# Young pulsars as ultra-luminous X-ray sources

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Porvoo, Haikko 2012

# Ultra-luminous X-ray sources

Ultra-luminous X-ray sources (ULXs) are non-nuclear, point-like objects with apparent X-ray luminosity exceeding the Eddington limit for a stellar mass black hole (Feng & Soria 2011).

About 500 sources (Swartz et al. 2011; Walton et al. 2011).

There are several hypotheses about the nature of ULXs:

- stellar mass objects with the supercritical regime of accretion and mild beaming with beaming factor $1/b = 4\pi/\Omega \lesssim 10$ (King et al. 2001; Poutanen et al. 2007) ;
- accreting intermediate mass black holes (IMBH) with masses M $\sim 10^3 - 10^5 M_\odot$ (e. g. Colbert & Mushotzky 1999).

It is very likely that the ULX class is not homogeneous, but contains different kind of objects.

Some of the bright, steady ULXs could be young, luminous rotation-powered pulsars.

X-ray luminosity of the pulsars is correlated with the rotation energy losses:

- Seward & Wang 1988; Becker & Truemper 1997 $L = \eta \dot{E}_{\rm rot}$
- Possenti et al. 2002 $L \propto \dot{E}_{\rm rot}^{1.34}$

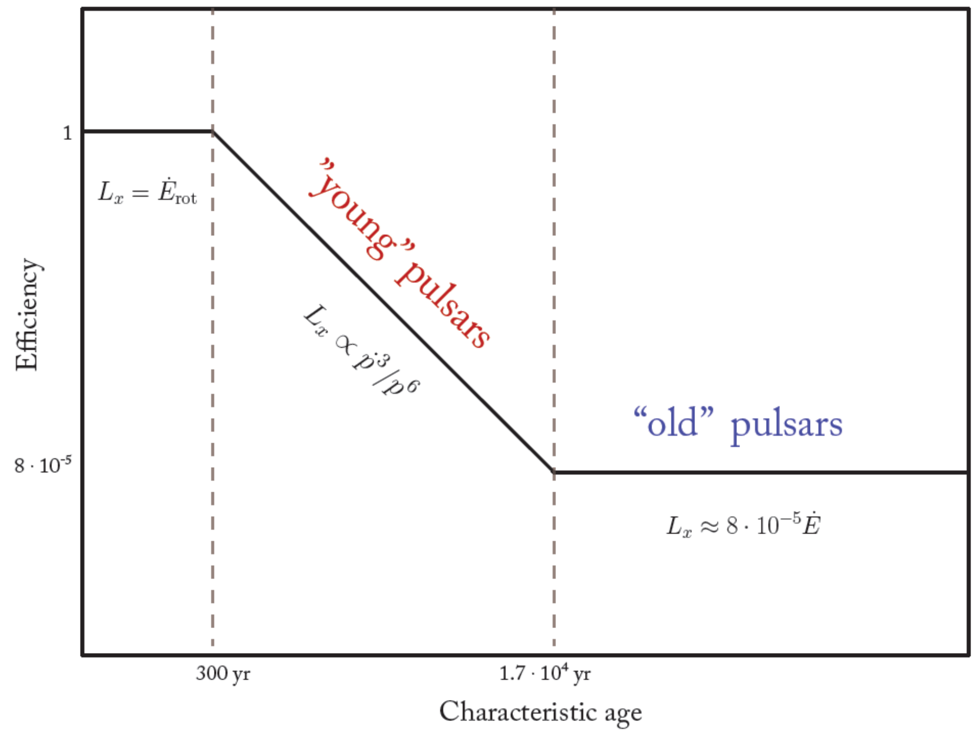
Perna & Stella (2004) first investigated this idea and found that pulsars can be very bright X-ray sources with luminosities L > $10^{39}$ erg $s^{-1}$.

# Efficiency-age dependence

Perna & Stella (2004) used distributions from Arzoumanian et al. (2002) with a very short mean birth period  5 ms.

A recent investigation of the X-ray properties of pulsars (Vink et al. 2011) revealed a more complicated efficiency–age dependence.

Radiative efficiency is not constant for pulsars with age < 1.7 × $10^4$ yr, but depends on the characteristic age.




We want to find a possible fraction of pulsars in the total population of ULX using new observational results.

# The model

Rotational energy losses are dominated by the magnetic dipole radiation:

$$\dot{E}_{\rm rot} = -I\Omega\dot{\Omega} = A\Omega^4 \qquad A = \frac{2R^6}{3c^3}B^2$$

The evolution of the pulsar period and frequency are described by equations

$$p\ \dot{p} = \frac{4\pi^2 A}{I}, \quad \dot{\Omega} = -\frac{A}{I}\Omega^3$$

The time-dependence of the pulsar period is then $p(t) = \sqrt{p_0^2 + 8\pi^2 At/I}$

Relation between luminosity and the period from Vink et al. (2011)

$$\log L \ = \ a + b \ \ \log p + c \ \ \log \dot{p}$$

We assume that the distributions of the magnetic field and birth period of the pulsars are lognormal:

$$f(\log x) \propto e^{-\frac{(\log x - \langle \log x \rangle)^2}{2\sigma_x^2}}$$

Monte-Carlo method: we can generate pulsars with a given birth rate, calculate their luminosity evolution and count a number of pulsars in each luminosity bin.

# The model

The XLF also can be obtained analytically by solving the evolution equation for the distribution function over the period:

$$\frac{\partial N(p)}{\partial t} = -\frac{\partial}{\partial p}\left[\dot{p}N(p)\right] + Q(p)$$

with the source function describing the production of new pulsars per unit period and time is given by

$$Q(p) \propto \dot{N}\ \frac{1}{p} f(\log p)$$

Steady state solution:

$$N(p) = \frac{1}{\dot{p}} \int_0^p Q(p')dp'$$

We can now obtain the XLF in form $N(L) = N(p)\frac{dp}{dL}$

For the power law dependence of luminosity on period v $L = C\ p^{-\alpha}$

For the power law dependence of luminosity on period

$$N(L) = 10^{15} B_{12}^{-2}\ \dot{N}\ \frac{C^{2/\alpha}}{\alpha} L^{-1-2/\alpha} \qquad L\,N(L) = \begin{cases} L^{-0.5} & \text{where } \eta = 1, \\ L^{-0.25} & \text{for “young” pulsars,} \\ L^{-0.51} & \text{for “old” pulsars.} \end{cases}$$

# Magnetic field and birth period distributions

| $\langle \log p_0 \rangle$ | $\sigma_p$ | $\langle \log B \rangle$ | $\sigma_B$ | $\dot{N}^a$ | Reference[b] |
|---|---|---|---|---|---|
| −2.3 | 0.3 | 12.35 | 0.4 | 0.007 | 1 |
| −1.52 | 0.0 | 12.75 | 0.46 | 0.01 | 2 |
| −0.52 | 0.8 | 12.65 | 0.55 | 0.028 | 3 |
| −1.7 | 0.1 | 12.6 | 0.1 | 0.01 | 4 |

[a] Birth rate of pulsars per year.
[b] References: (1) Arzoumanian et al. (2002); (2) Gonthier et al. (2002); (3) Faucher-Giguère & Kaspi (2006); (4) Takata et al. (2011).

We have to know parameters of magnetic field and birth period distributions to calculate the XLF.

Distributions of the pulsars over magnetic field and birth period were investigated in several papers.

Parameters of the birth period distributions have significant difference: the mean period varies from 5 to 200 ms!

# Estimation of birth periods

In order to estimate the period distribution we use a method proposed by Perna et al. (2008): the analysis of the observed luminosity distribution of the historical core-collapse supernovae (SNe)

We use the data on the ages and the X-ray luminosities of core-collapse SNe from Perna et al. (2008), which contains about 100 sources with ages from 0.01 to 80 yr. We also add new measurements from the compilation of Dwarkadas & Gruszko (2012).

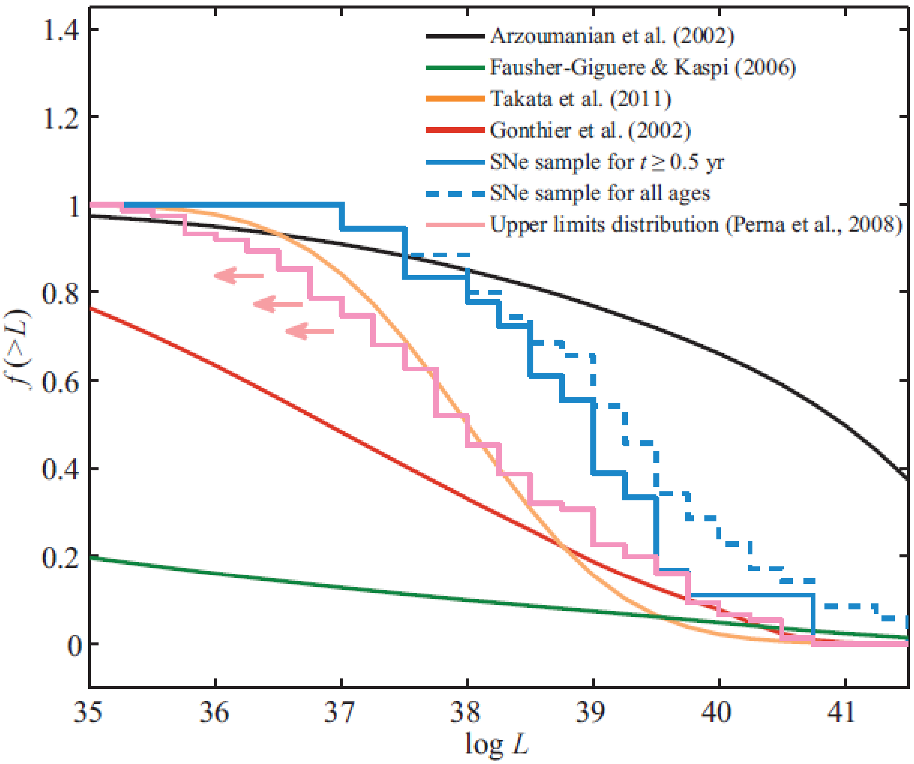
Table 1. X-ray luminosities of historical supernovae.

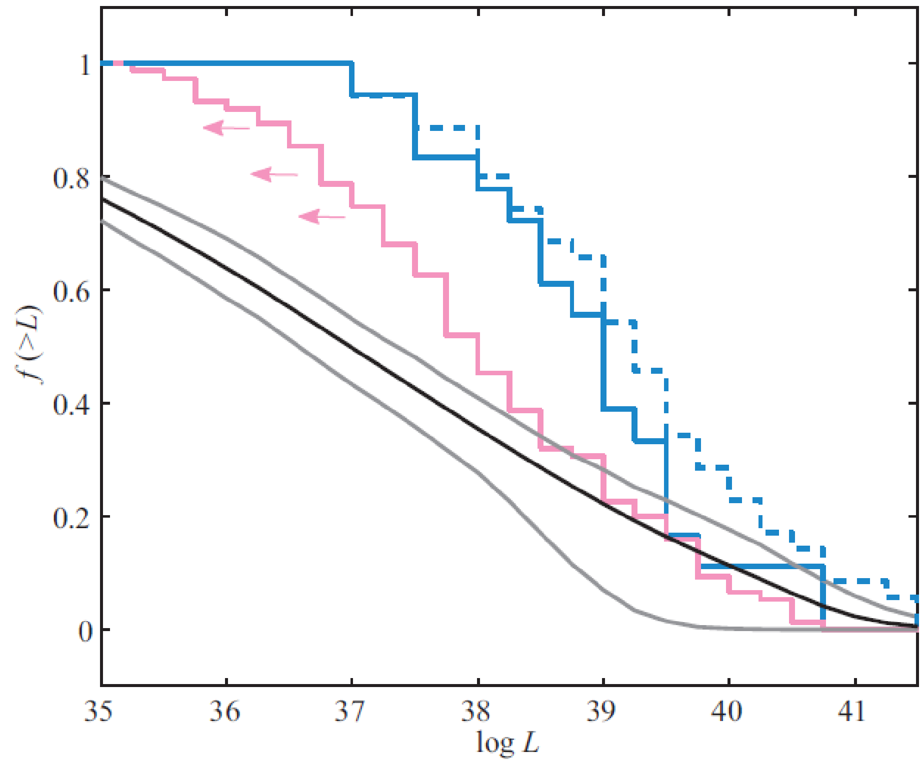
| SN | Age (yr)[a] | $L(\mathrm{erg\,s^{-1}})$ | References[b] |
|---|---|---|---|
| 1979C | 26.8 | $2.7^{+0.4}_{-0.4} \times 10^{38}$ | 1 |
| 1986E | 19.6 | $1.4^{+0.5}_{-0.5} \times 10^{38}$ | 1 |
| 1986J | 21.2 | $8.5^{+0.5}_{-0.5} \times 10^{38}$ | 1 |
| 1988Z | 15.5 | $2.9^{+0.5}_{-0.5} \times 10^{39}$ | 1 |
| 1990U | 10.9 | $1.1^{+0.6}_{-0.5} \times 10^{39}$ | 1 |
| 1994I | 8.2 | $8.0^{+0.3}_{-0.7} \times 10^{36}$ | 1 |
| 1995N | 8.9 | $4.3^{+1.0}_{-1.0} \times 10^{39}$ | 1 |
| 1996cr | 4.2 | $1.9^{+0.4}_{-0.4} \times 10^{39}$ | 1 |
| 1998S | 3.6 | $3.8^{+0.5}_{-0.5} \times 10^{39}$ | 1 |
| 1998bw | 3.5 | $4.0^{+1.0}_{-0.9} \times 10^{38}$ | 1 |
| 1999ec | 5.9 | $3.1^{+0.4}_{-0.4} \times 10^{39}$ | 1 |
| 1999gi | 0.10 | $2.6^{+0.6}_{-0.6} \times 10^{37}$ | 1 |

We split our full sample of SNe onto three sub-samples: SNe with upper limits on luminosity, SNe with known luminosities and with ages t > 0.5 yr (because of fall-back accretion and optical depth of the remnant) and all SNe with known luminosities .

We generate pulsars at the same age as SNe in our samples, taking into account that that 13% of the SNe creates black hole, and calculate a cumulative luminosity distribution which can be compared with the observed distribution.

# Estimation of the birth periods




We freeze the parameters of the magnetic field distribution at log B = 12.6 and $\sigma_B$ = 0.4 (as the average from different papers) and vary only the mean period and its width.

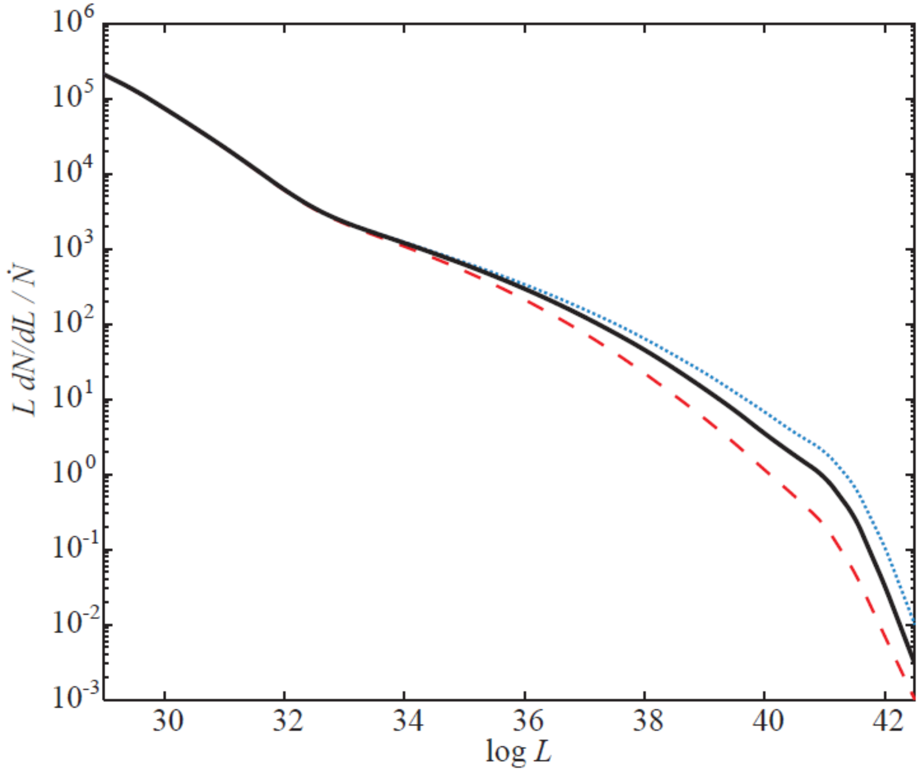
The distribution corresponding to log $p_0 = -1.6$ (25 ms) and $\sigma_p = 0.2$ well describes the data (the fiducial set of parameters).

Also we find the corresponding upper and lower limits for the period: log $p_0 = -1.47$ (34 ms) and $-1.69$ (20 ms).

# Differential X-ray luminosity function

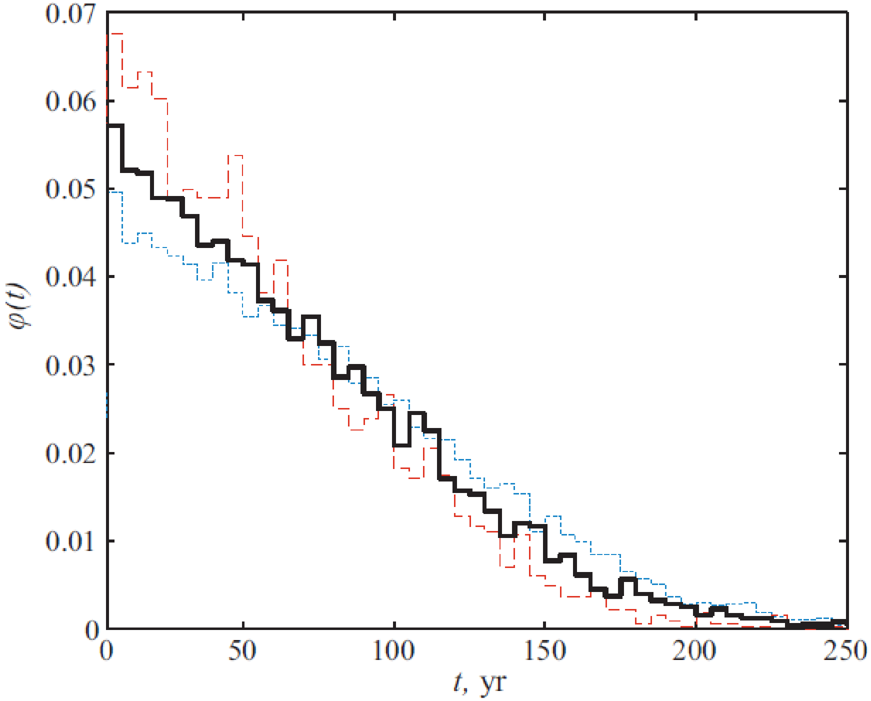
The shape of XLF depends on the adopted magnetic field and birth period distributions. The XLF has a complex shape reflecting the behaviour of the X-ray radiative efficiency.

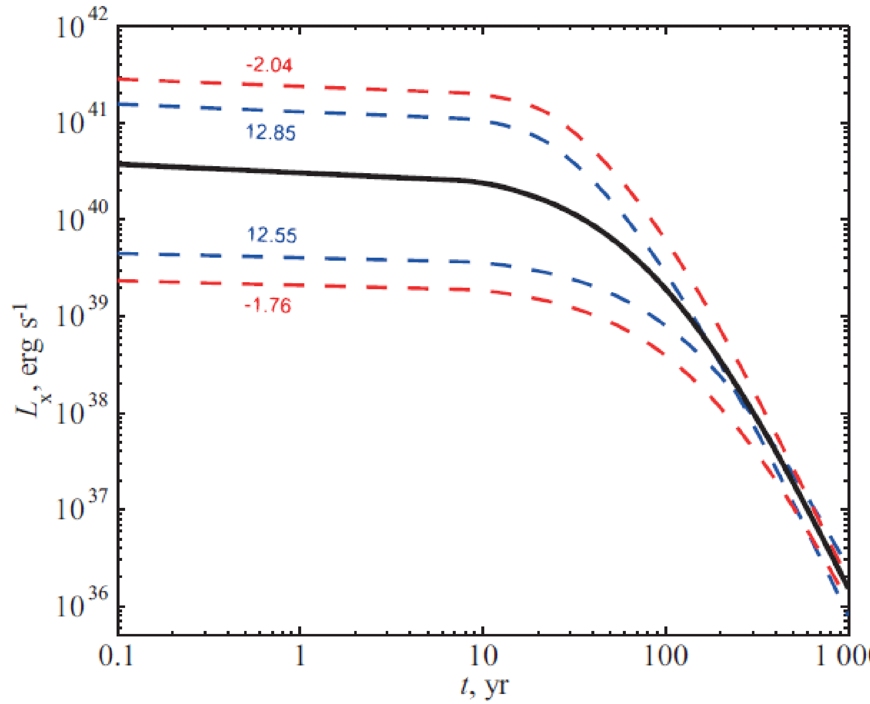
Smaller mean periods and larger magnetic fields lead to a larger initial luminosity and therefore to a larger number of luminous sources.




The presented XLFs have a break at luminosity log L ≈ 41 We thus may expect a presence of very luminous rotation-powered pulsars in a galaxy, if its SFR is high enough.

# Differential X-ray luminosity function




We find a posteriori distribution of pulsars with luminosities $L > 10^{39}$ erg $s^{-1}$

Magnetic fields and birth periods corresponding to the most luminous pulsars have lognormal distributions: log B = 12.7, B = 0.15 and log $p_0 = -1.9$ (12 ms), $\sigma_p = 0.14$. All these pulsars have ages below 200 yr.

# Number of bright pulsars versus SFR

The conversion between the pulsar birth rate and the SFR is based on the rate ≈ 3 pulsars per century in the Milky Way as found by Faucher-Giguere & Kaspi (2006) and we adopt the Galactic SFR of 2 $M_{\odot}$ $yr^{-1}$

$$\dot{N}\,[\mathrm{yr}^{-1}] = 1.4 \times 10^{-2} \times \mathrm{SFR}\,[\mathrm{M}_{\odot}\ \mathrm{yr}^{-1}]$$

Using the XLFs from Fig. 5 we get the number of bright pulsars and find

$$N(\log L > 39) \approx \left(14^{+12}_{-9}\right) \times \dot{N}$$

In order to get the observed number of pulsars, we must introduce the beaming

$$b = 4\pi/\Omega$$

$$N_{\mathrm{obs}}(\log L > 39) \approx \left(14^{+12}_{-9}\right) \times \frac{1}{b} \times \dot{N}$$

We can rewrite this expression in terms of SFR

$$N_{\mathrm{obs}}(\log L > 39) \approx \left(0.016^{+0.013}_{-0.01}\right) \times \frac{4\pi}{b} \times \mathrm{SFR} \gtrsim 0.01\,\mathrm{SFR}.$$

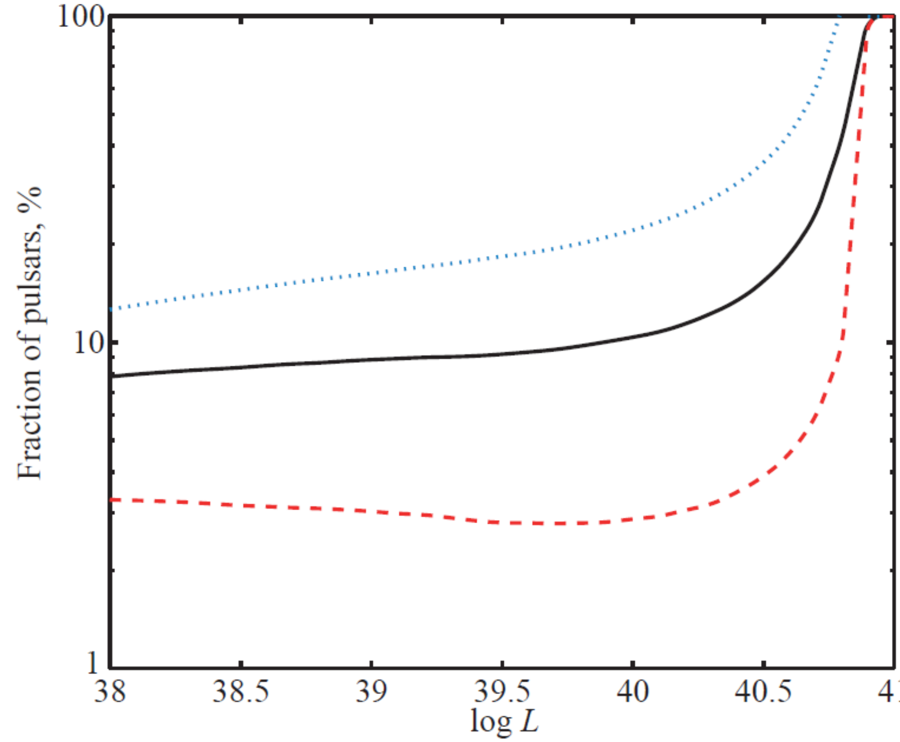
A simple order-of-magnitude estimate for the fraction of bright pulsars can be obtained, Assuming, that ULXs are SS 433-like objects.

$$N_{\mathrm{SS433}} \sim \mathrm{SFR}/(b \times \mathrm{SFR}_{\mathrm{MW}})$$

The fraction of pulsars appears to be about 10 per cent.

# Fraction of the luminous pulsars

Using the luminosity distributions of sources in the nearby galaxies with a variety of star formation rates from $\sim 0.1$ to $\sim 100\ M_{\odot}\ yr^{-1}$, Mineo et al. (2012) have derived the averaged XLF: $N(L) = 1.88\ L_{38}^{-1.58}$ with $L_{cut} = 10^{41}$ erg/s.




We derive cumulative distributions from the XLF of pulsars and the observed XLF from Mineo et al. (2012) and calculate the fraction of pulsar for objects with luminosity greater than L.

We find that the fraction of pulsars in the total XLF should be $\sim 10\%$

# Conclusions

- We have investigated the question whether rotation-powered pulsars could be observed as some subclass of ULXs, and, if this is so, what is the fraction of pulsars in the whole ULX population.

- We estimated parameters of magnetic field and birth spin period distributions. Observed luminosities of the SNe are consistent with the mean birth period of $p_0 \approx 25$ ms. This value is in agreement with the one derived by Takata et al. (2011), Gonthier et al. (2002) and Popov & Turolla (2012).

- XLF has a broken power-law shape, reflecting the complex behaviour of the efficiency. Bright pulsars can be potentially observed as ULXs in galaxies with high SFR.

- Contribution of rotation-powered pulsars and pulsar wind nebulae to the ULX population is at the level of $\sim$10 per cent.