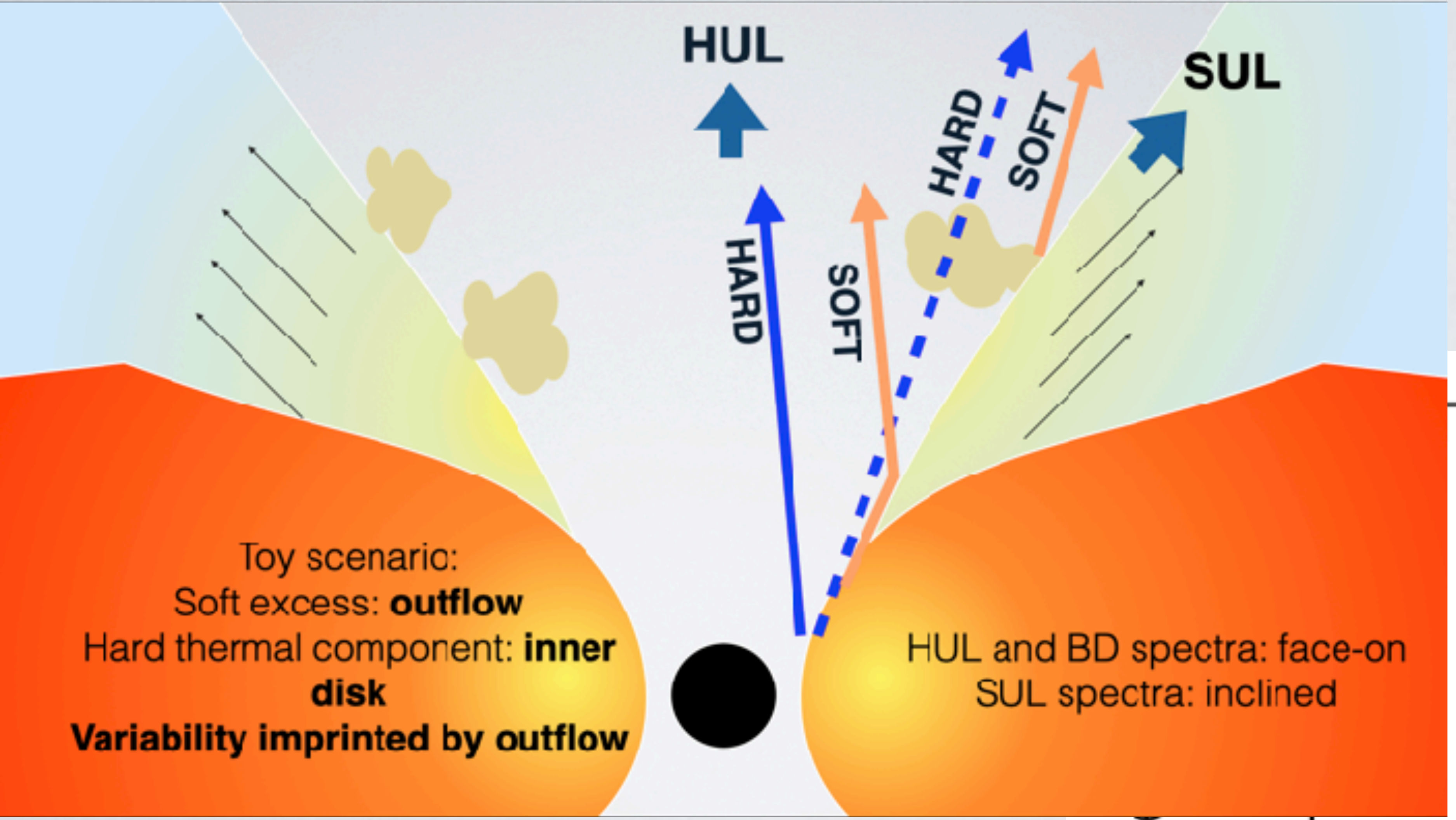


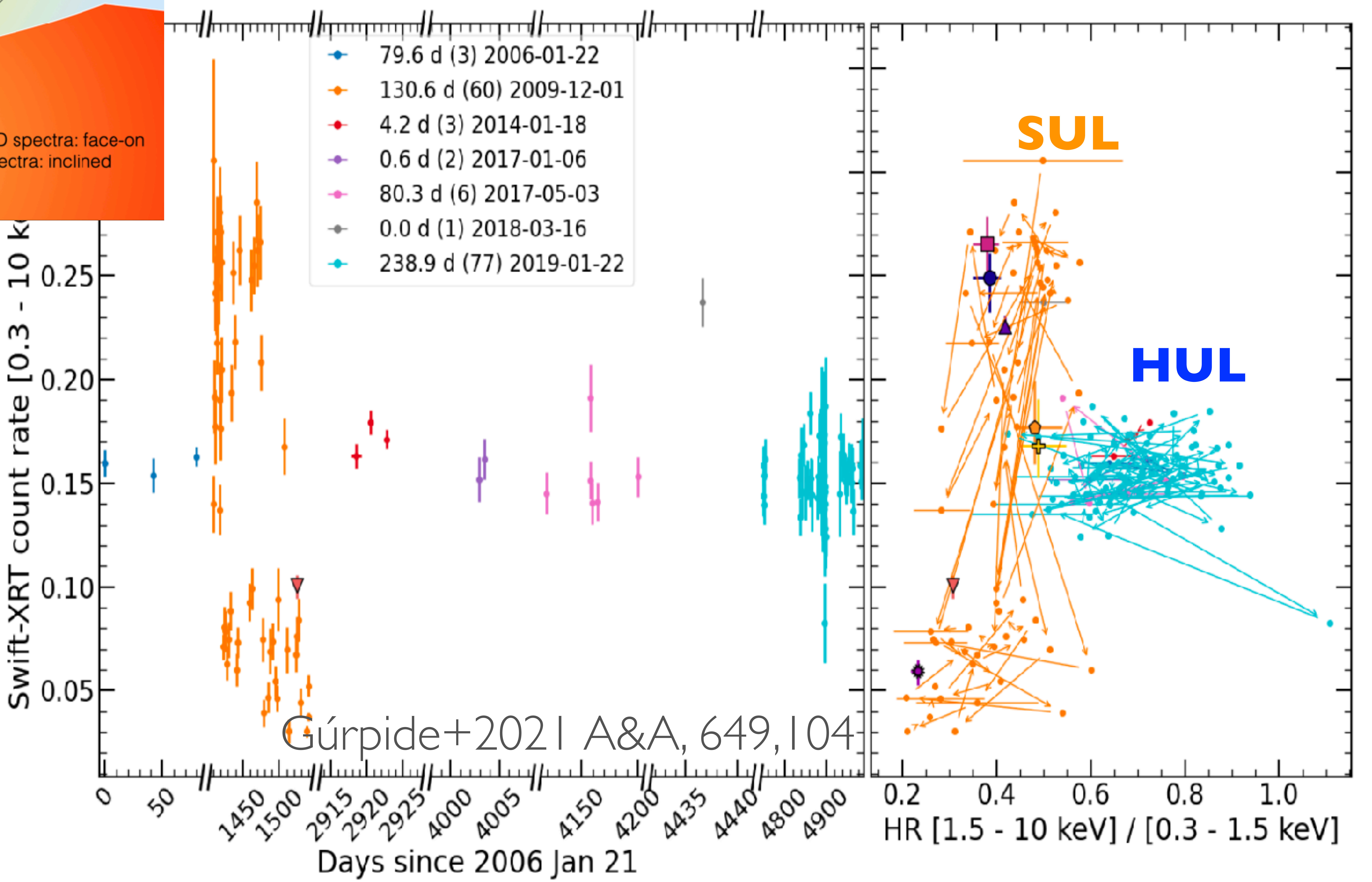
Kaaret, Feng, & Roberts,
ARA&A **55**, 303 (2017)



Kaaret, Feng, & Roberts,
ARA&A **55**, 303 (2017)

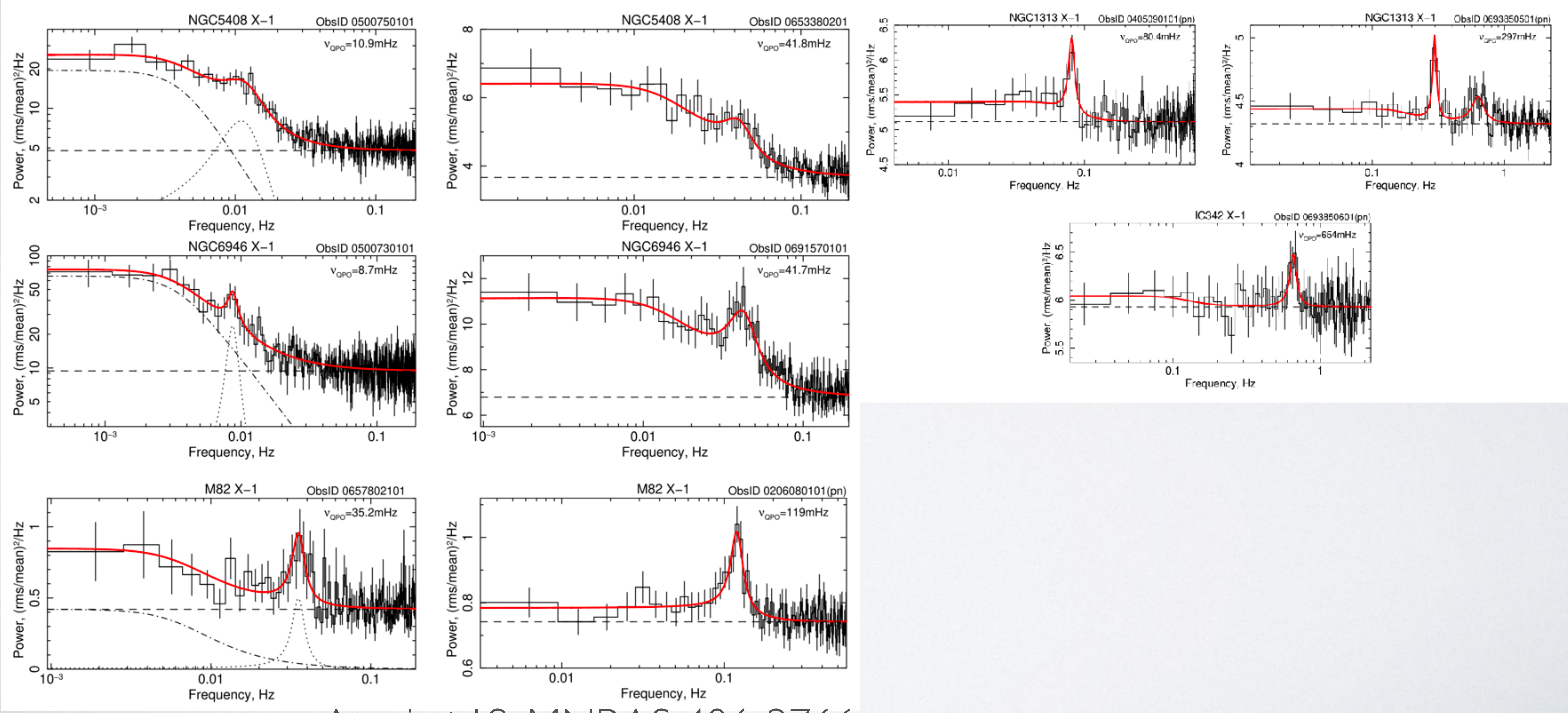

HUL
SUL
HARD
SOFT
HARD
SOFT
Toy scenario:
Soft excess: **outflow**
Hard thermal component: **inner disk**
Variability imprinted by outflow
HUL and BD spectra: face-on
SUL spectra: inclined





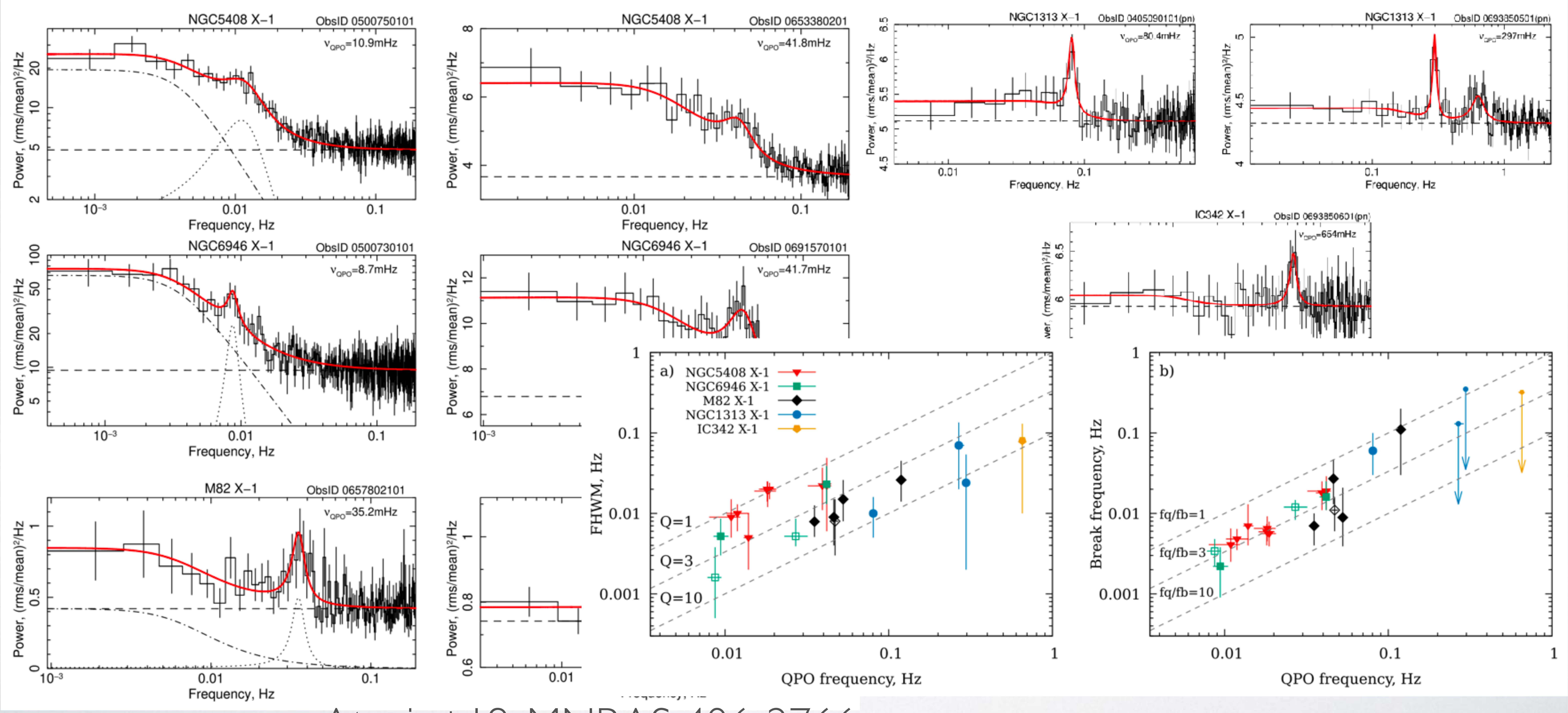
Gúrpide+2021 A&A, 649, 104

APERIODIC VARIABILITY



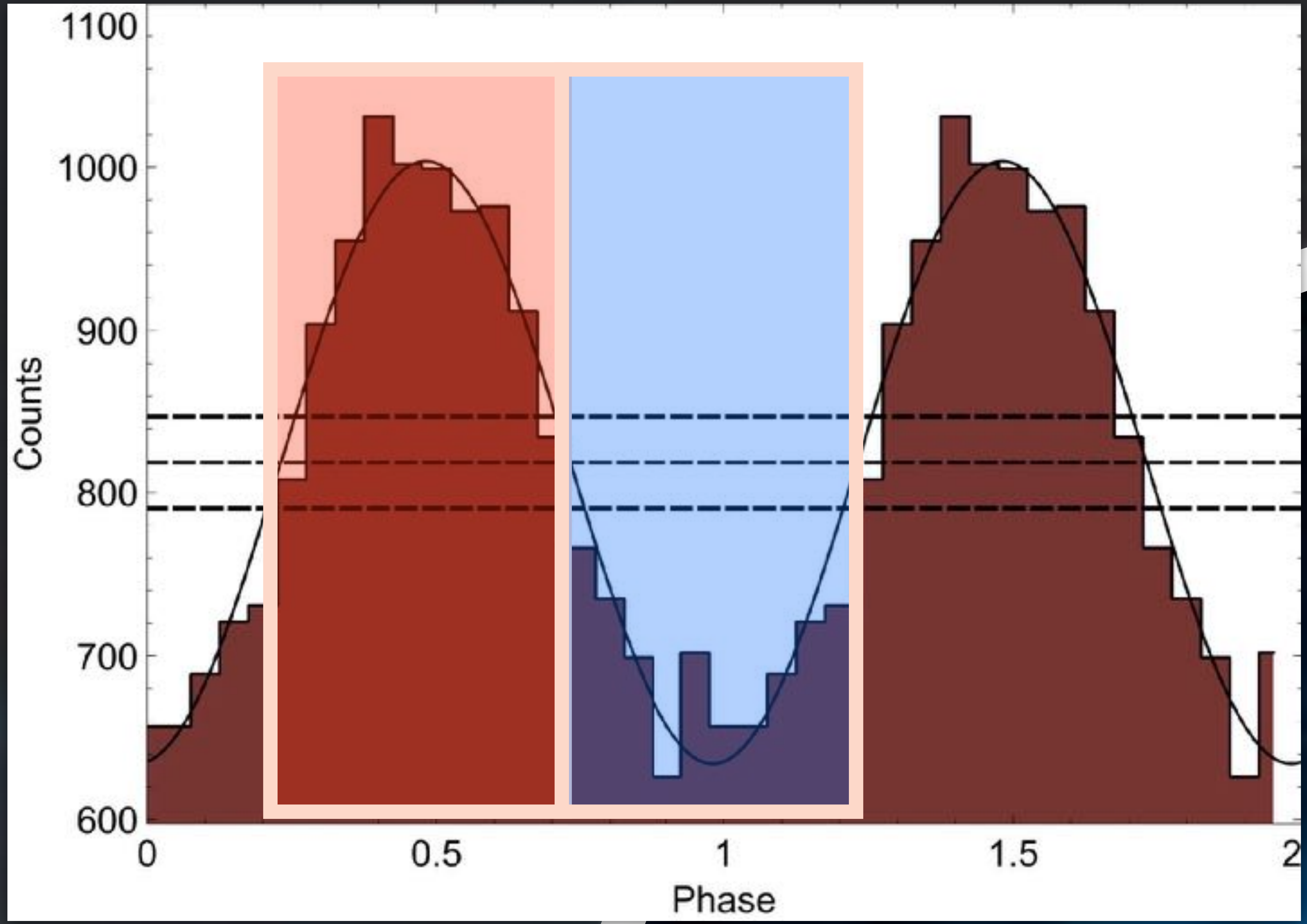
Atapin+19, MNRAS 486, 2766

APERIODIC VARIABILITY



Atapin+19, MNRAS 486, 2766

MIGHTY MICE

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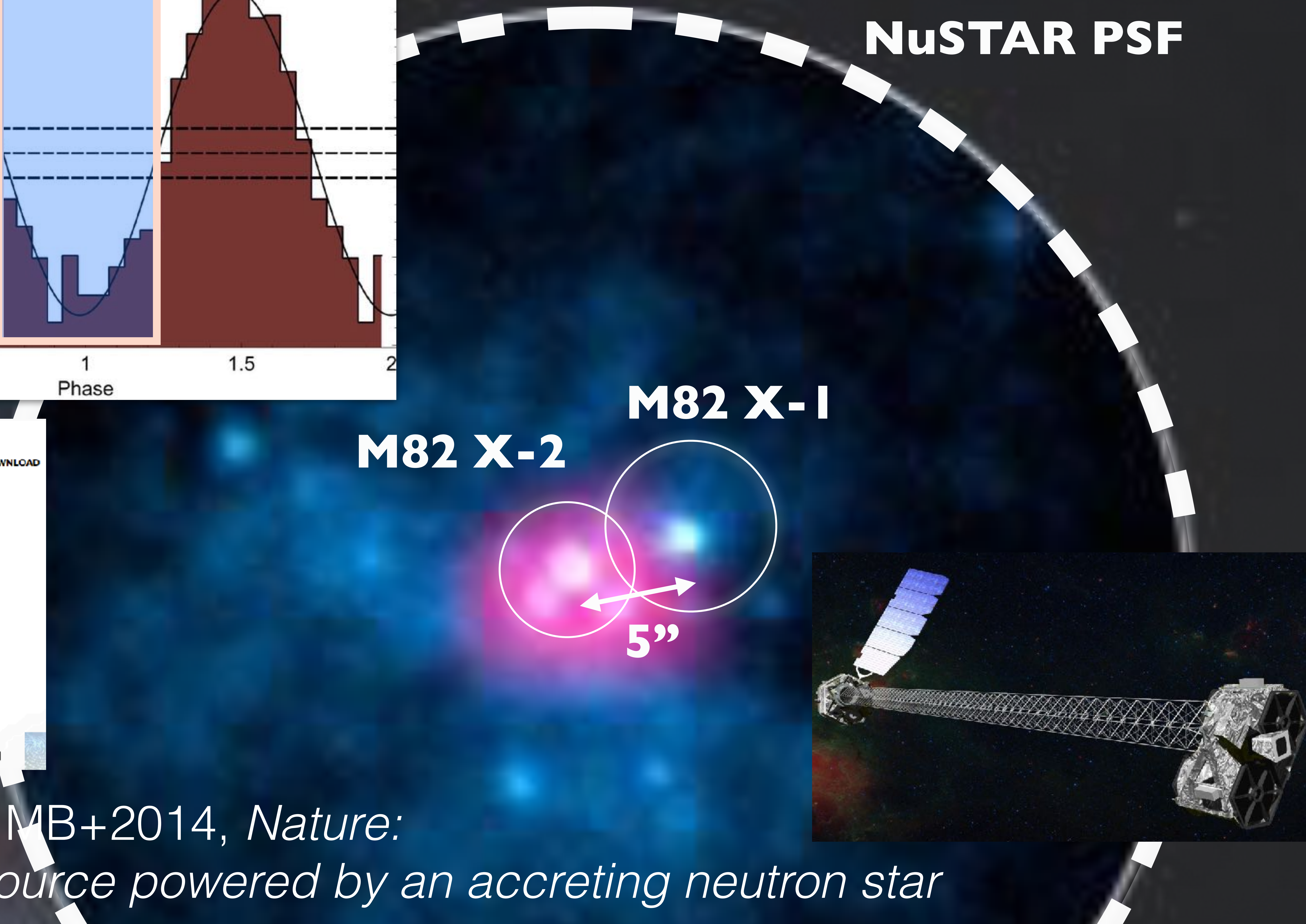
SCI-TECH

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:*

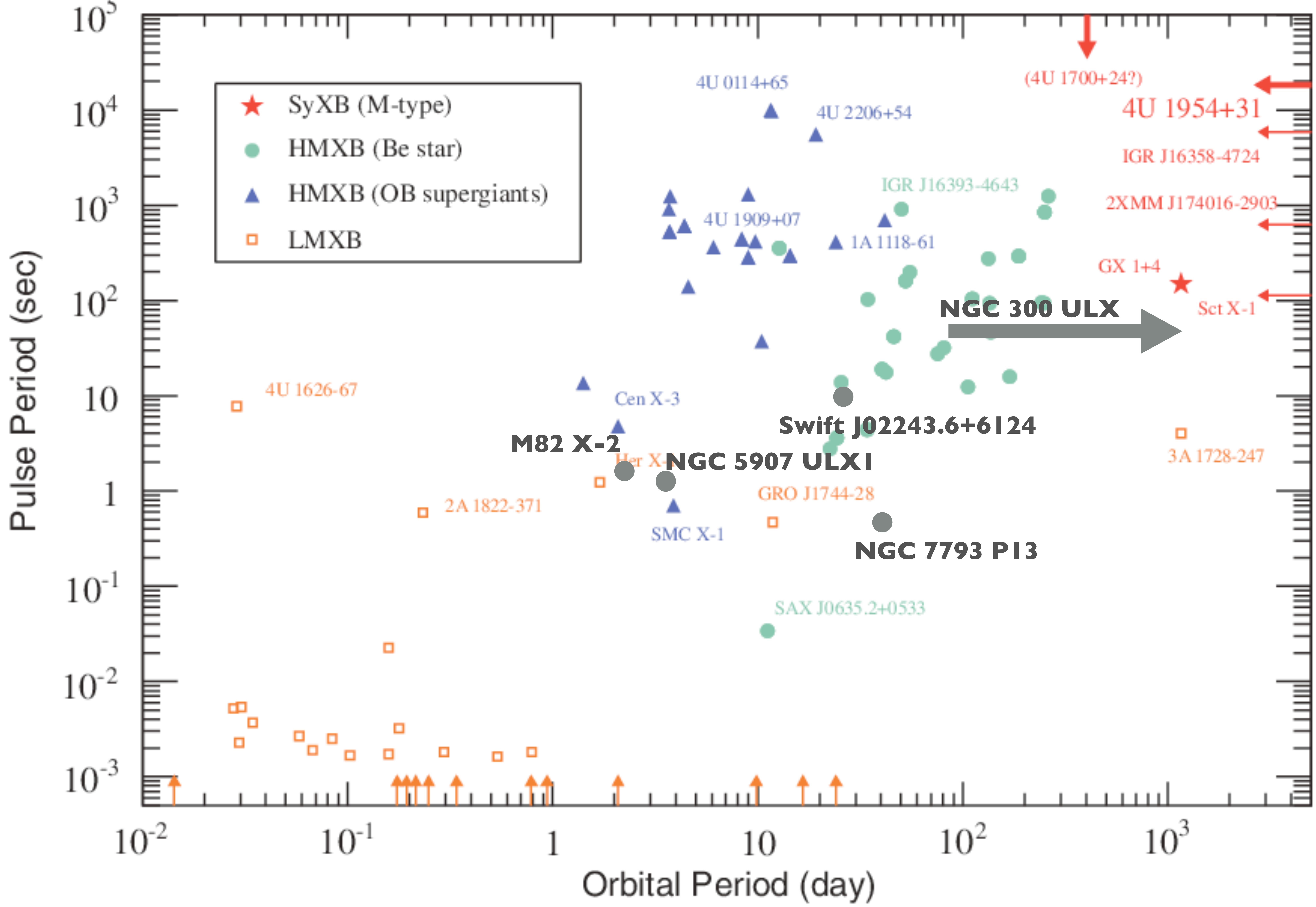
An ultraluminous X-ray source powered by an accreting neutron star

PULX COMPARISON

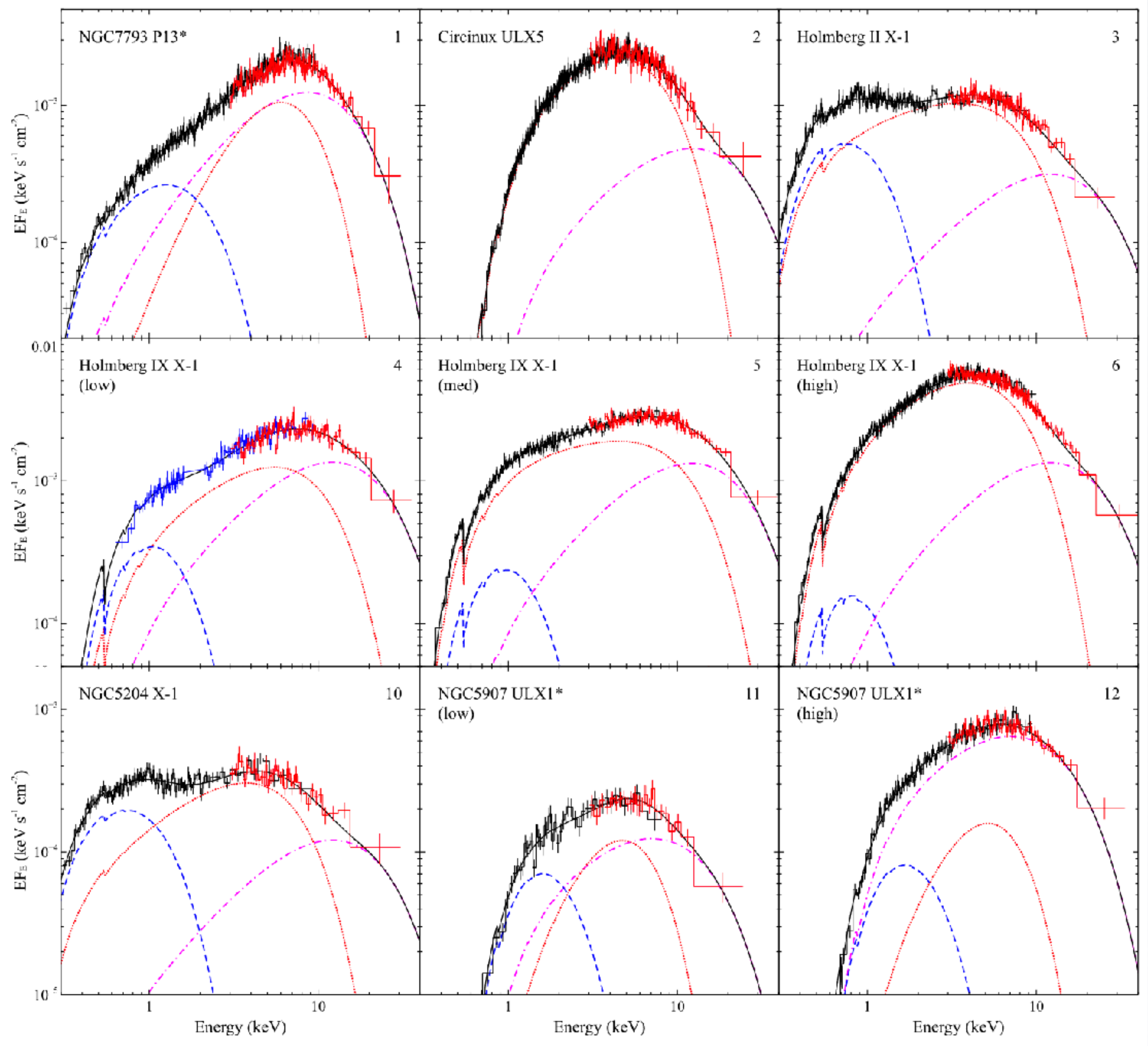
Source	P_{spin}	$L_{X,peak}$ (10^{39} erg/s)	Discovery Reference(s)
NGC5907 ULX1	1.1	100	Israel+17b
M82 X-2	1.4	20	Bachetti+14
NGC7793 P13	0.4	15	Furst+16, Israel+17a
NGC1313 X-2	1.5	10	Sathyaprakash+19
M51 ULX-7	2.8	10	Rodriguez-Castillo+21
NGC300 ULX1	126—20	4	Carpano+18
Swift J0243.6+6124	9.8	2	Kennea+17

PULX COMPARISON

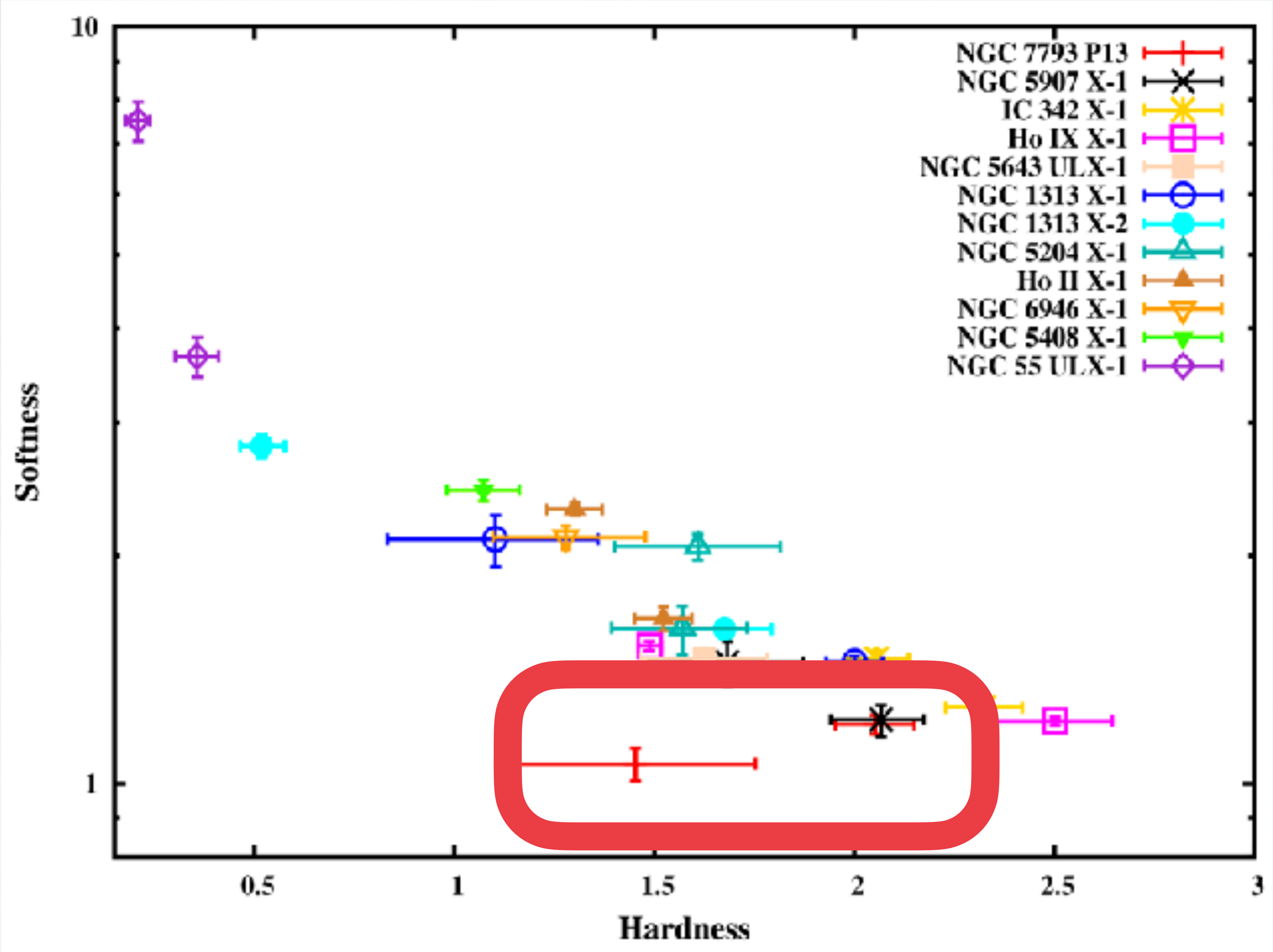
	P.F. (%)	f (Hz)	$\dot{f}$ (10^{-10} Hz/s)	Porb (d)	Donor	Notes
NGC 5907 ULX1	~15	0.7 – 0.9	**-20 — +60**	5?		
M82 X-2	>20	0.7	-0.5 — +1	2.52	O/B? >5 Mo	
NGC 7793 P13	~20	**2.4**	~2	64	BSG?	
NGC 1313 X-2	5	0.68	6—20?	?		Only detected in <30 ks
M51 ULX-7	5-20	0.36	0.2 — 1.2	2	MS?	
NGC 300 ULX	**~90**	0.008—0.05	9	many?	RSG?	
Swift J0243.6+6124	50	0.1		27	Be	
SMC X-1		1.4	0.23	3.9	B0 ~17 Mo	
LMC X-4		0.07	~1	1.4	O8 ~16 Mo	



SyXB (M-type)
HMXB (Be star)
HMXB (OB supergiants)
LMXB
Pulse Period (sec)
Orbital Period (day)
4U 0114+65
4U 2206+54
(4U 1700+24?)
4U 1954+31
IGR J16358-4724
IGR J16393-4643
2XMM J174016-2903
4U 1909+07
1A 1118-61
GX 1+4
Sct X-1
NGC 300 ULX
4U 1626-67
Cen X-3
Swift J02243.6+6124
M82 X-2
NGC 5907 ULX1
GRO J1744-28
2A 1822-371
SMC X-1
NGC 7793 P13
3A 1728-247
SAX J0635.2+0533



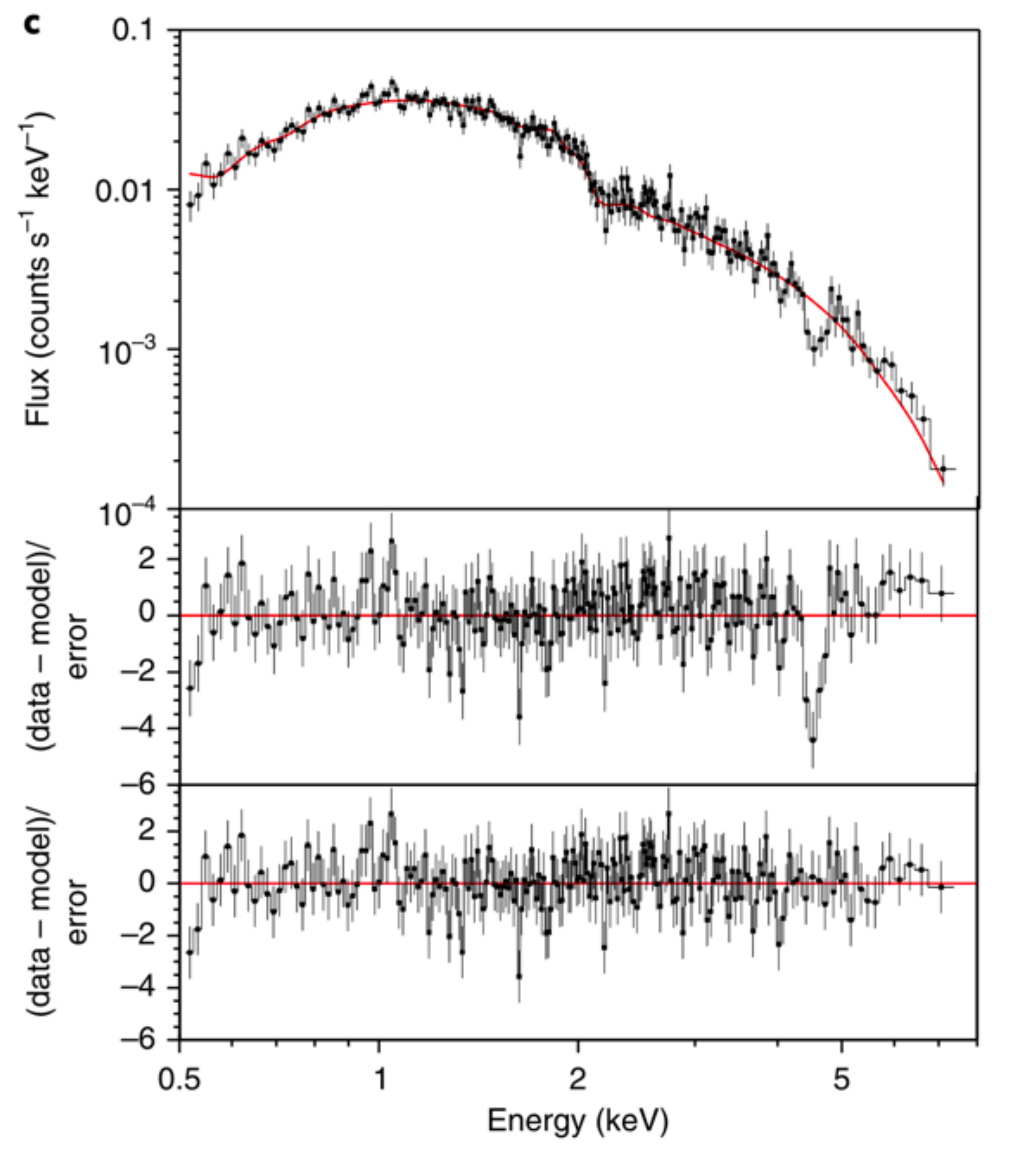
Walton+18, ApJ 856, 128



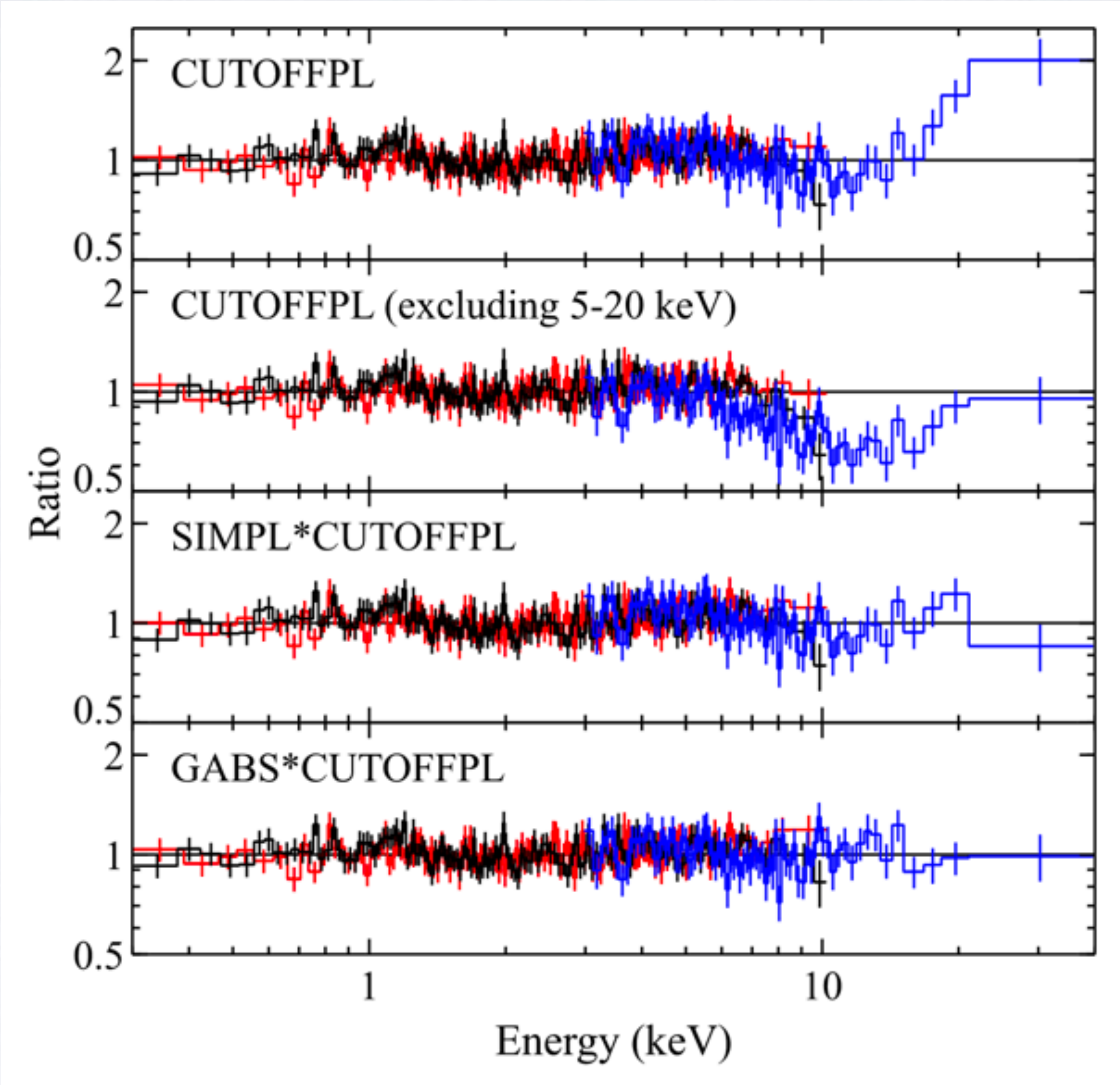
Pintore+17, ApJ 836, 113

CYCLOTRON-LIKE FEATURES

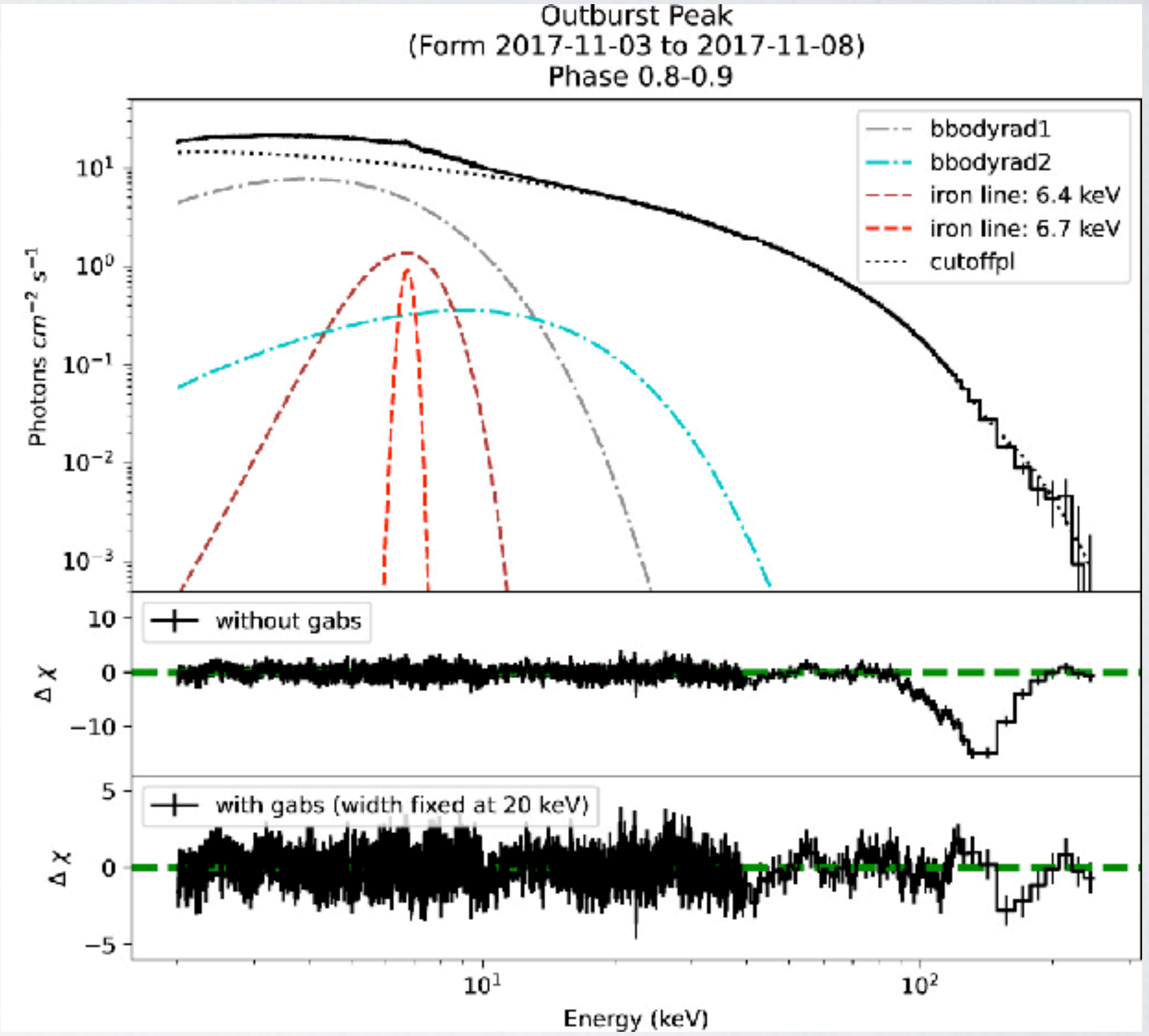
M51 ULX8 (proton line?)



NGC 300 ULX1

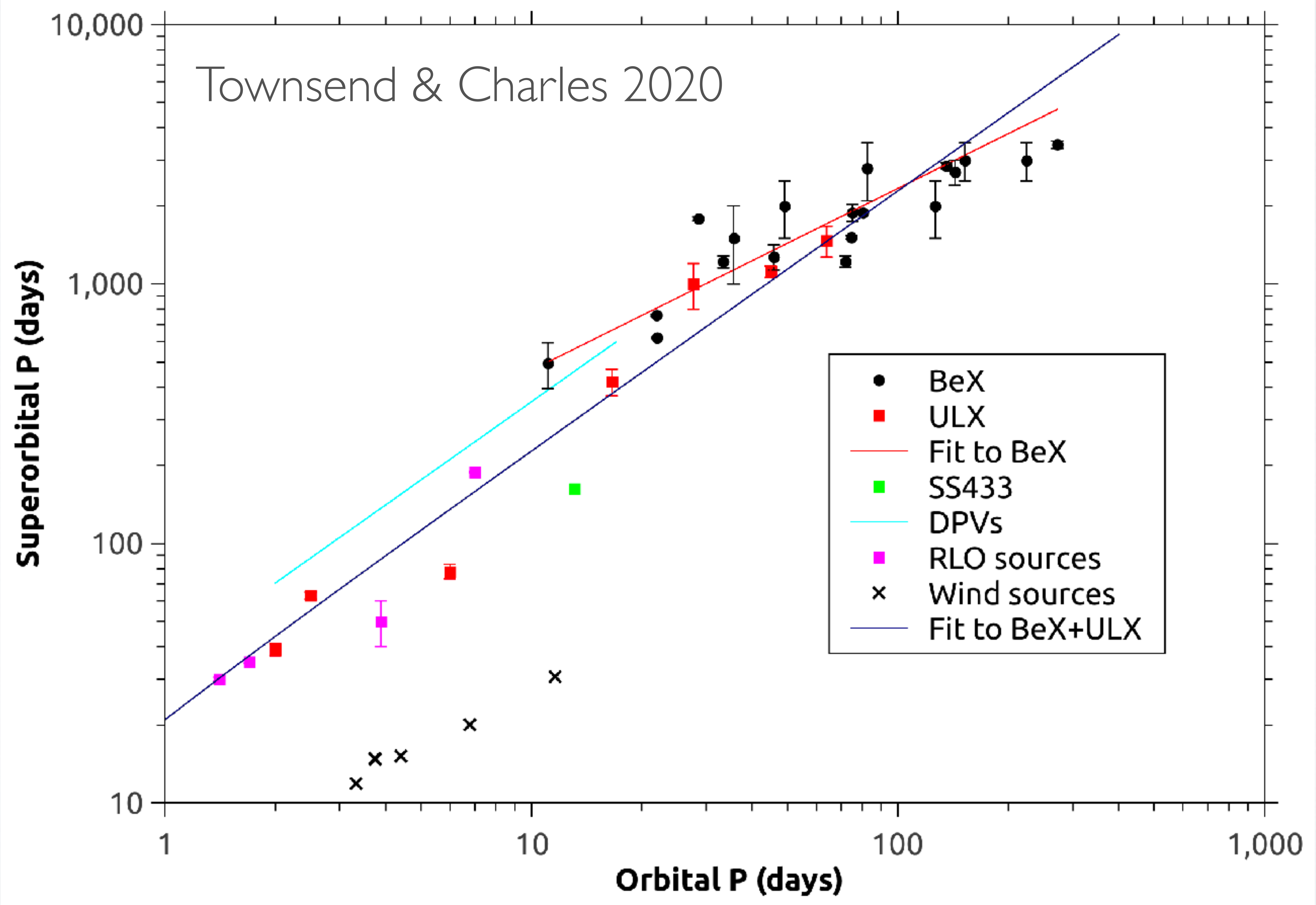


Swift J0243.6+6124

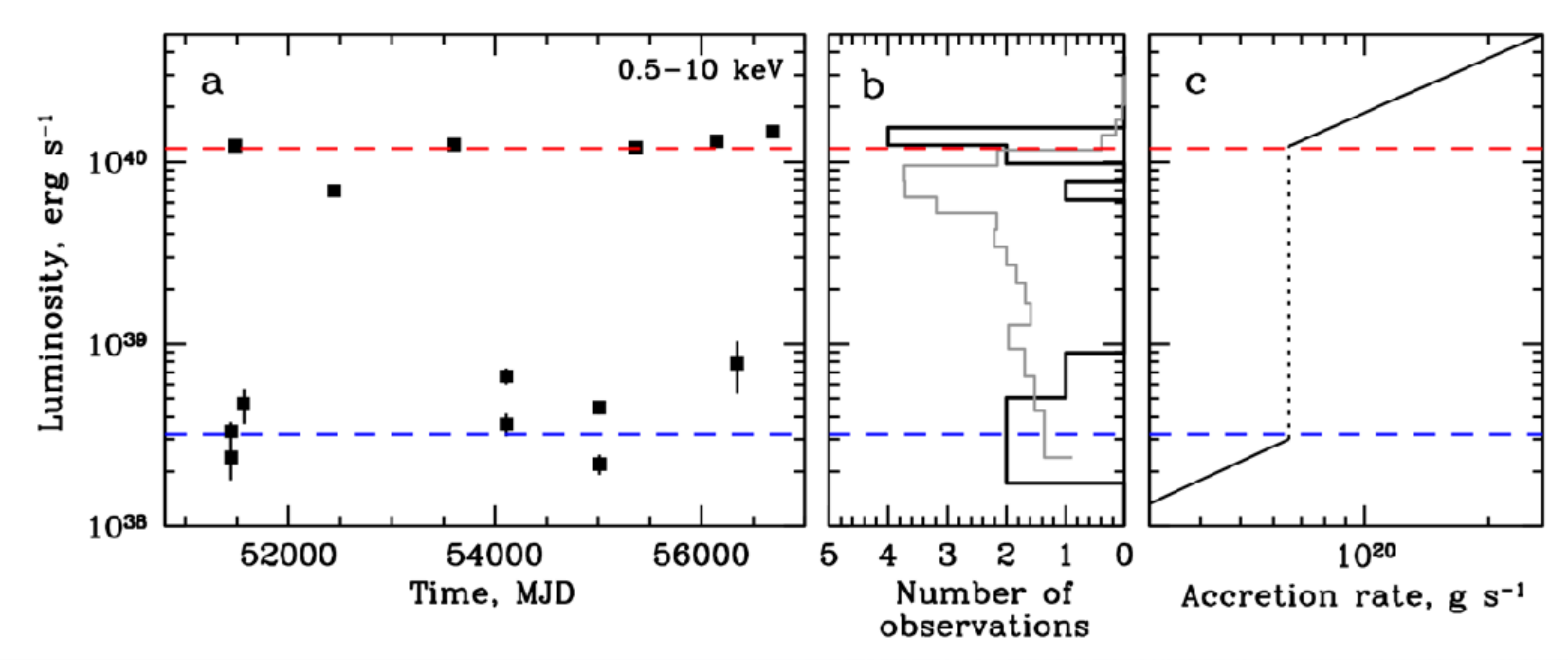


Brightman+18 Nat. Ast. 2, 312 Walton+18 ApJL 857, L3 Kong+22, ApJL 933, 3

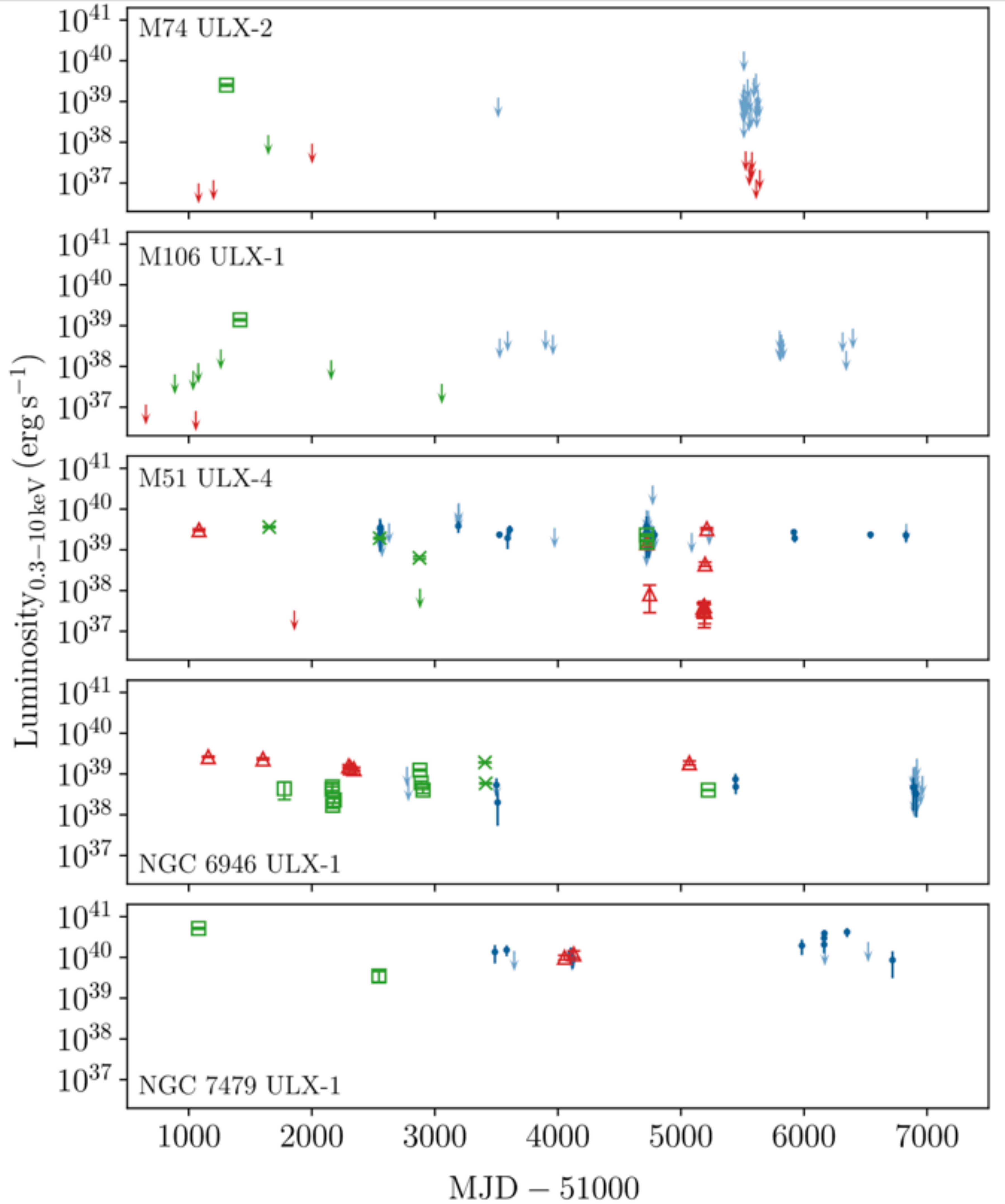
SUPER-ORBITAL PERIODS



(SUPER-ORBITAL?) BI-MODAL LUMINOSITY AS SIGN OF PROPELLER?

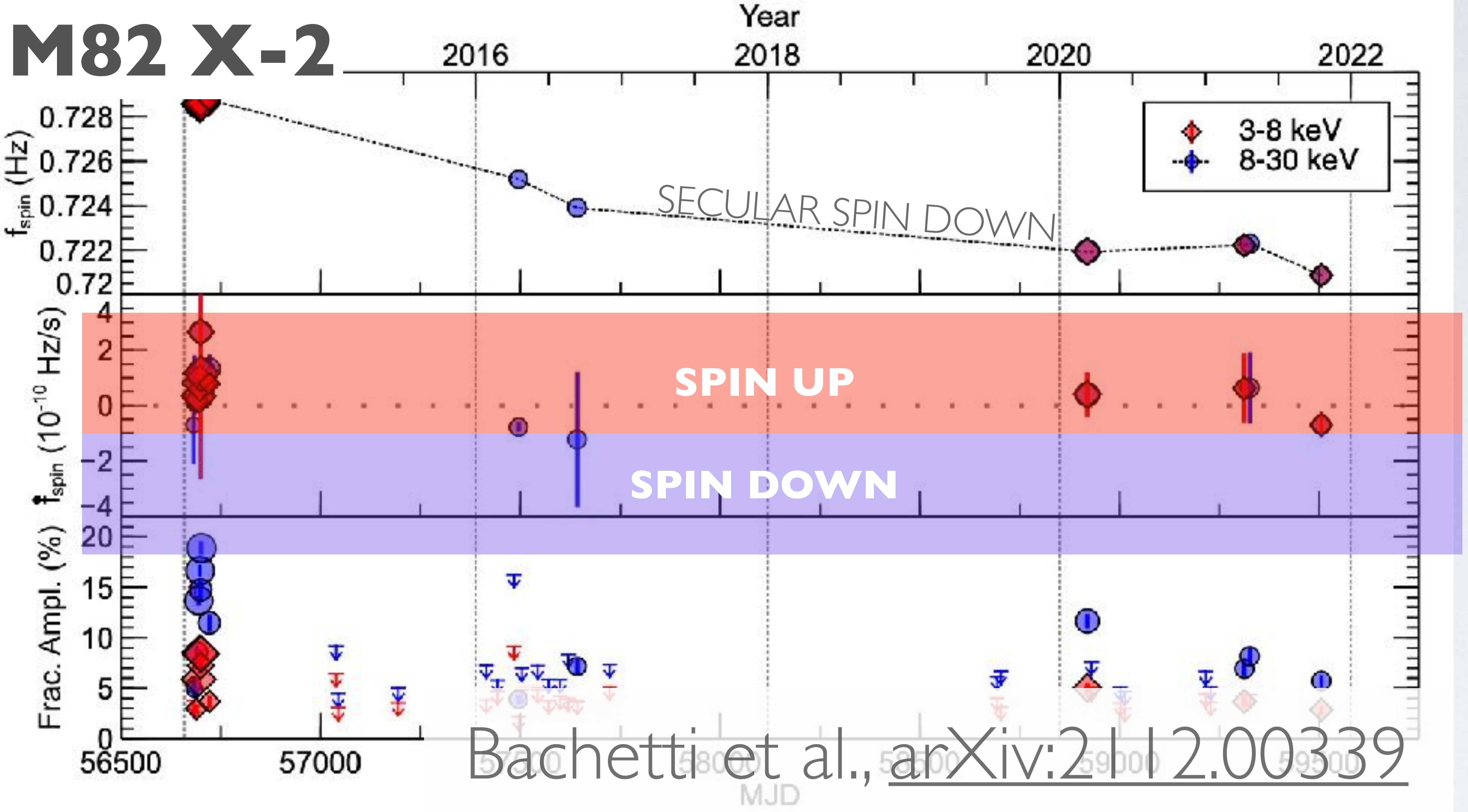


Tsygankov+15



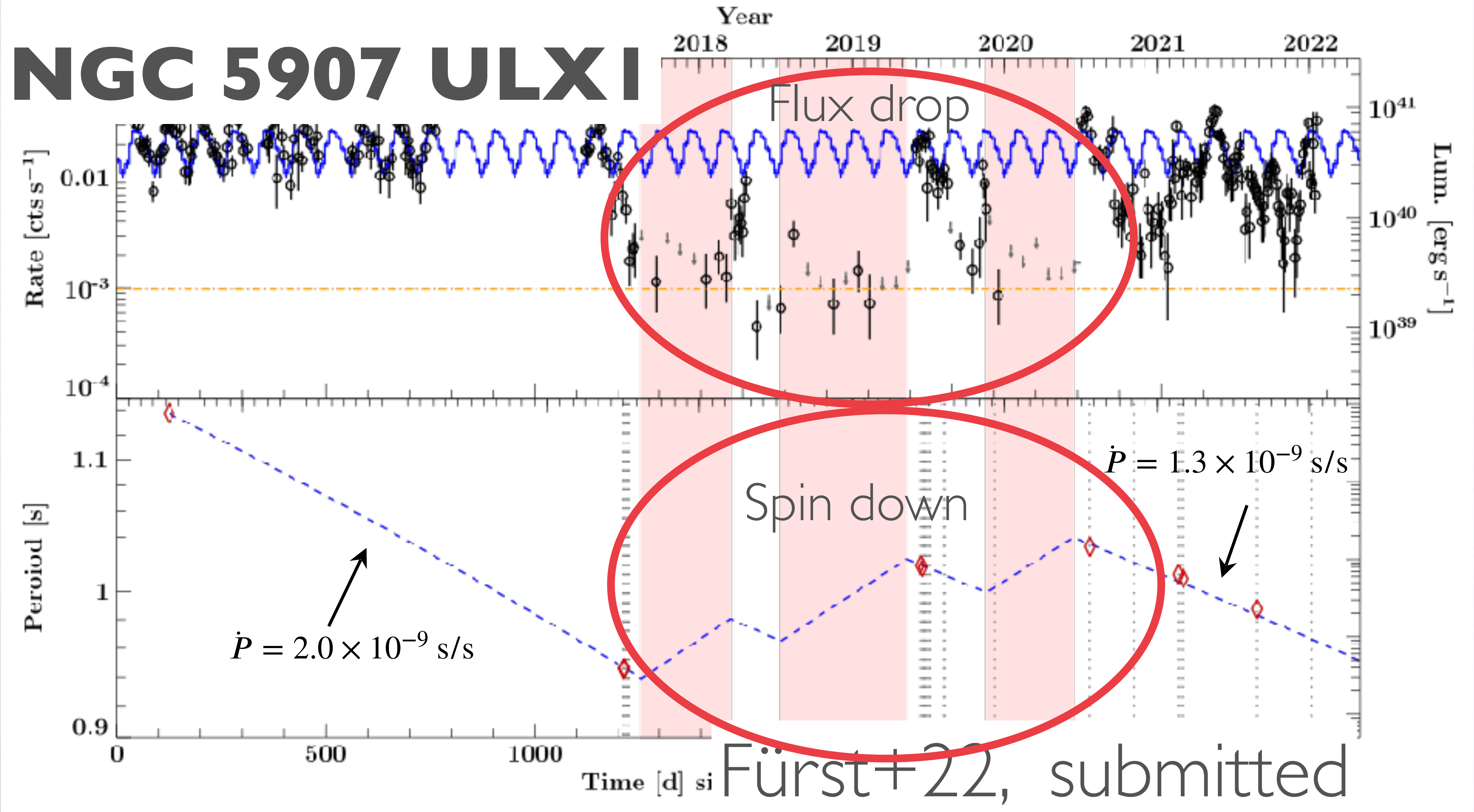
Earnshaw+18

M82 X-2

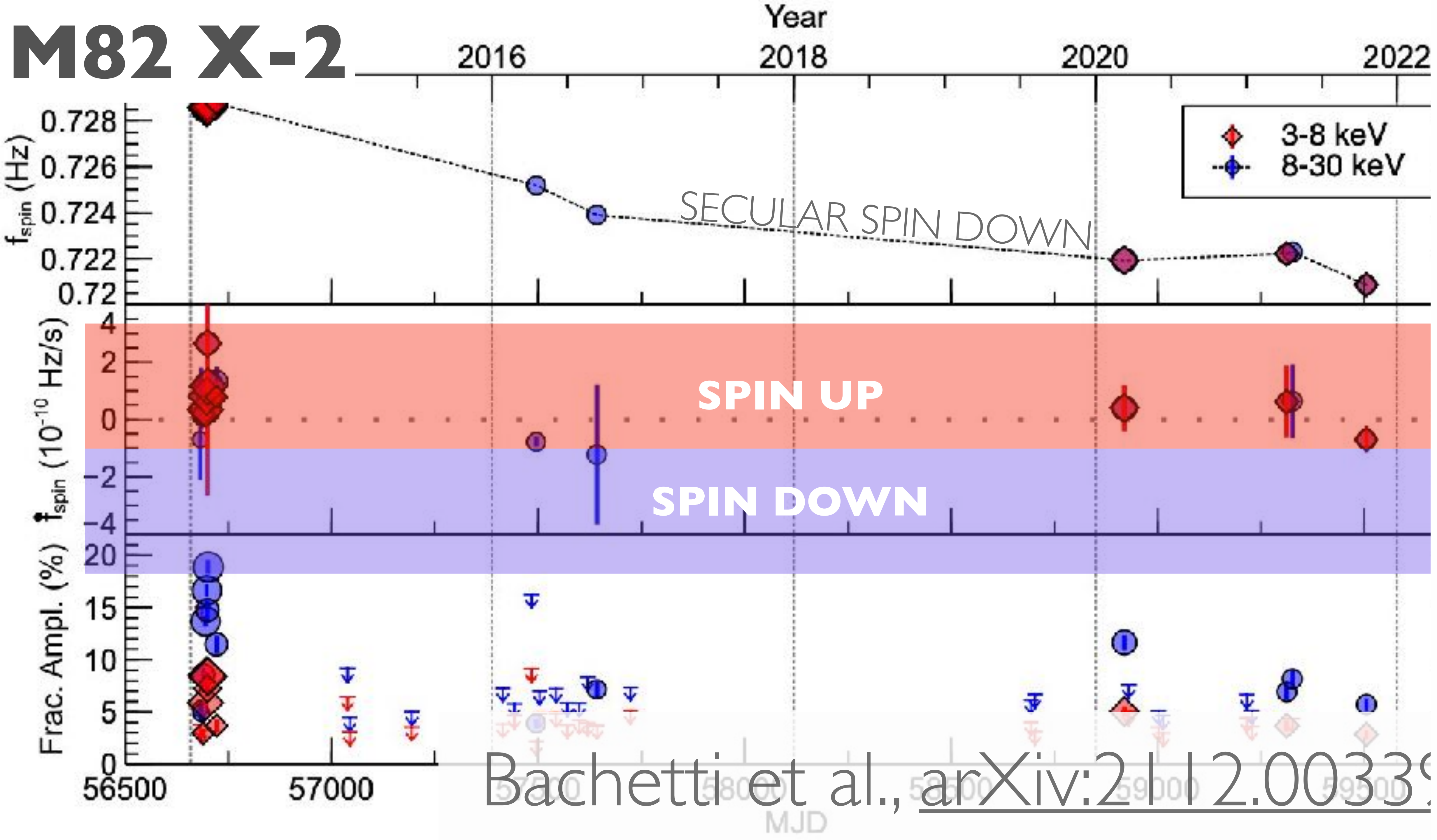


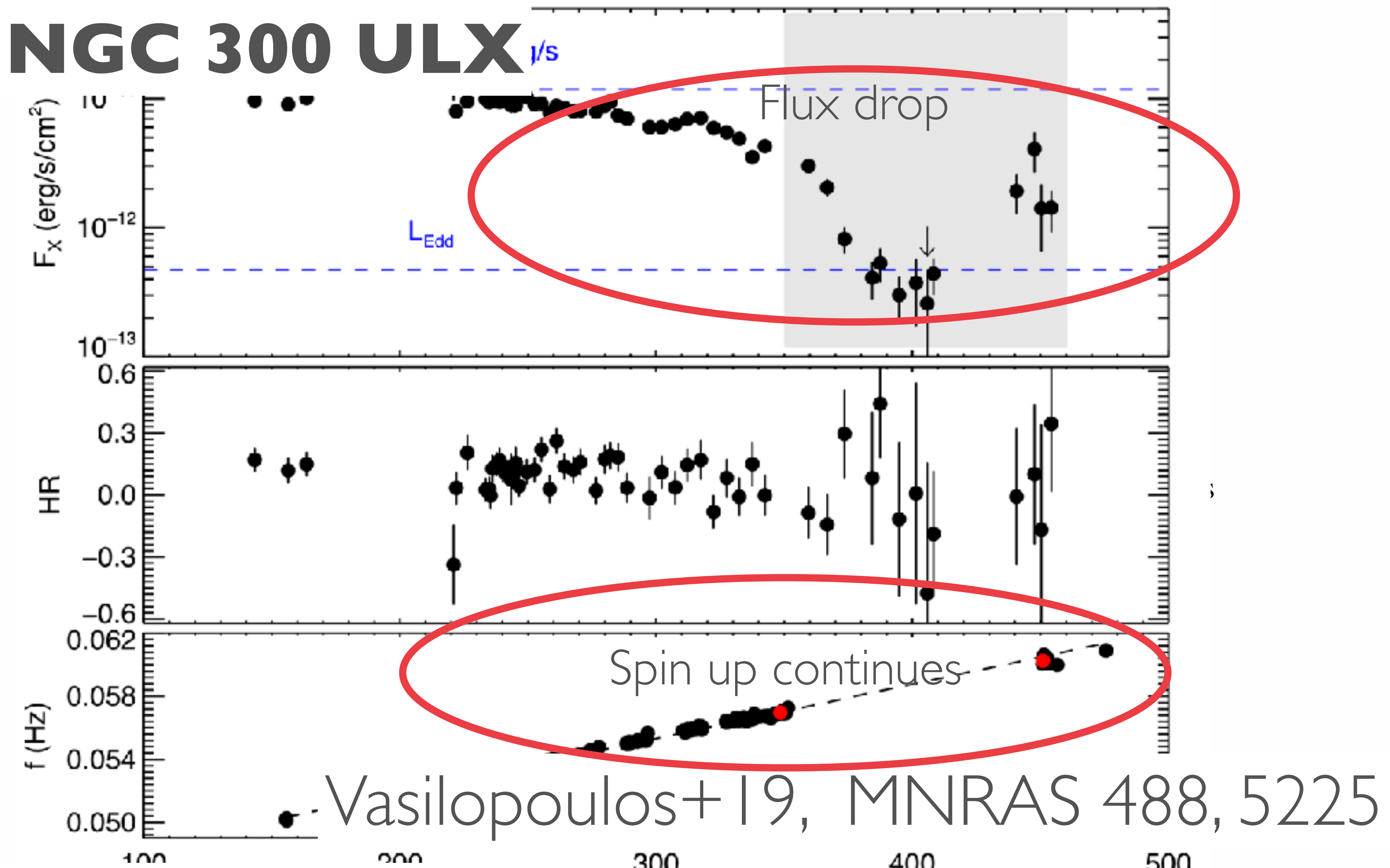
Bachetti et al., arXiv:2112.00339

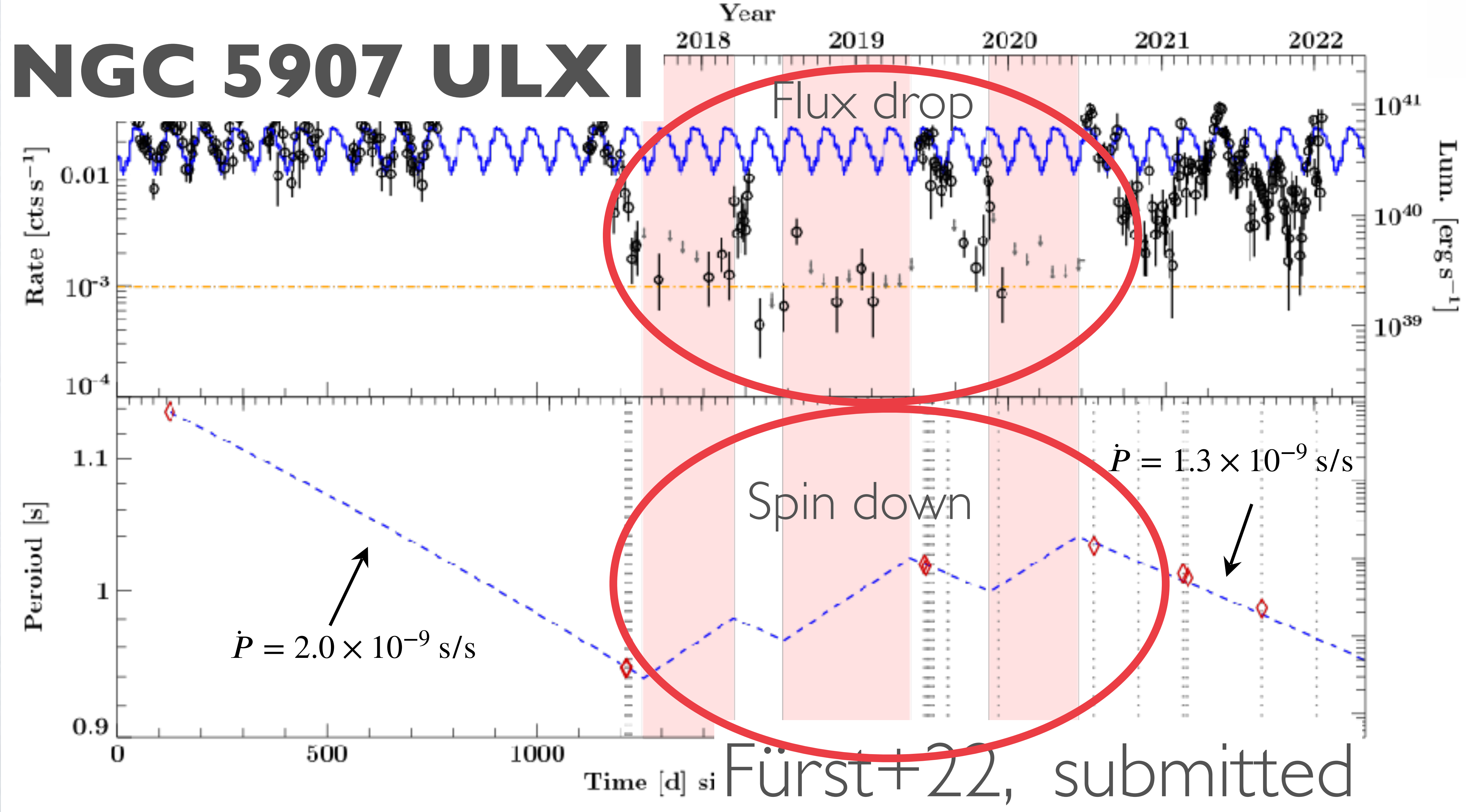
NGC 5907 ULX1

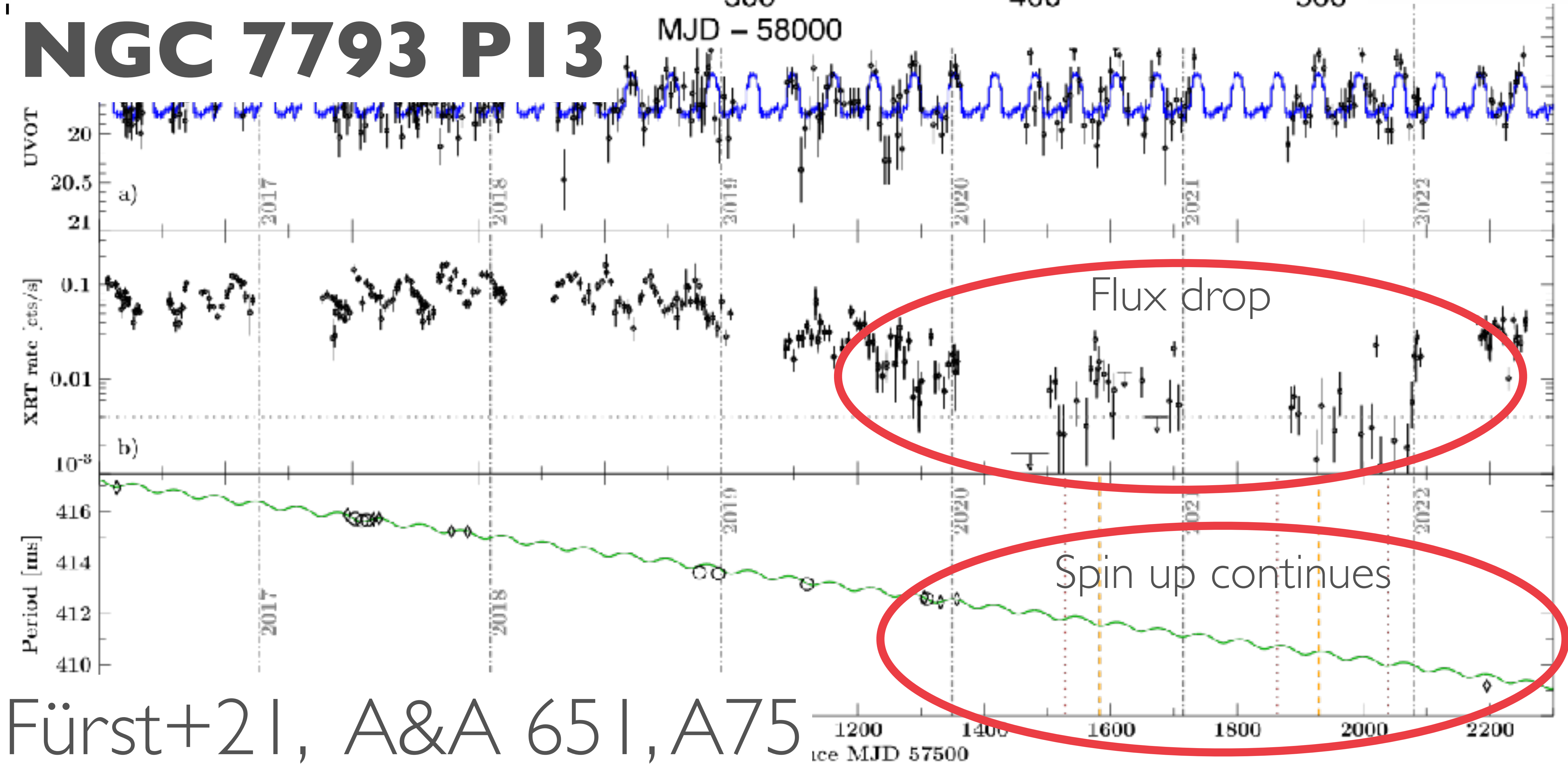


Fürst+22, submitted


M82 X-2
Year
2016
2018
2020
2022
3-8 keV
8-30 keV
SECULAR SPIN DOWN
SPIN UP
SPIN DOWN
Frac. Ampl. (%)
MJD
Bachetti et al., arXiv:2112.00339


NGC 300 ULX
Flux drop
L_{Edd}
HR
f (Hz)
Spin up continues
MJD – 58000
Vasilopoulos+19, MNRAS 488, 5225


NGC 5907 ULX1
Year
2018
2019
2020
2021
2022
Flux drop
Rate [cts s⁻¹]
Lum. [erg s⁻¹]
Spin down
$\dot{P} = 1.3 \times 10^{-9}$ s/s
$\dot{P} = 2.0 \times 10^{-9}$ s/s
Period [s]
Time [d]
Fürst+22, submitted


NGC 7793 P13
UVOT
XRT rate [cts/s]
Flux drop
Period [ms]
Spin up continues
MJD 57500
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?

HOW DO YOU FEED THEM?

- Simulations with MESA (Fragos+15, Quast+19, Misra+20) seem to point at short-lived accretion phases
- (Beaming is often an ad-hoc parameter)

MEASURING (DIPOLAR) B INDIRECTLY?

$$R_{\mathrm{M}} \approx \xi 10^{8}\,\mathrm{cm}\left(\frac{B}{10^{12}\mathrm{G}}\right)^{4/7}\left(\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}}\right)^{-2/7}$$

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

$$R_{\rm M} \approx \xi 10^8\,{\rm cm} \left(\frac{B}{10^{12}{\rm G}}\right)^{4/7} \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{-2/7}$$

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

"Slow rotator"

$$R_{\rm M} \approx \xi 10^8\,{\rm cm} \left(\frac{B}{10^{12}{\rm G}}\right)^{4/7} \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{-2/7}$$

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

Spin down and/or "Propeller regime"

$$R_{\mathrm{M}} \approx \xi 10^{8}\,\mathrm{cm}\left(\frac{B}{10^{12}\mathrm{G}}\right)^{4/7}\left(\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}}\right)^{-2/7}$$

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

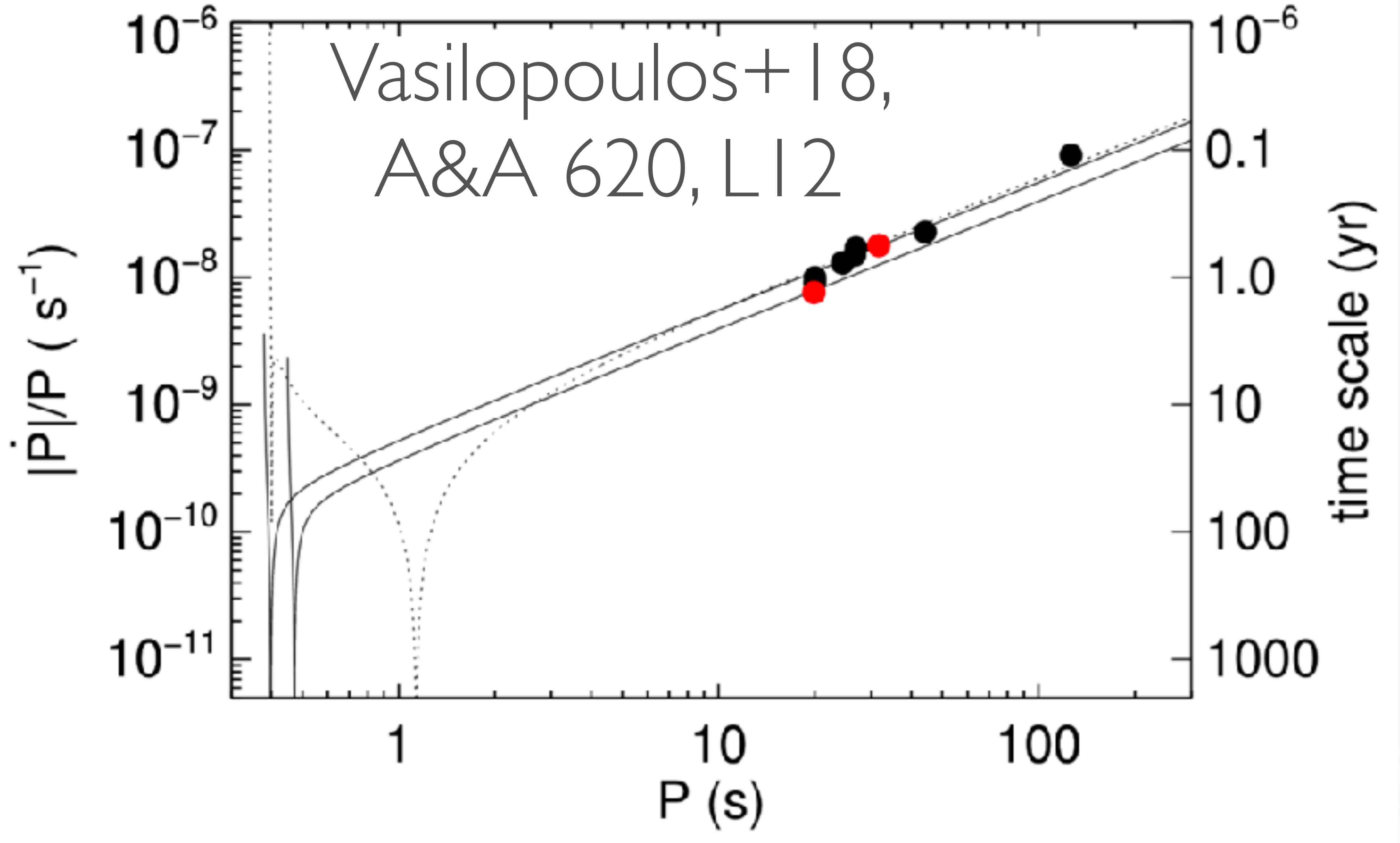
$$R_{\mathrm{M}} \approx \xi 10^8\,\mathrm{cm} \left(\frac{B}{10^{12}\mathrm{G}}\right)^{4/7} \left(\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}}\right)^{-2/7}$$

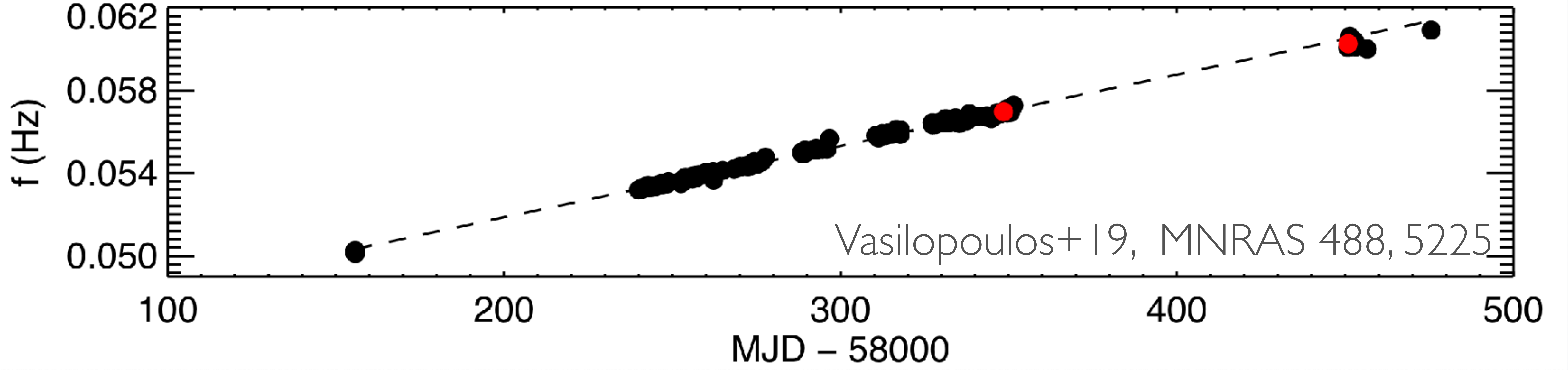
$$R_{\mathrm{co}} = \left(\frac{GMp^2}{4\pi^2}\right)^{1/3}$$

- Rotation Period
- Mass accretion rate
- Mass

- **NGC 300:** monotonic spin up
- Compatible with standard NS torque formulas far from equilibrium

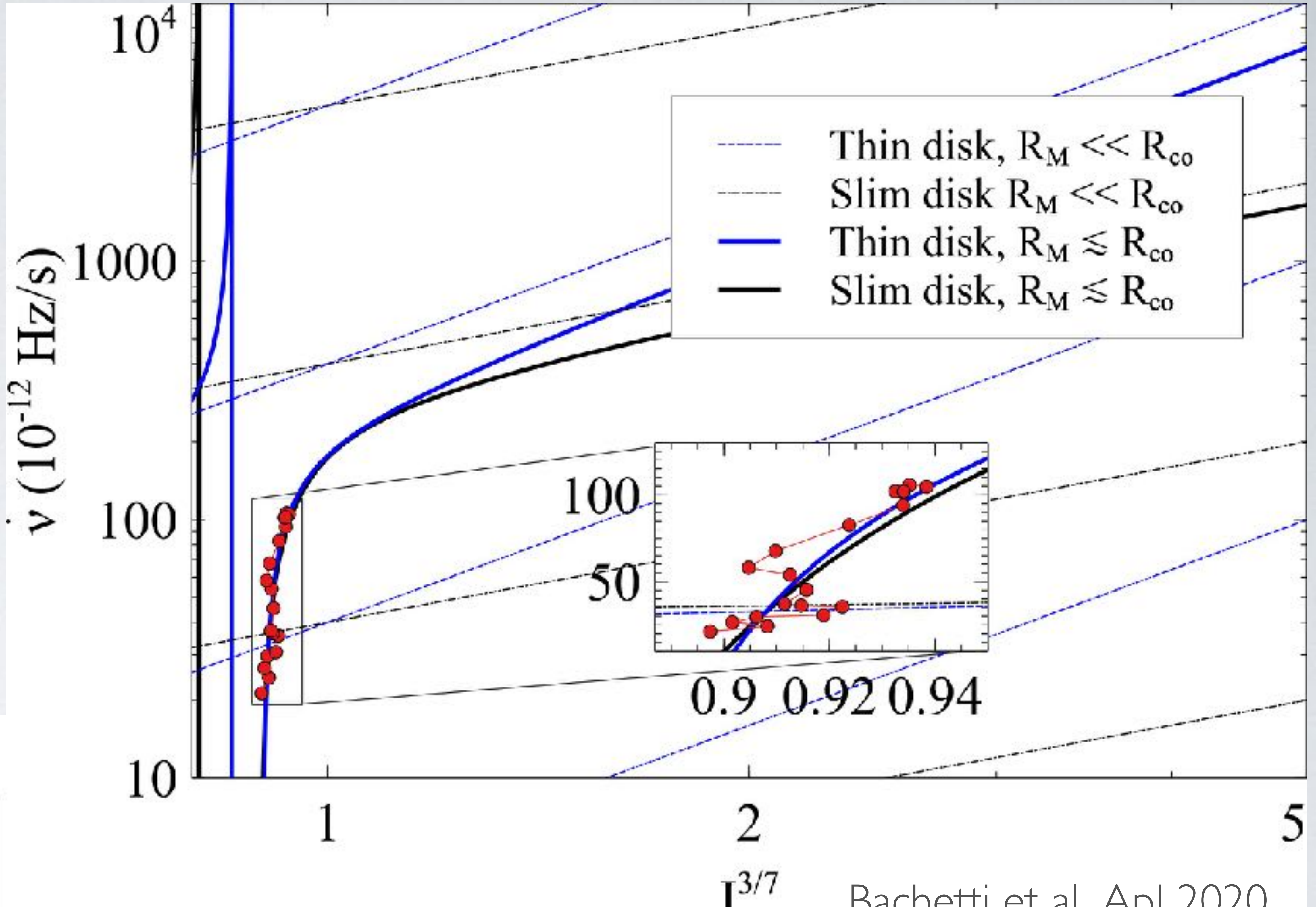
SLOW ROTATOR



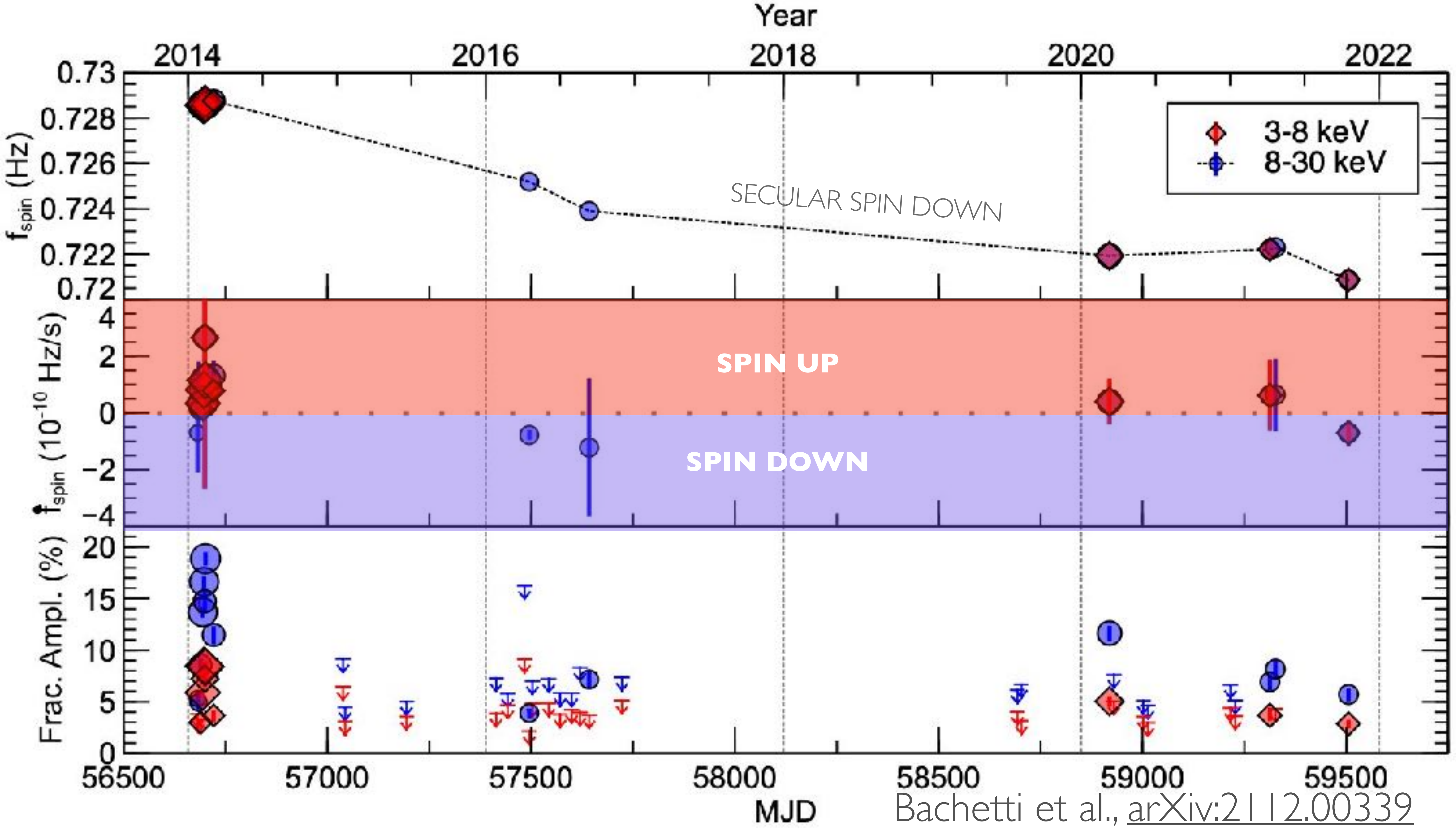


- **M82 X-2:** alternating spin down and spin up
- frequency derivative versus luminosity incompatible with "slow rotator"

SPIN EQUILIBRIUM



Bachetti et al., ApJ 2020



Bachetti et al., arXiv:2112.00339

$$R_{\mathrm{M}} \approx \xi 10^8\,\mathrm{cm} \left(\frac{B}{10^{12}\mathrm{G}}\right)^{4/7} \left(\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}}\right)^{-2/7}$$

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

- Rotation Period
- Mass accretion rate
- Mass

$$R_{\mathrm{M}} \approx \xi 10^{8}\,\mathrm{cm}\left(\frac{B}{10^{12}\mathrm{G}}\right)^{4/7}\left(\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}}\right)^{-2/7}$$

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

- ✔ Rotation Period
- Mass accretion rate
- Mass

$$R_{\rm M} \approx \xi 10^8\,{\rm cm}\left(\frac{B}{10^{12}{\rm G}}\right)^{4/7}\left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{-2/7}$$

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

WHAT IS THE MASS ACCRETION RATE?

WHAT IS THE MASS ACCRETION RATE?

Estimates from luminosity:

- $L \sim \eta c^2 \dot{M}$ (proportional to luminosity, $\eta \sim 0.15$ for a NS):
  but… **highly super Eddington.** -> estimated B often **incompatible with accretion on star (due to propeller)**

WHAT IS THE MASS ACCRETION RATE?

Estimates from luminosity:

- $L \sim \eta c^2 \dot{M}$ (proportional to luminosity, $\eta \sim 0.15$ for a NS): but… **highly super Eddington.** -> estimated B often **incompatible with accretion on star (due to propeller)**

- $L_{\rm obs} = L_{\rm iso}/b, b \sim 73/\dot{m}^2 \rightarrow L_{\rm obs} \propto \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^2$: more comfortable, but very **ad-hoc** and does not explain **sinusoidal profiles**

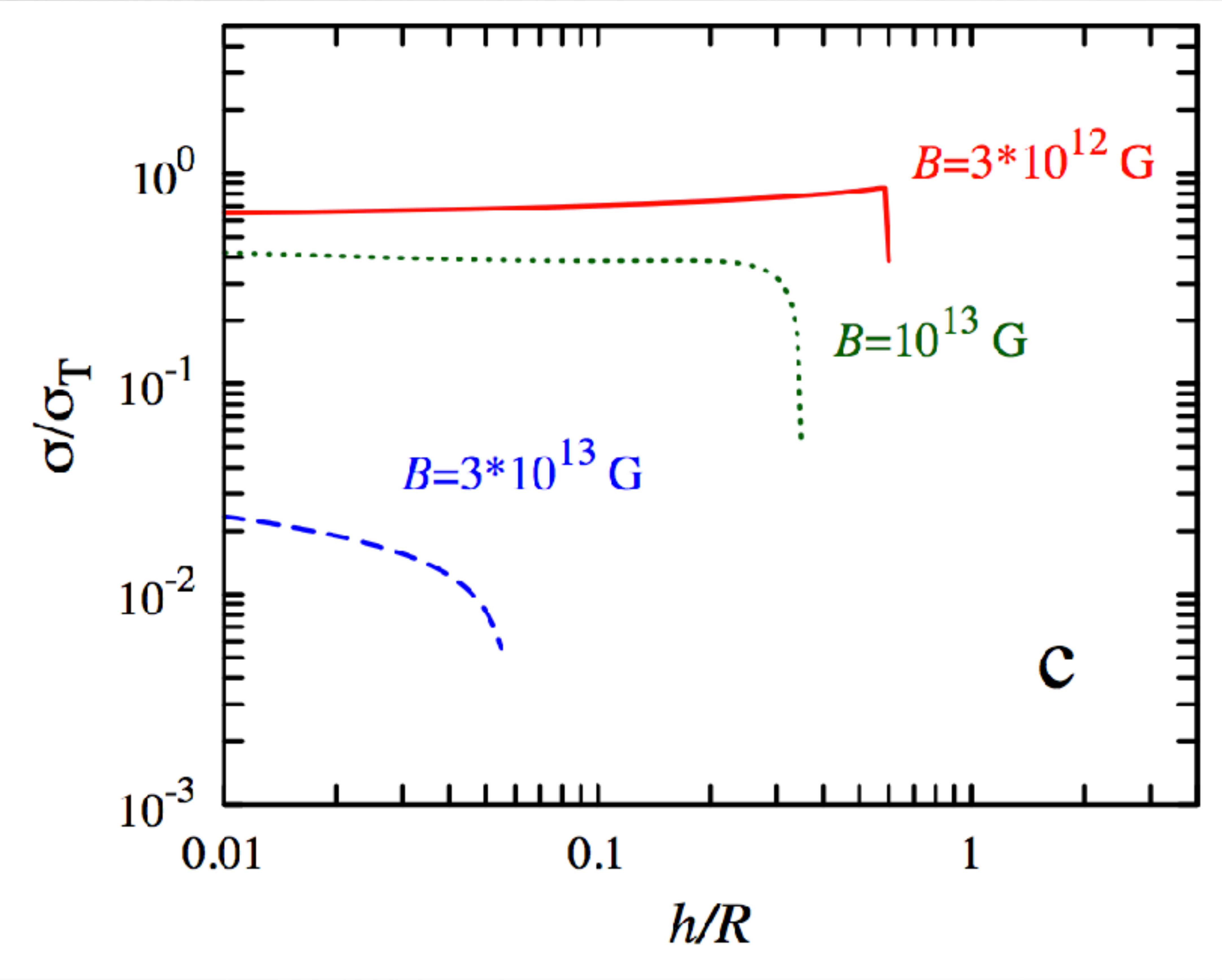
SUPER-EDDINGTON LUMINOSITY AS AN EFFECT OF BEAMING

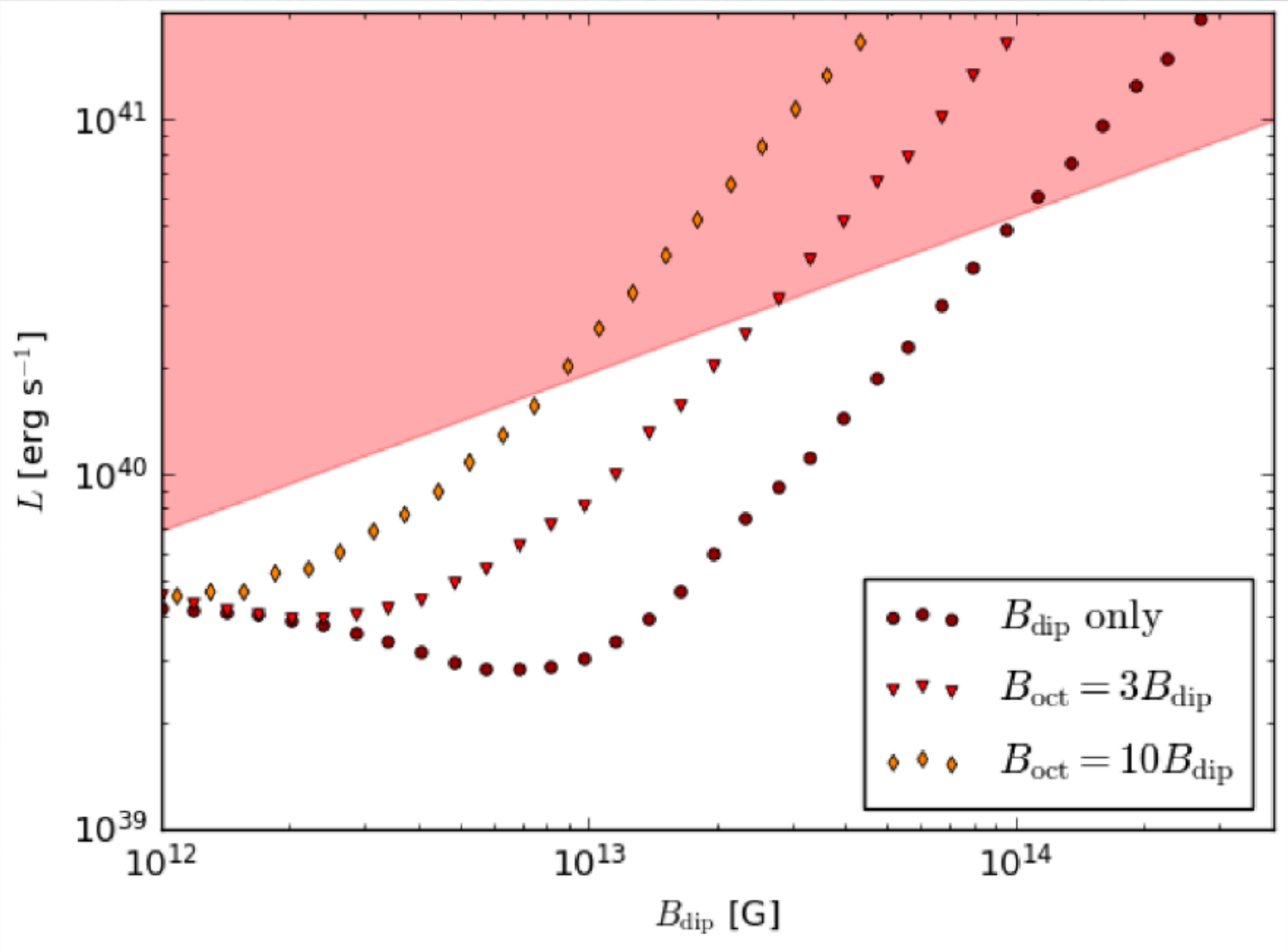
King 2009 MNRAS **320**, L45

$$b \sim \frac{73}{\dot{m}^2}$$

HUL and BD spectra: face-on
SUL spectra: inclined
Sutton+2013, **MNRAS** 435,1758
Gúrpide+2021, arXiv:210605708
Outflows:
Pinto+2016, Nat. **533**, 64

SUPER-EDDINGTON LUMINOSITY FROM HIGH MAGNETIC FIELD

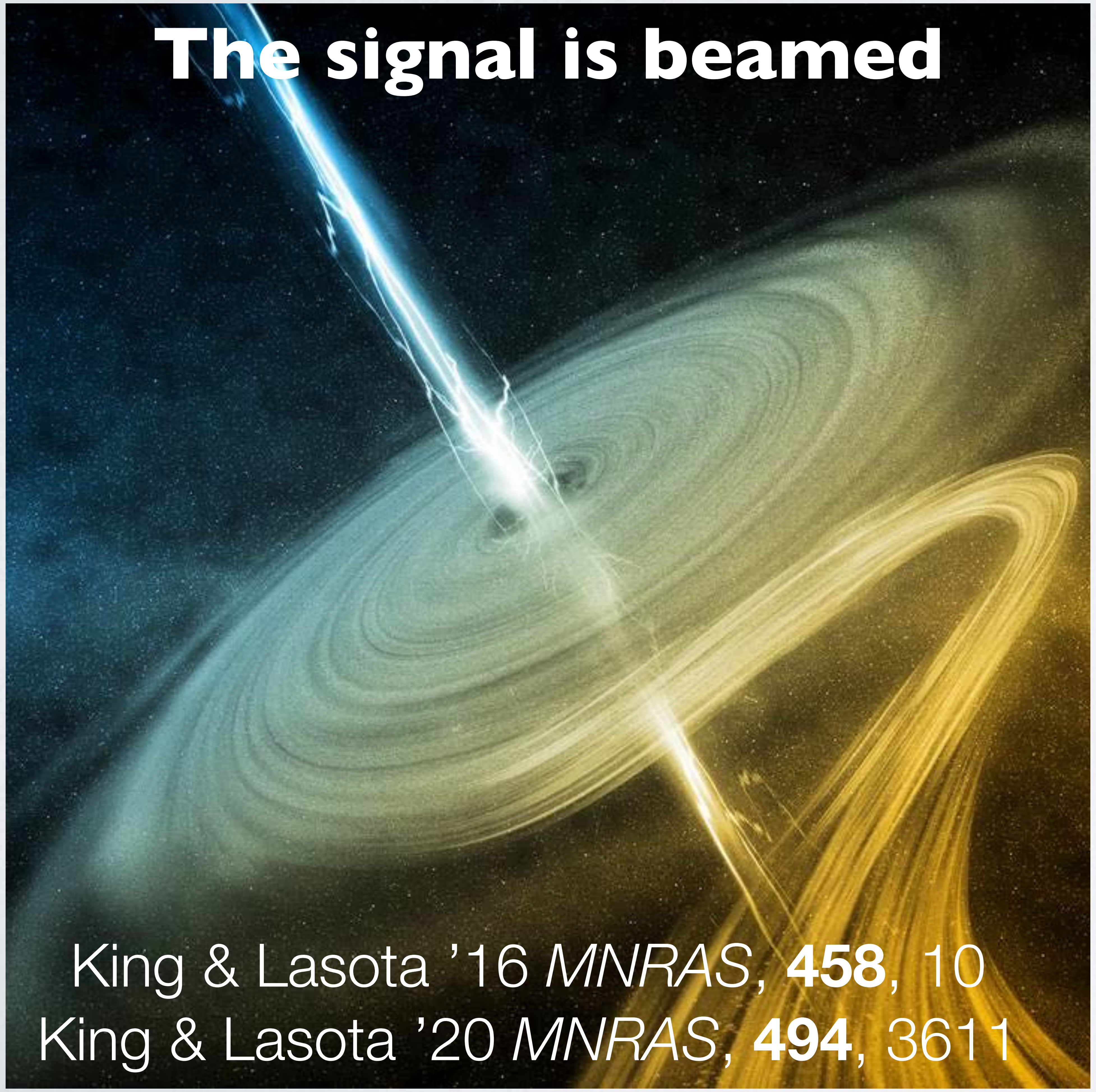


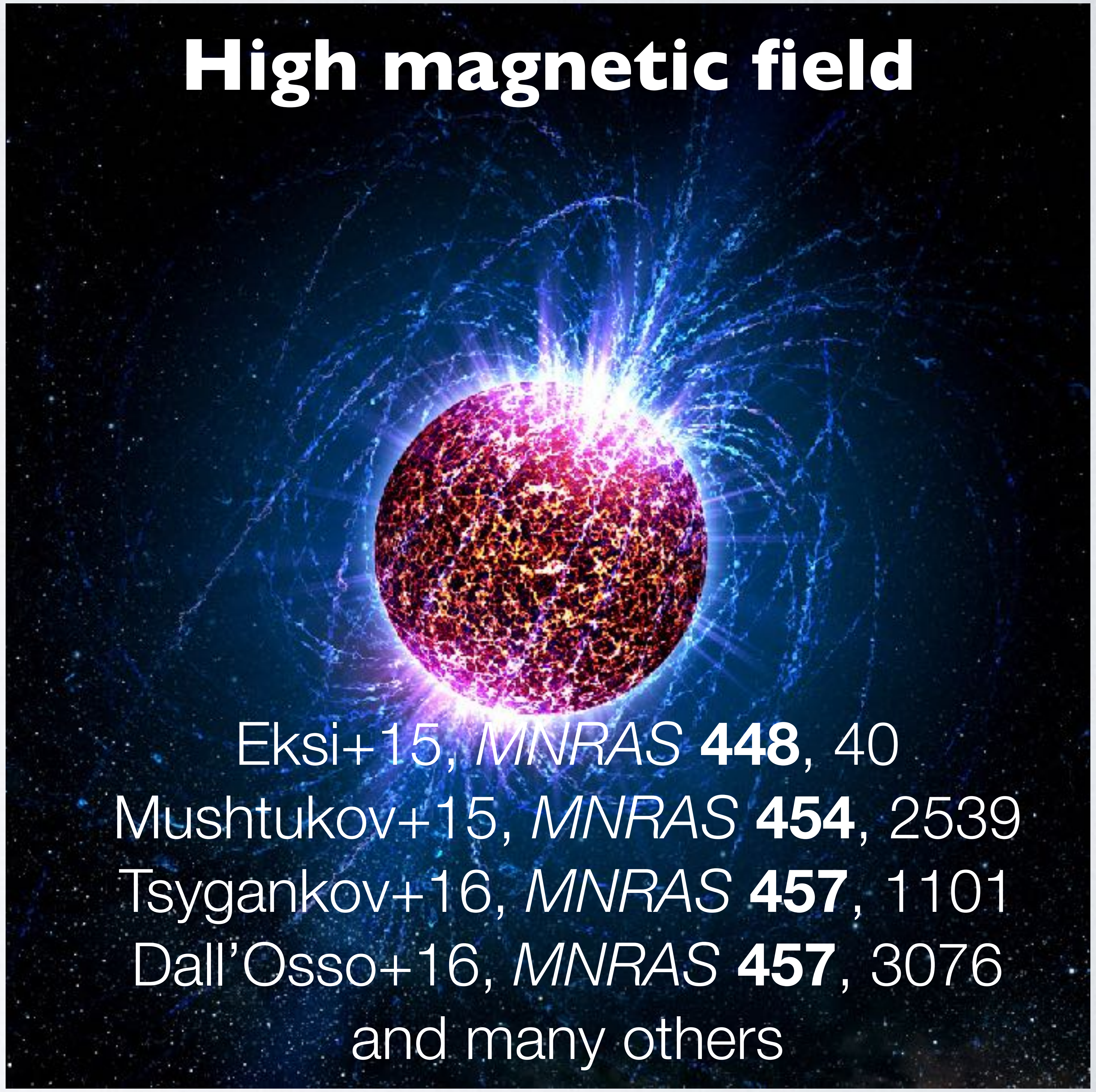


Basko & Sunyaev 1976, MNRAS 175, 395
Mushtukov+2015, MNRAS, 454, 2539
High B alters the Thomson cross-section

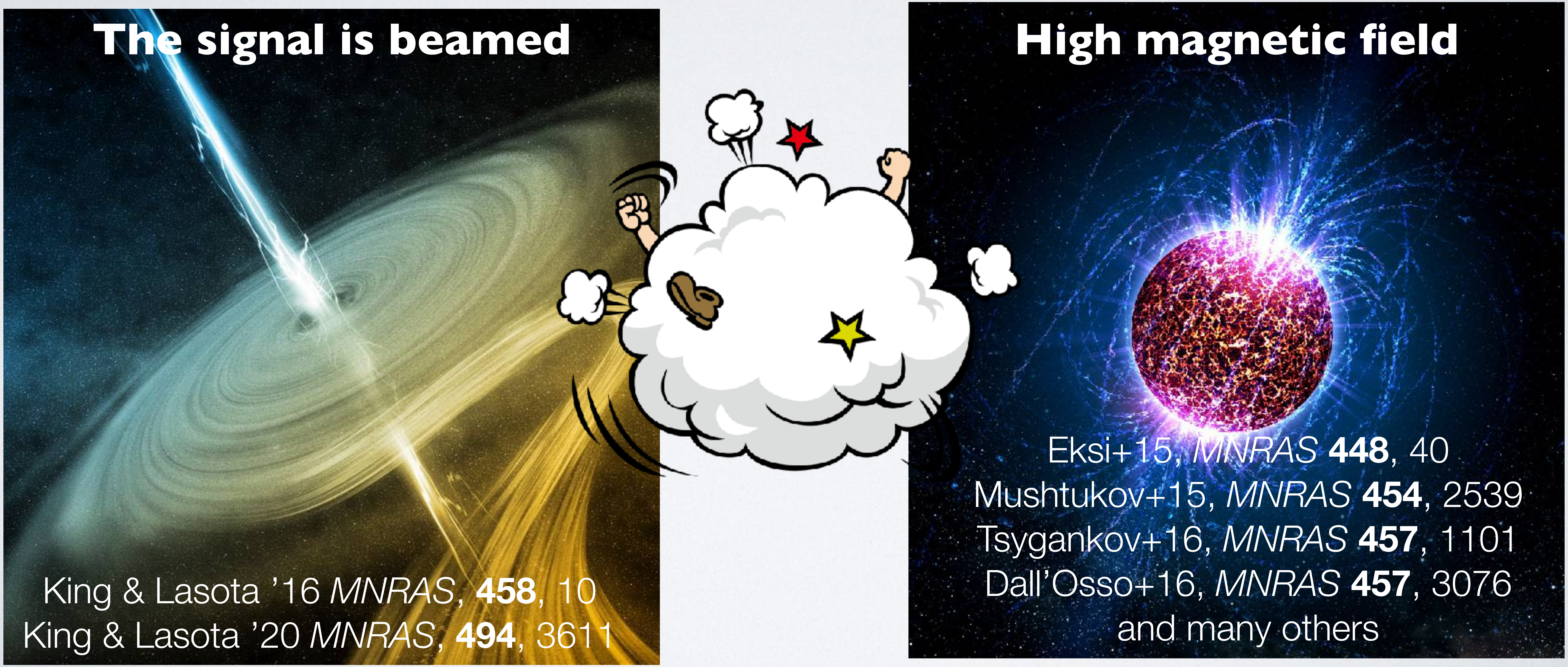
Brice+2021, MNRAS 504, 701
multipolar components allow to avoid the propeller regime

AN ONGOING FRIENDLY DEBATE

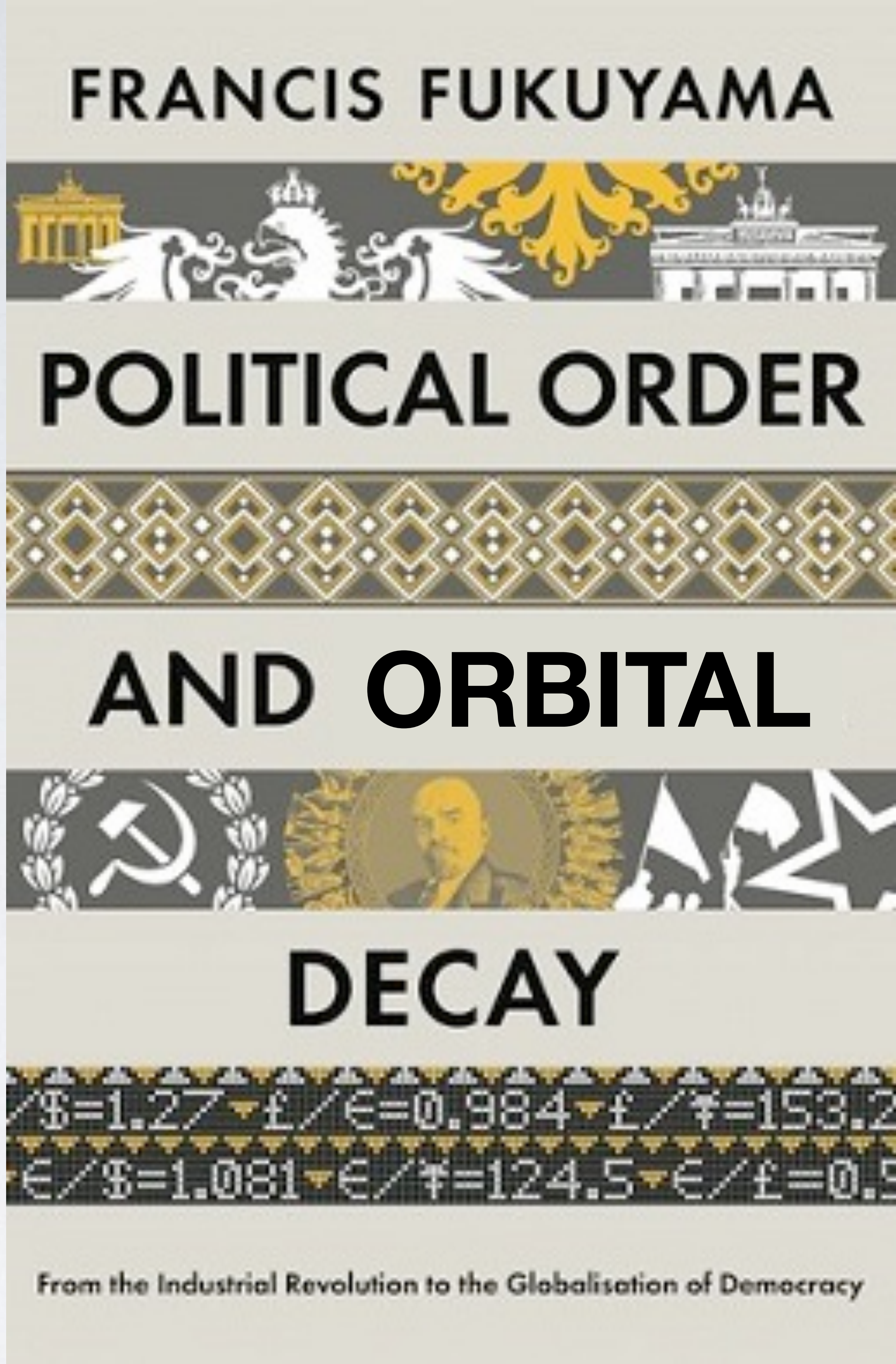




AN ONGOING FRIENDLY DEBATE



ORBITAL DECAY

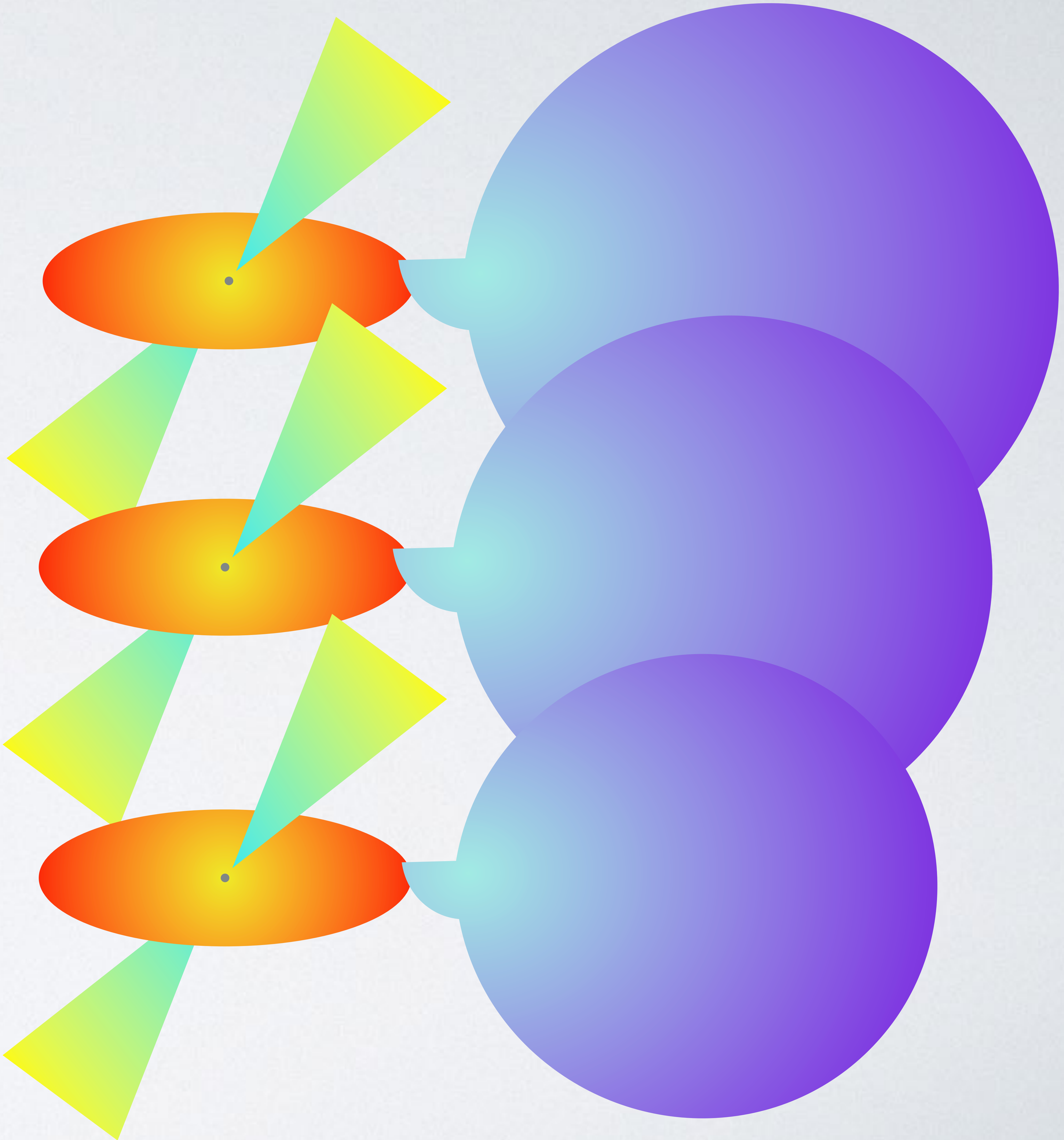


POSSIBILITY: MEASURE MASS EXCHANGE

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

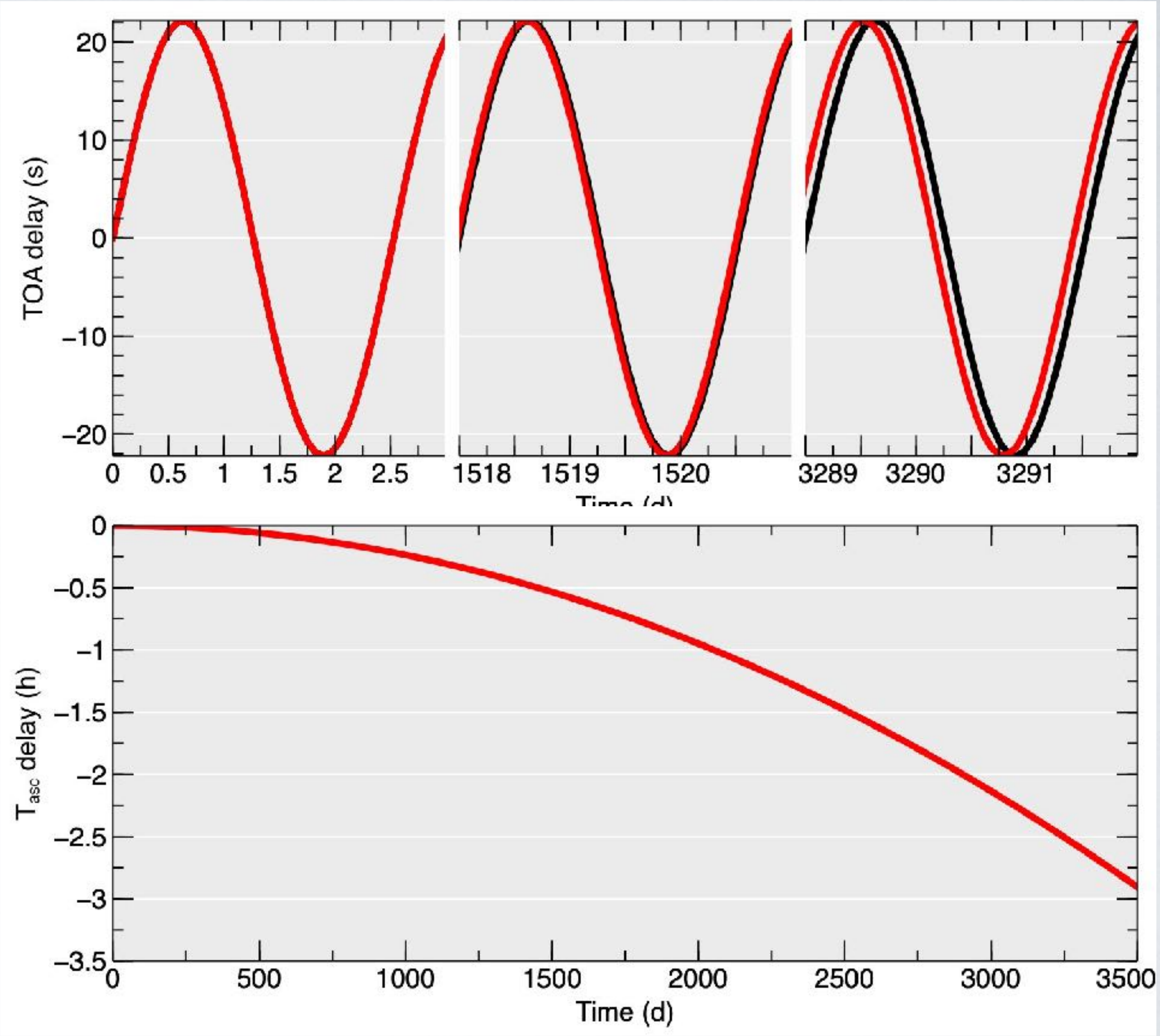
$$\dot{P}_{\rm orb} \sim -3.5 \times 10^{-8} \left(\frac{M_p}{1.4 M_\odot} \right)^{-1} \left(\frac{-\dot{M}_c}{100 \dot{M}_{\rm Edd}} \right)$$

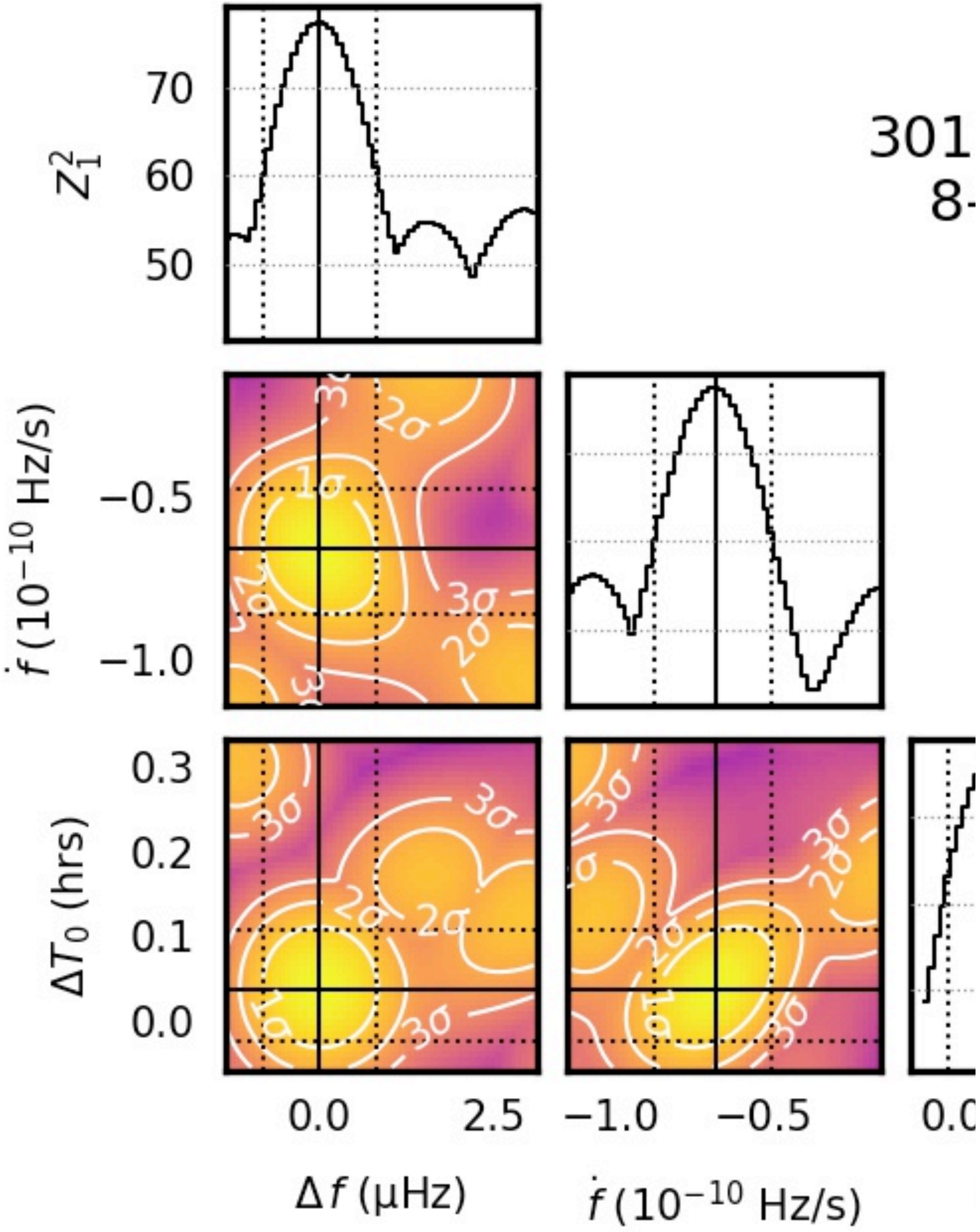
- For M82 X-2, hundreds of seconds of orbital drift over years. MEASURABLE!

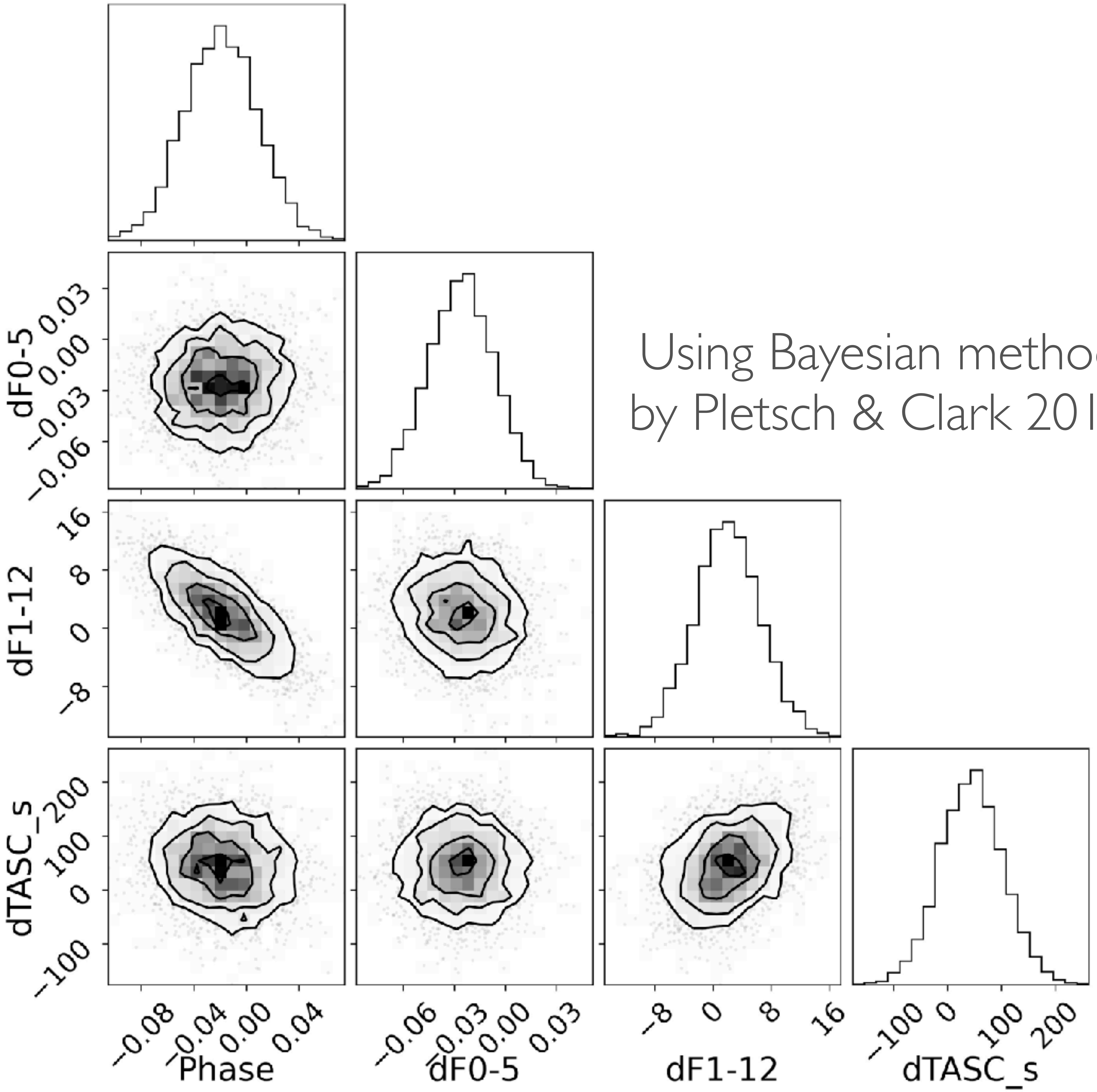


MEASURING THE ORBITAL DECAY

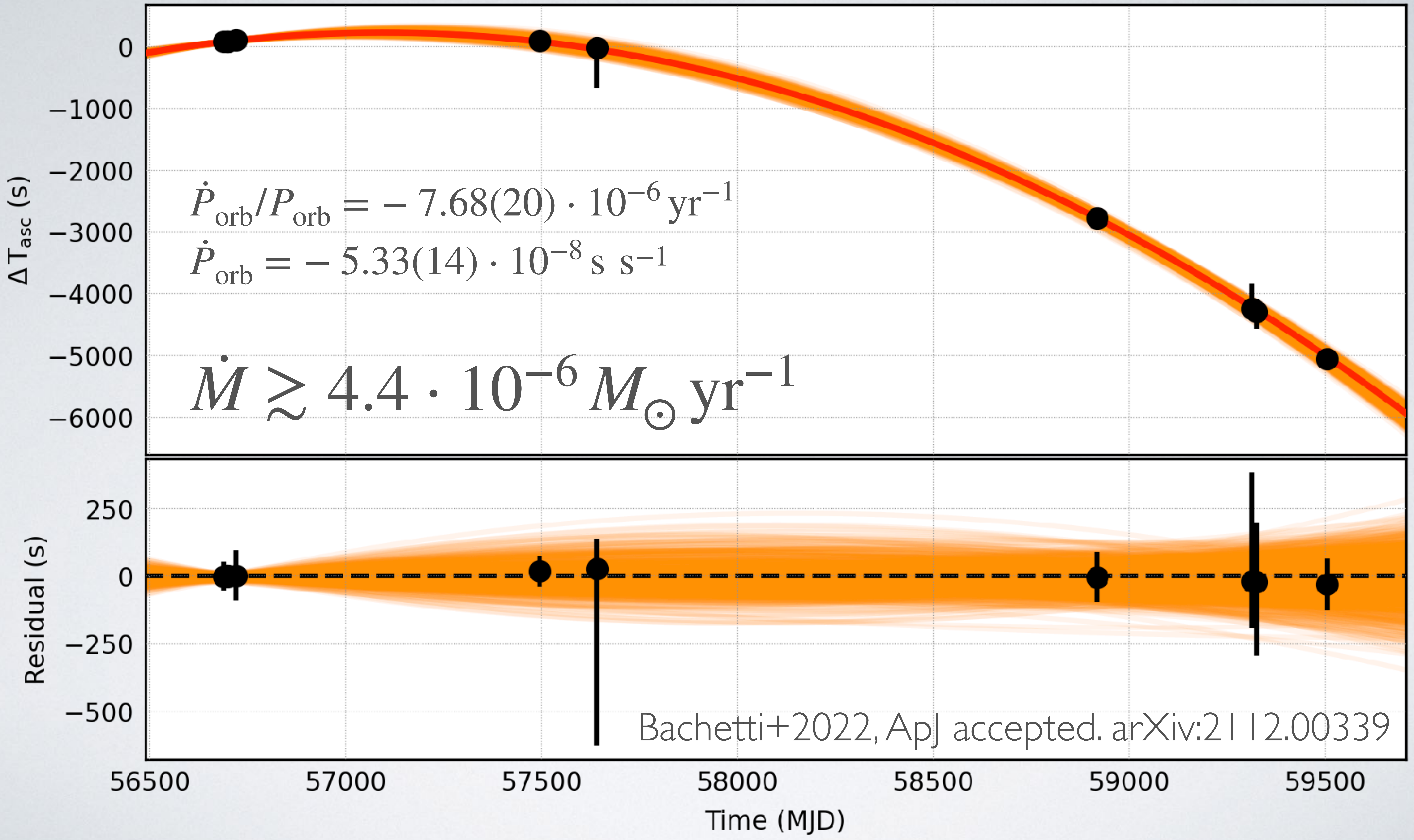
$$\delta T_{\rm asc}(t) = \frac{1}{2}\frac{\dot{P}_{\rm orb}}{P_{\rm orb}}\left(t - t_0\right)^2$$



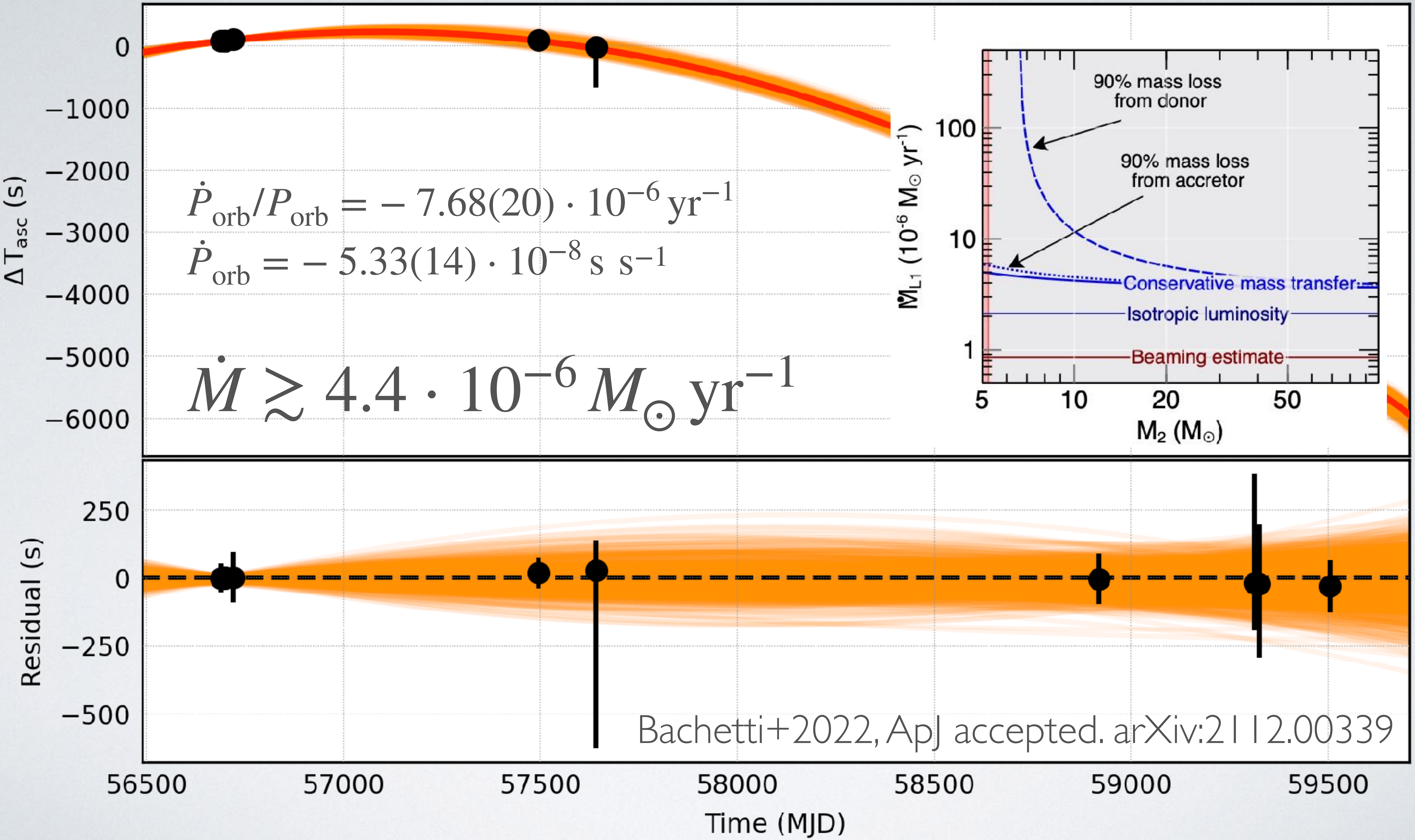




Using Bayesian method
by Pletsch & Clark 2015



$\dot{P}_{orb}/P_{orb} = -7.68(20) \cdot 10^{-6}\,yr^{-1}$
$\dot{P}_{orb} = -5.33(14) \cdot 10^{-8}\,s\ s^{-1}$
$\dot{M} \gtrsim 4.4 \cdot 10^{-6}\, M_{\odot}\, yr^{-1}$
ΔT_{asc} (s)
0
−1000
−2000
−3000
−4000
−5000
−6000
Residual (s)
250
0
−250
−500
56500
57000
57500
58000
58500
59000
59500
Time (MJD)
Bachetti+2022, ApJ accepted. arXiv:2112.00339



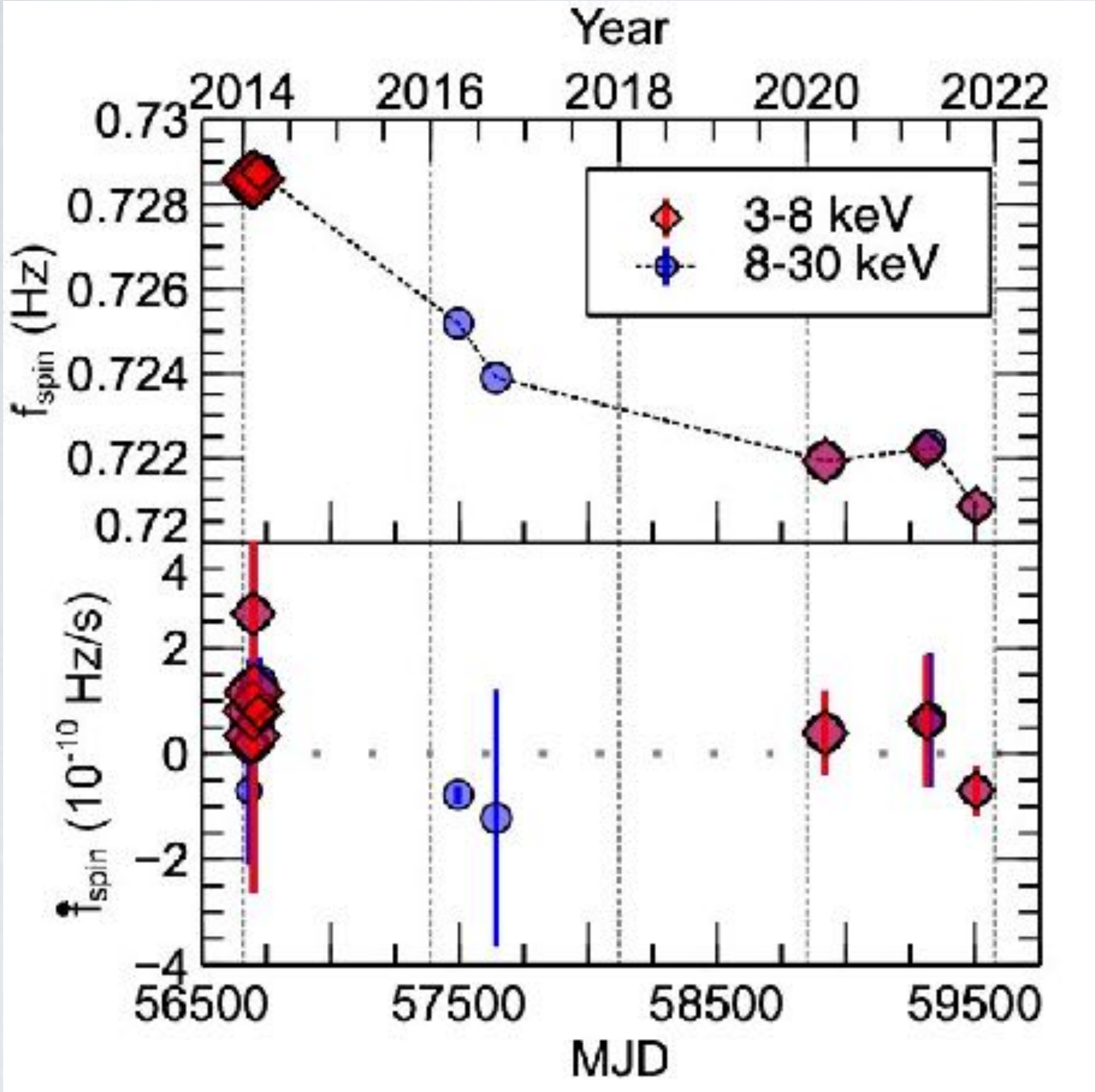
$$\dot{P}_{\rm orb}/P_{\rm orb} = -7.68(20)\cdot 10^{-6}\,{\rm yr}^{-1}$$

$$\dot{P}_{\rm orb} = -5.33(14)\cdot 10^{-8}\,{\rm s\ s}^{-1}$$

$$\dot{M} \gtrsim 4.4\cdot 10^{-6}\,M_{\odot}\,{\rm yr}^{-1}$$

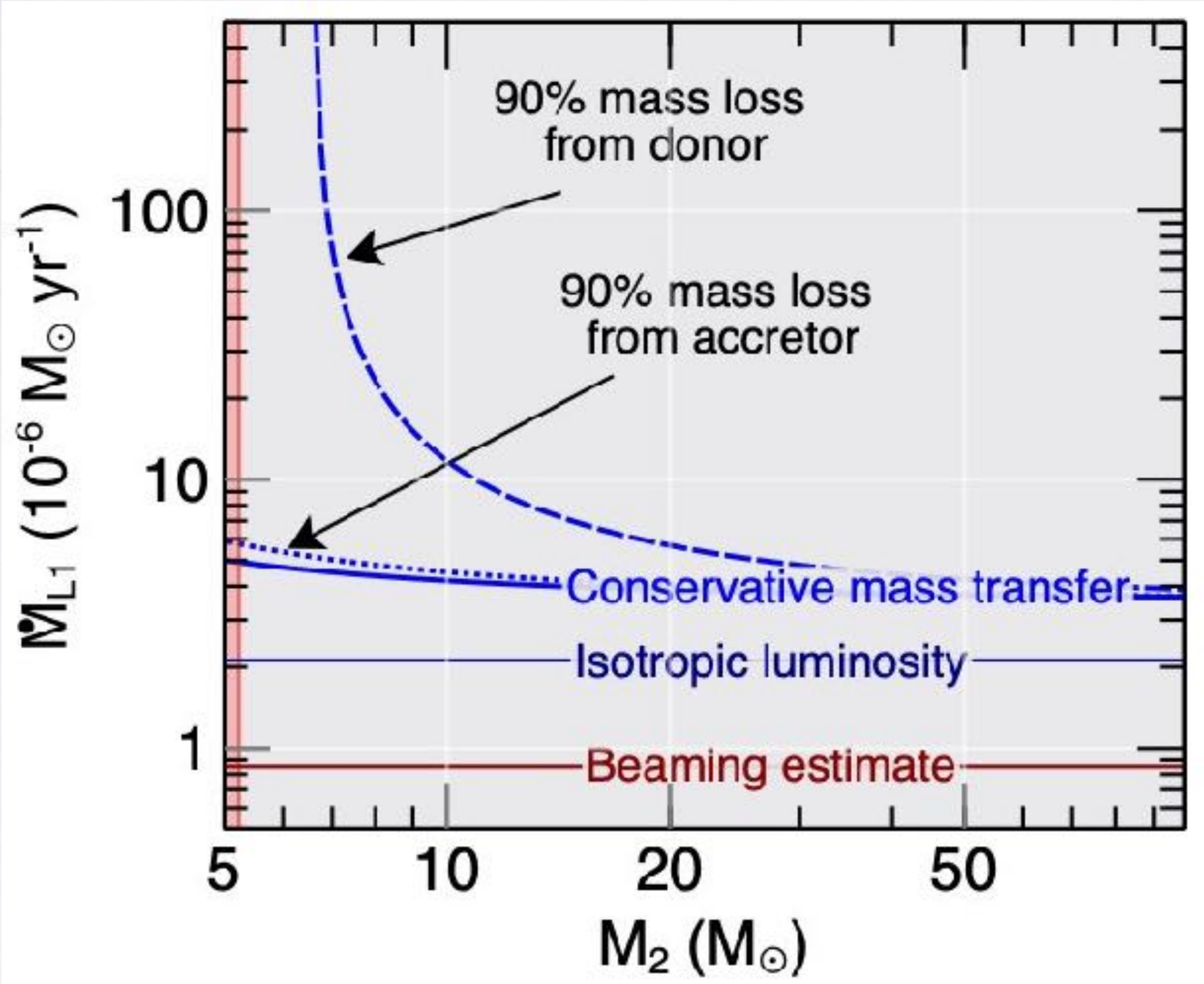
Bachetti+2022, ApJ accepted. arXiv:2112.00339

MASS TRANSFER?



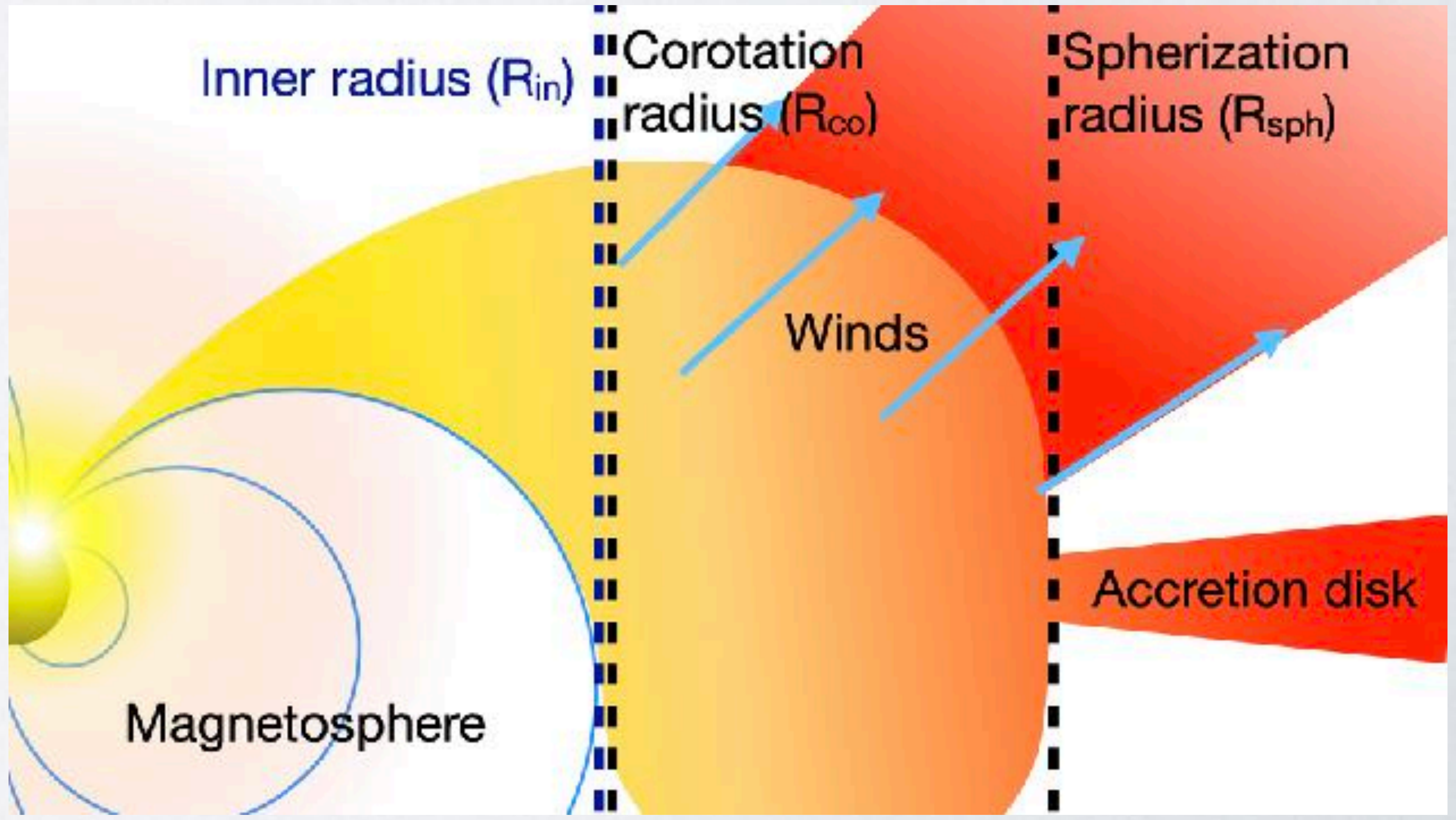
Spin equilibrium

+



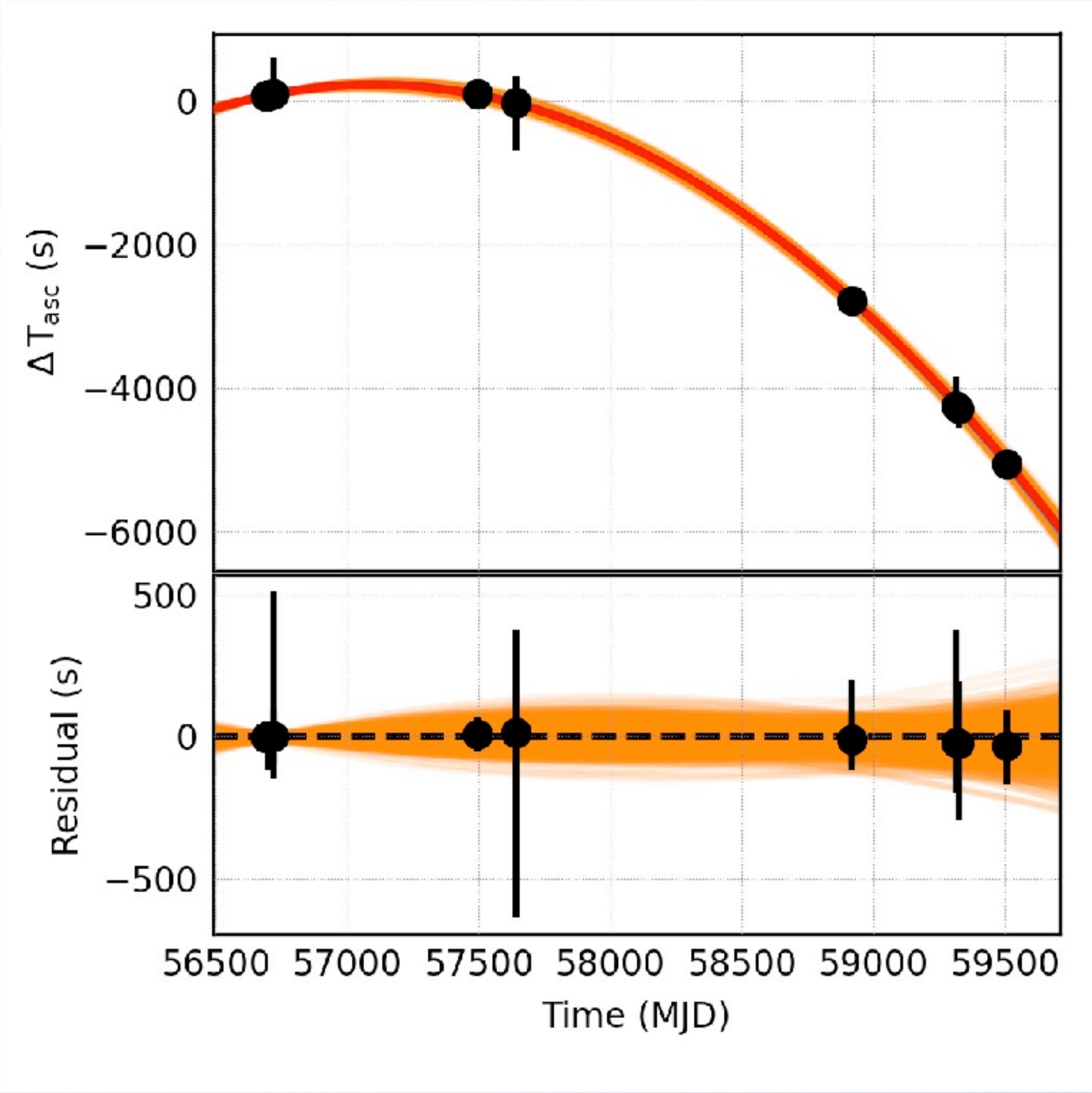
Extreme mass transfer

→ $B_{\rm dip} \sim 5 \cdot 10^{13}\,{\rm G}$



OPEN QUESTIONS

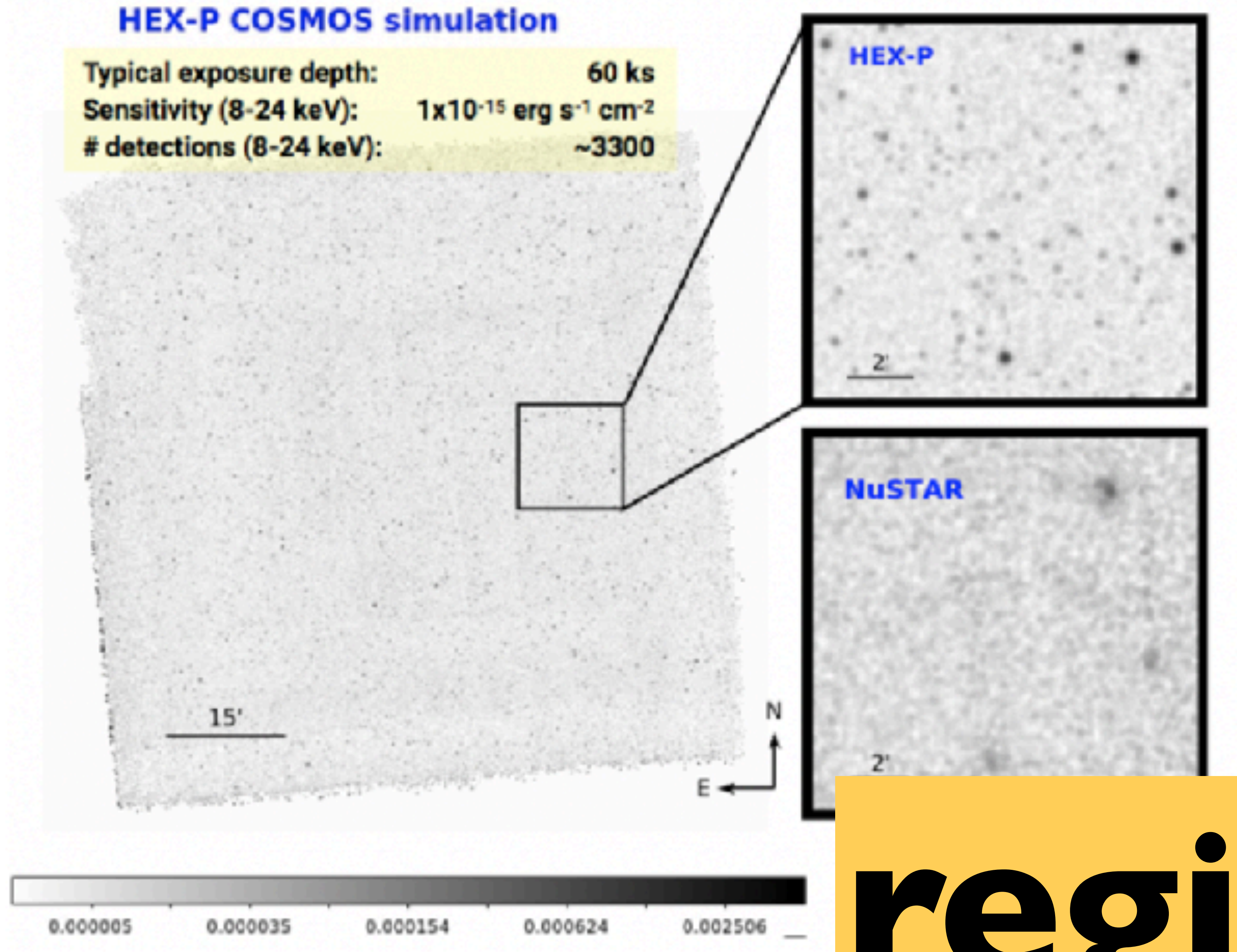
- How short-lived is this accretion regime? (e.g. Fragos+2015, Quast+2019, Misra+2020)
- What is the mass of the donor star? And the accretor?
- What about magnetic field configuration and decay?
- Can they be progenitors of binary MSP? Binary BHs? GW sources? FRBs?? SMBH seed?
- Is the observed orbital decay due to mass transfer?



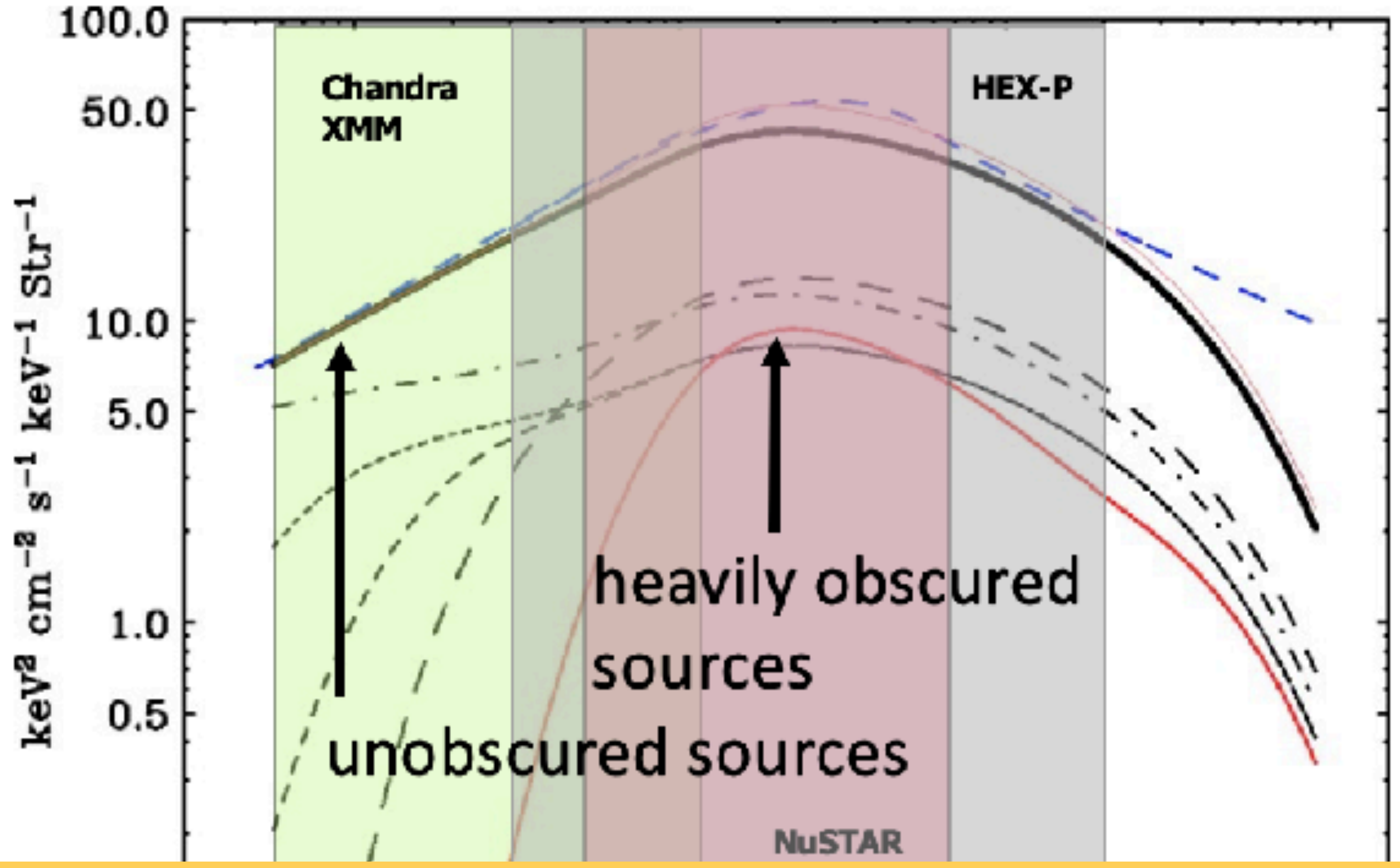
TAKE - HOME MESSAGE

- (P)ULXs are a gift that keeps on giving
- **Extreme** luminosity, **extreme** spin up, **extreme** orbital decay
- BUT a lot still to be learned: binary population studies do not seem to like them
- MOAR observations!

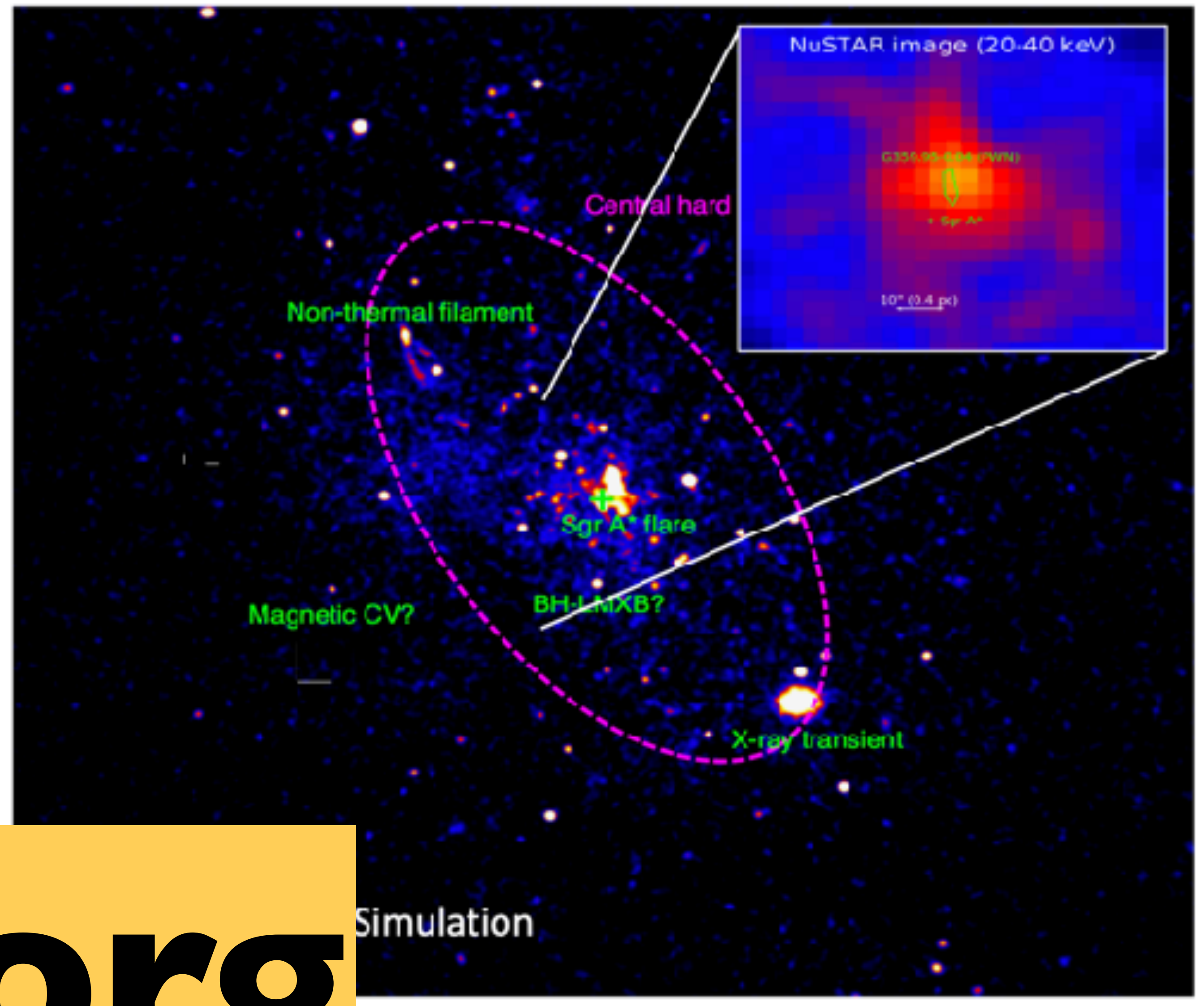
HEX-P: ~~1-slide summary~~ a spectacular ULX machine



cosmic X-ray background

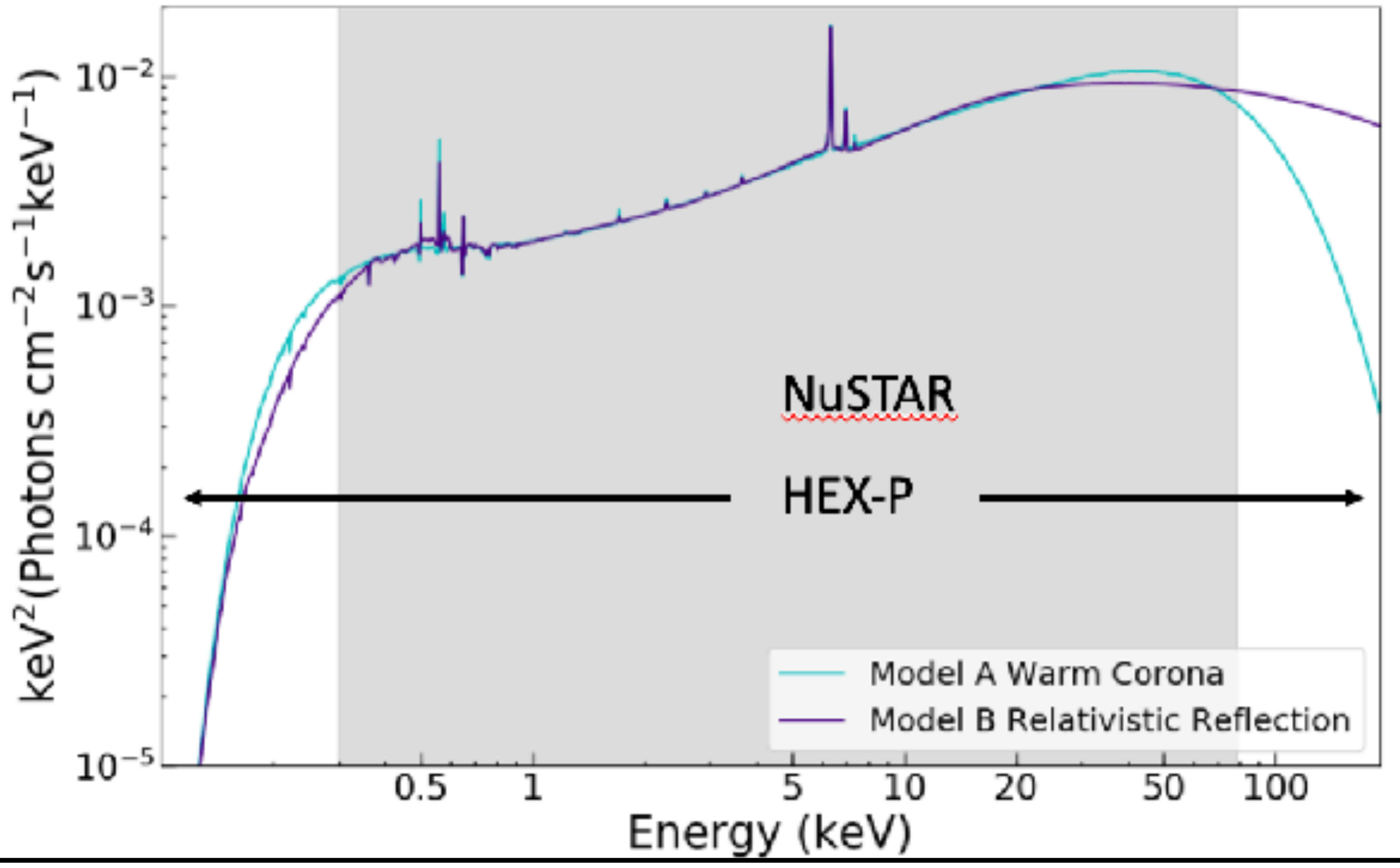


Galactic Center

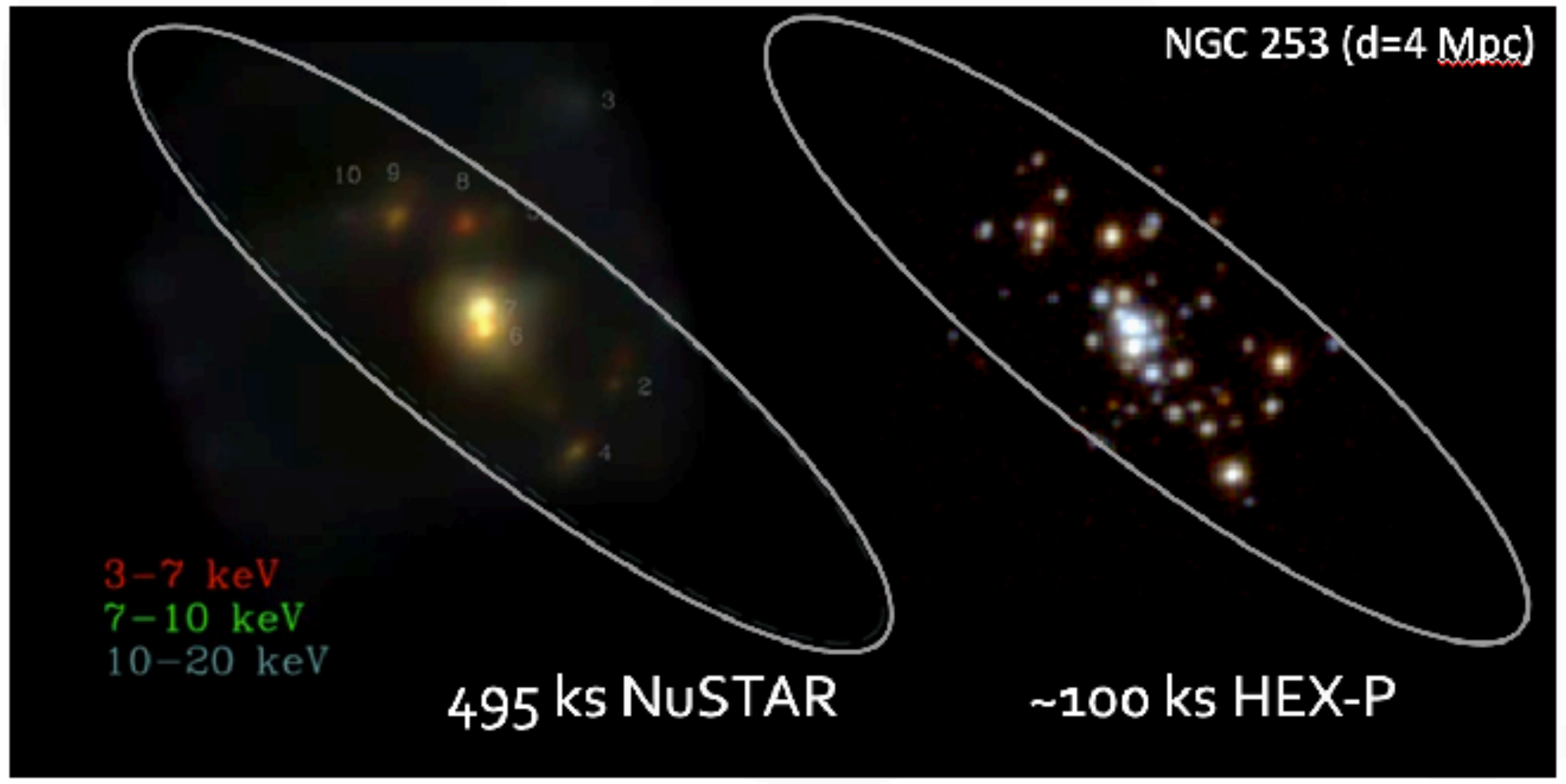


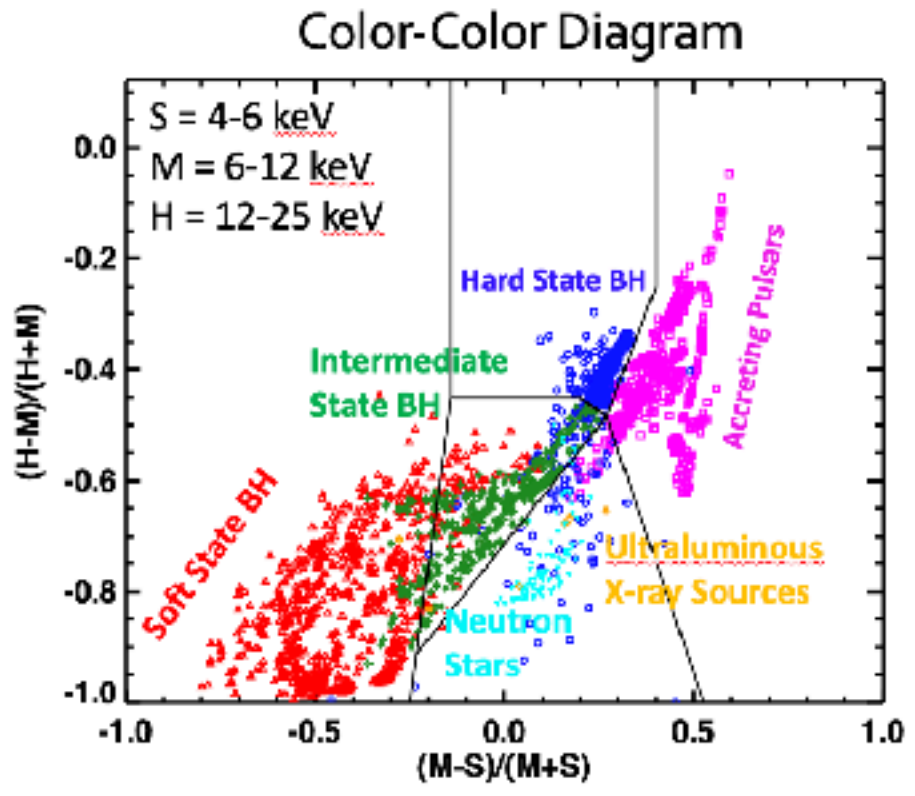
register at hexp.org

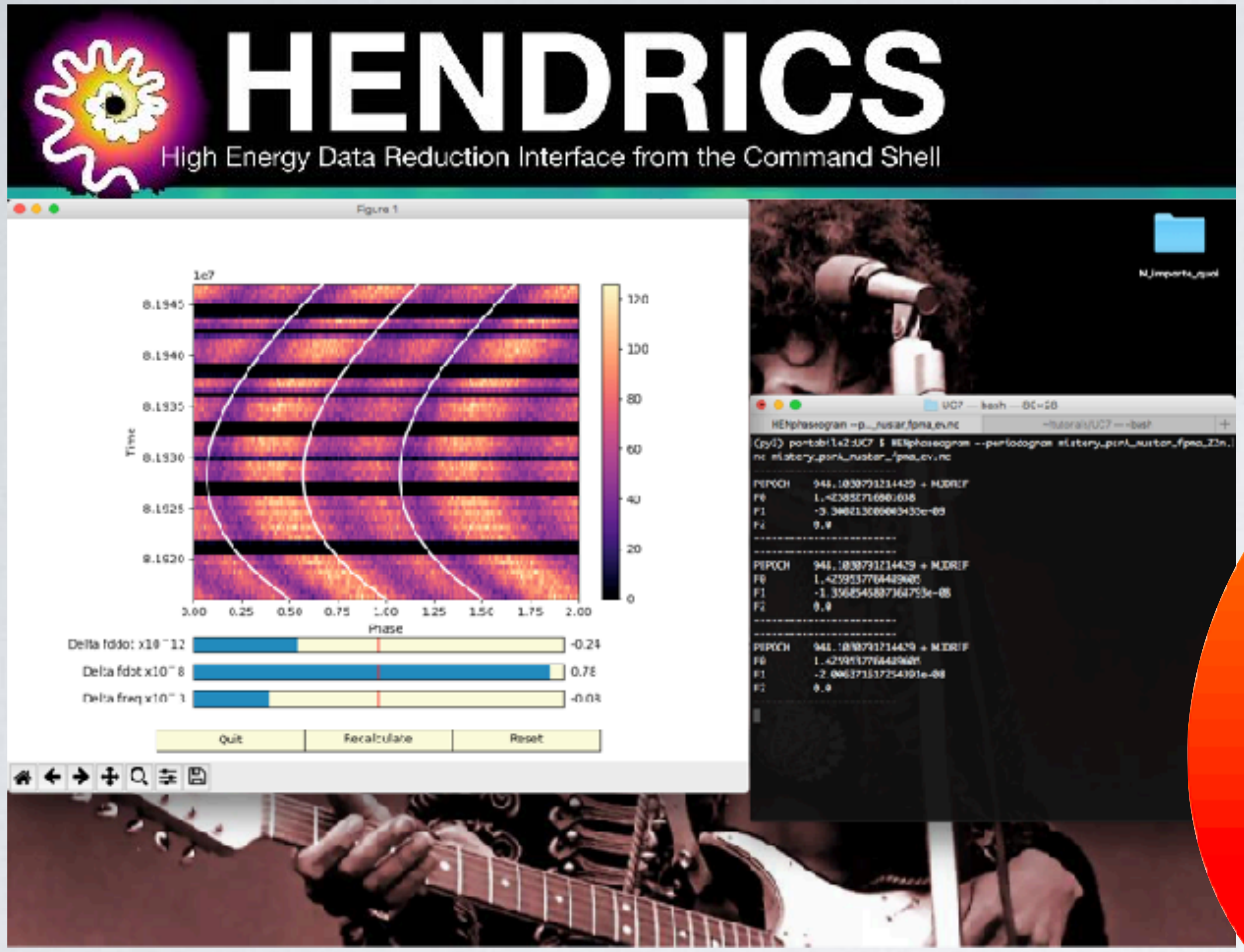
Higher-energy coverage of HEX-P unamb
between the two scenarios



galaxies







hendrics.readthedocs.io

https://veusz.github.io/

https://www.cv.nrao.edu/~sransom/presto/

PRESTO

www.astropy.org

Stingray

The Next Generation
Spectral-Timing Software

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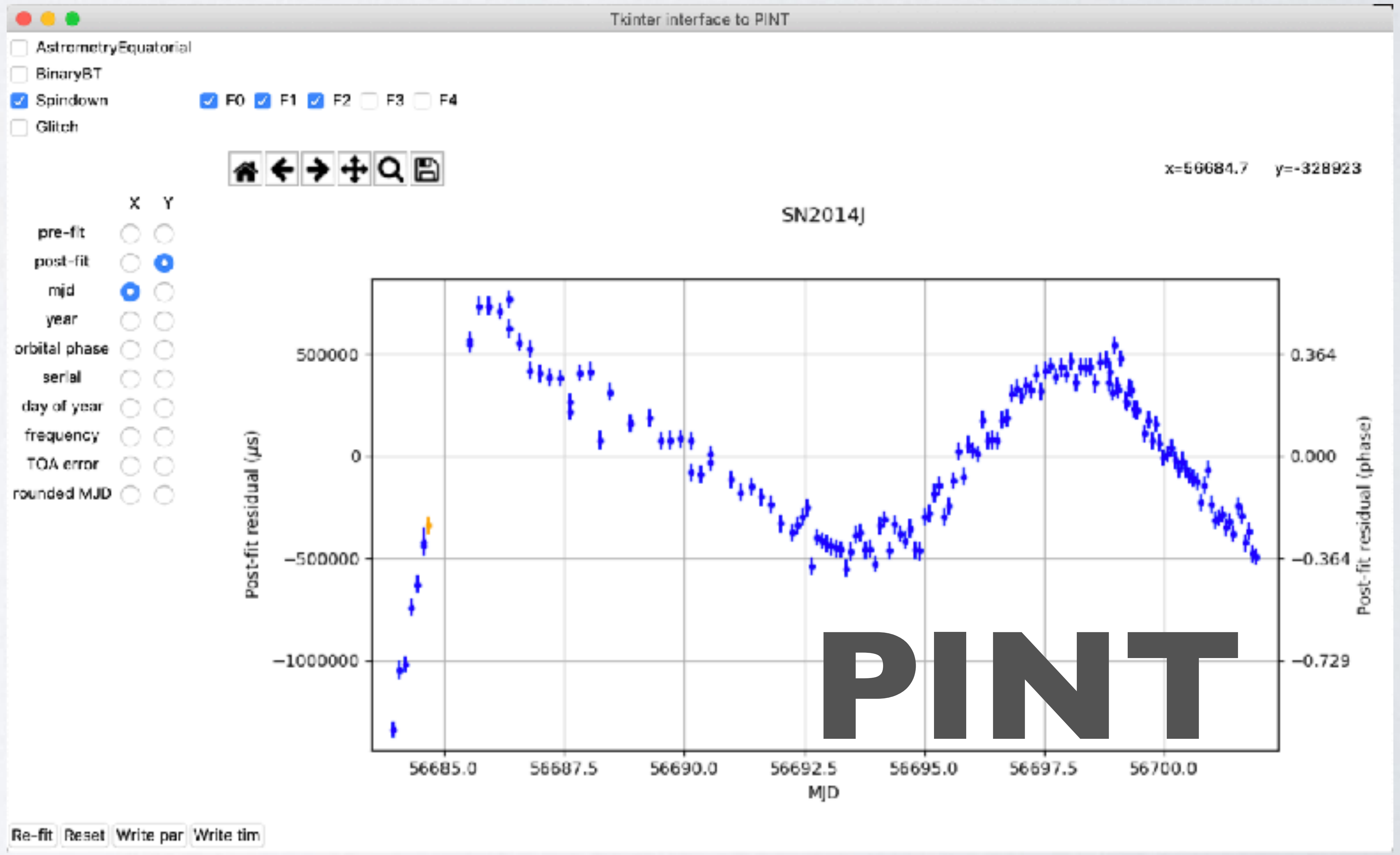
TEMPO2

tempo2

psrsoft/tempo2



https://nanograv-pint.readthedocs.io