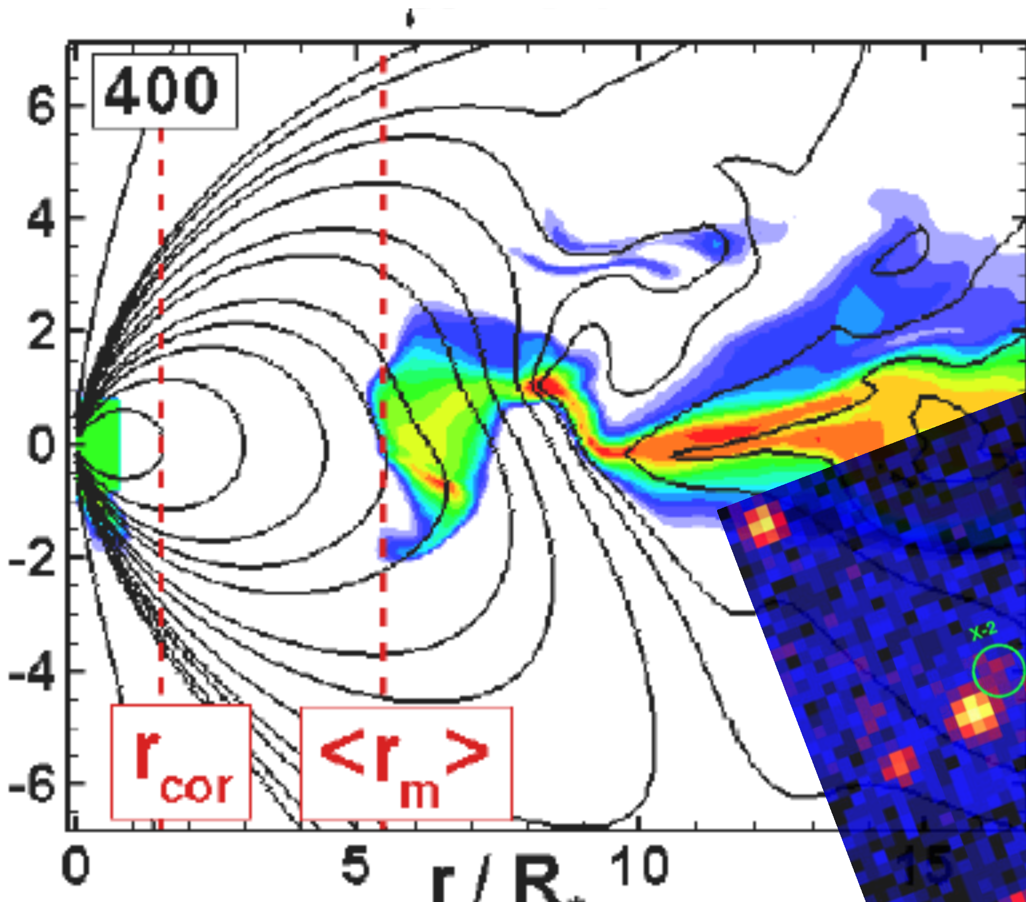
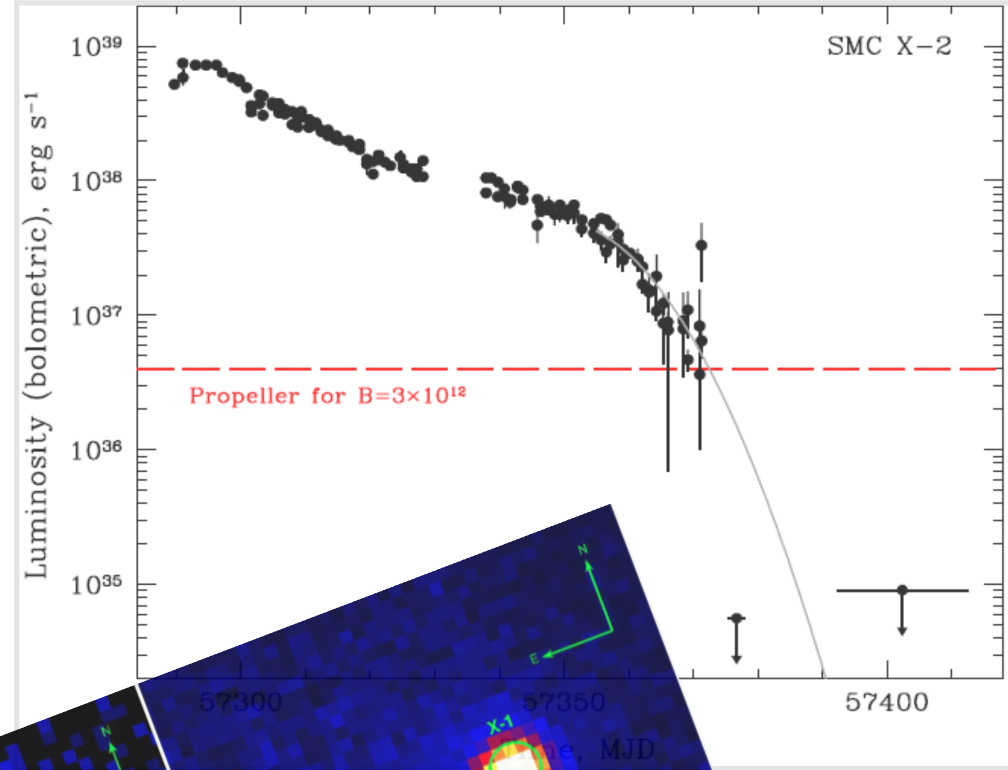
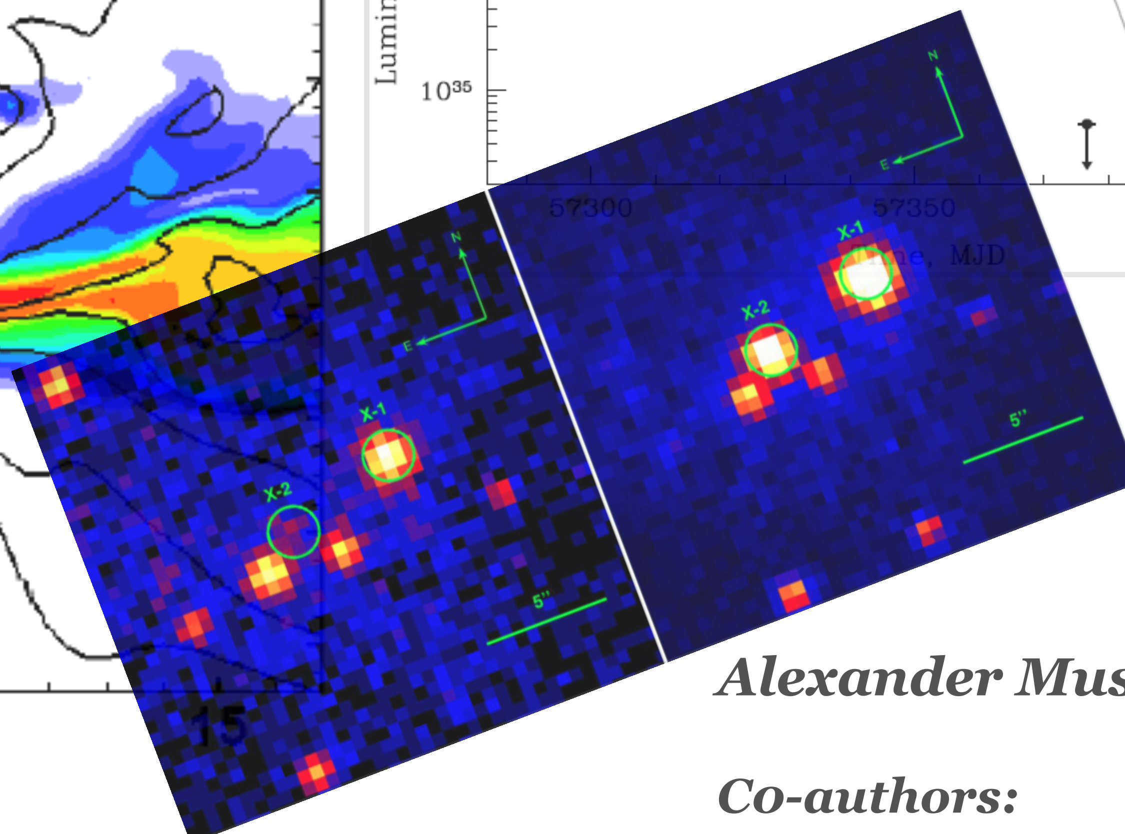
Some Theory of Propeller Accretion







Alexander Mushtukov

Co-authors:
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Victor Doroshenko
Valery F. Suleimanov
Juri Poutanen

Universiteit Leiden

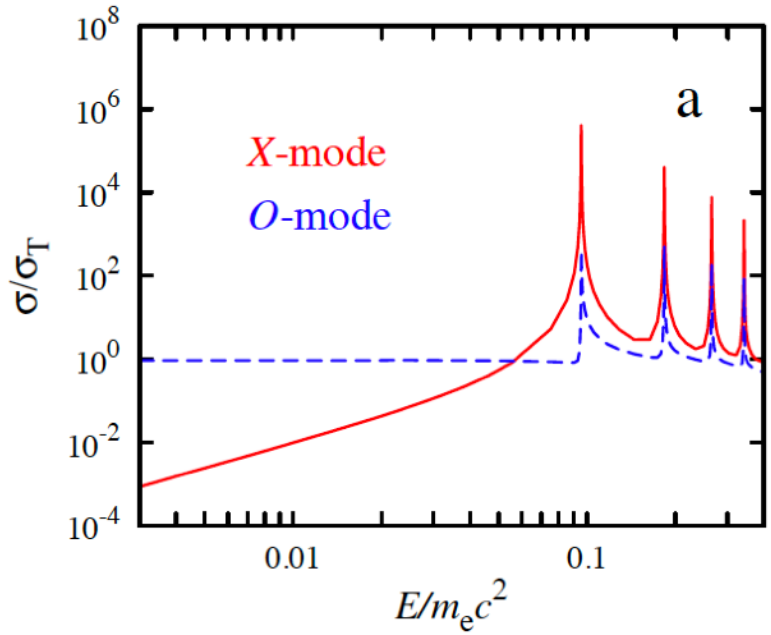
NWO
Netherlands Organisation for Scientific Research

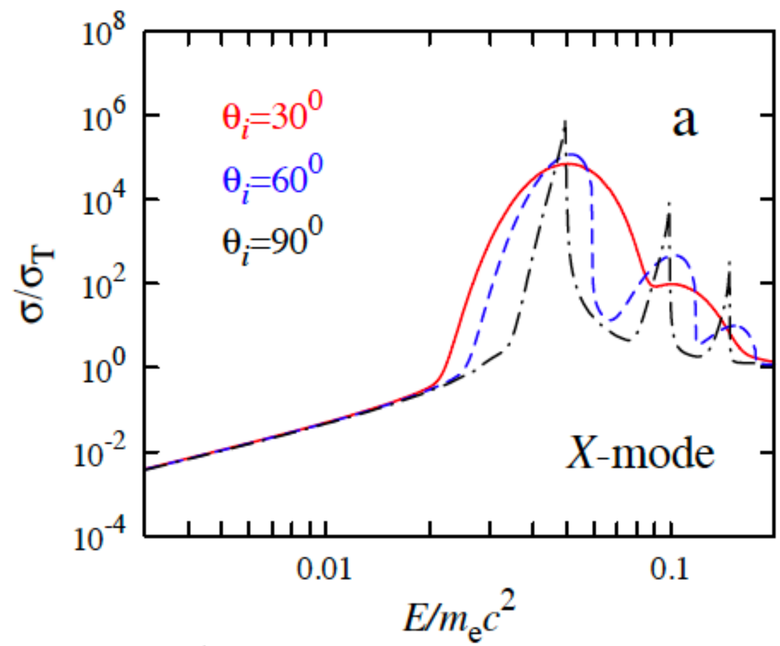
X-ray pulsar

Rotating Neutron Star in binary systems

X-ray pulsar

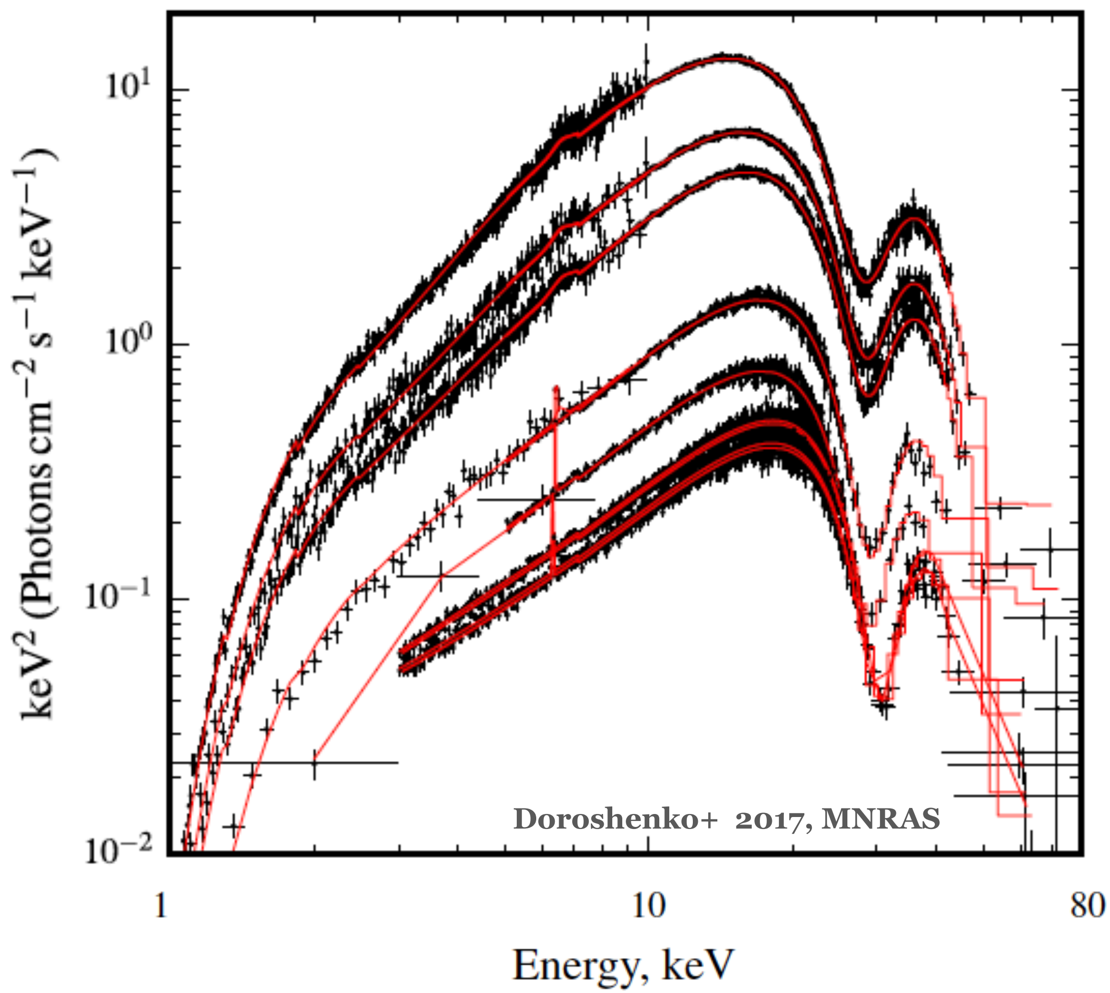
Typical spectra





AM+ 2012, 2016, Phys.Rev.D

Spectra of V 0332+53 at different luminosity states

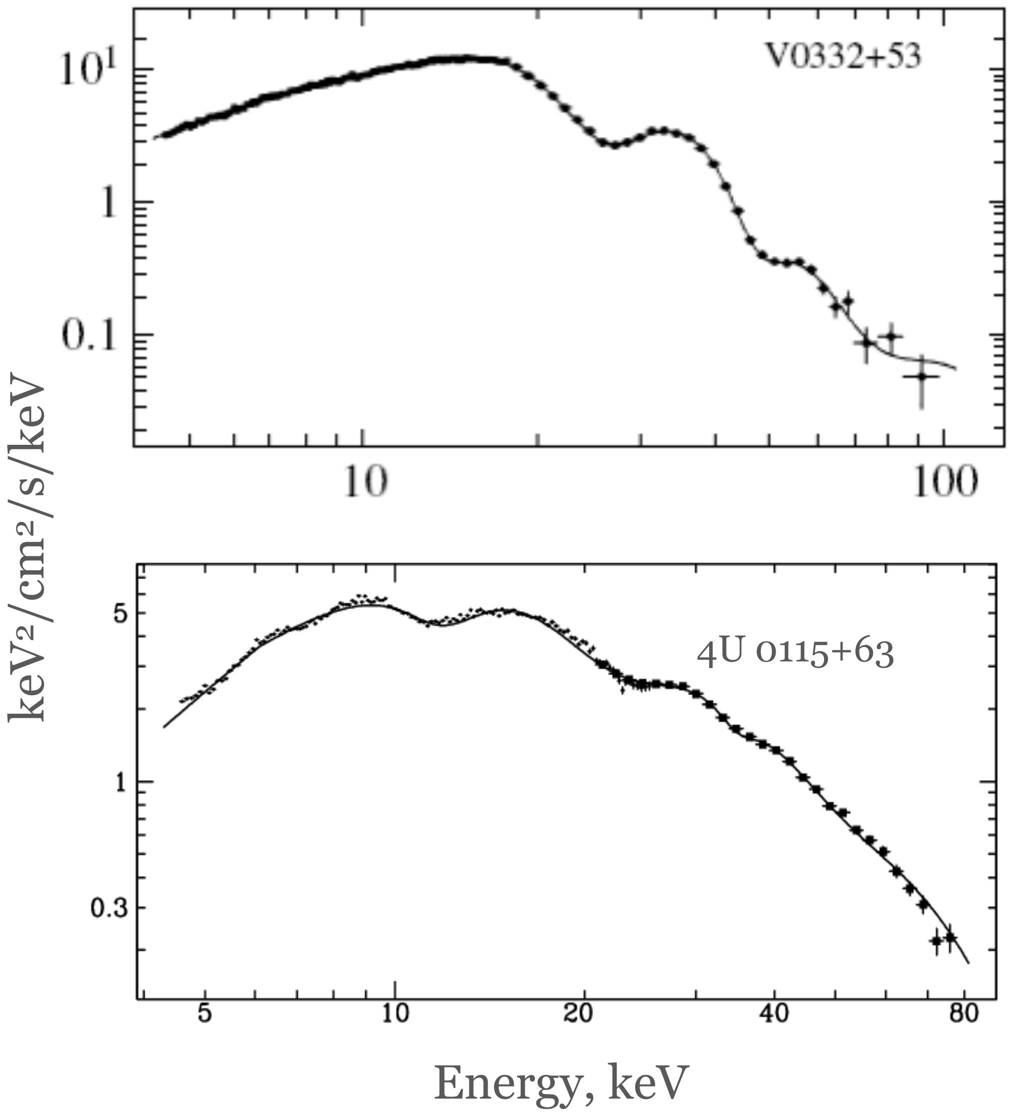


Doroshenko+ 2017, MNRAS

$$E_{\rm cyc} = 11.6\, B_{12}\,{\rm keV}$$

X-ray pulsar

Typical spectra



$$E_{\mathrm{cyc}} = 11.6\, B_{12}\, \mathrm{keV}$$

Source name	Cyclotron energy, keV
4U 0115+63 (–)	11.5, 20.1, 33.6, 49.5, 53
V 0332+53 (–)	28, 53, 74
4U 0352+309 (X Per)	29
RX J0440.9+4431	32
RX J0520.5-6932	31.5
A 0535+262	50, 110
MXB 0656–072	36
Vela X-1 (+)	27,54
GRO J1008-57	88?, 75.5
1A 1118–61	55
Cen X-3	28
GX 301–2	37, 48
GX 304–1 (+)	50.8
4U 1538–52	20, 47
Swift J1626.6–5156	10
4U 1626–67	37
Her X-1 (+)	42
OAO 1657–415	36
GRO J1744–28	4.7
IGR J18179–1621	21
GS 1843+00	20
4U 1907+09	19, 40
4U 1909+07	44?
XTE J1946+274	36
KS 1947+300	12.5
EXO 2030+375	11?, 36?, 63?
Cep X-4	30

X-ray pulsar

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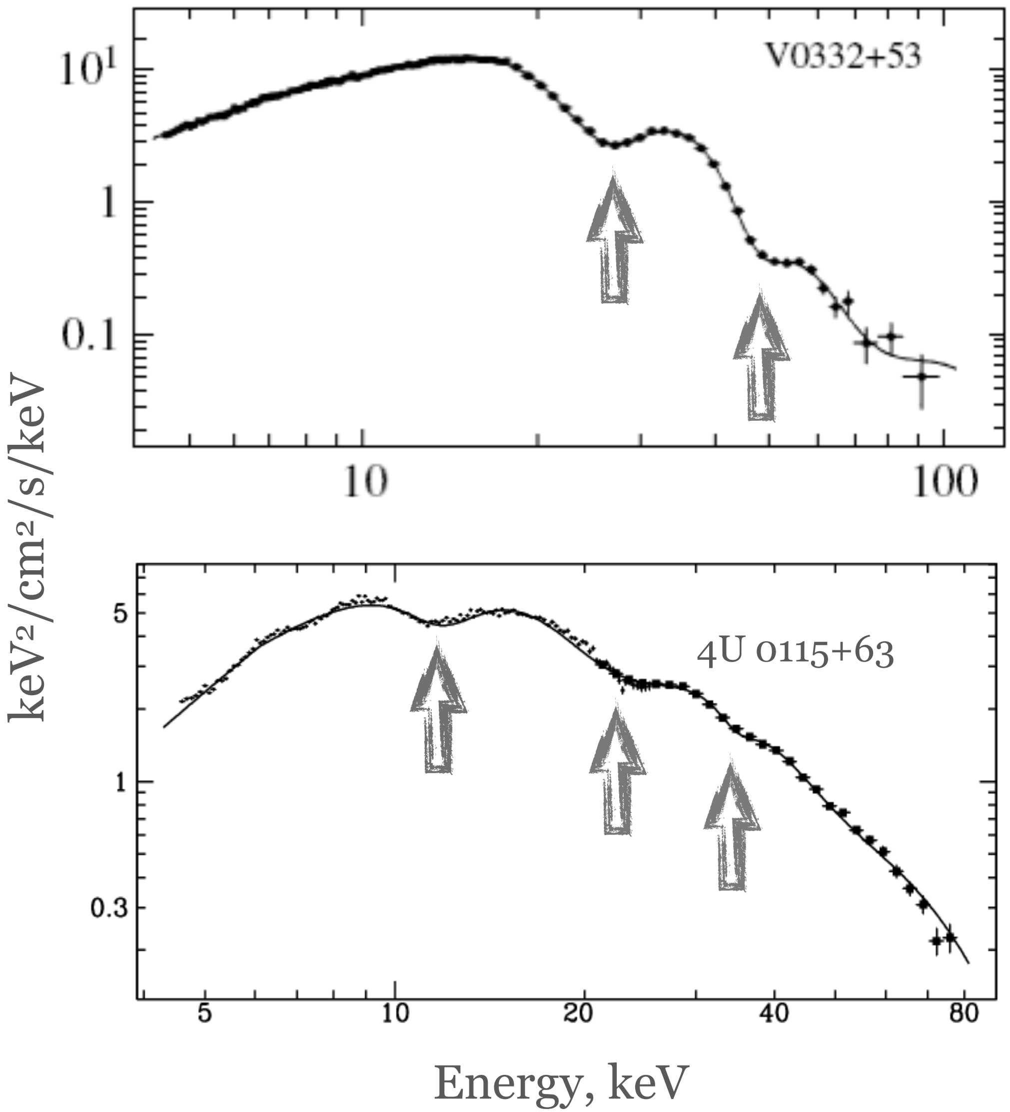

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X-ray pulsar

Typical radii

Light cylinder:

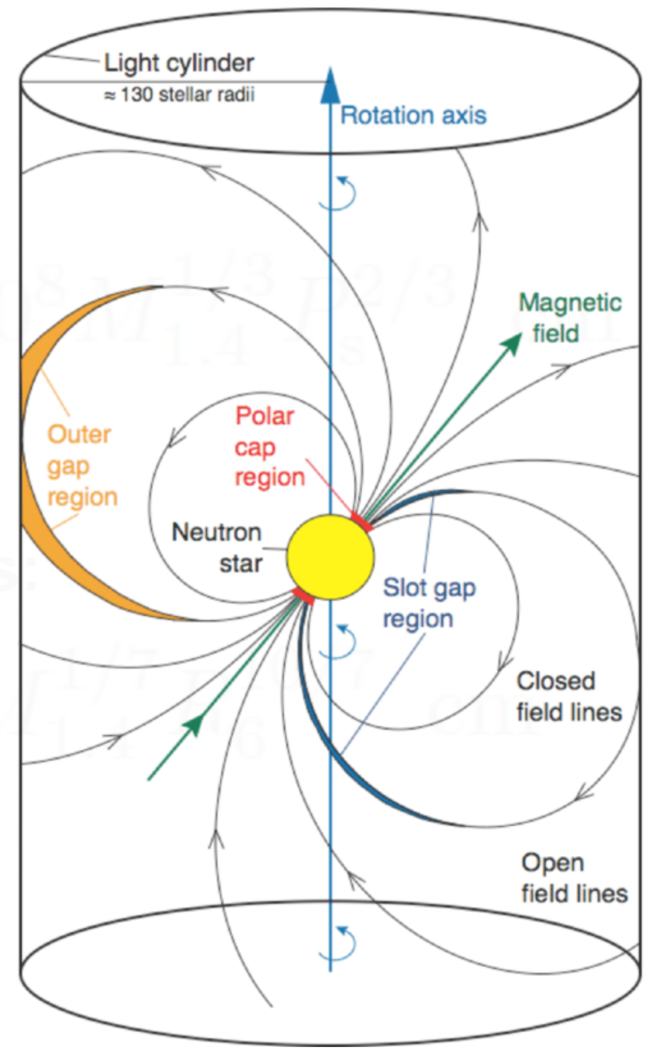
$$R_\mathrm{l} = 5 \times 10^9 \, P_\mathrm{s} \ \mathrm{cm}$$

Corotational radius:

$$R_\mathrm{cor} = \left(\frac{GMP^2}{4\pi^2} \right)^{1/3} = 1.68 \times 10^8 M_{1.4}^{1/3} P_\mathrm{s}^{2/3} \ \mathrm{cm}$$

Magnetospheric radius:

$$R_\mathrm{m} = 2.5 \times 10^8 \Lambda B_{12}^{4/7} L_{37}^{-2/7} M_{1.4}^{1/7} R_6^{10/7} \ \mathrm{cm}$$



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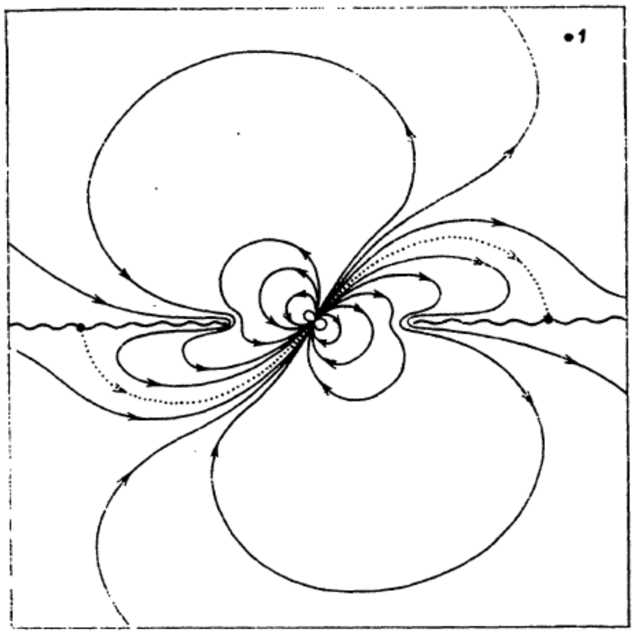

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Lipunov, Sov. Ast., 1978
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Mushtukov +, MNRAS, 2019

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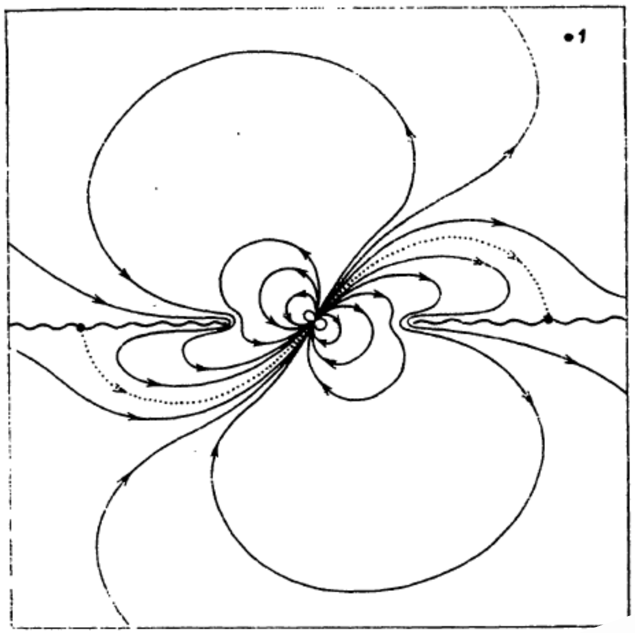 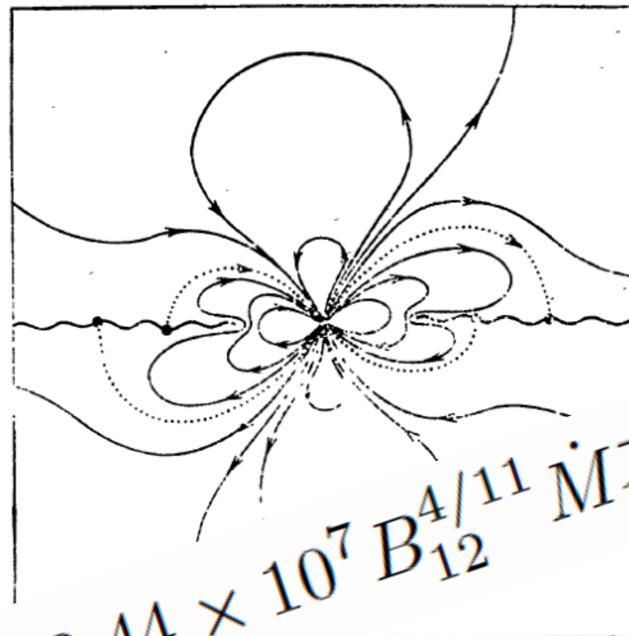

$$R_{\rm m}^{\rm (quad)} = 3.44 \times 10^{7} B_{12}^{4/11} \dot{M}_{17}^{-2/11} m^{1/11} R_{6}^{16/11} \;\; \text{cm}$$

$)^8 M_{1.4}^{1/3} P_{\rm s}^{2/3}$ cm

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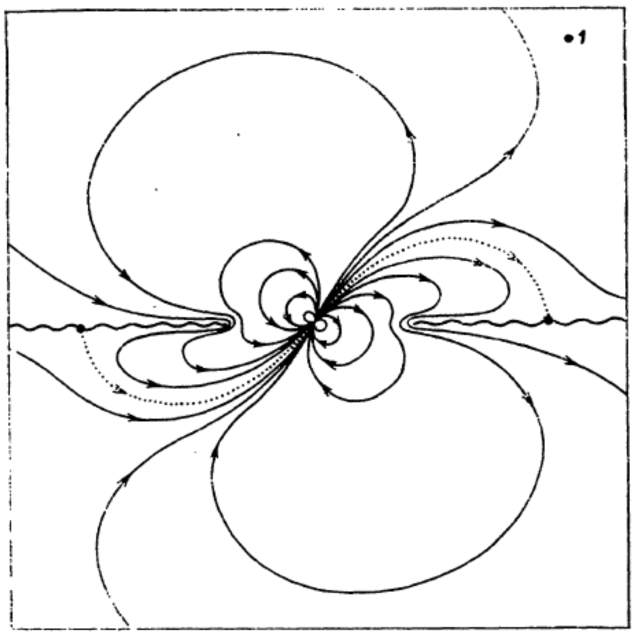

vs.

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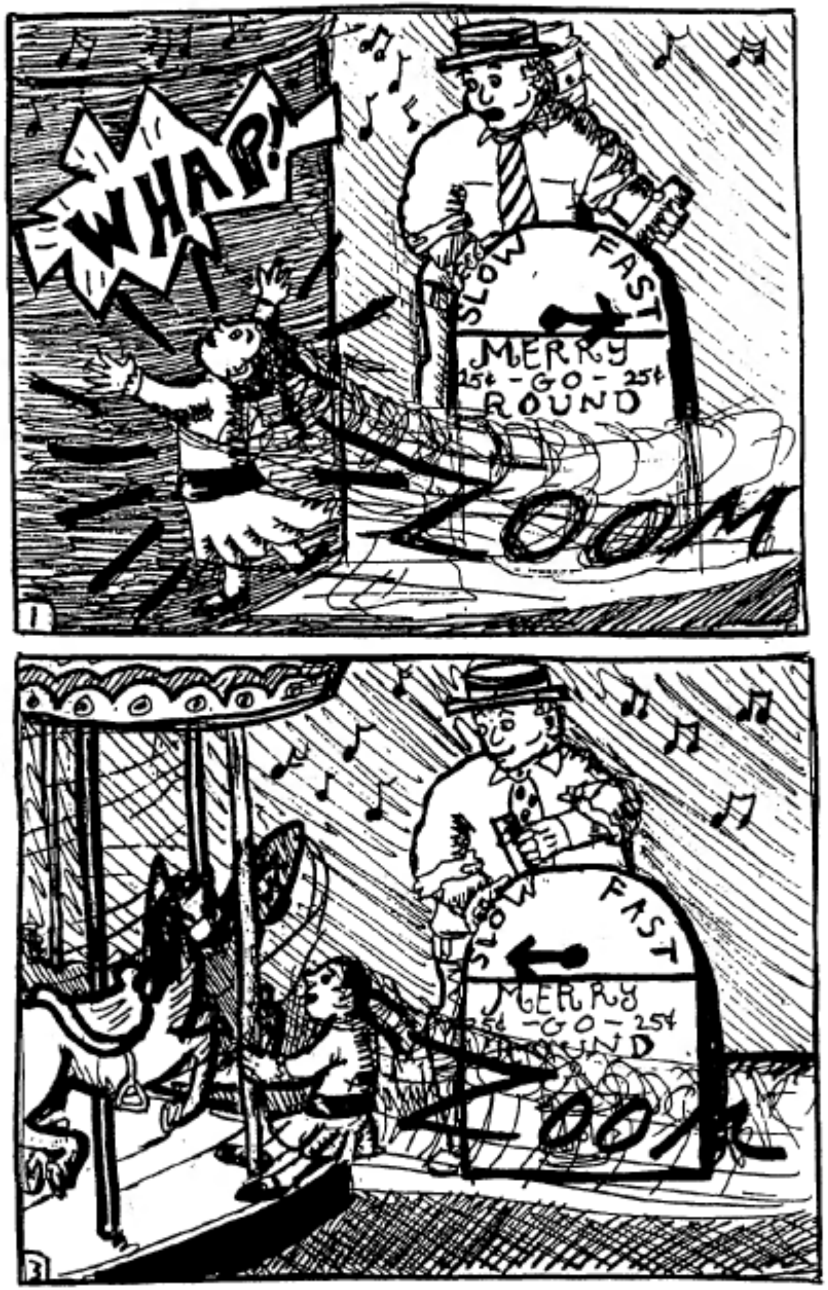
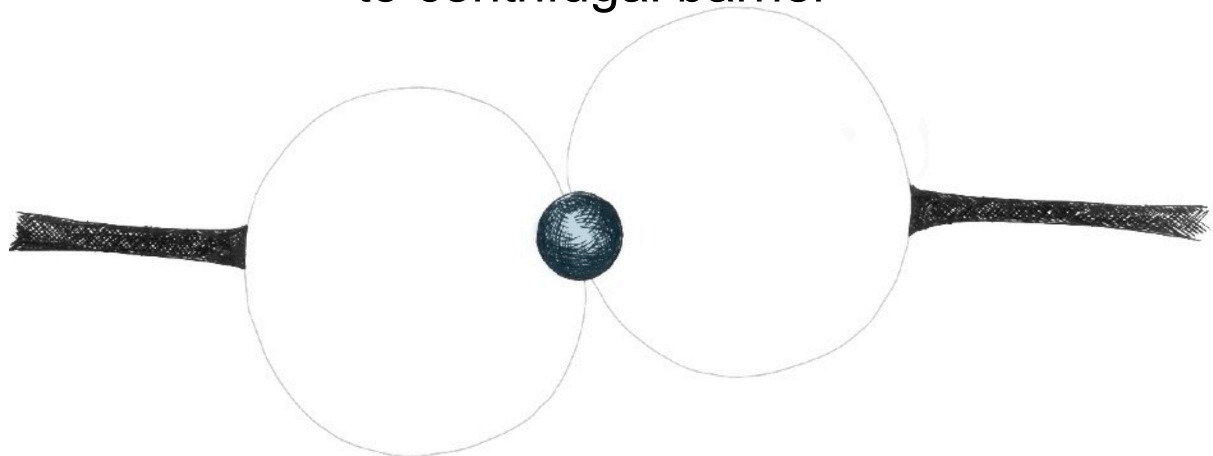
"Propeller" effect



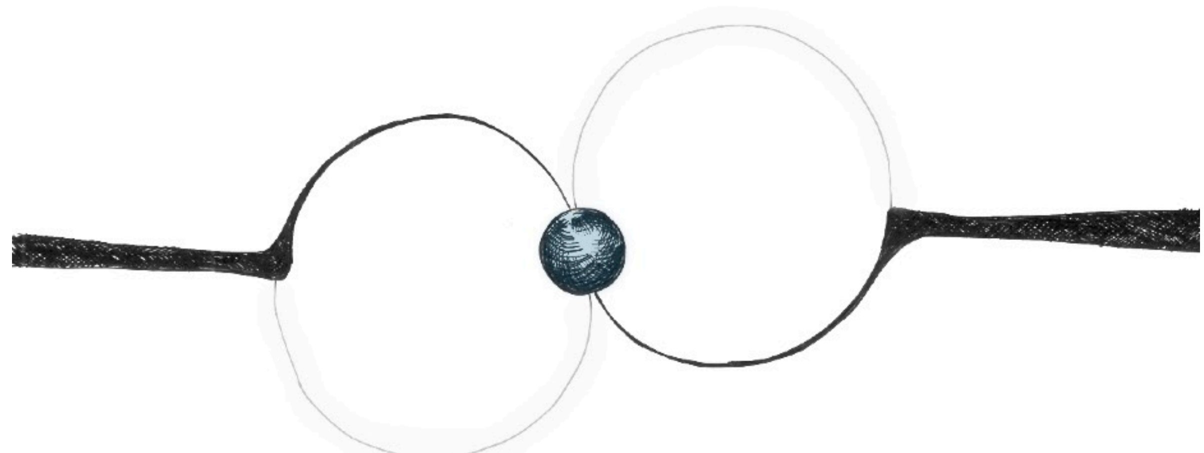
$R_m > R_{cor}$

accretion is prohibited due to centrifugal barrier



$R_m < R_{cor}$

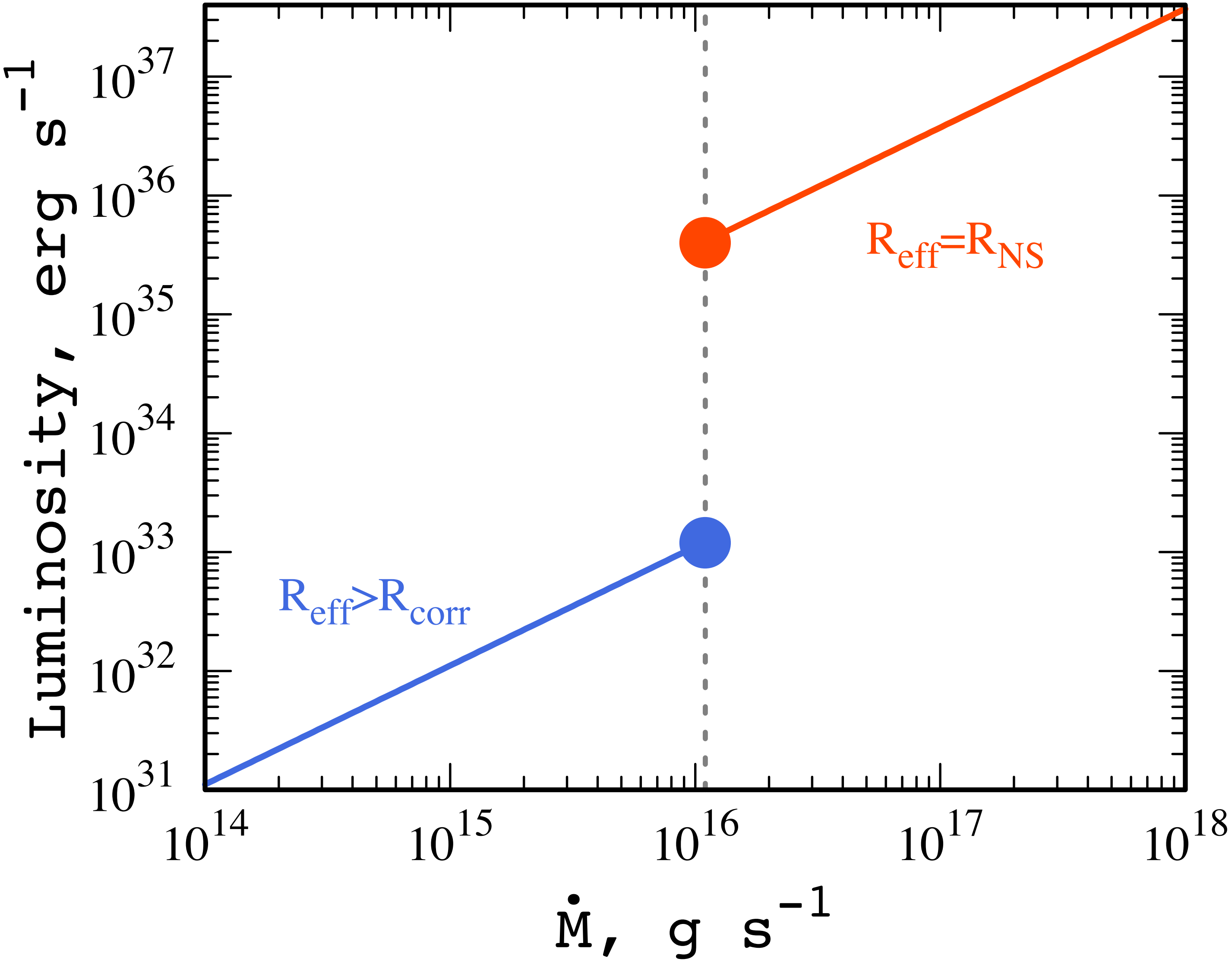
accretion is possible



Illarionov & Sunyaev, 1975
Lovelace+, 1999
D'Angelo & Spruit, MNRAS, 2010, 2012
Romanova+, New Astr.,2018

"Propeller" effect

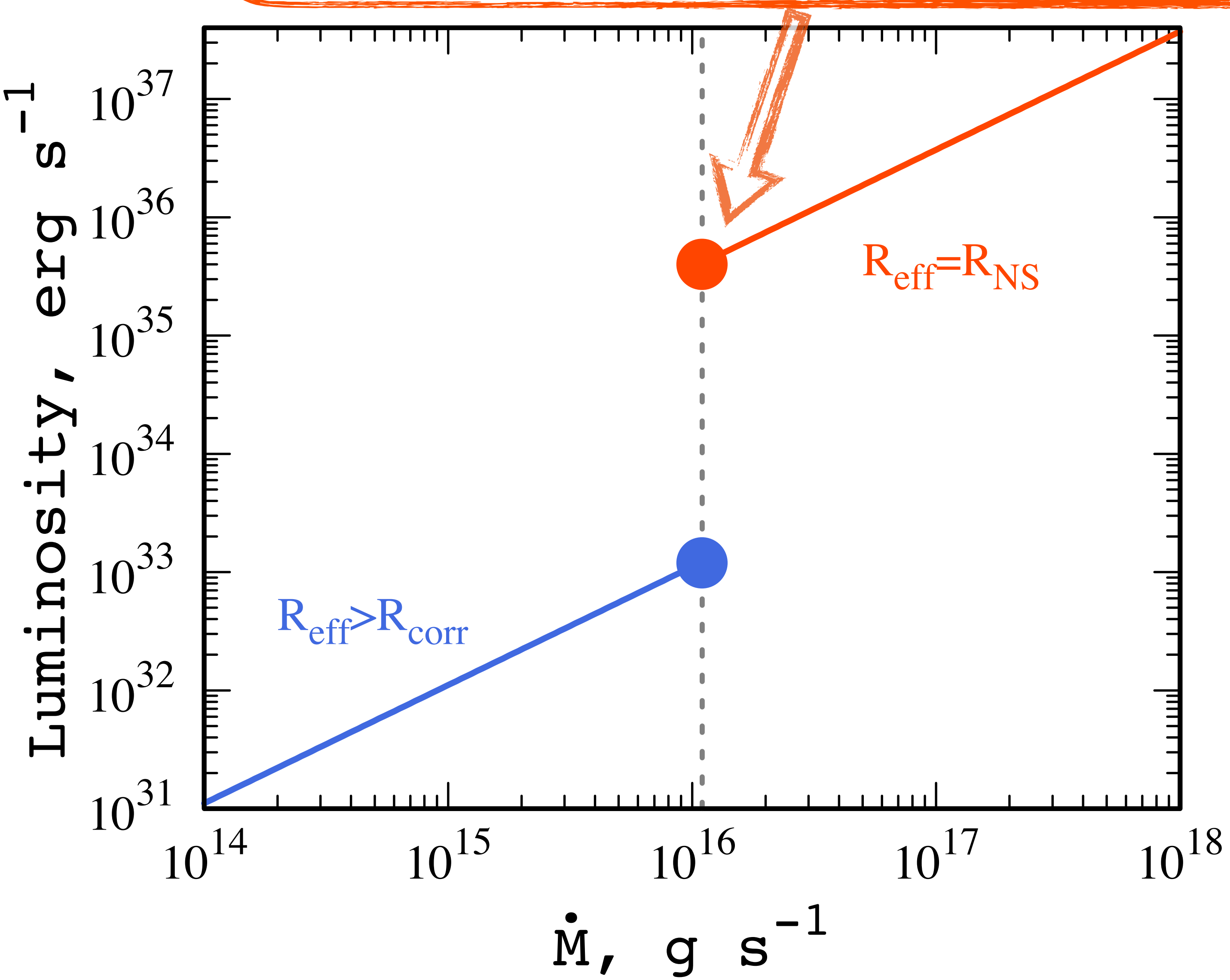
$$L_{\rm acc} = \frac{GM\dot{M}}{R_{\rm eff}}$$



“Propeller” effect

$$R_c = R_m$$

$$L_{prop} \approx 3.5\times10^{36} B_{12}^2 P^{-7/3} M_{1.4}^{-2/3} R_6^5 \text{ erg s}^{-1}$$



“Propeller” effect and episodic accretion events

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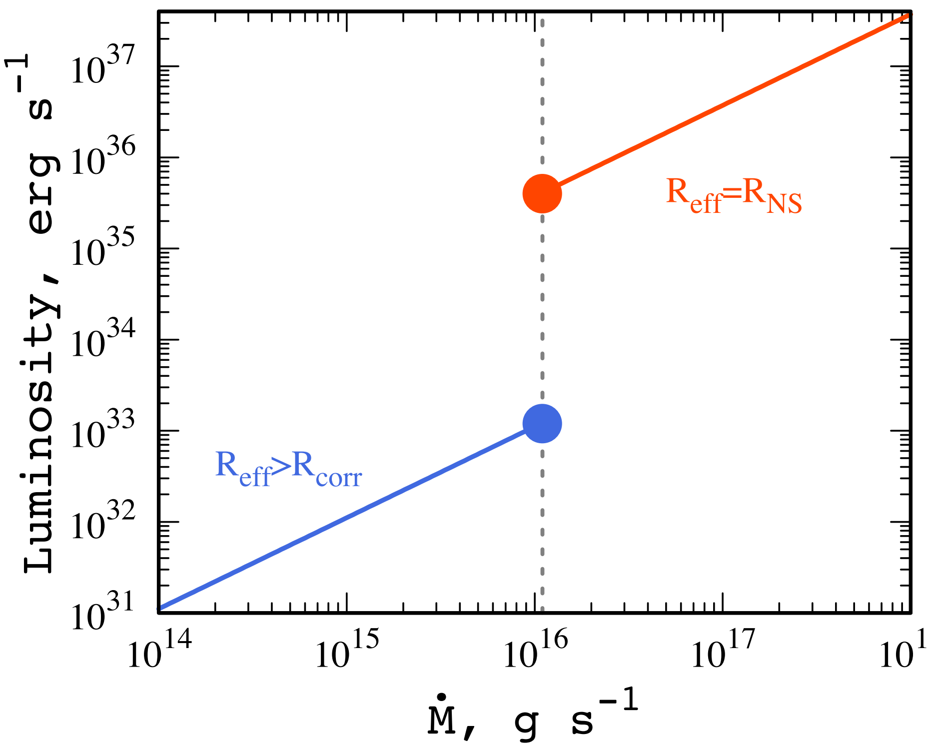
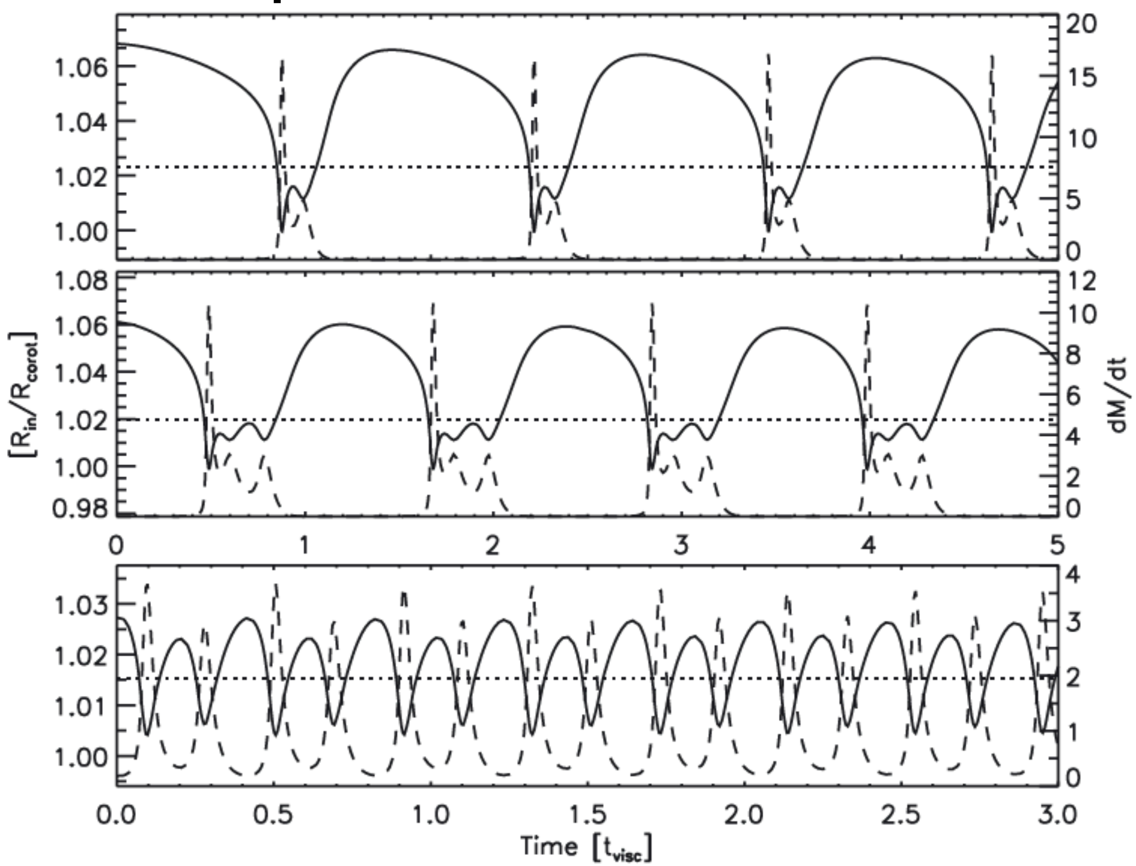


Behaviour of accretion disc behind the corotational radius & **episodic accretion** on to NS

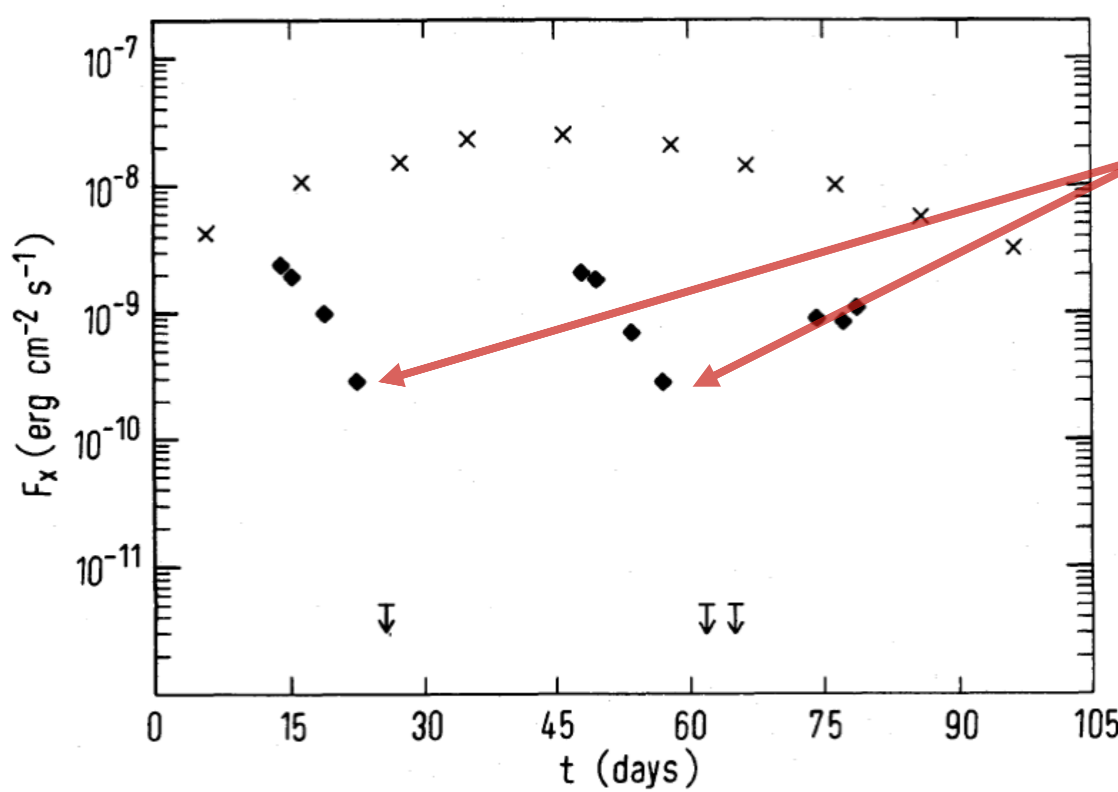


D’Angelo & Spruit, MNRAS, 2010, 2012

“Propeller” effect

V 0332+53

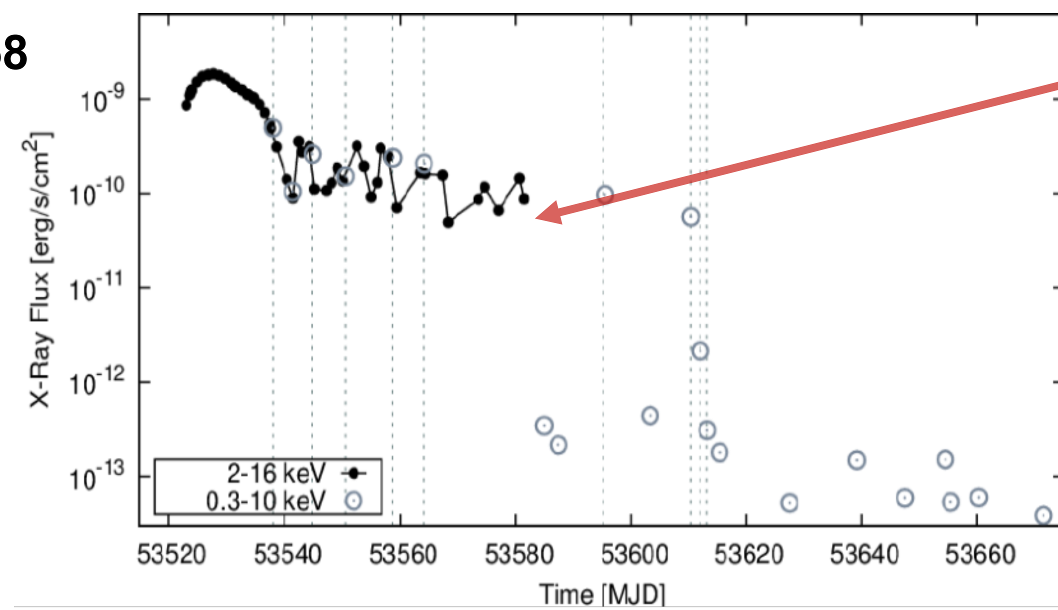
Stella +, 1986



L_{prop} = 2.6 x 10^{36} erg/s

SAX J1808.4-3658

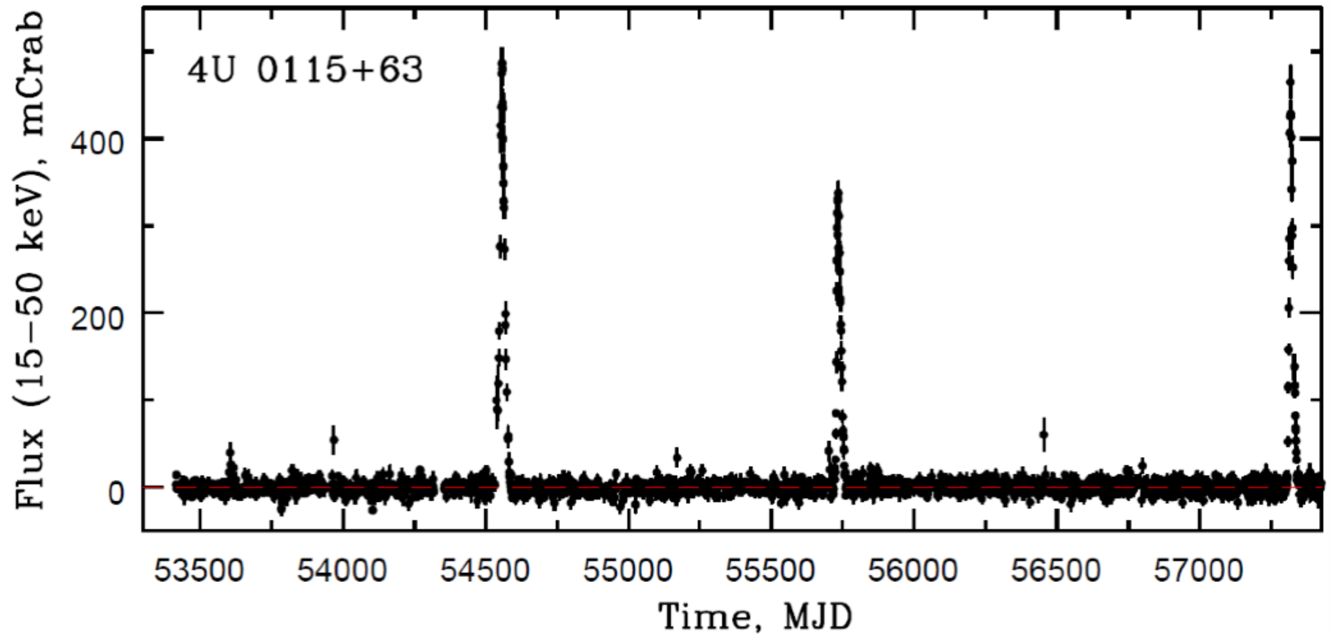
Patruno +, ApJ, 2009



L_{prop} = 5 x 10^{35} erg/s

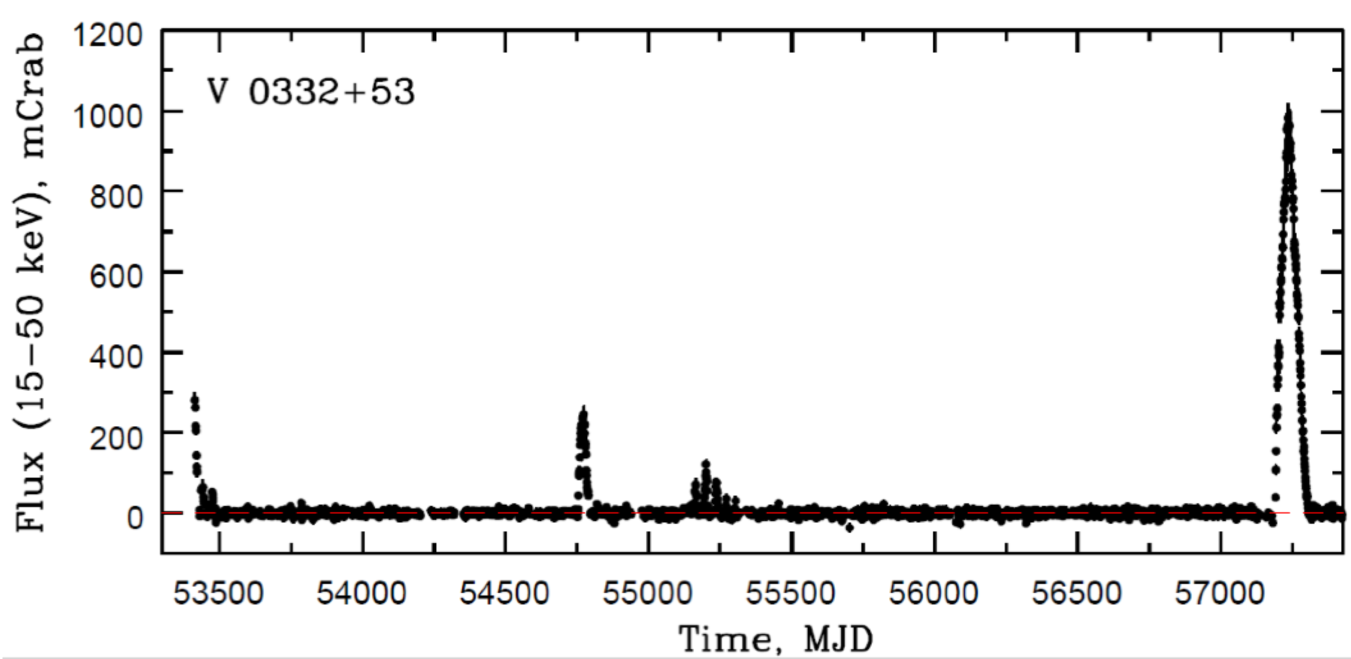
X-ray pulsars 4U 0115+63 & V 0332+53

Swift/BAT + XRT monitoring



P_{spin} = 3.6 s

E_{cyc} ~ 12 keV

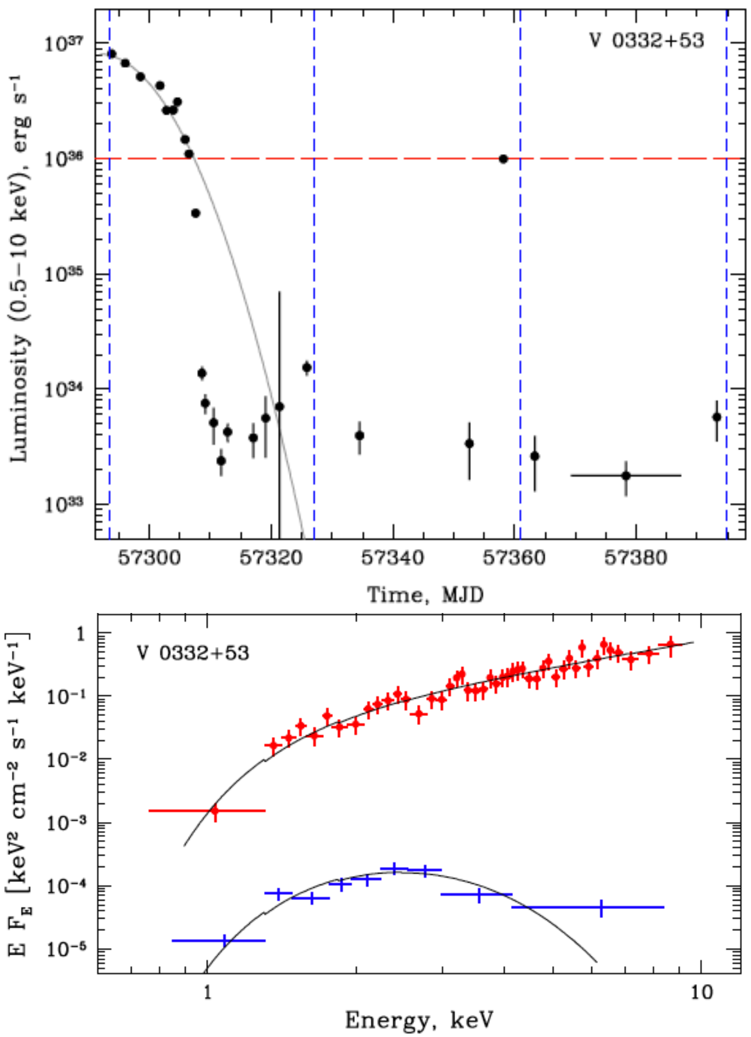


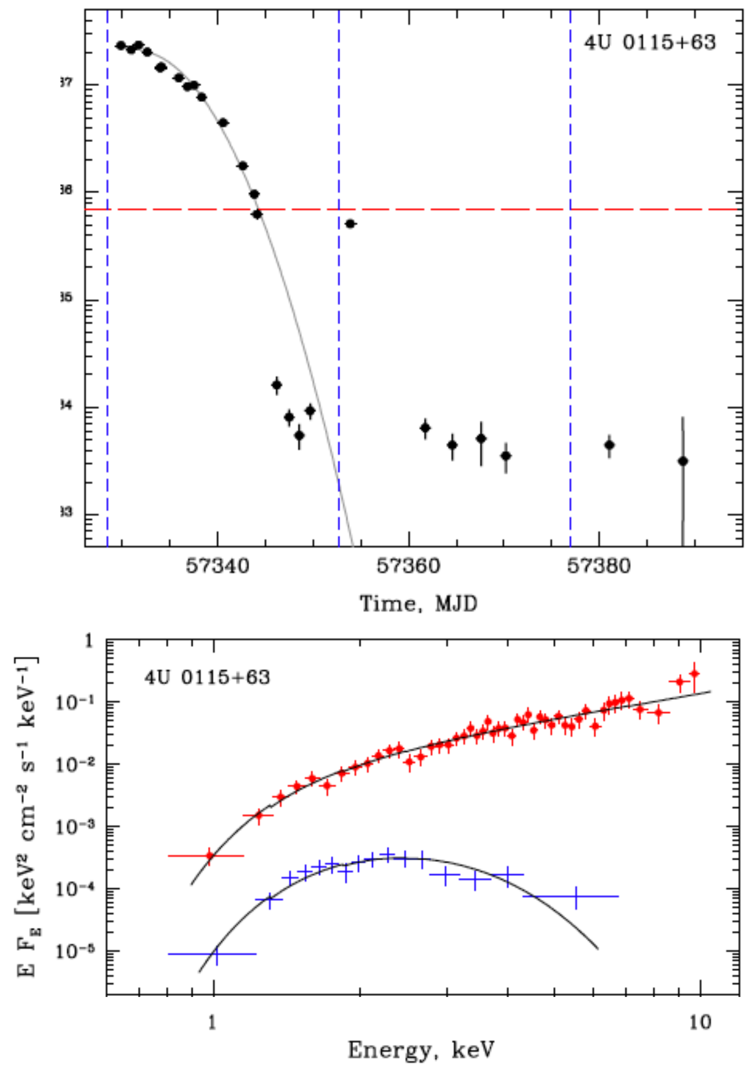
P_{spin} = 4.3 s

E_{cyc} ~ 30 keV

“Propeller” effect

Detection





Tsygankov + 2016, A&A, 593

Propeller luminosity:

$$L_{\rm prop} \approx 3.5\times10^{36} B_{12}^2 P^{-7/3} M_{1.4}^{-2/3} R_6^5 \ \ \mathrm{erg\ s^{-1}}$$

"Propeller" effect

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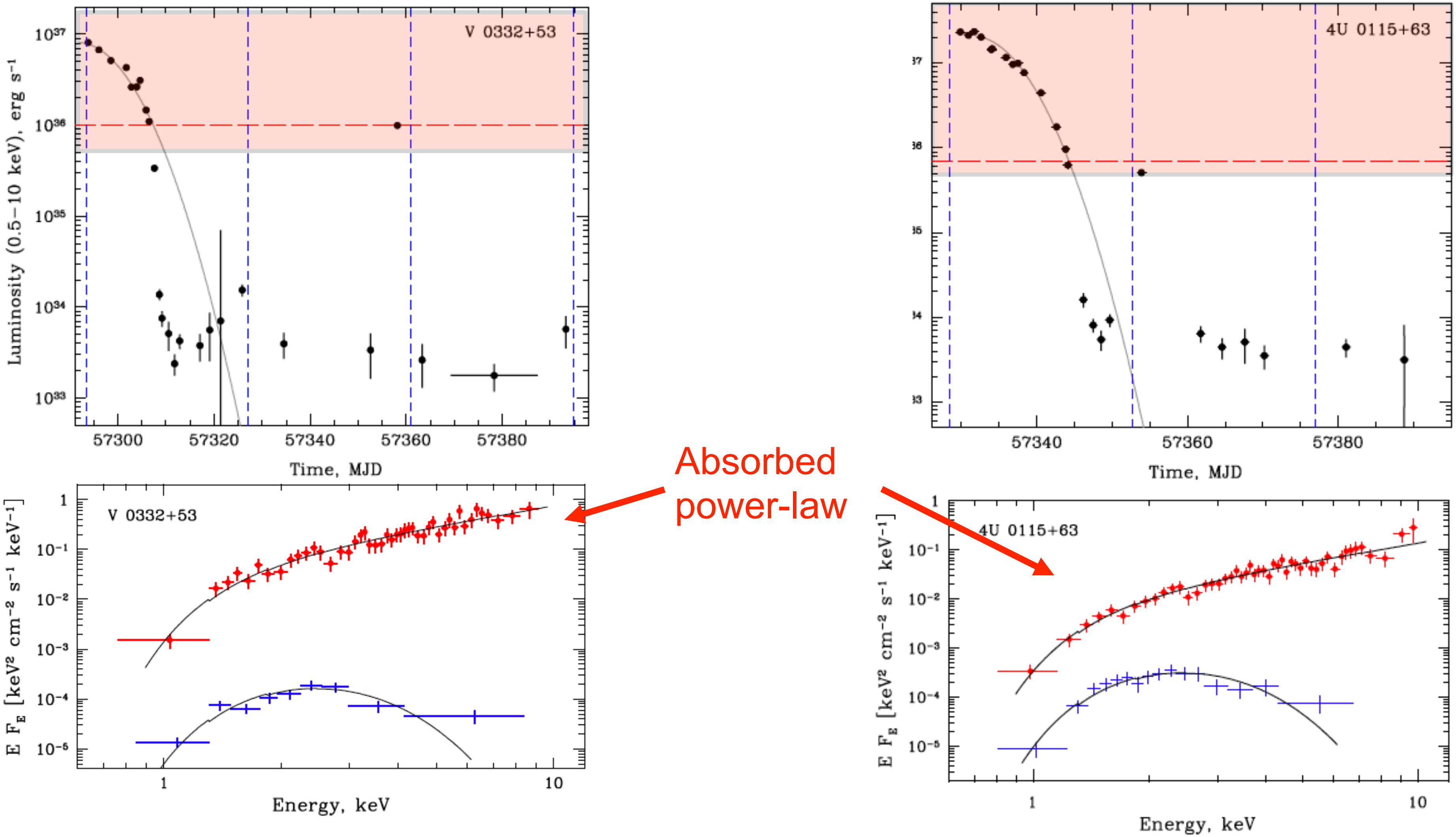

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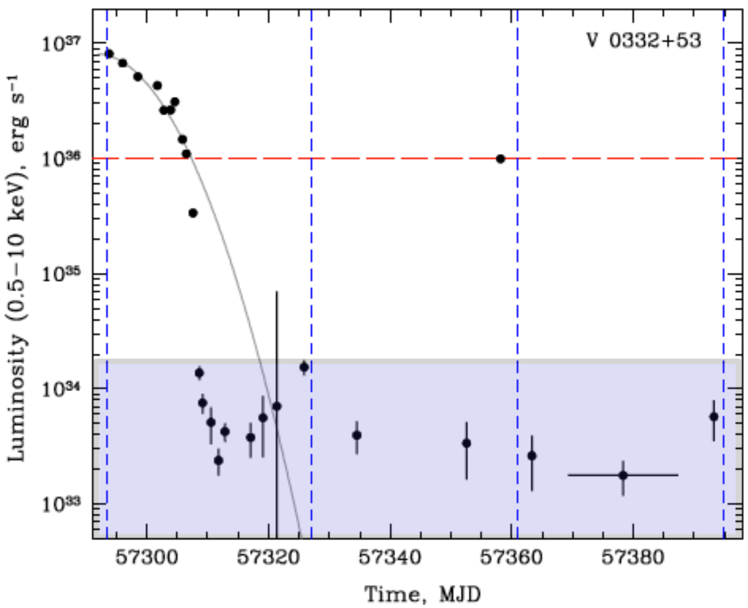
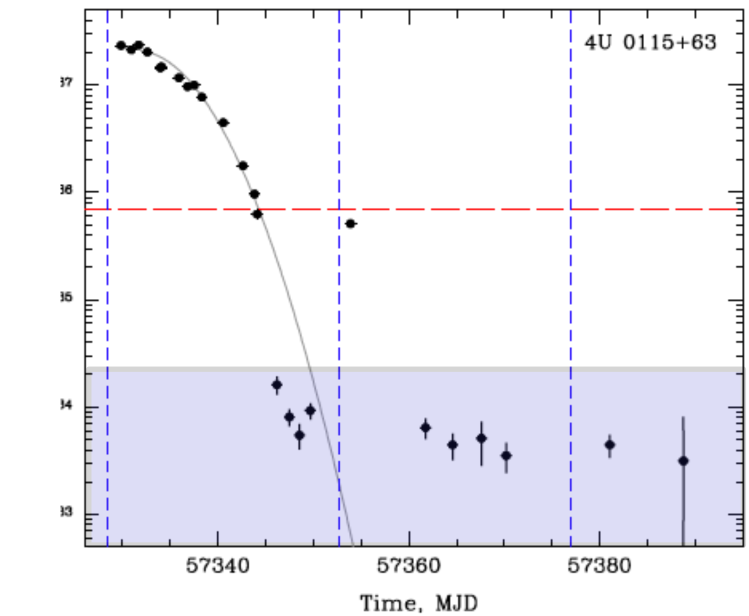
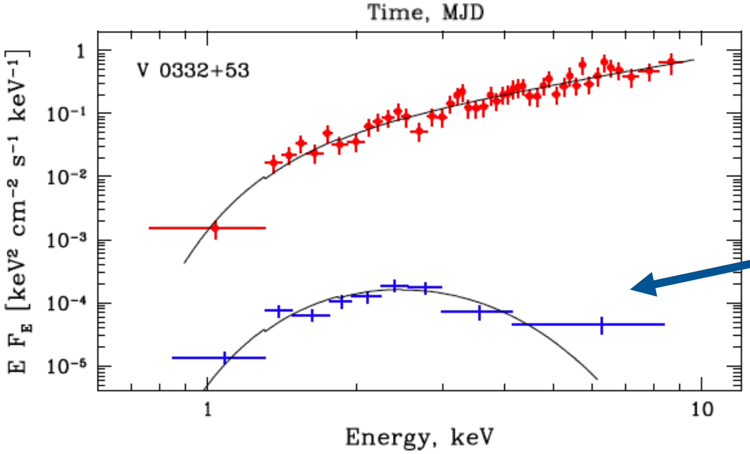
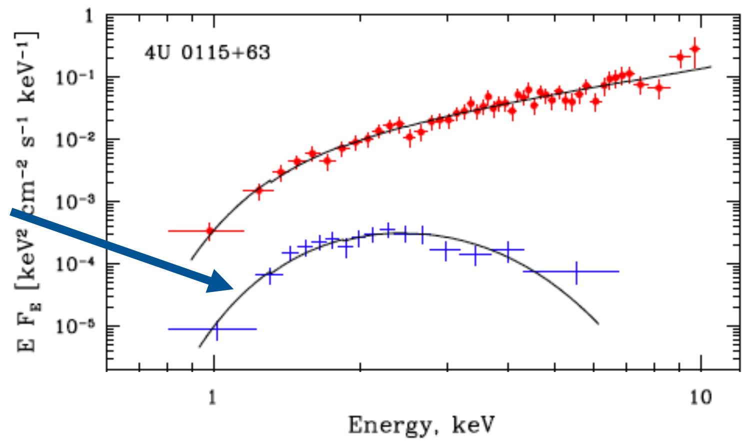






Black body with T=0.5 keV



Tsygankov + 2016, A&A, 593

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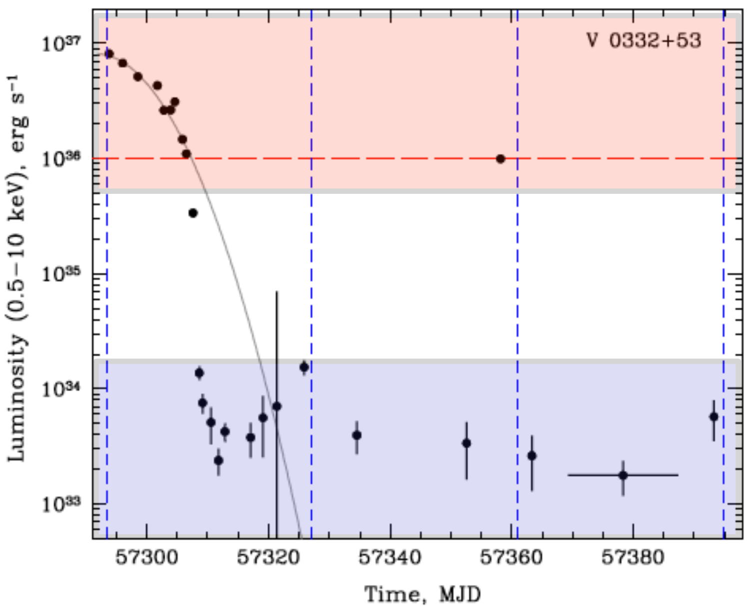

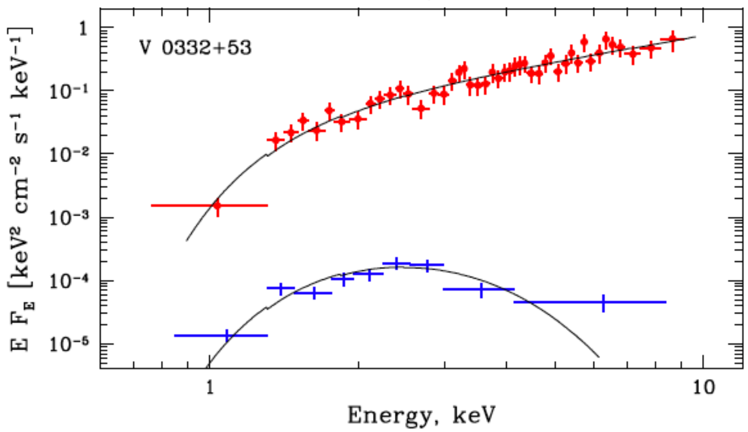

Important details:

(1) Predictions based on a very simple model work well;
(2) Dramatic spectral changes;
(3) Re-brightings near the periastrons;

Some conclusions
Detection of “propeller” state can be used to measure B-field strength/structure

Uncertainties:

(1) Nature of low-luminosity spectra;

(2) Fastness of transition into “propeller” state.

Tsygankov + 2016, A&A, 593

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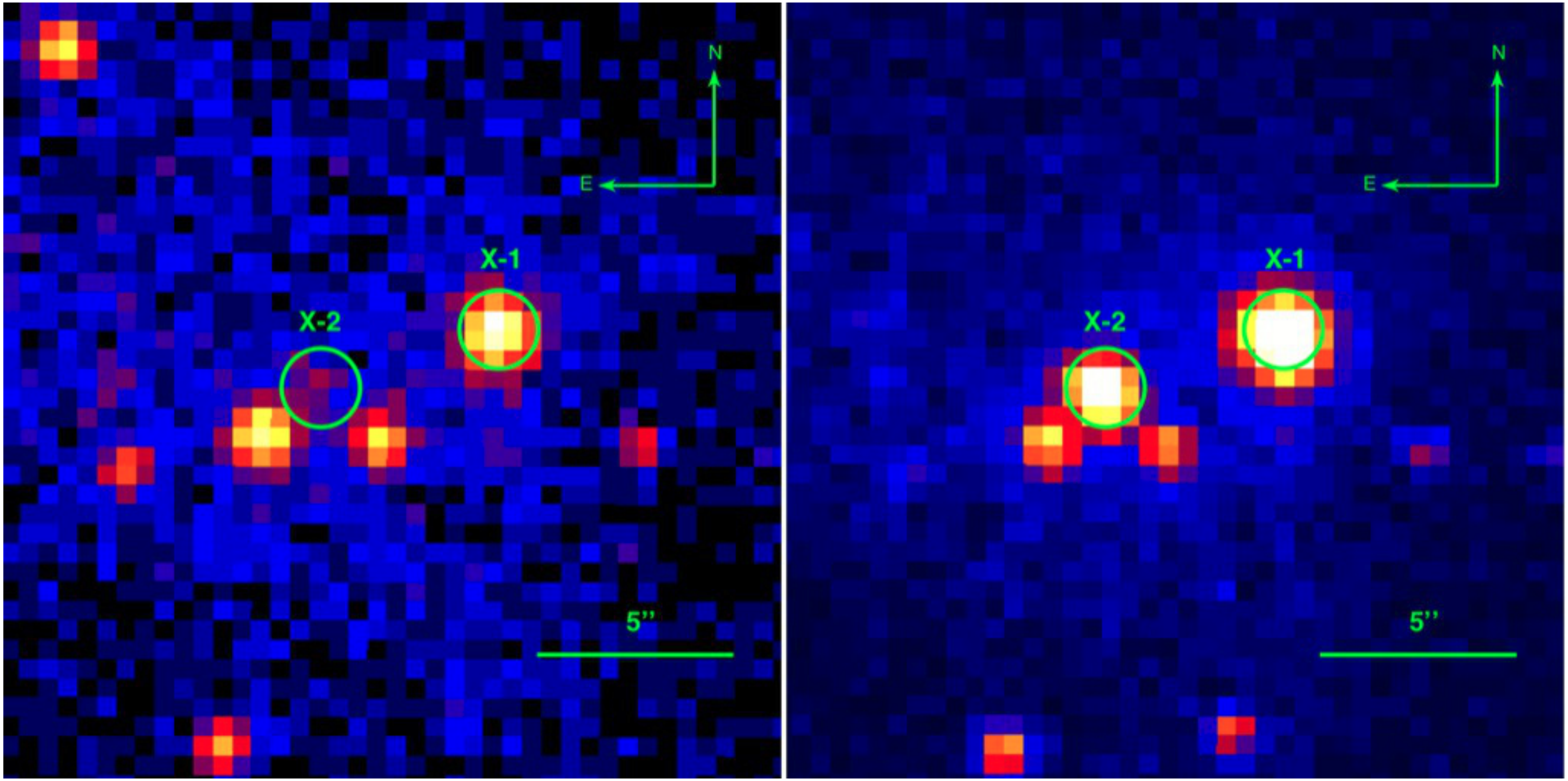
Magnetic field strength in ULXs: M82 as seen by Chandra



Tsygankov, AM+, MNRAS, 2016

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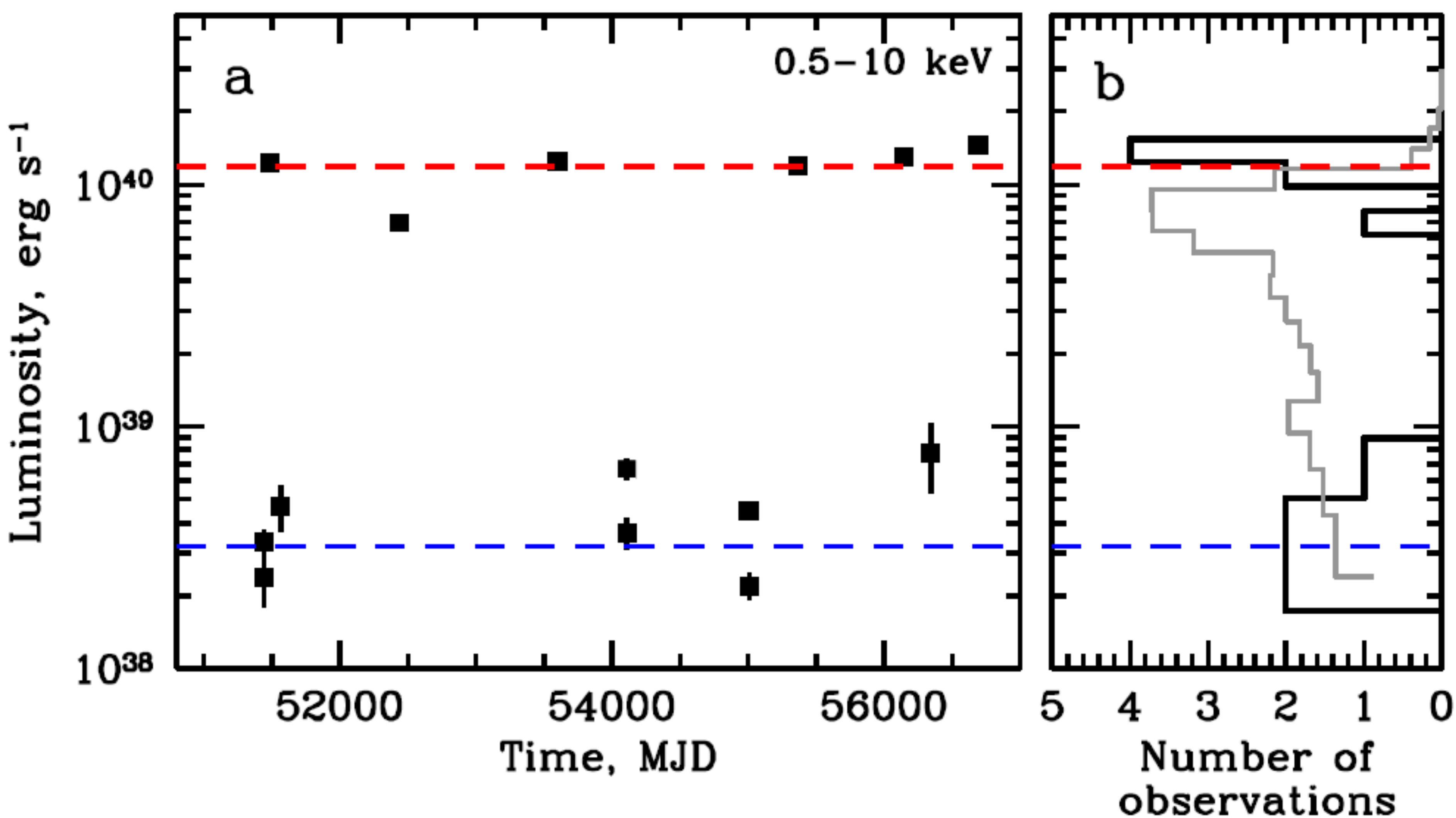

Tsygankov, AM+, MNRAS, 2016

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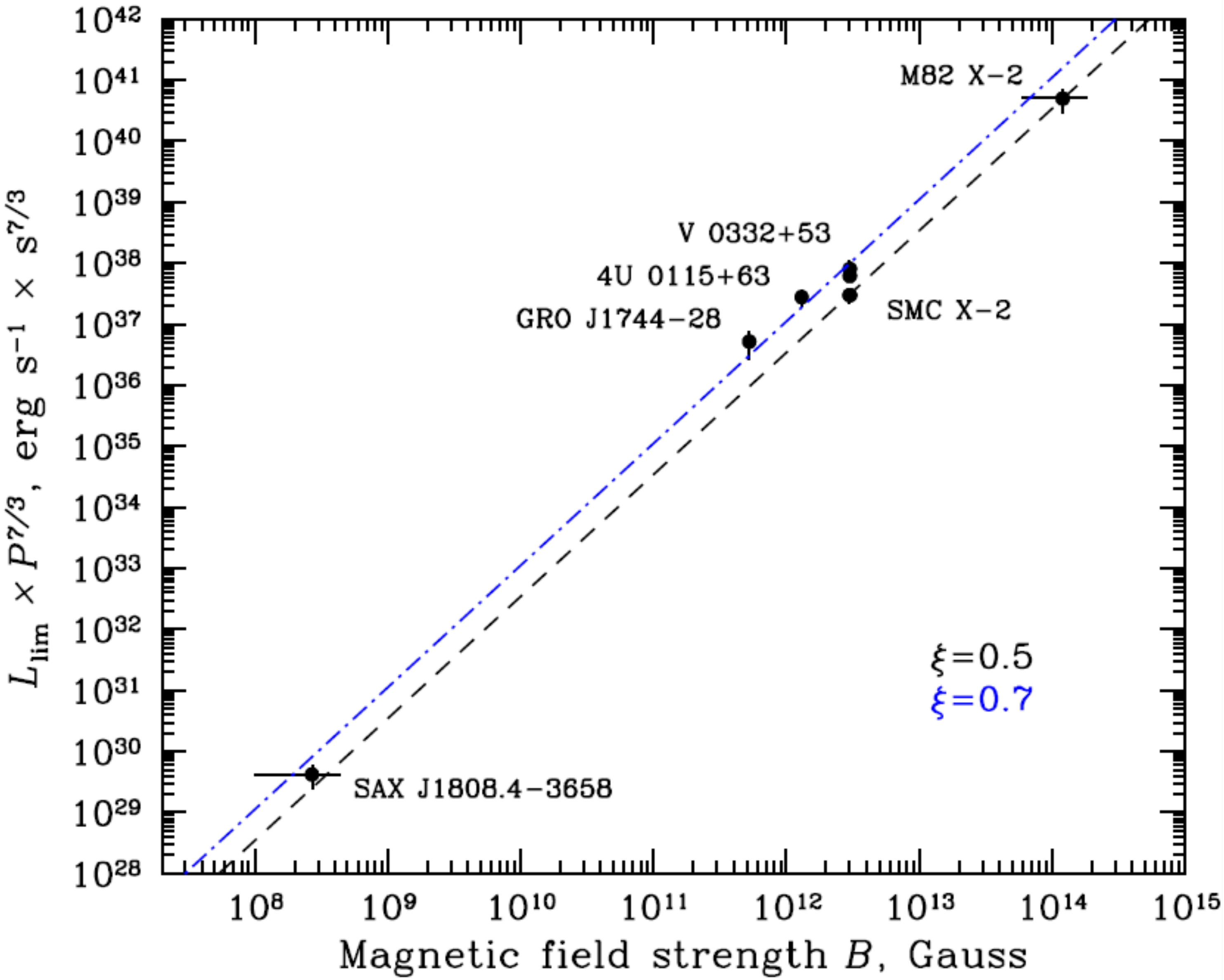


P=1.37 s

ξ = 0.5

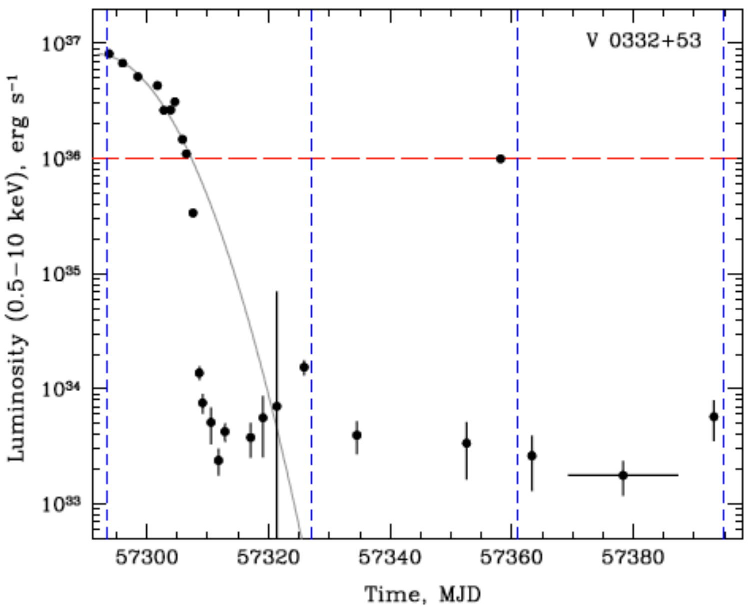
L_{lim}=2.0 x 10^{40} erg s^{-1}

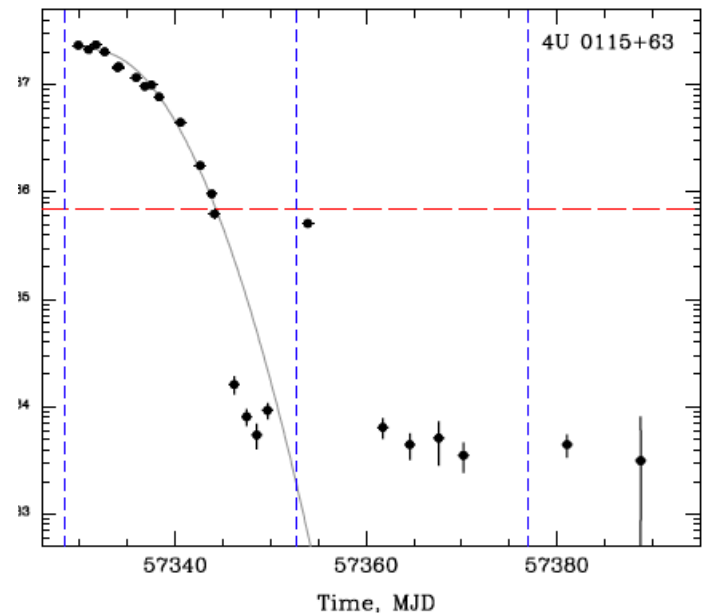
B~1.1 x 10^{14} G

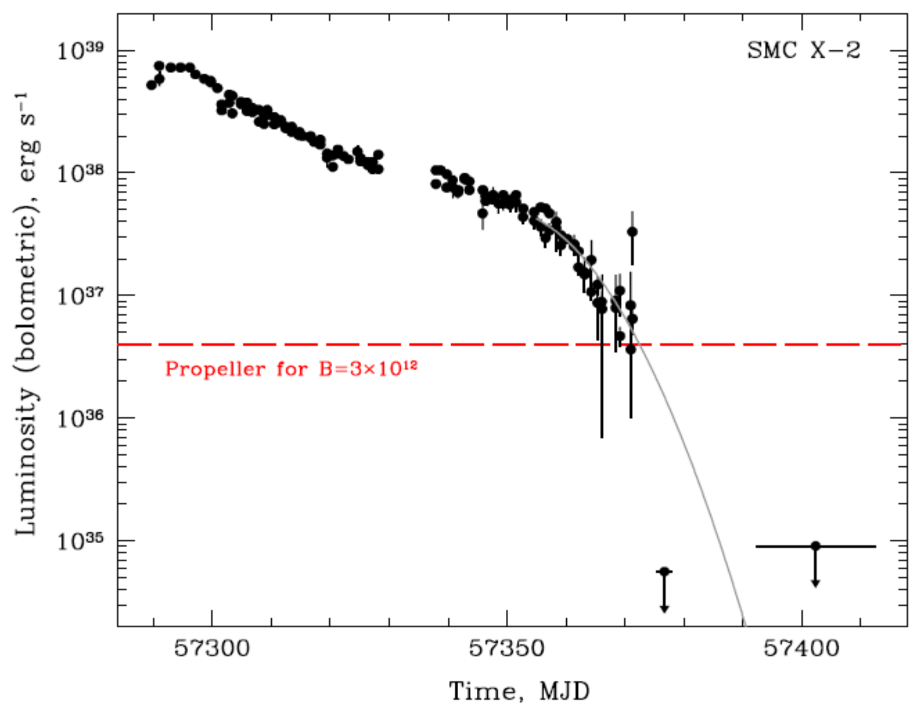
But
the inner radius can be affected by
(i) disc structure
and
(ii) accretion luminosity from the central object

Tsygankov, AM+, MNRAS, 2016

Disc instability







Tsygankov + 2016, A&A, 593
Litovinov+ 2017, ApJ, 834

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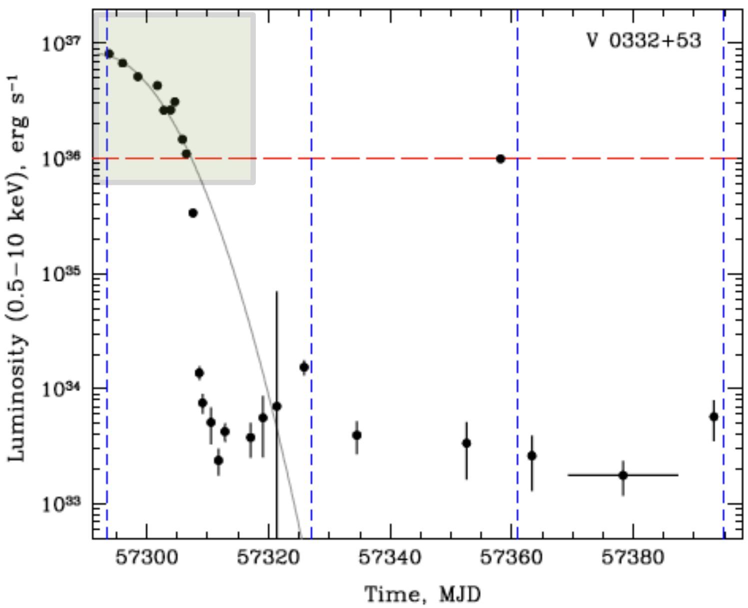

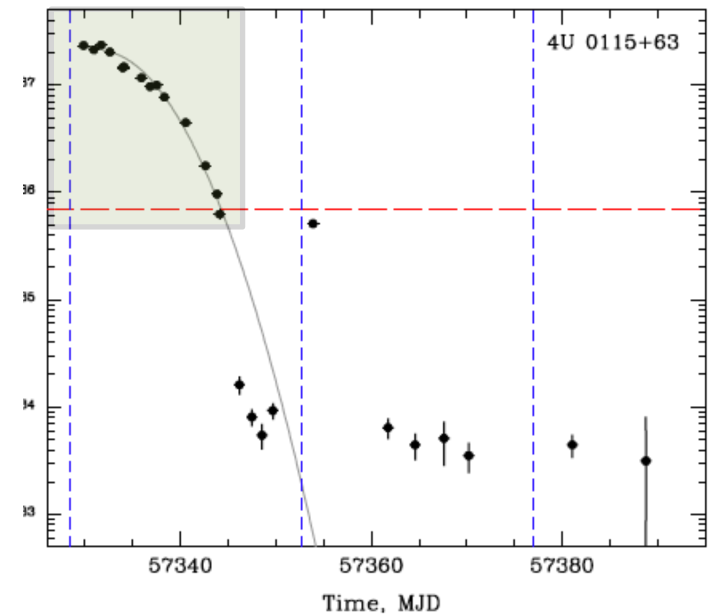

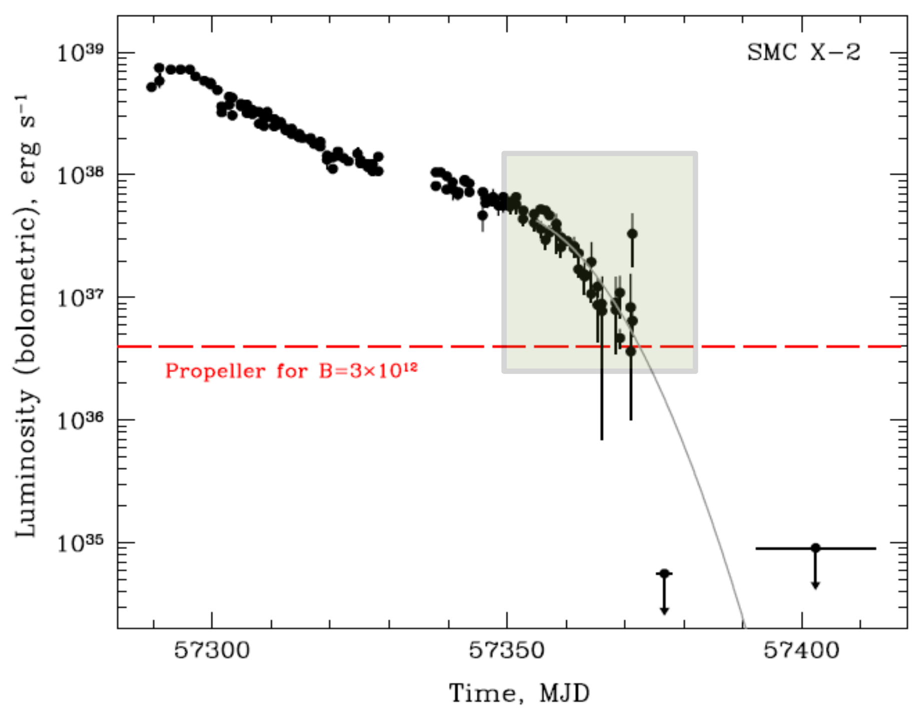

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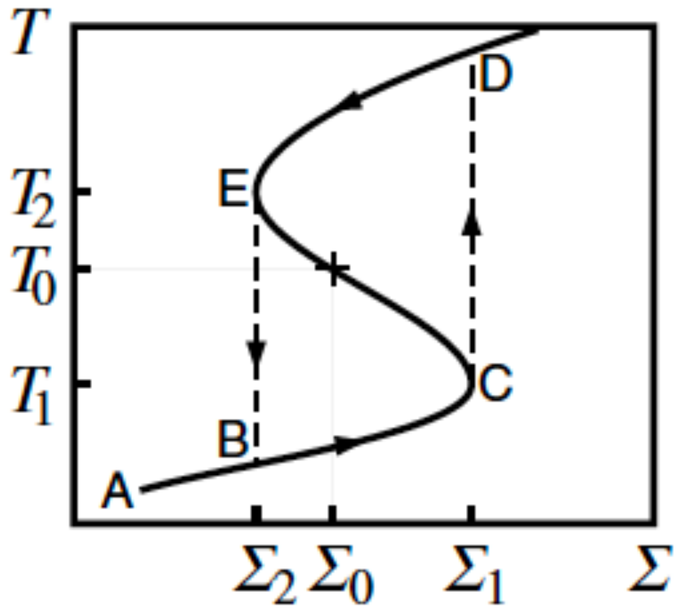
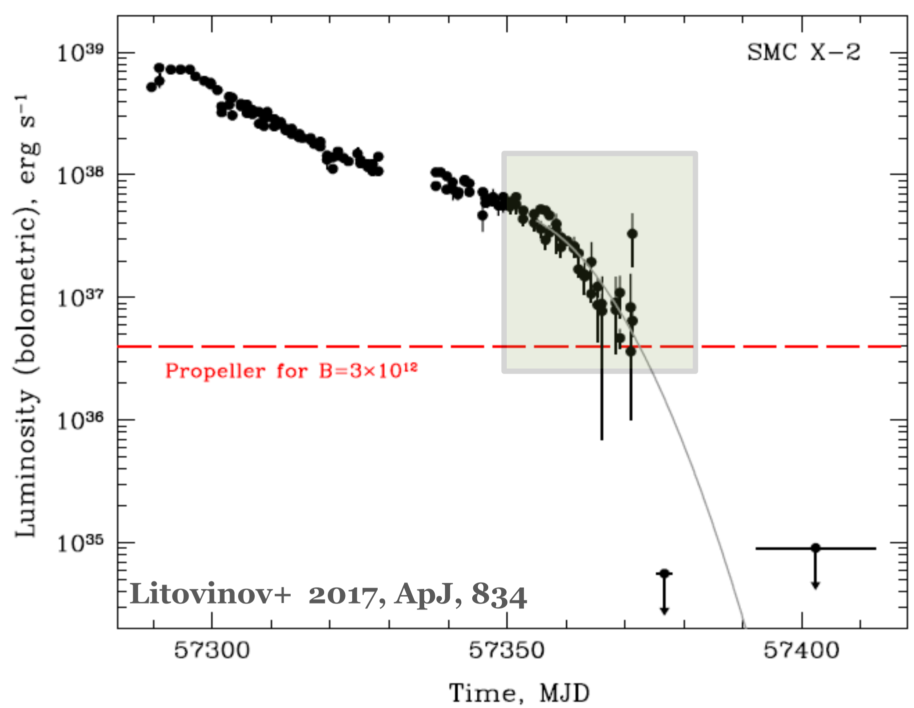


$$\sigma_{SB} T_{\rm eff}^4 = \frac{3}{8\pi} \frac{GM\dot{M}}{r^3} \left[1 - \beta \left(\frac{R_{\rm in}}{r} \right)^{1/2} \right]$$

Radial coordinate where the effective temperature turns to 6500 K:

$$R_{6500} = 3.8 \times 10^9 L_{37}^{1/3} R_6^{1/3} \text{ cm}$$



Smak, 1984
Meyer, 1984
Meyer & Meyer-Hofmeister, 1984
Cannizzo+, 1988, 1993
Lasota, 1997,2001
King & Ritter, 1998
King+, 2007
Kotko & Lasota, 2012
Hameury & Lasota, 2016

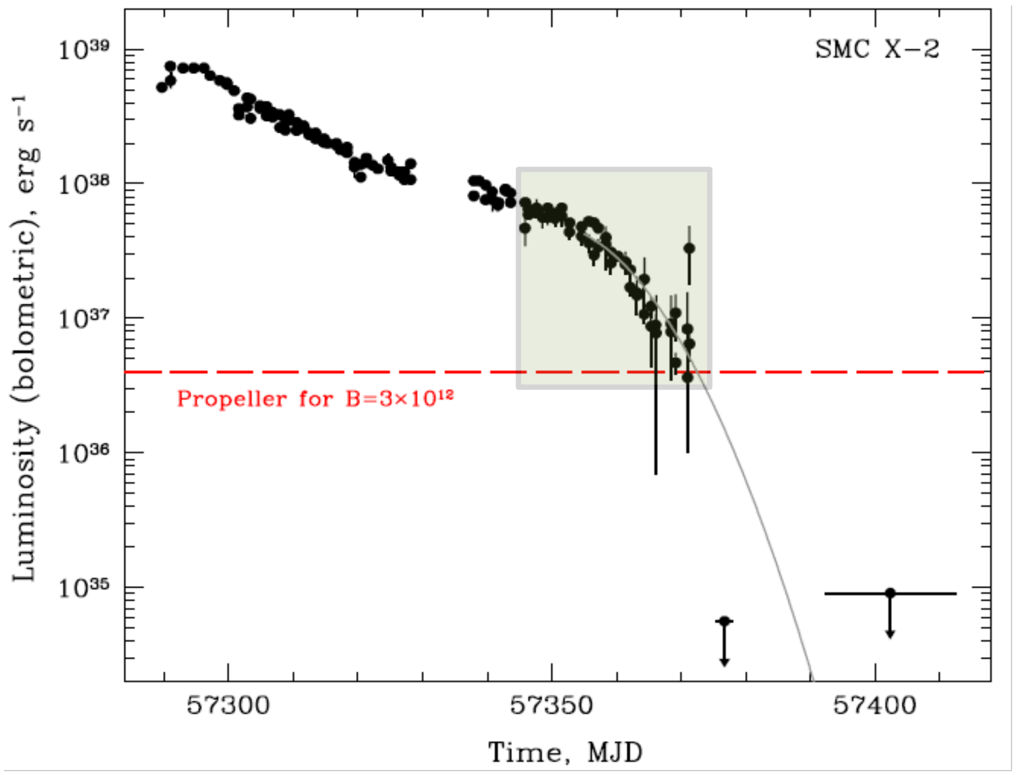
and many many other papers

Accretion process can be stable if

$$\dot{M} > \dot{M}_{\rm hot} \approx 6 \times 10^{16} r^3_{\rm out,10}\ {\rm g\,s^{-1}}$$

or

$$\dot{M} < \dot{M}_{\rm cold} \simeq 3.5 \times 10^{15}\, r_{10}^{2.65}\, M_{1.4}^{-0.88}\quad {\rm g\,s^{-1}}$$

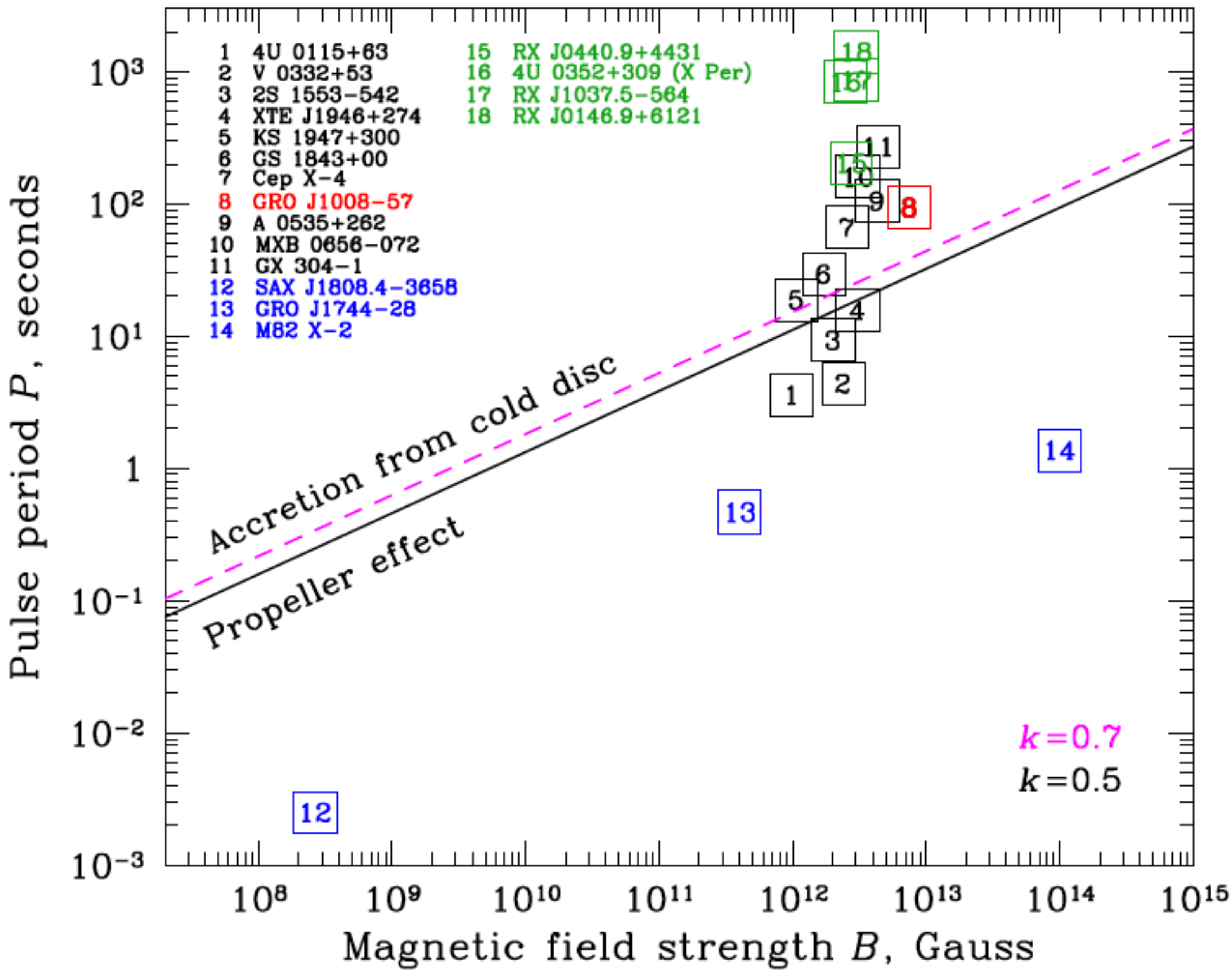


Inner disc radius and cooling front are going towards each other

$$R_{\rm m} = 2.5 \times 10^8 \Lambda B_{12}^{4/7} L_{37}^{-2/7} M_{1.4}^{1/7} R_6^{10/7}\quad {\rm cm}$$

$$R_{6500} = 3.8 \times 10^9 L_{37}^{1/3} R_6^{1/3}\ {\rm cm}$$

Stable accretion from a cold disc
vs.
"propeller" effect

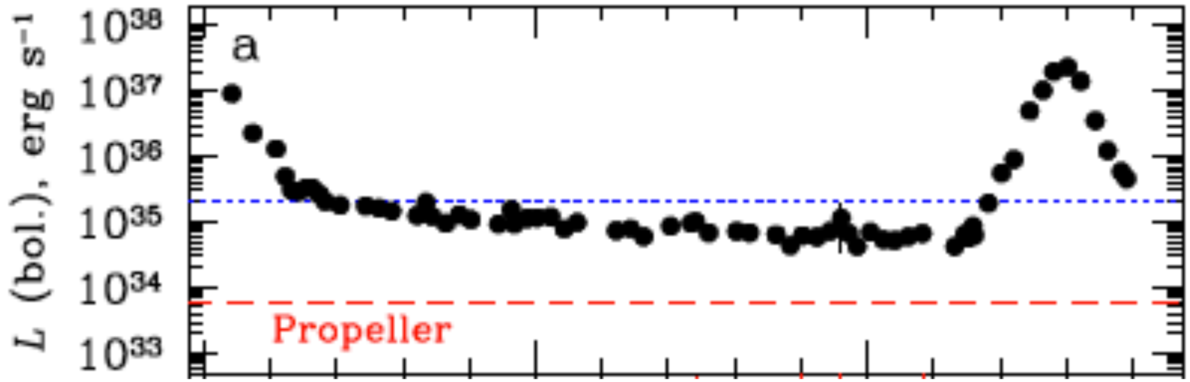


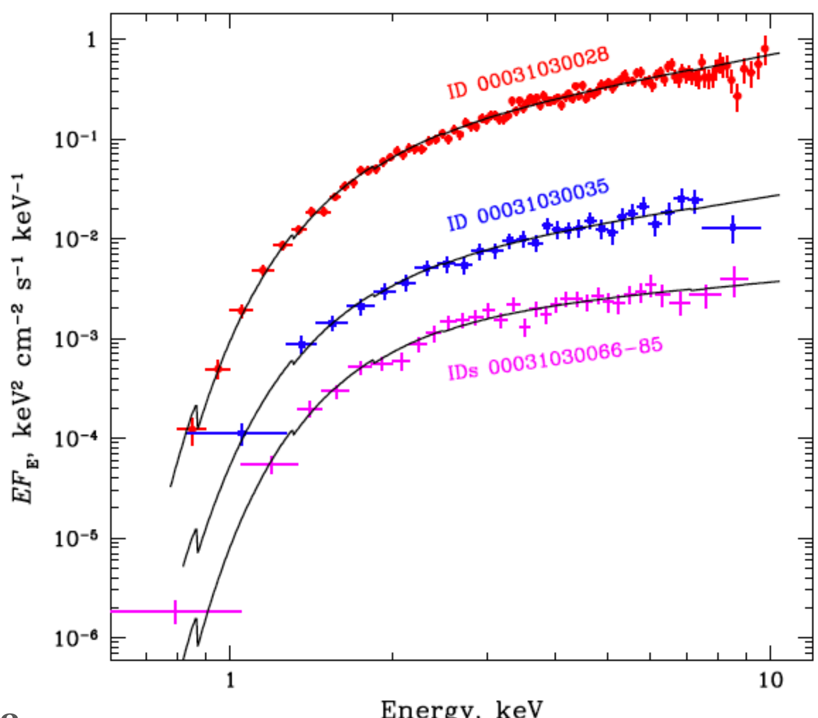
Tsygankov, AM+ 2017, A&A, 608

Stable accretion from a cold disc

Detection in GRO 1008

P_{spin} = 94 sec E_{cyc} ~ 80 keV





Tsygankov, AM+ 2017, A&A, 608

Stable accretion from a cold disc

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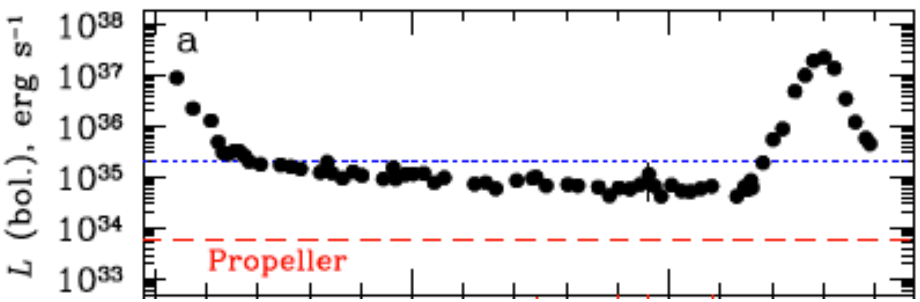
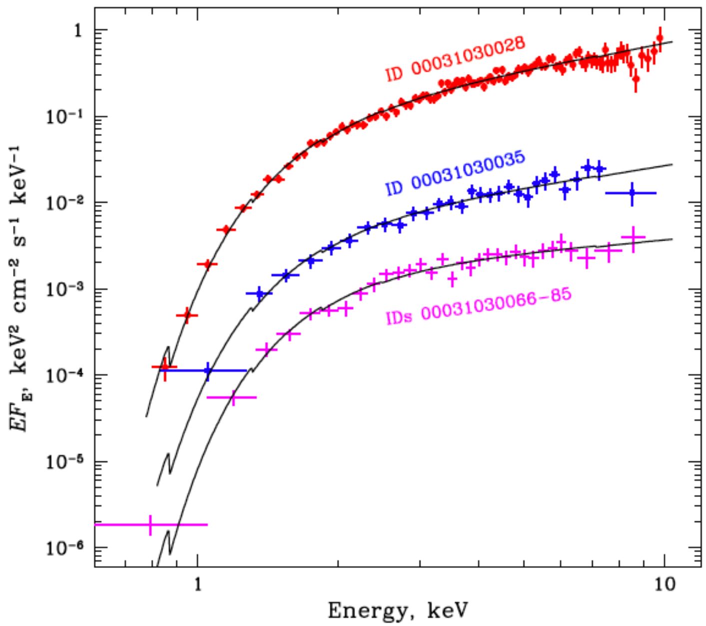
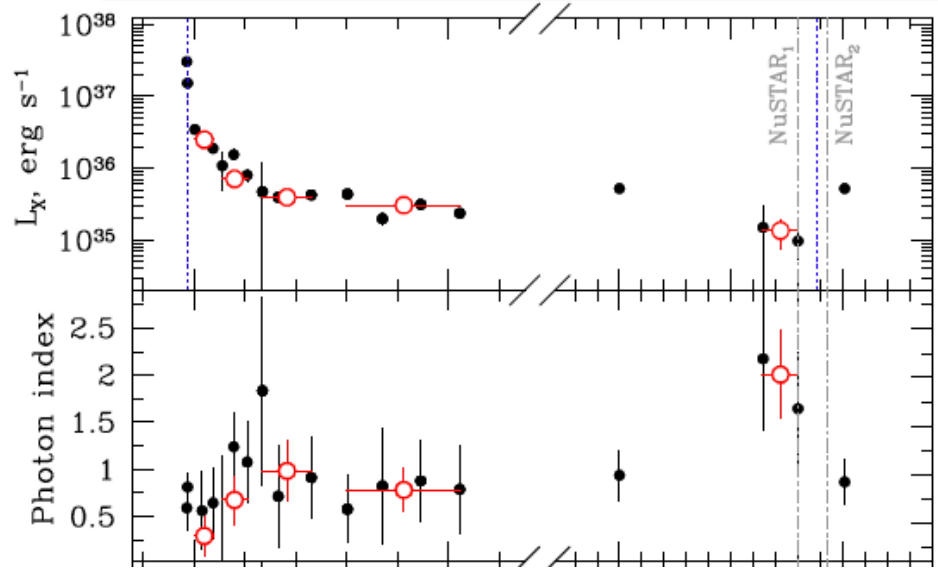
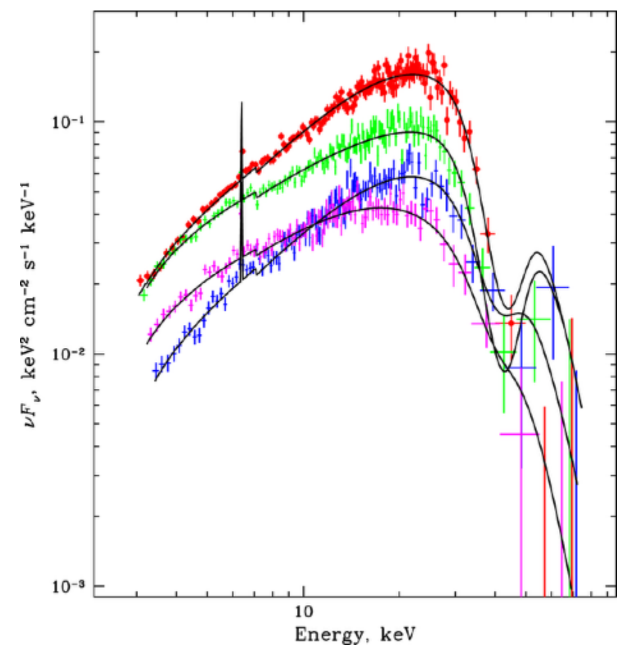




Detection in IGR J19294+1816

P_{spin} = 12.4 sec E_{cyc} ~ 42 keV

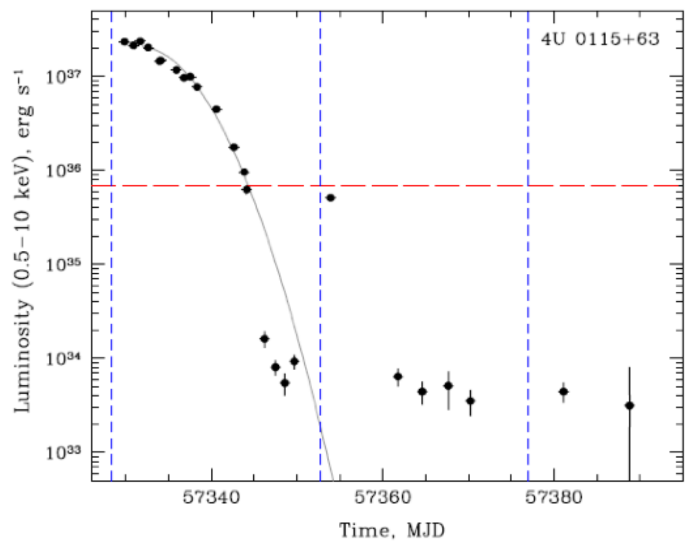


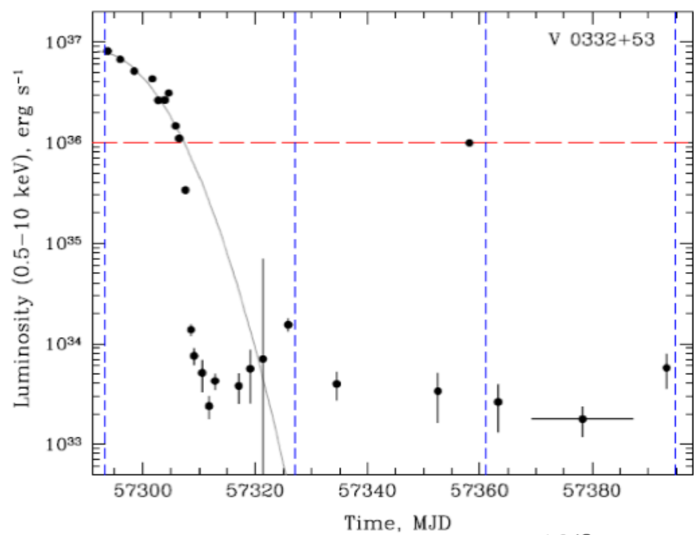


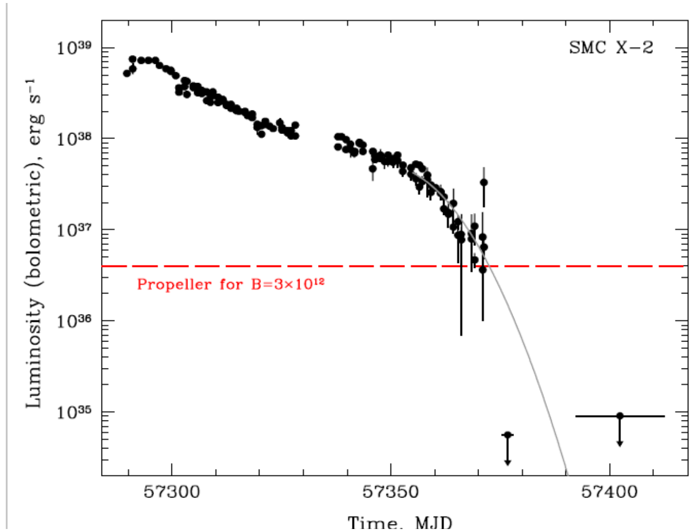
Tsygankov, AM+ 2017, A&A, 608
Tsygankov, Doroshenko, AM +,A&A 2019

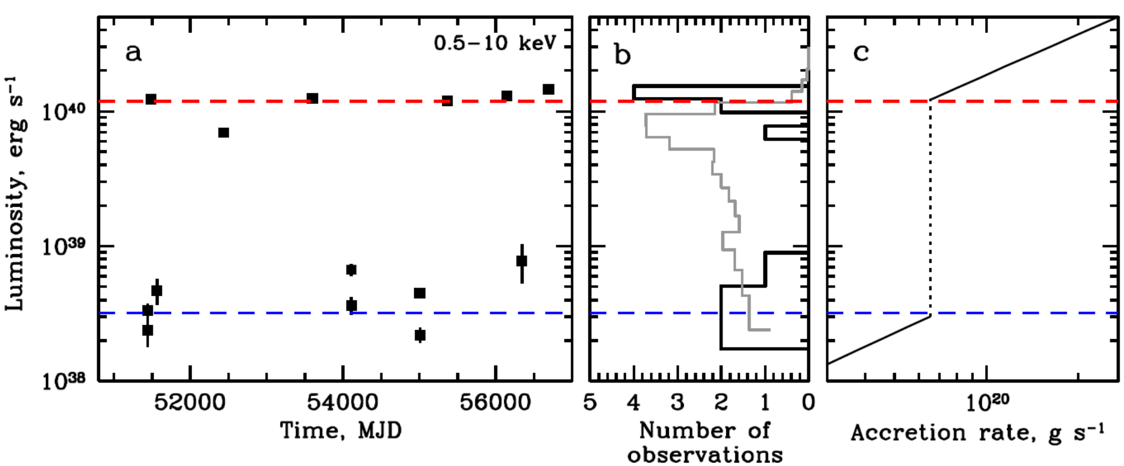
Summary (I)

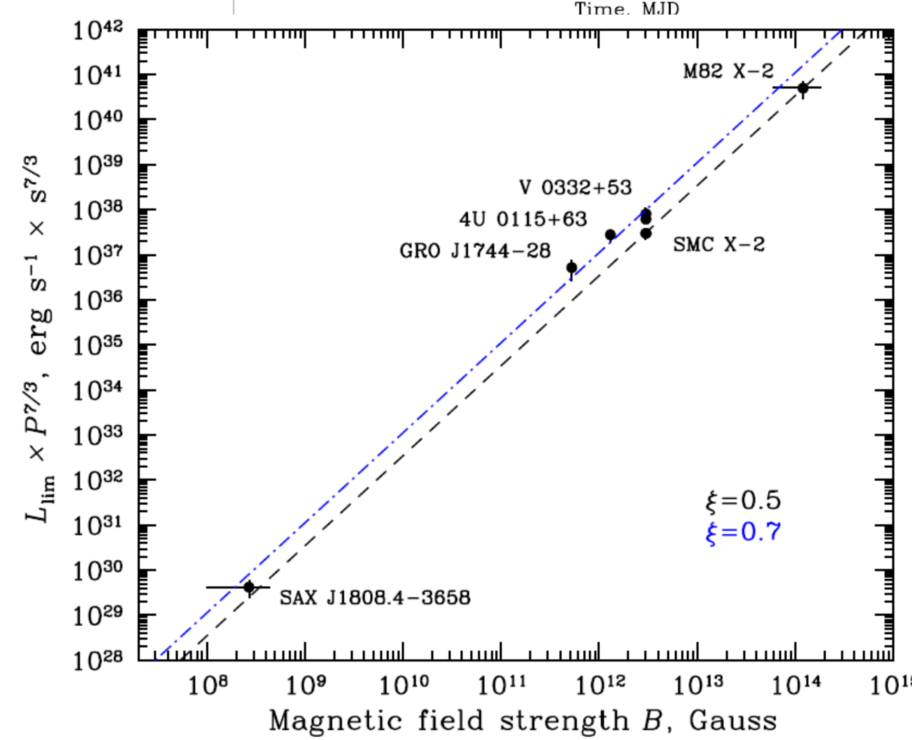
Detection of “propeller” state is a perfect way to measure dipole component of magnetic field











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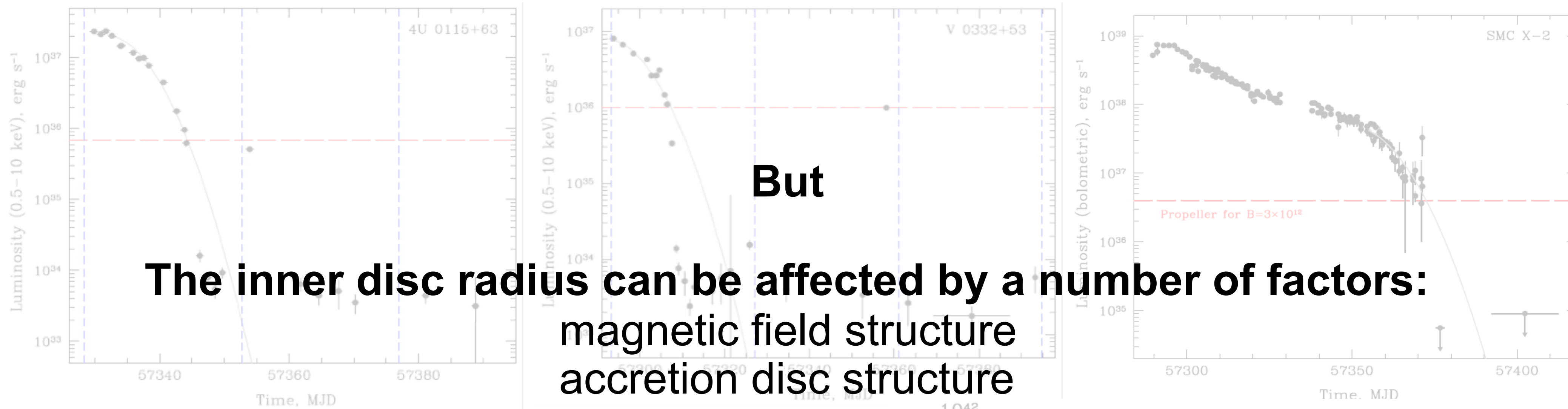


But

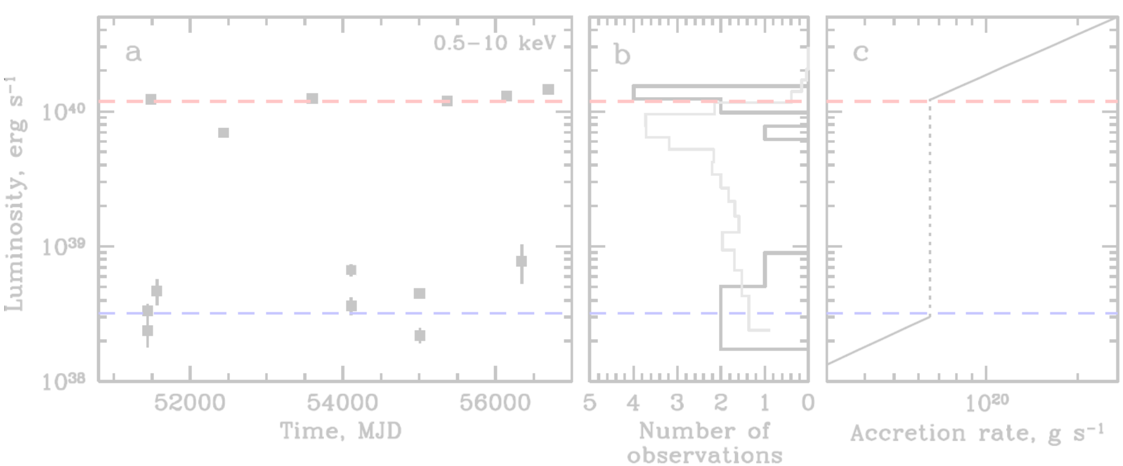
The inner disc radius can be affected by a number of factors:

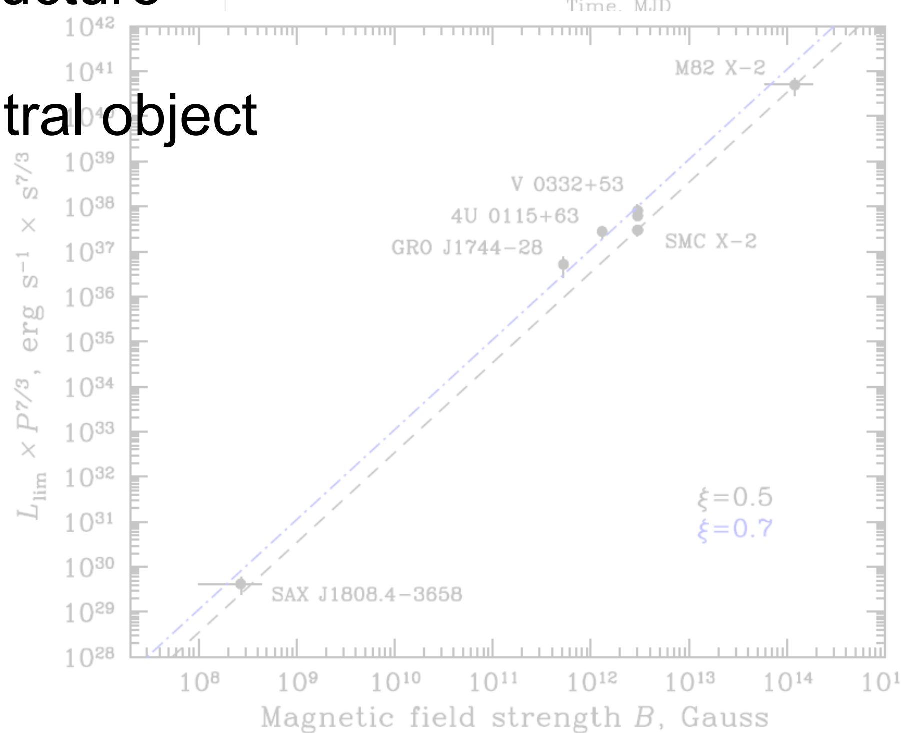
magnetic field structure

accretion disc structure

viscosity

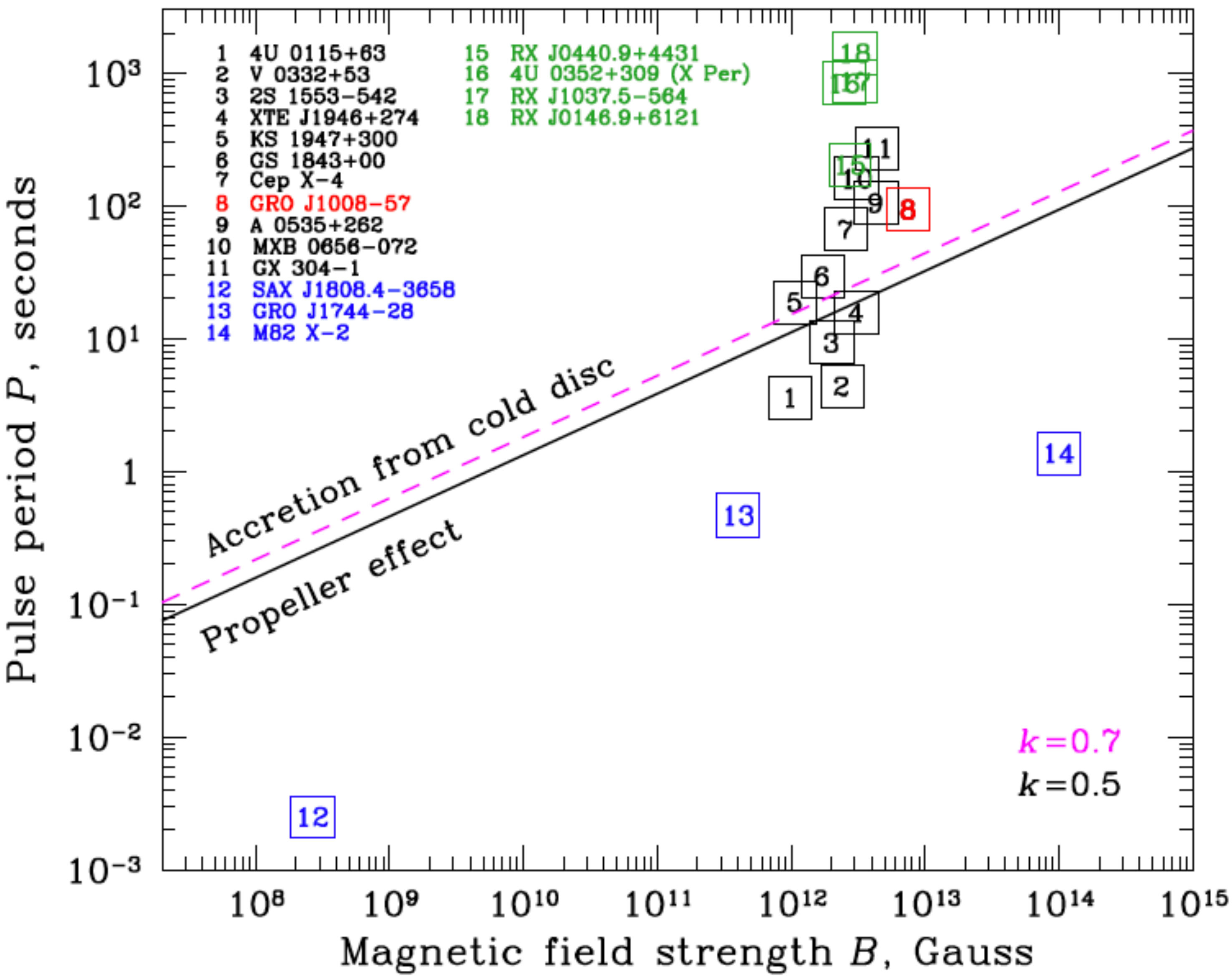
luminosity of the central object





Summary (II)

There is a class of X-ray pulsars which will **never turn into "propeller" regime** but will accrete stably from a cold recombined disc.



Summary (II)

Questions

How cold disc interacts with a magnetic field?

Cold Disc vs. ADAF