Ultraluminous X-ray pulsars:

the high-B interpretation

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Plan:

- ULX before 2014
- A short history of ULXPs
- Supercritical accretion onto a magnetized neutron star
- Large or low B? Propeller?
- Beamed?
- Winds?

Models for ULX (before 2014)

- Super-Eddington accretion onto a stellar-mass black hole (e.g. King 2001, Begelman et al. 2006, Poutanen et al. 2007)
- Sub-Eddington accretion onto intermediate mass black holes (Colbert & Mushotzky 2001)
- Young rotation-powered pulsar (Medvedev & Poutanen 2013)

Super-Eddington accretion

- Slim disk models Accretion rate is large, but most of the released energy is advected towards the BH.

$$\dot{M}(r) = \dot{M}_0$$

- Super-disks with winds

  Accretion rate is large, but most of the mass is blown away by radiation. Only the Eddington rate goes to the BH.

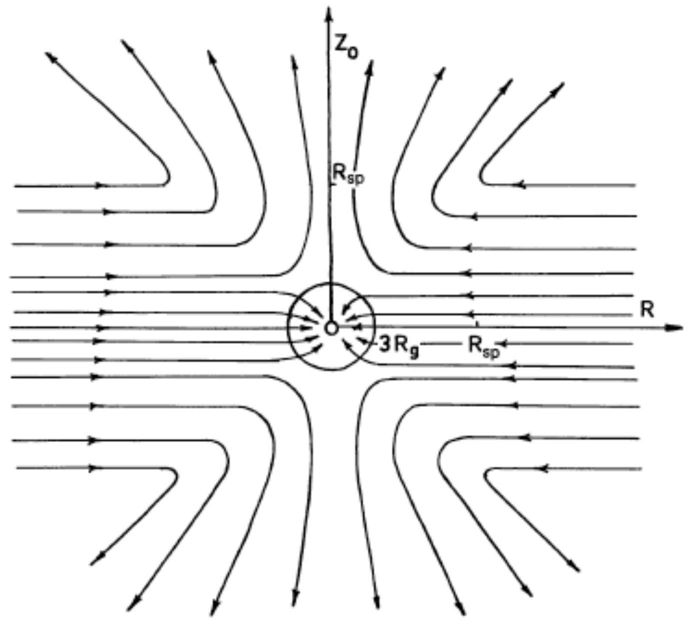

Fig. 8. Lines of matter flow at supercritical accretion (the disk section along the Z-coordinate). When $R < R_{sp}$ spherization of accretion takes place and the outflow of matter from the collapsar begins

$$\dot{M}(r) = \dot{M}_0 \frac{r}{R_{sph}}$$

$$\dot{M}(r_{in}) = \dot{M}_{Edd}$$

$$R_{sph} \approx R_{\text{in}} \frac{\dot{M}_0}{\dot{M}_{Edd}}$$ - spherization radius

Shakura & Sunyaev 1973

Super-Eddington accretion

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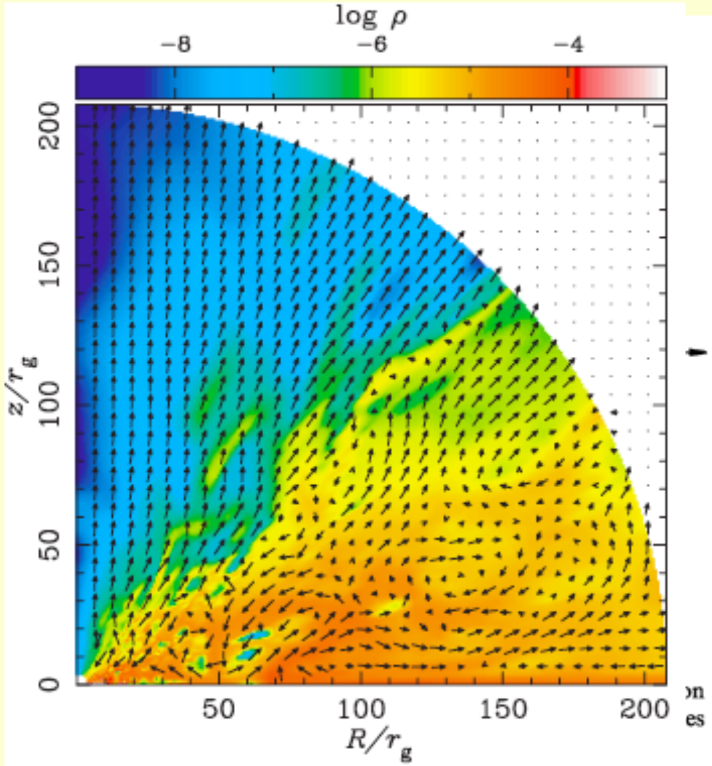


$$\dot{M}(r) = \dot{M}_0 \frac{r}{R_{sph}}$$

$$\dot{M}(r_{in}) = \dot{M}_{Edd}$$

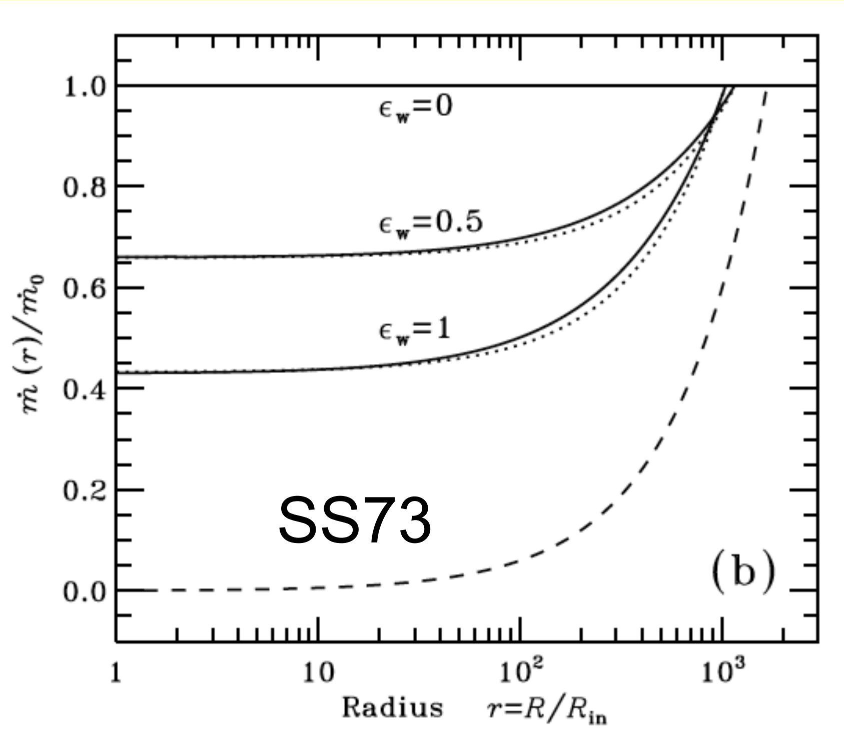
$$R_{sph} \approx R_S \frac{\dot{M}_0}{\dot{M}_{Edd}}$$ -spherization radius

Ohsuga et al. 2005

Super-Eddington accretion

Super-disks with winds and advection

Accretion rate is large, a lot of mass is blown away by radiation (using fraction ε_W of available radiative flux), but still a significant fraction goes to the BH.



$$\dot{M}(r) = \dot{M}_0 + \left(\dot{M}_0 - \dot{M}_{in}\right)\frac{r}{R_{sph}}$$

$$\frac{\dot{M}_{in}}{\dot{M}_0} = \frac{1-a}{1-a(0.4\dot{m}_0)^{-1/2}}$$

$$a = \varepsilon_W(0.83 - 0.25\varepsilon_W)$$

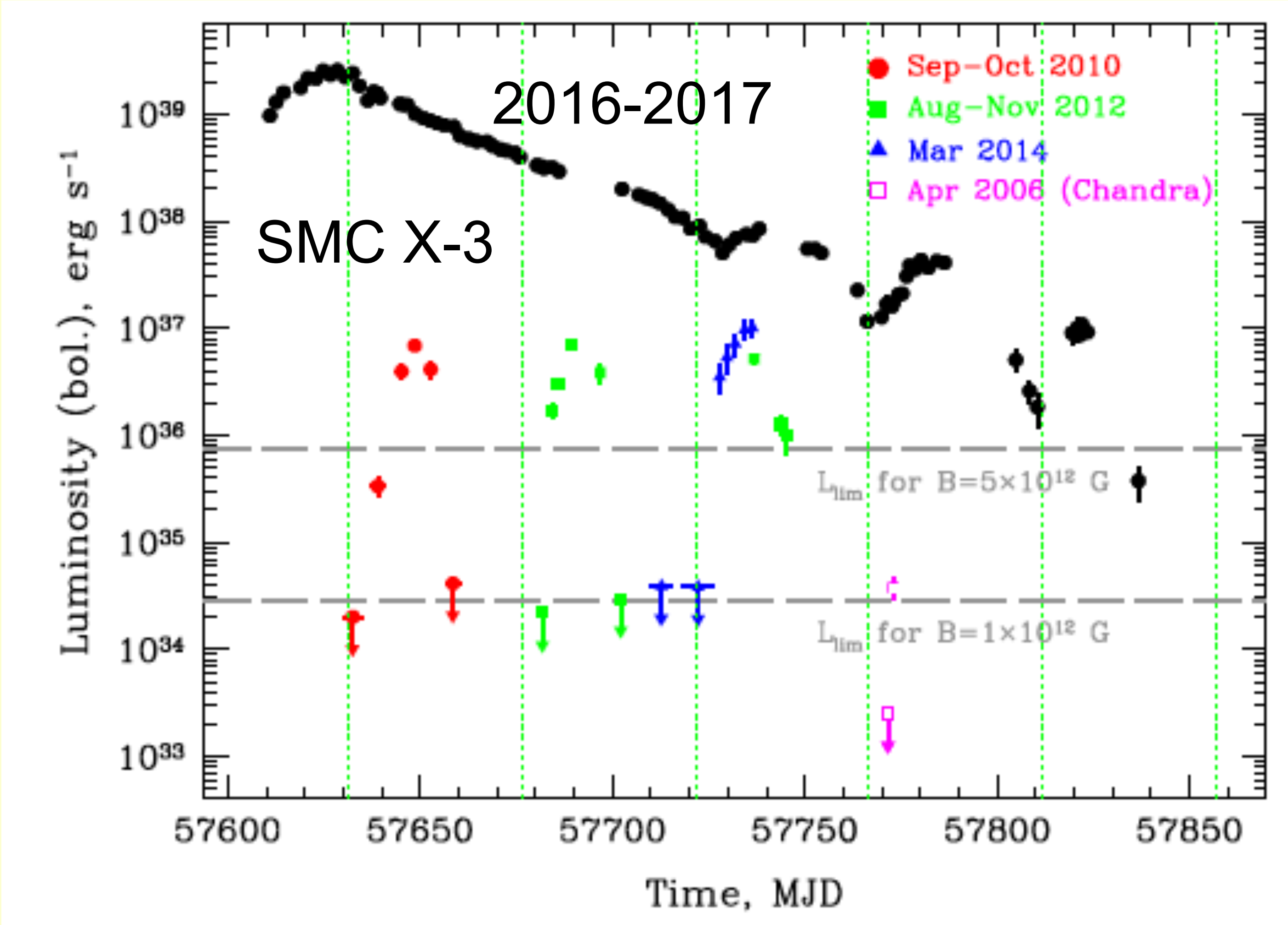
Poutanen et al. (2007)

ULX pulsars

- If we define ULX as L>10^{39} erg/s then ULX pulsars have been discovered >40 years ago
- Sources in the Magellanic Clouds

1. SMC X-1 (L=1.5E39, Price+1971; Coe+1981)
2. LMC X-4 (L=1E39)
3. A0538-66 (L=0.85E39, Skinner+1982).
4. SMC X-2 (L=1E39, Lutovinov+2016)
5. SMC X-3 (L=2.5E39, Tsygankov+2017)

ULX pulsars

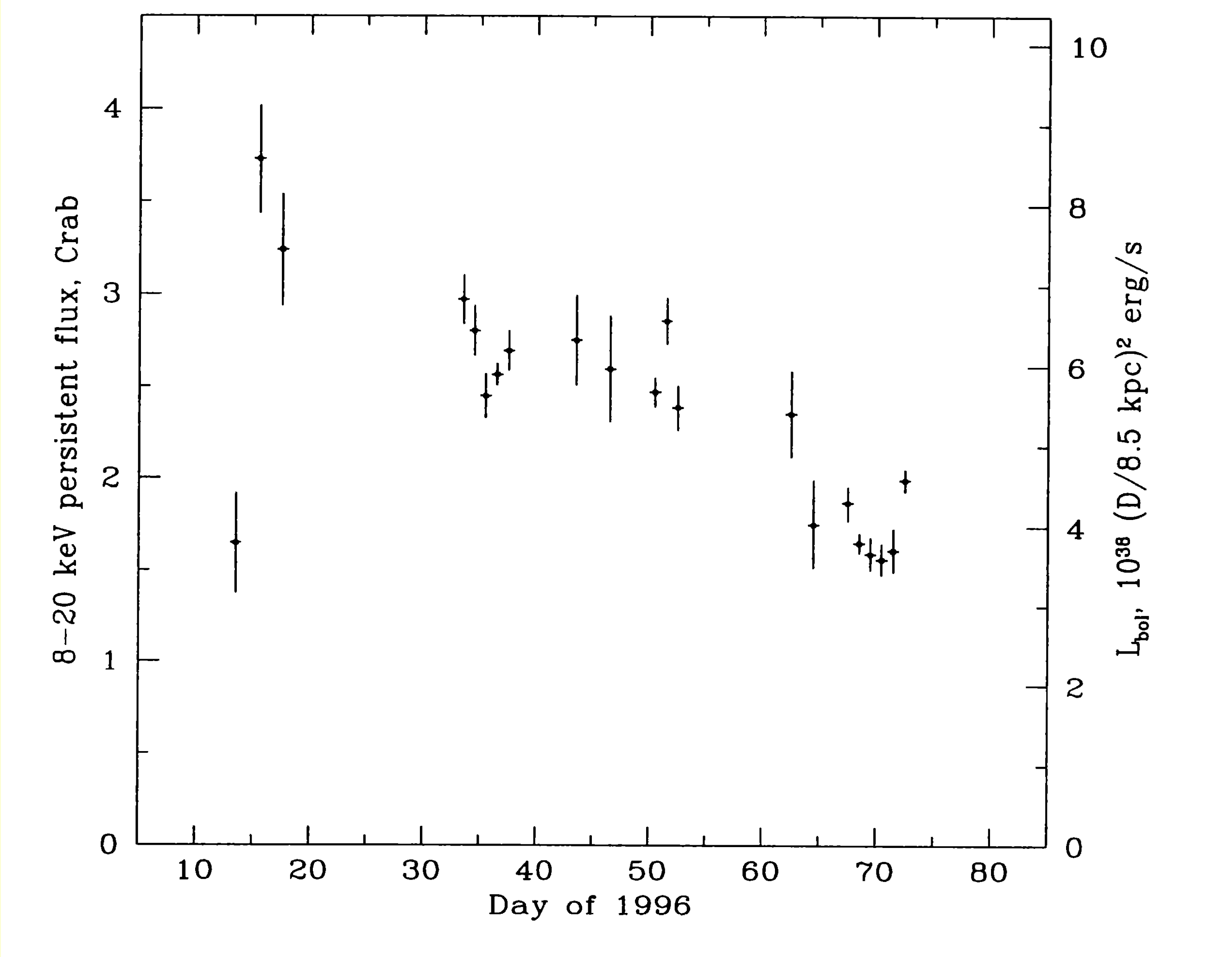


B≈2E12 G

Tsygankov+2017

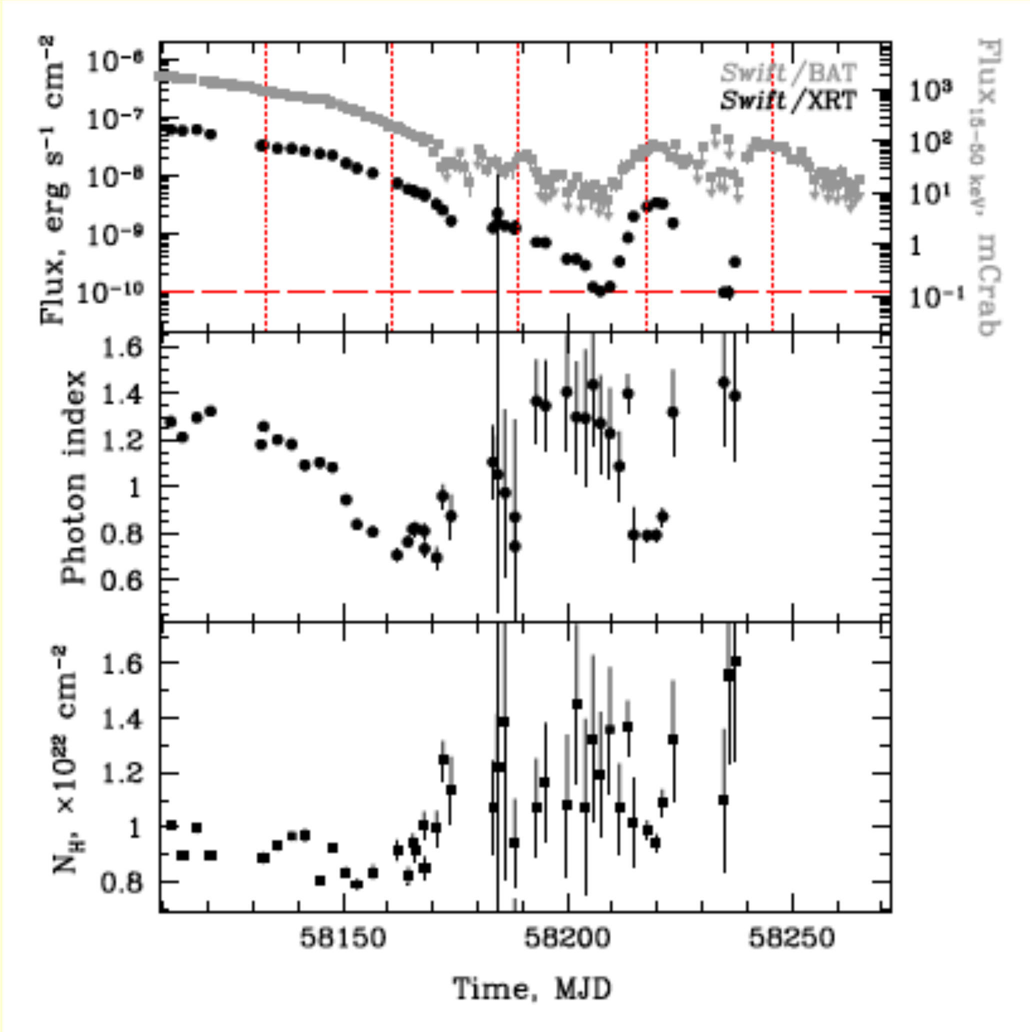
ULX pulsars

- in the Milky Way: GRO J1744-28 (Kouveliotou+1996, Sazonov+1997); L=1E39



ULX pulsars

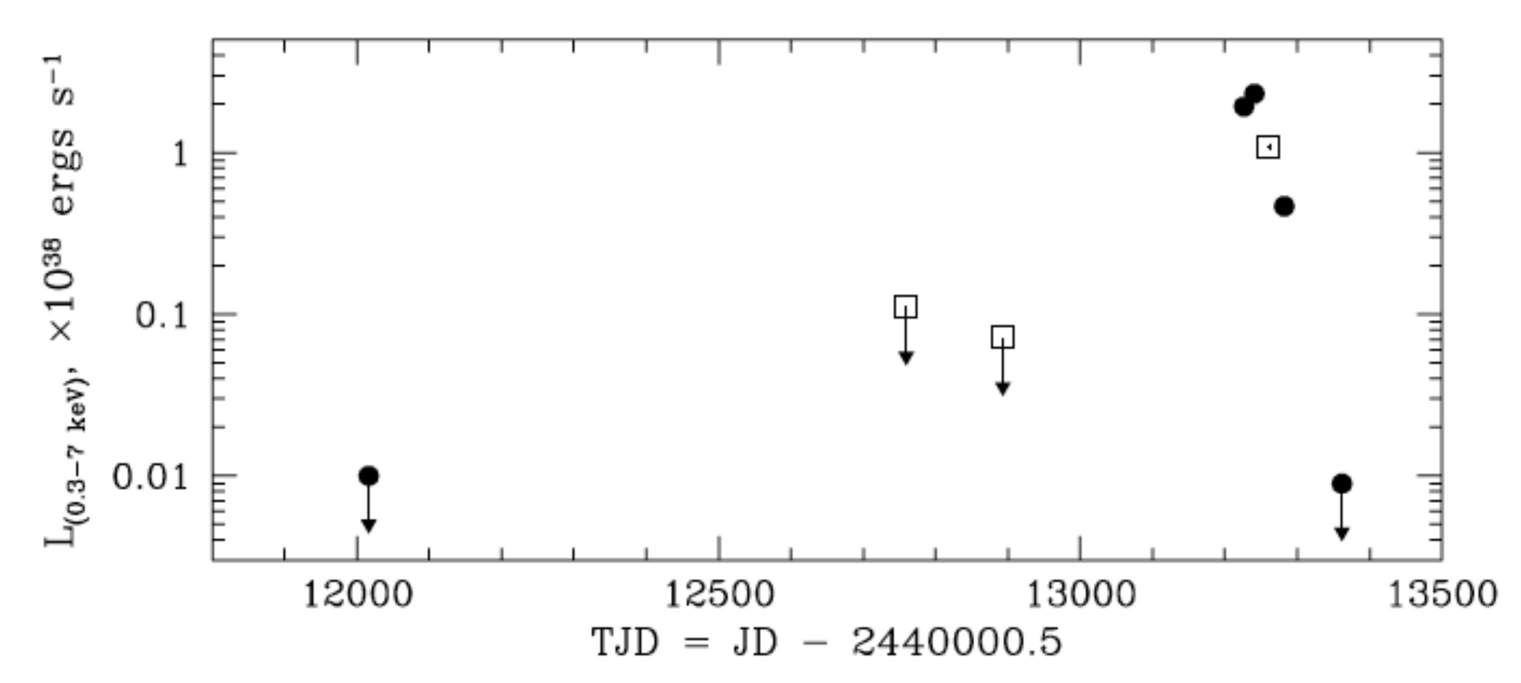
- in the Milky Way: Swift J0243.6+6124 (Tsygankov+2018, arxiv:1806.02283); L=5E39



ULX pulsars

- As well as in other galaxies:

1. 18 s pulsar CXOU J073709.1+653544 in NGC 2403 at 3.2 Mpc (*L*=1E39, Trudolyubov+2007)



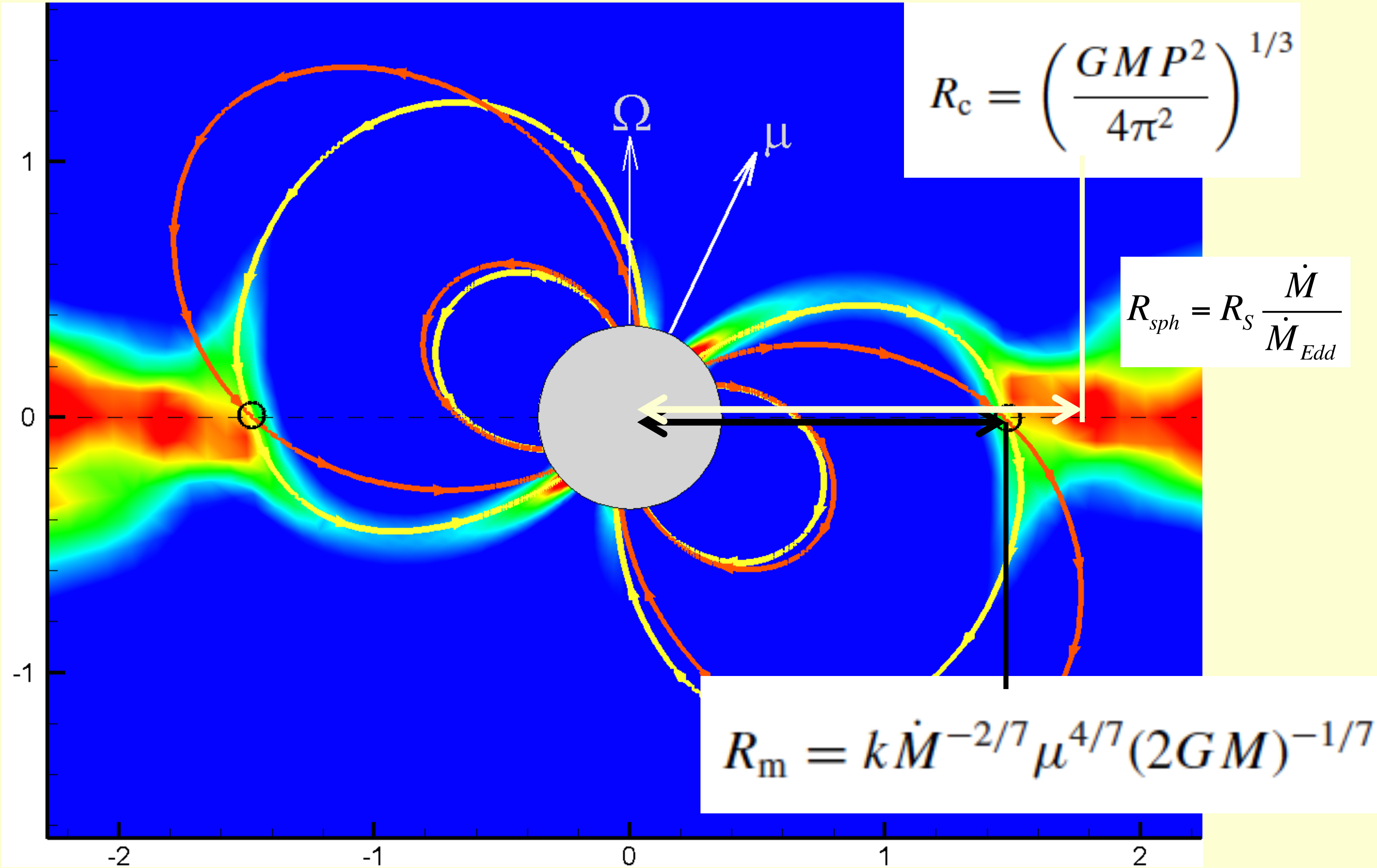
2. 766 s pulsar XMMU J031747.5-663010 in NGC 1313 ar 4.1 Mpc (*L*=1.6E39, Trudolyubov+2008)

ULX pulsars

- Extragalactic even brighter ULXPs:

1. M82 X-2 (Bachetti et al. 2014)
2. NGC 5907 X-1 (Israel+2017a)
3. NGC 7793 P13 (Israel+2017b, Fürst+2016)
4. NGC 300 ULX1 (Carpano+2018)
5. ULX7 in M51 (Israel+2018)

Accretion in ULX-pulsars

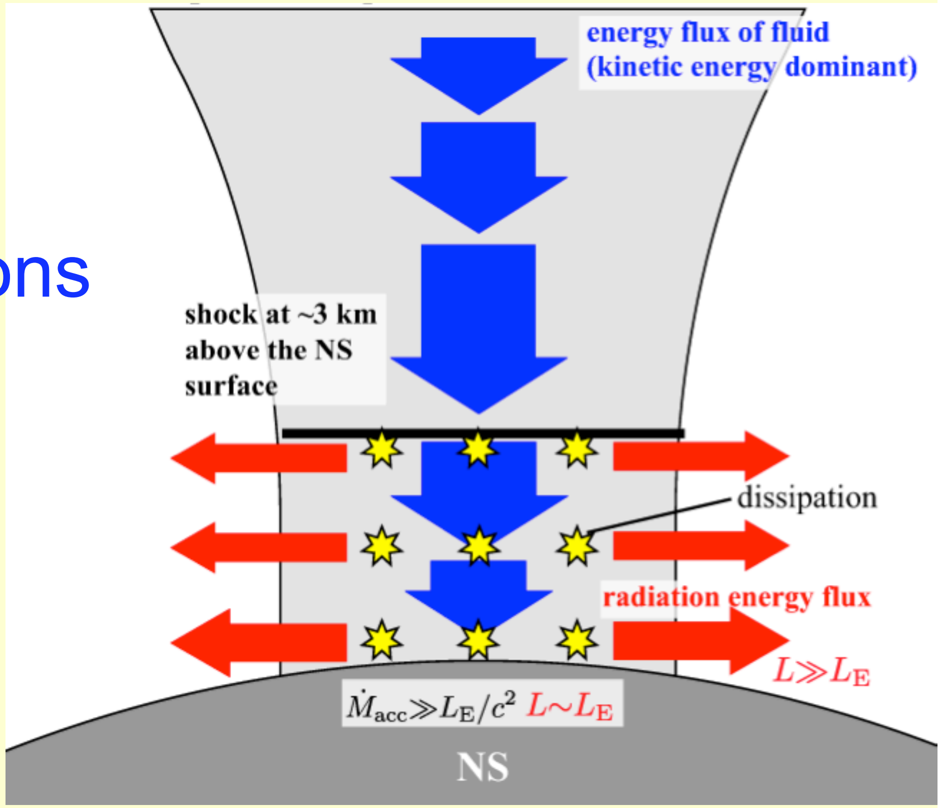


Kulkarni & Romanova 2013

How to exceed the Eddington limit?

- Supply a lot of gas!

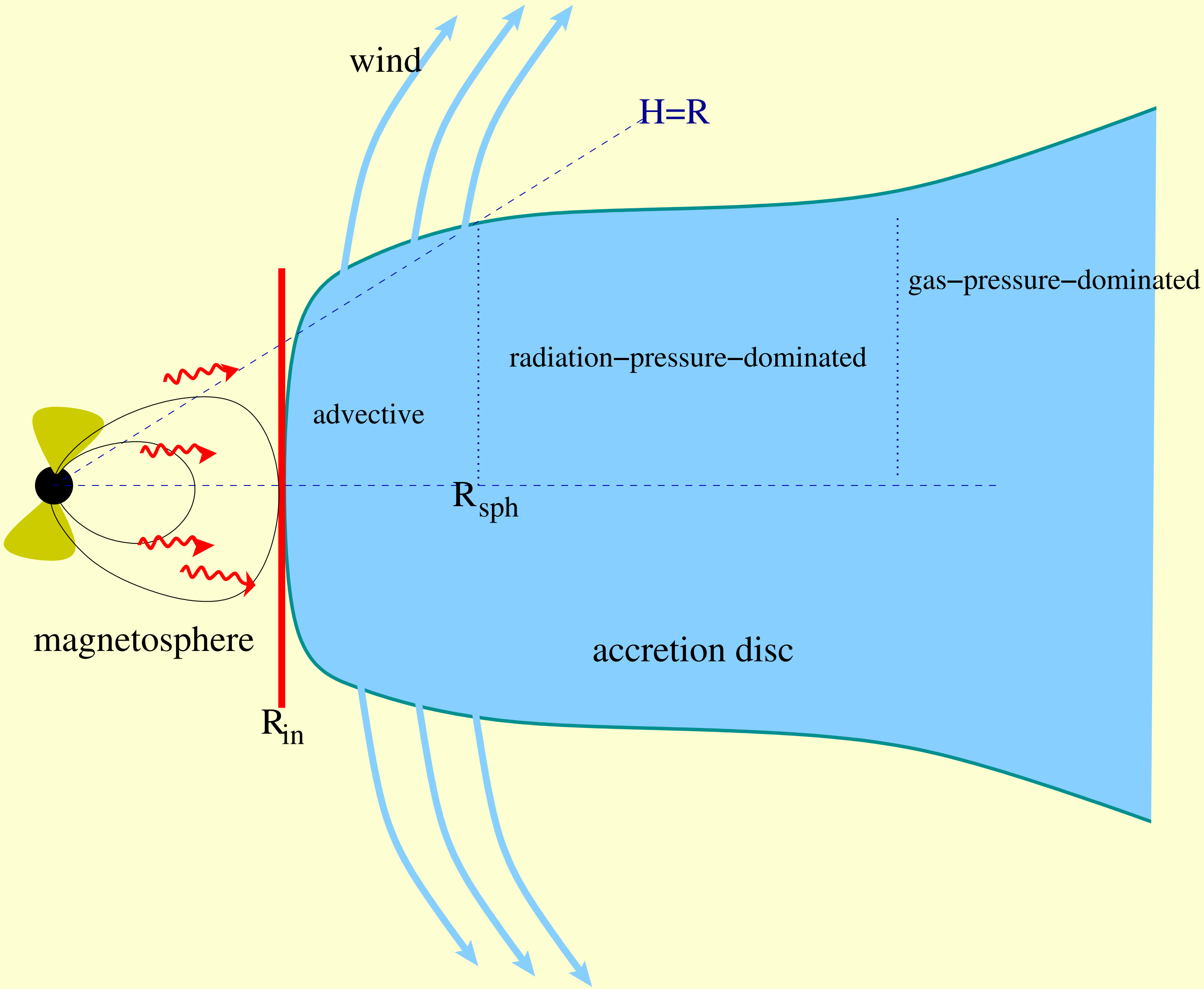
- Geometrical effect (photons escape sideways)



Basko & Sunyaev 1976
Wang & Frank 1981
Lyubarskij & Sunyaev 1988
Mushtukov et al. 2015
Postnov et al. 2015
Kawashima et al. 2016

- Photon bubbles (Klein+1996; Begelman 2006)
- Strong B-field reduction of the scattering cross-section; for X-mode $\sigma_\perp(E) \simeq \sigma_T (E/E_{cycl})^2$

Accretion on to a magnetized NS



Characteristic radii

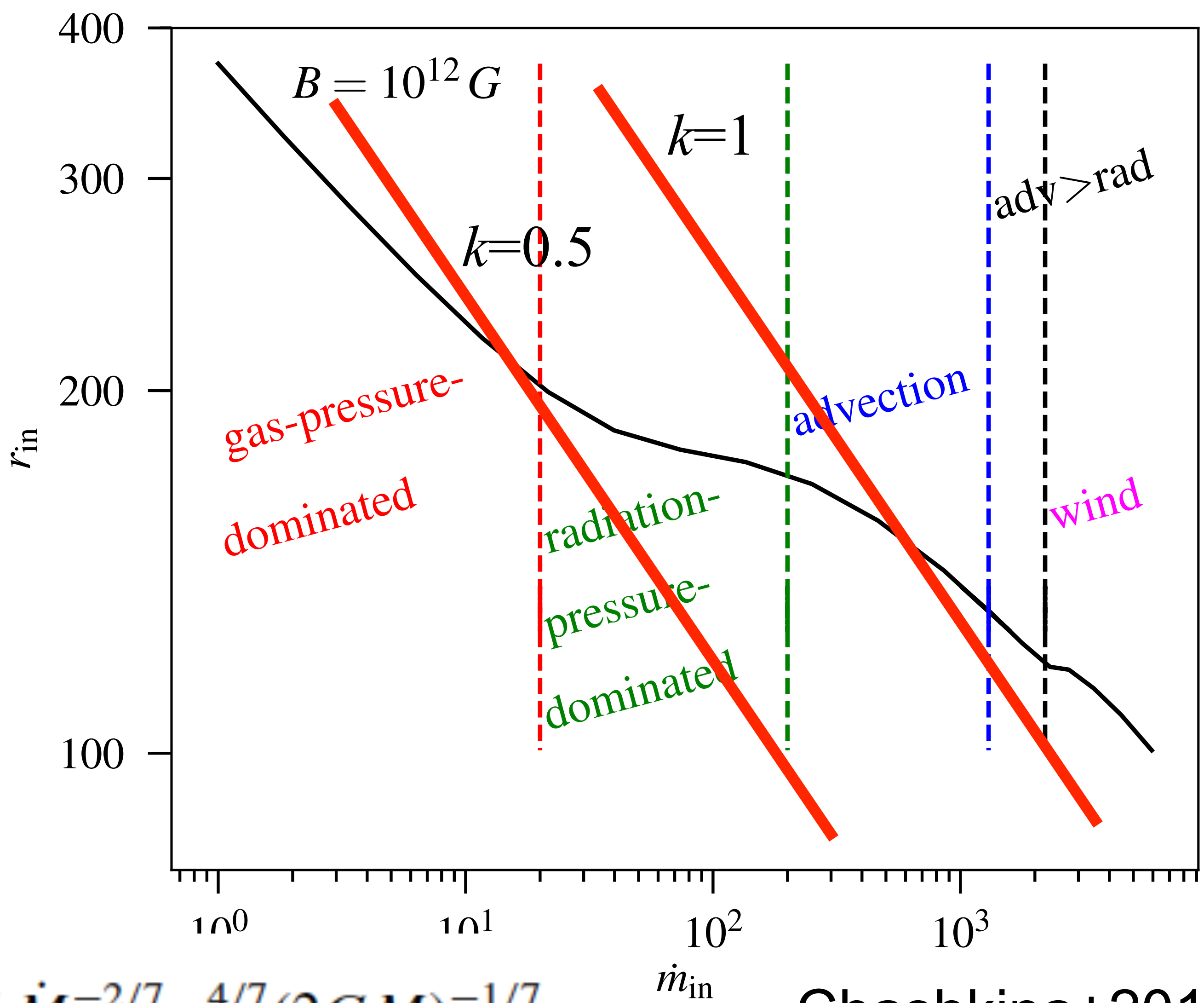
$$R_c = \left(\frac{GMP^2}{4\pi^2}\right)^{1/3}$$ ≈10^8 cm Corotation radius

$$R_{sph} = R_* \frac{\dot{M}}{\dot{M}_{Edd}}$$ Spherization (wind) radius

$$R_m = k\dot{M}^{-2/7}\mu^{4/7}(2GM)^{-1/7}$$ Magnetospheric radius

k - depends on the disc structure
(Chashkina, Abolmasov, JP 2017; Chashkina+2018)

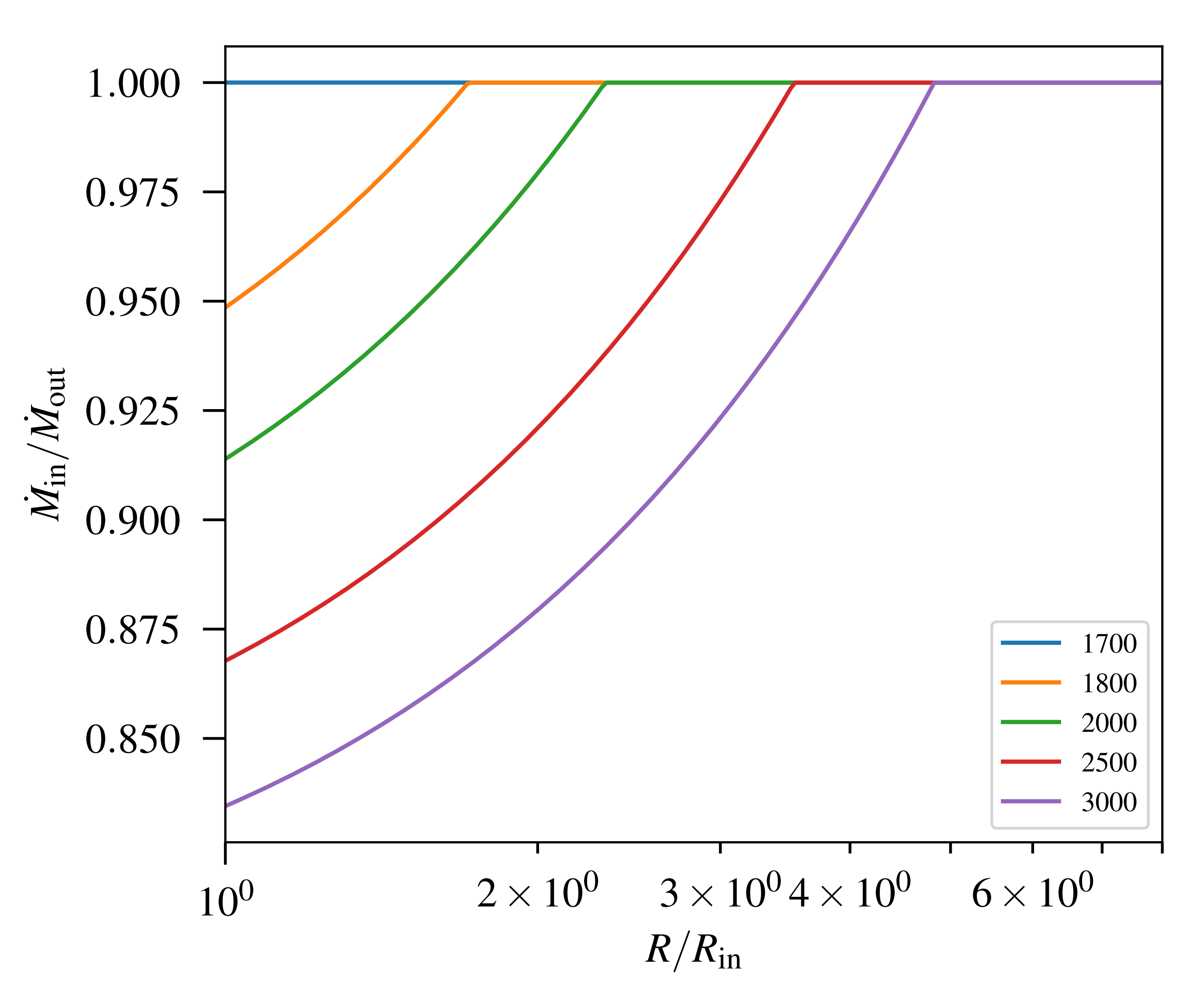
Magnetospheric radius



$$R_m = k\dot{M}^{-2/7}\mu^{4/7}(2GM)^{-1/7}$$

Chashkina+2018

The mass accretion rate to the NS



Chashkina+2018

Large or small B?

Arguments in favour of large B:

- Large B reduces cross-section, so that Eddington luminosity is higher
- At high Mdot, the source is close to spin equilibrium, so Rco≈Rm and high-B is needed
- High spin-up easy to explain
- Explains bimodal distribution by *propeller effect*

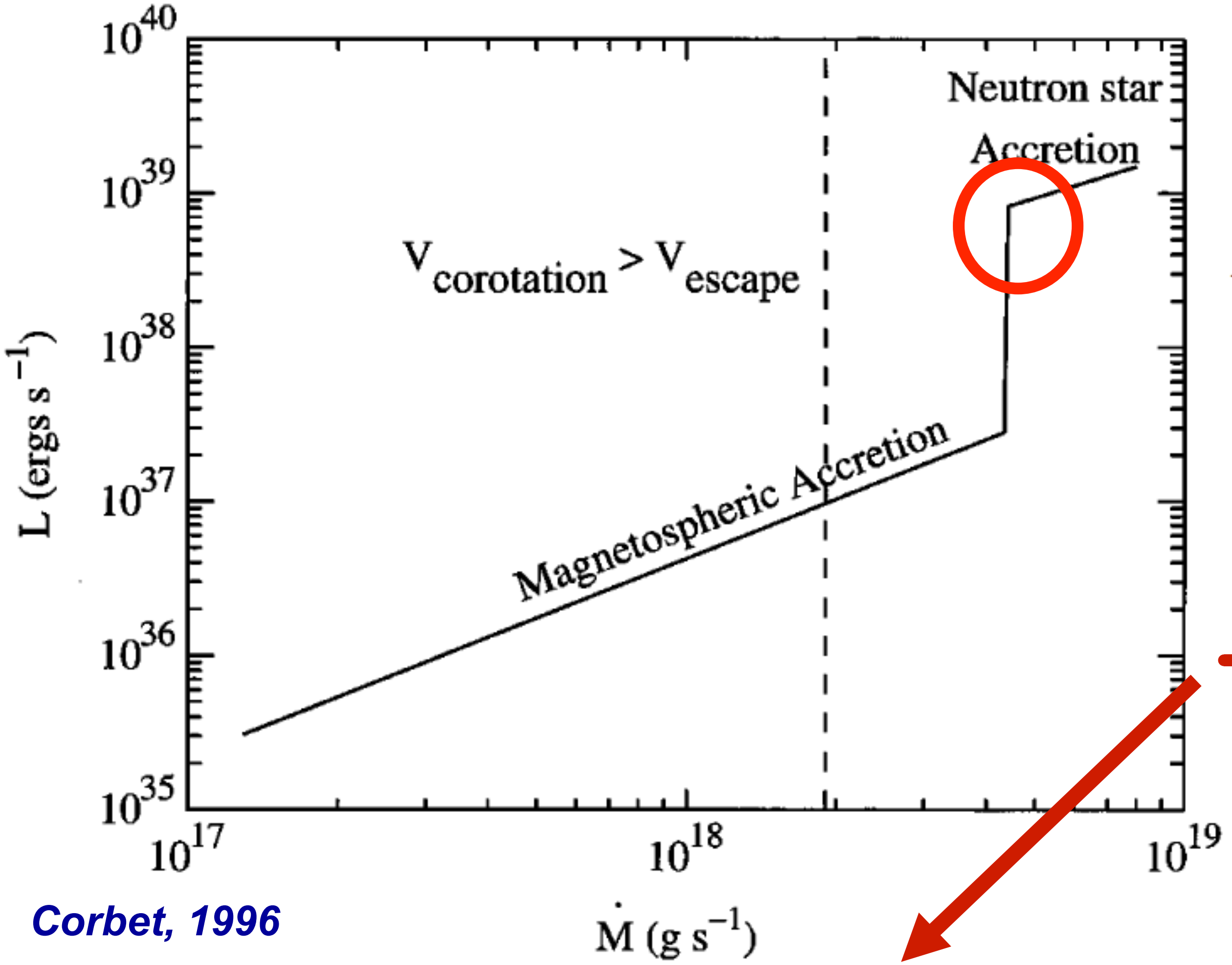
Arguments against (very) large B:

- Can magnetar-like field survive up to a Myr? What about B=3E13 G?

Arguments against (very) low-B:

- Rm<<Rco, strong spin-up is expected, not observed
- Rm<<R_{NS} no pulsations are possible
- Maximum luminosity about Eddington (i.e. a few 10^{38} erg/s)

Propeller effect



Corbet, 1996

$$R_c = R_m$$

$$L_{\rm lim}(R) \simeq \frac{GM\dot{M}_{\rm lim}}{R}$$

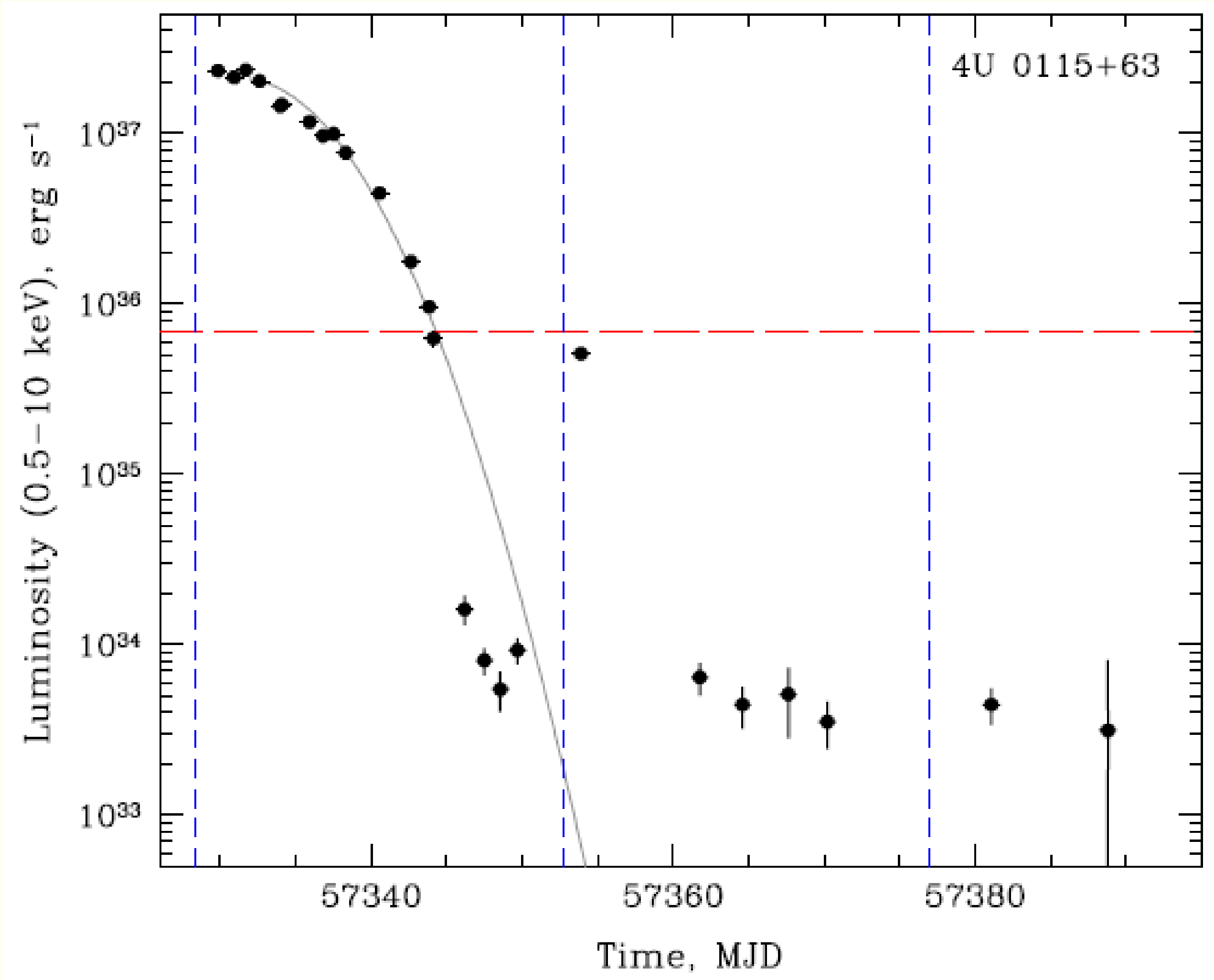
$$r_{\rm co} = \left(\frac{GM}{\Omega^2}\right)^{1/3}$$

$$r_A = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7}$$

$$r_m = \xi r_A$$

$$L_{\rm lim}(R) \simeq \frac{GM\dot{M}_{\rm lim}}{R} \simeq 4\times10^{37}\xi^{7/2}B_{12}^2P^{-7/3}M_{1.4}^{-2/3}R_6^5\,{\rm erg\ s^{-1}}$$

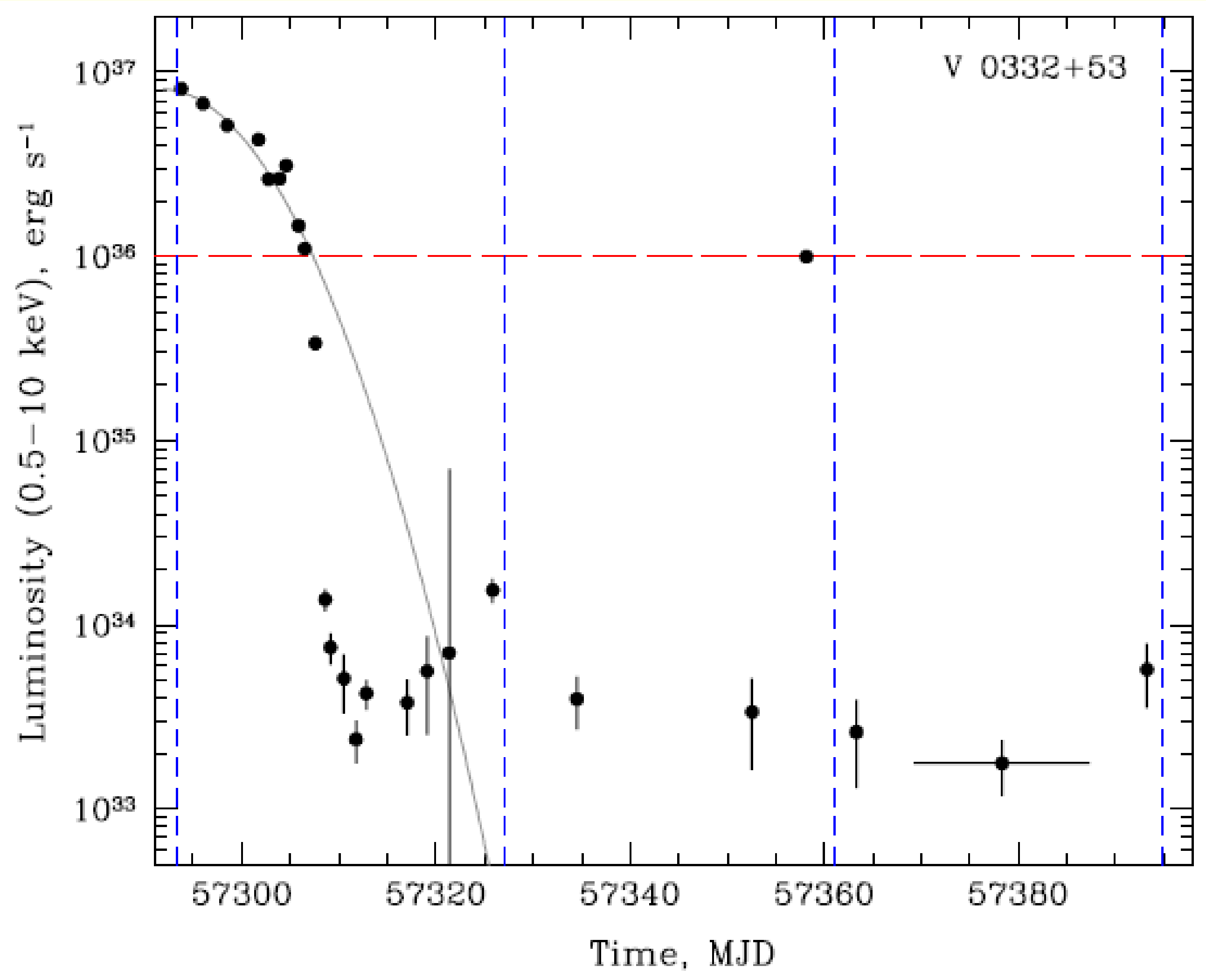
4U 0115+63 in 2015



L_{lim} = 7 x 10^{35} erg/s

Tsygankov +2016

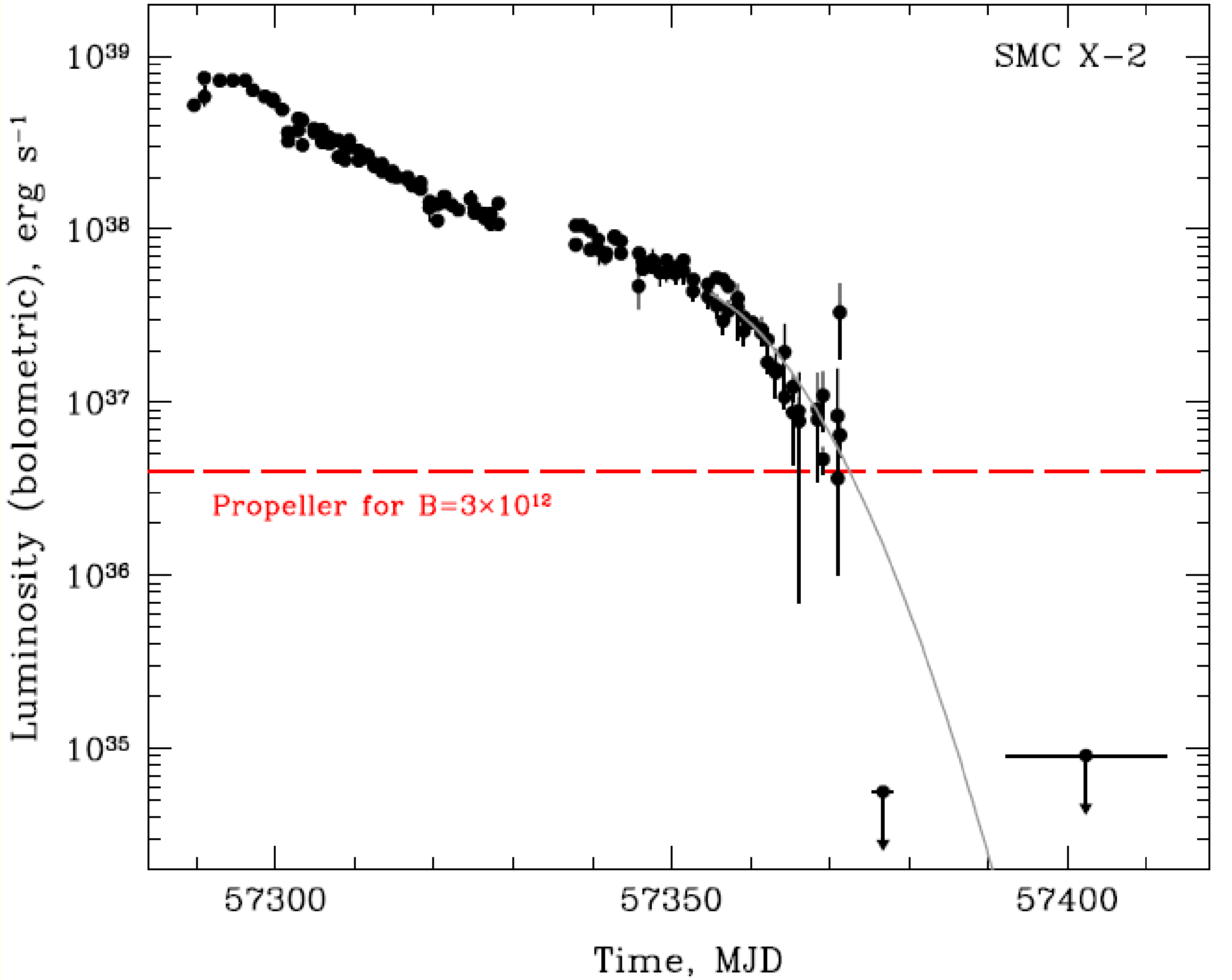
V 0332+53 in 2015



$L_{lim} = 1 \times 10^{36}$ erg/s

Tsygankov +2016

SMC X-2 in 2015

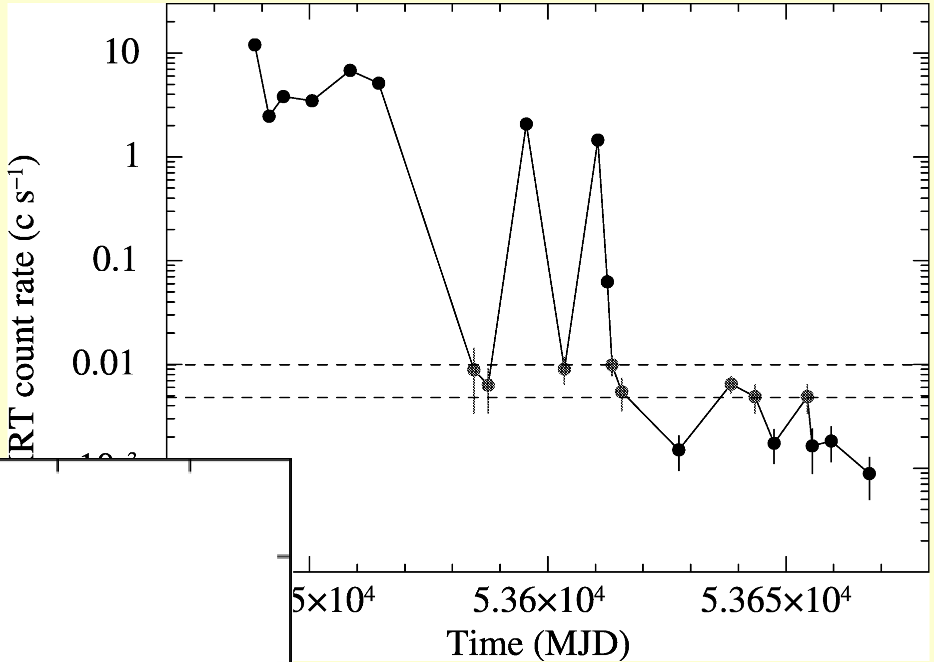


$L_{lim} = 4 \times 10^{36}$ erg/s

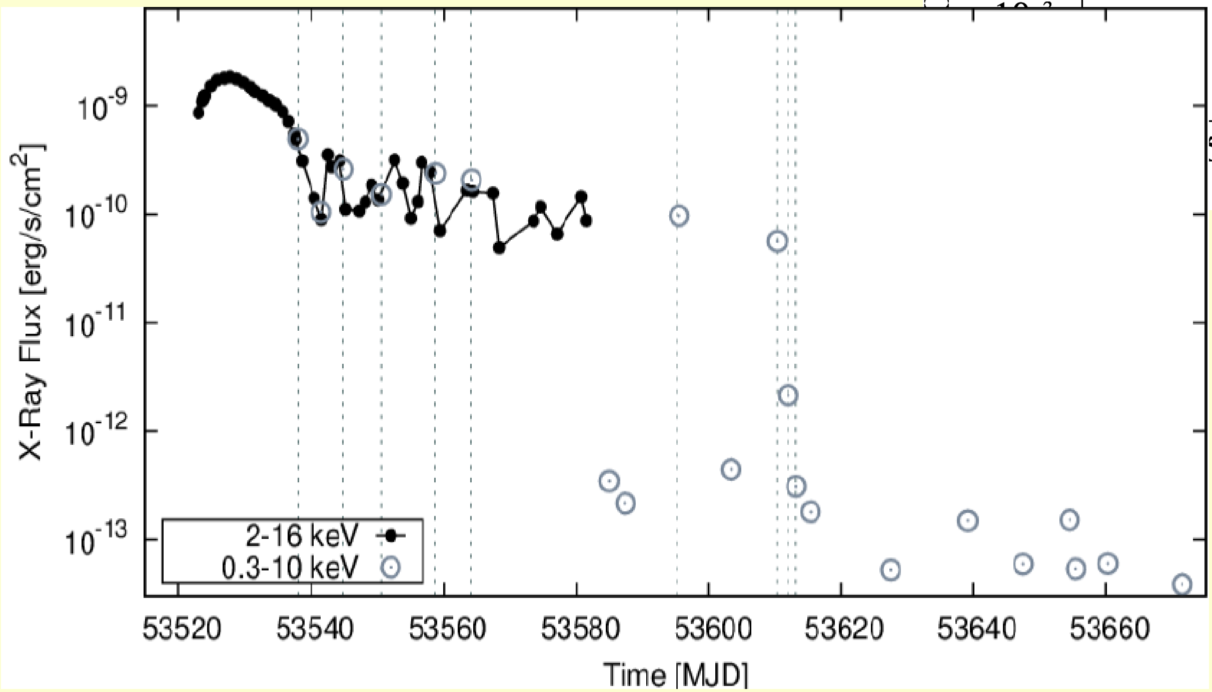
Lutovinov +2016

SAX J1808.4-3658

$L_{lim} = 5 \times 10^{35}$ erg/s



Campana et al., 2008



Patruno et al., 2016

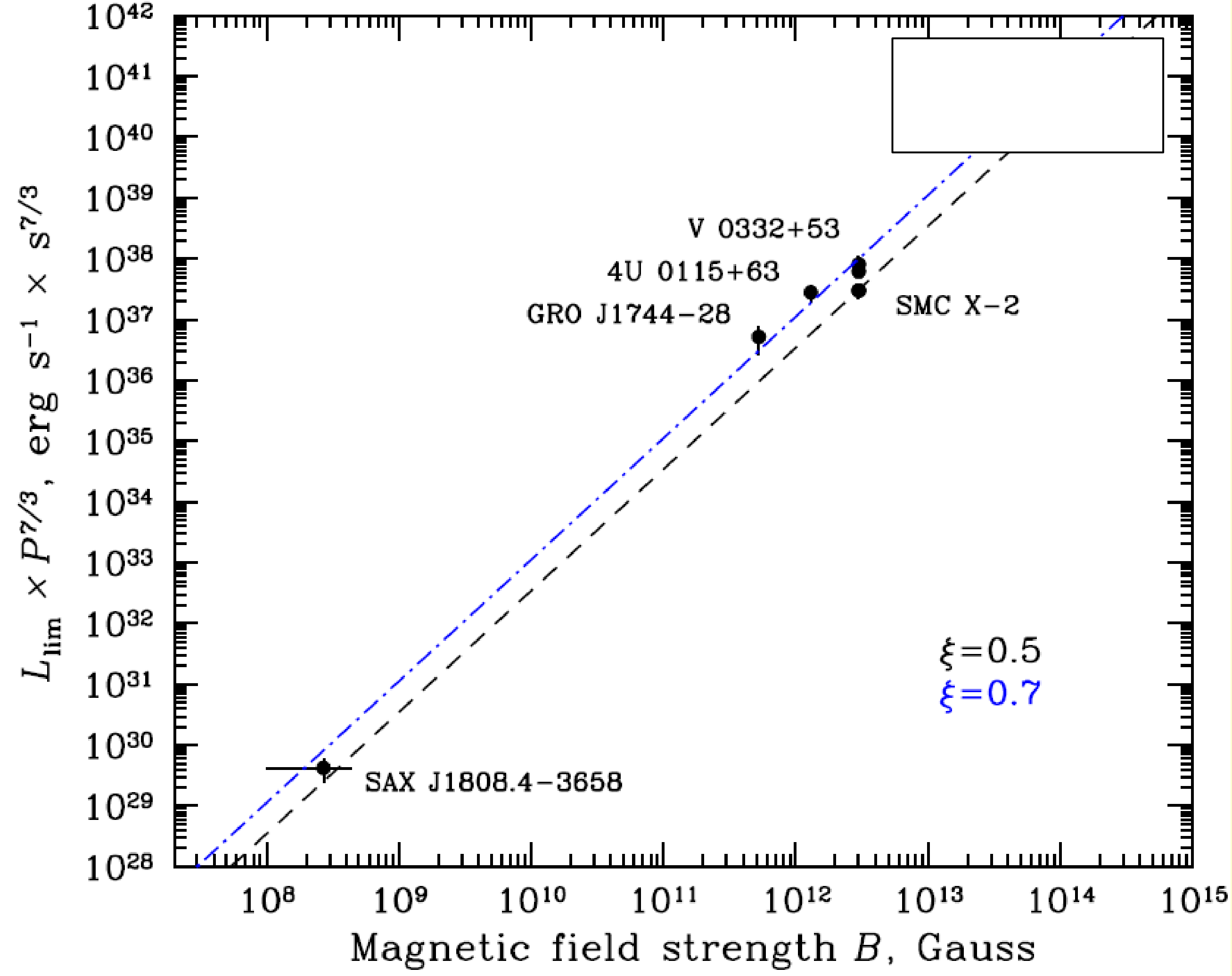
Propeller in action

$$L_{\rm lim}(R) \simeq \frac{GM\dot{M}_{\rm lim}}{R} \simeq 4\times10^{37}\xi^{7/2}B_{12}^{2}P^{-7/3}M_{1.4}^{-2/3}R_6^5\,{\rm erg\ s^{-1}}$$

$$r_{\rm co} = \left(\frac{GM}{\Omega^2}\right)^{1/3}$$

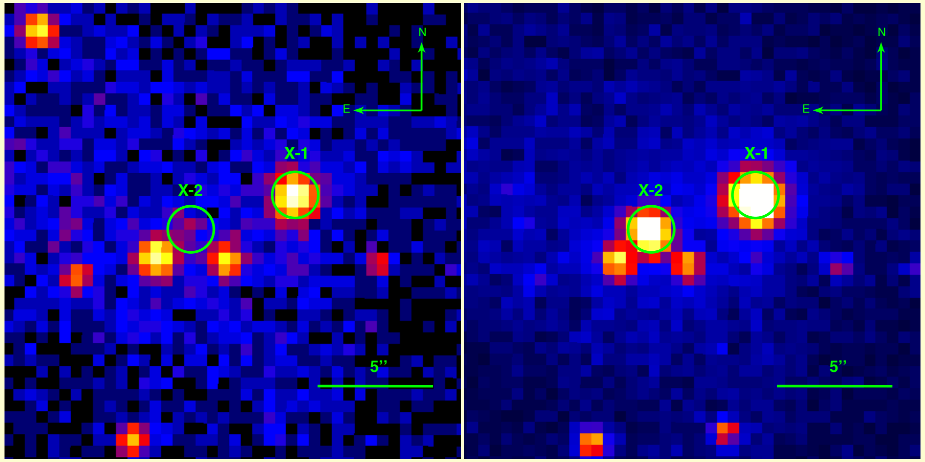
$$r_{\rm A} = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7}$$

$$r_{\rm m} = \xi r_{\rm A}$$

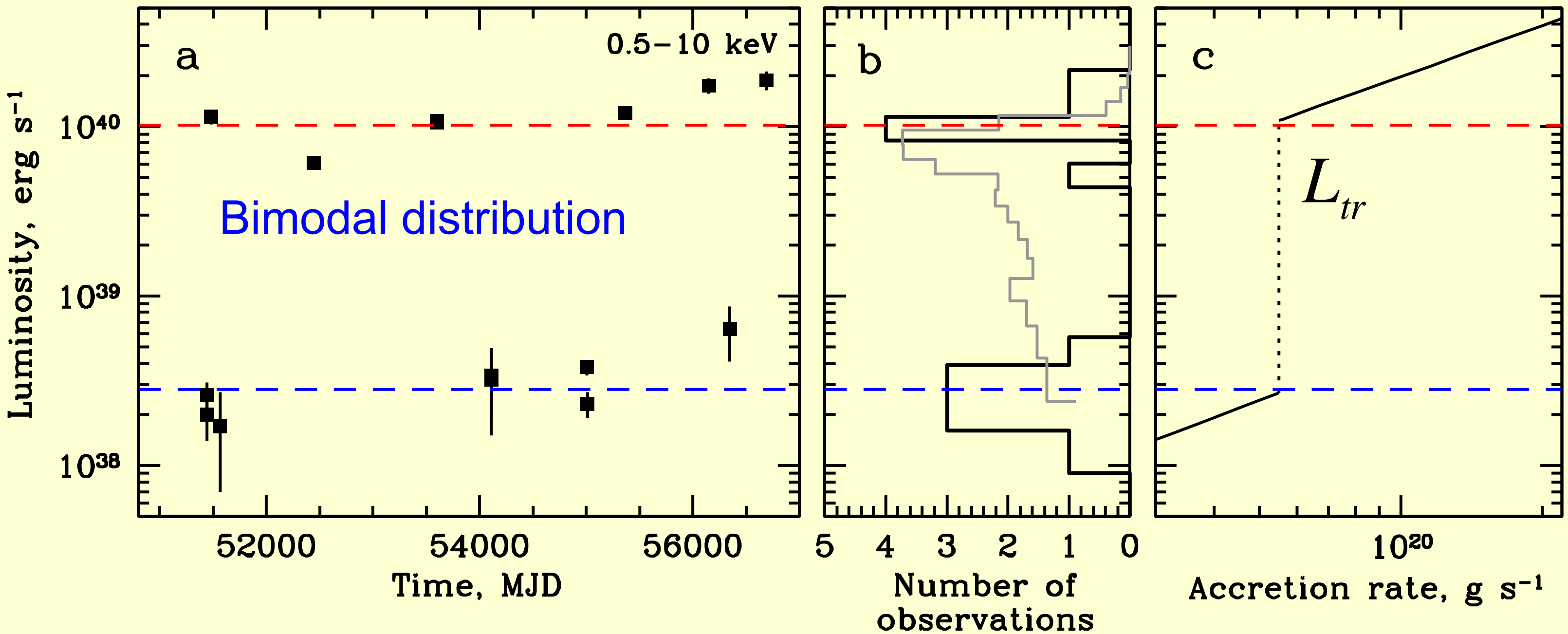


Tsygankov+ 2016

Possible propeller effect in M 82 X-2



Tsygankov et al. 2016



Transitions due to propeller effect at $R_m = R_{CO}$?

Possible propeller effect in M 82 X-2

$$L_{\rm lim}(R) \simeq \frac{GM\dot{M}_{\rm lim}}{R} \simeq 4\times10^{37}\xi^{7/2}B_{12}^{2}P^{-7/3}M_{1.4}^{-2/3}R_{6}^{5}\,{\rm erg~s^{-1}}$$

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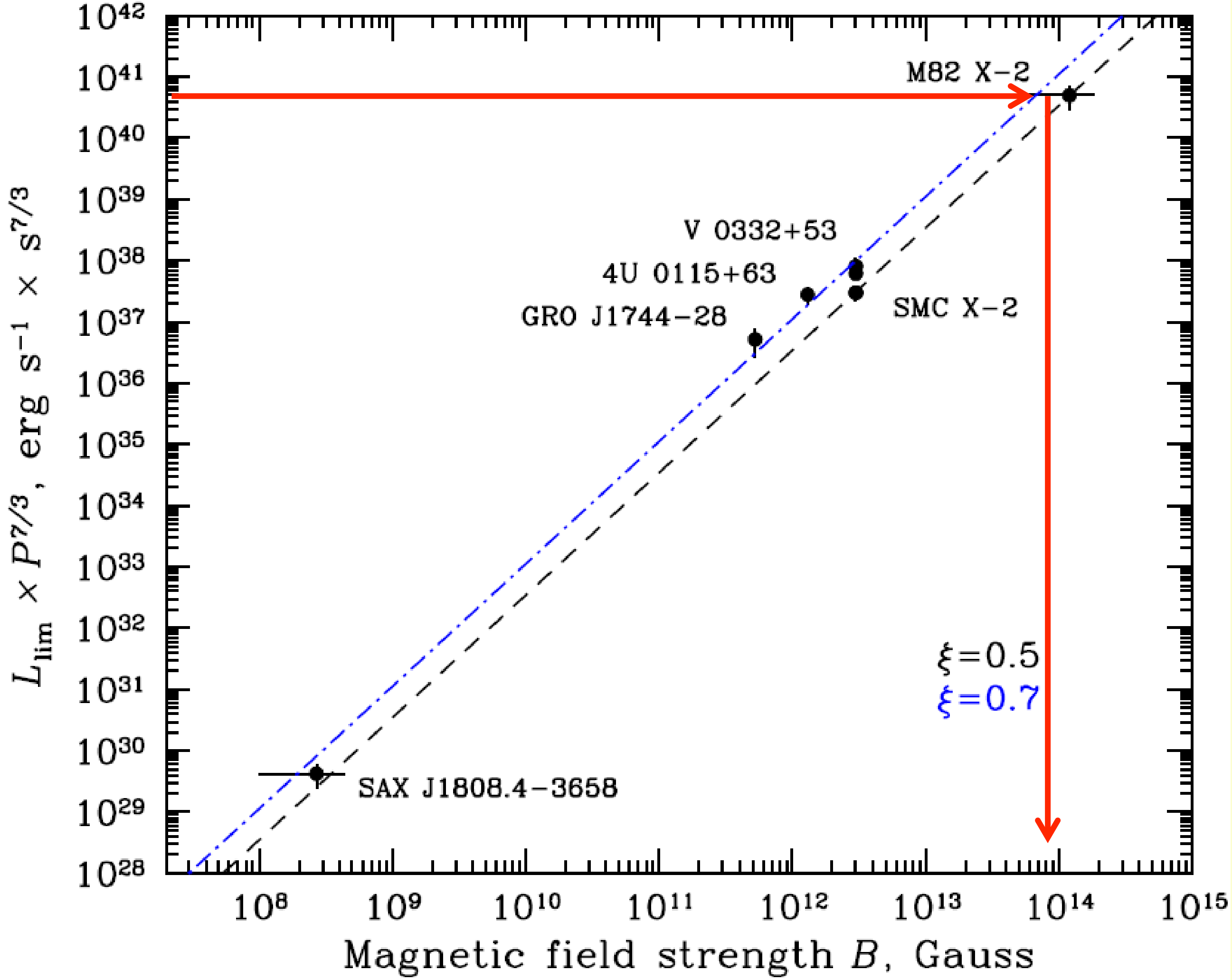


Tsygankov+ 2016

Beaming?

- Arguments against:

1. Photoionized nebulae directly measure total L -> no beaming
2. Beaming -> small inclination -> Number of unbeamed sources might be too large
3. Ordinary X-ray pulsars pass through 10^{39} erg/s without any problems. They are not beamed, likely observed at large inclinations and there is no evidence for winds.
4. Large beaming factor implies that the accretion rate is about Eddington. No winds are expected as $R_m >> R_{NS}$! Beaming is then not possible.
5. Large pulsed fraction (>30%) is not consistent with beaming factors more than 2-3. (Beaming means a lot of reprocessing and scattering, coherent signal will be lost.)

Minimum Mdot

- Maximum spin up torque is $\dot{M}(GMr_{\rm c})^{1/2}$

$$-2\pi I\dot{P}/P^2 \leq \dot{M}(GMr_{\rm c})^{1/2}$$

$$\dot{M} \geq 3.55\times 10^{18}\dot{P}_{-10}P^{-7/3}\,{\rm gs}^{-1}$$

- M82 X-2 $\dot{P} \simeq -2.7\times 10^{-10}\,{\rm ss}^{-1}$ $\dot{M} \geq 4.6\times\ 10^{18}\,{\rm gs}^{-1}$
- NGC 5907 $-9.6\times 10^{-9}\,{\rm ss}^{-1}$ $\dot{M} \geq 1.5\ \times\ 10^{20}\,{\rm gs}^{-1}$

Winds?

- Arguments against:

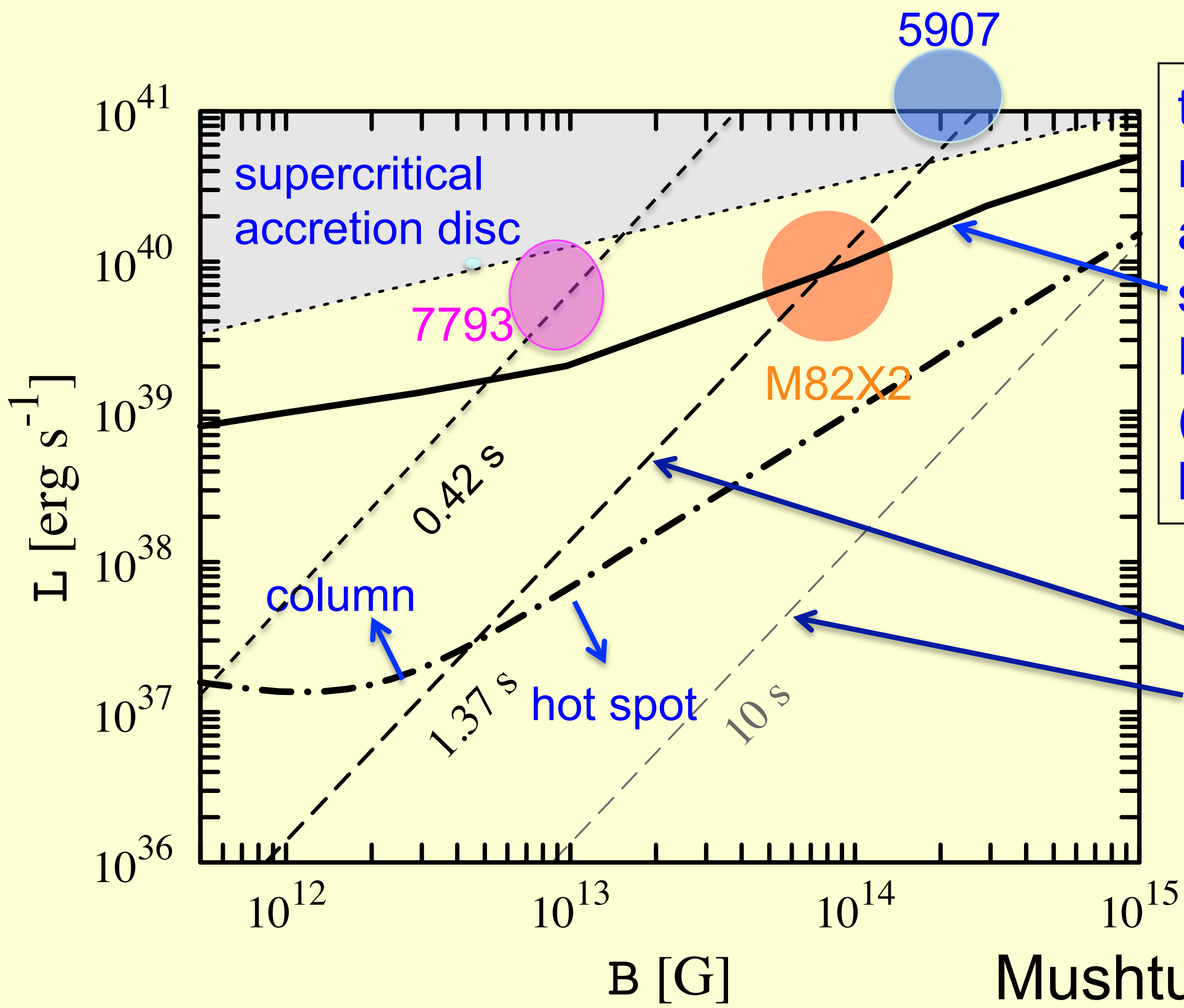
1. Requires huge accretion rate, so that $R_{sph}>R_m$.
2. Accounting for advection makes discs thinner, more difficult to launch the wind.

- Arguments for:

1. May explain large variations in luminosity. Increase of Mdot leads to stronger wind, which blocks the central source (Grebenev 2017).

Large mass loss in a wind still allows large fraction of the initial Mdot to be accreted to the neutron star.

ULX-pulsars: luminosity, B-field



theoretical curve for maximum luminosity of an Eddington supported column by Mushtukov +2015 (apparent can be larger due to beaming)

propeller effect

Mushtukov +2015

None of the lines is a real hard boundary!

Open questions

- Cause of huge variations in luminosity:

  propeller or superorbital (with occultation by wind)?

  Evidence for winds in the low states?

- Strength of the B-field: 10^{12} or $3x10^{13}$ G?

Conclusions

- ULX-pulsars clearly show that neutron stars can exceed Eddington limit by a factor of >100
- Highly super-Eddington luminosities can be reached due to geometric effects, reduced opacity and photon bubbles.
- There is probably no strong beaming involved
- If the sources are close to the equilibrium (as supported by huge luminosity variations), the B-field has to be rather high: $>10^{13}$ G.
- Propeller or winds and precession may play a role in making them strongly variable.