X線連星進化と
中性子星ULX

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～中性子星の観測と理論～研究活性化ワークショップ 2021

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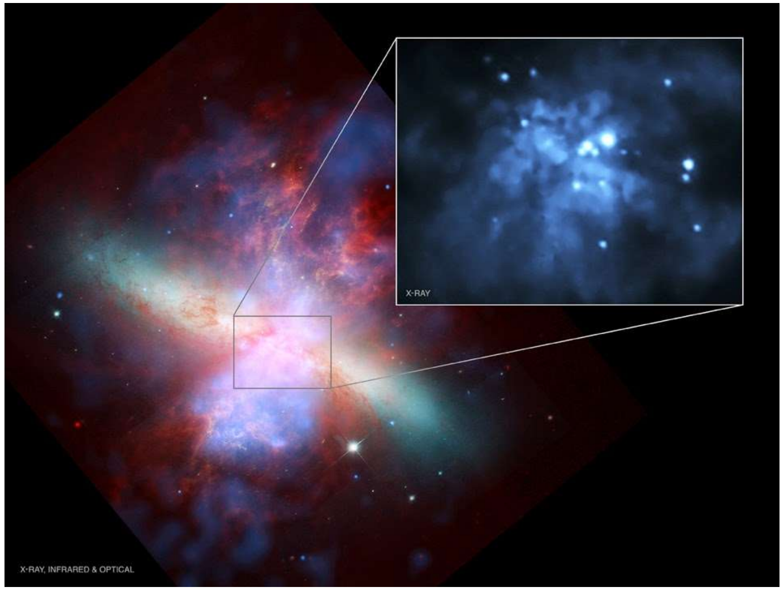
Ultra-Luminous X-ray (ULX) Source

- Super luminous X-ray objects
  - Luminous object over the Eddington luminosity of the stellar mass object (assuming isotropic radiation)
  - ~10^{40}erg/s, typically
  - Out of the centre of the galaxy



(C)NASA/Caltech/SAO/NOAO

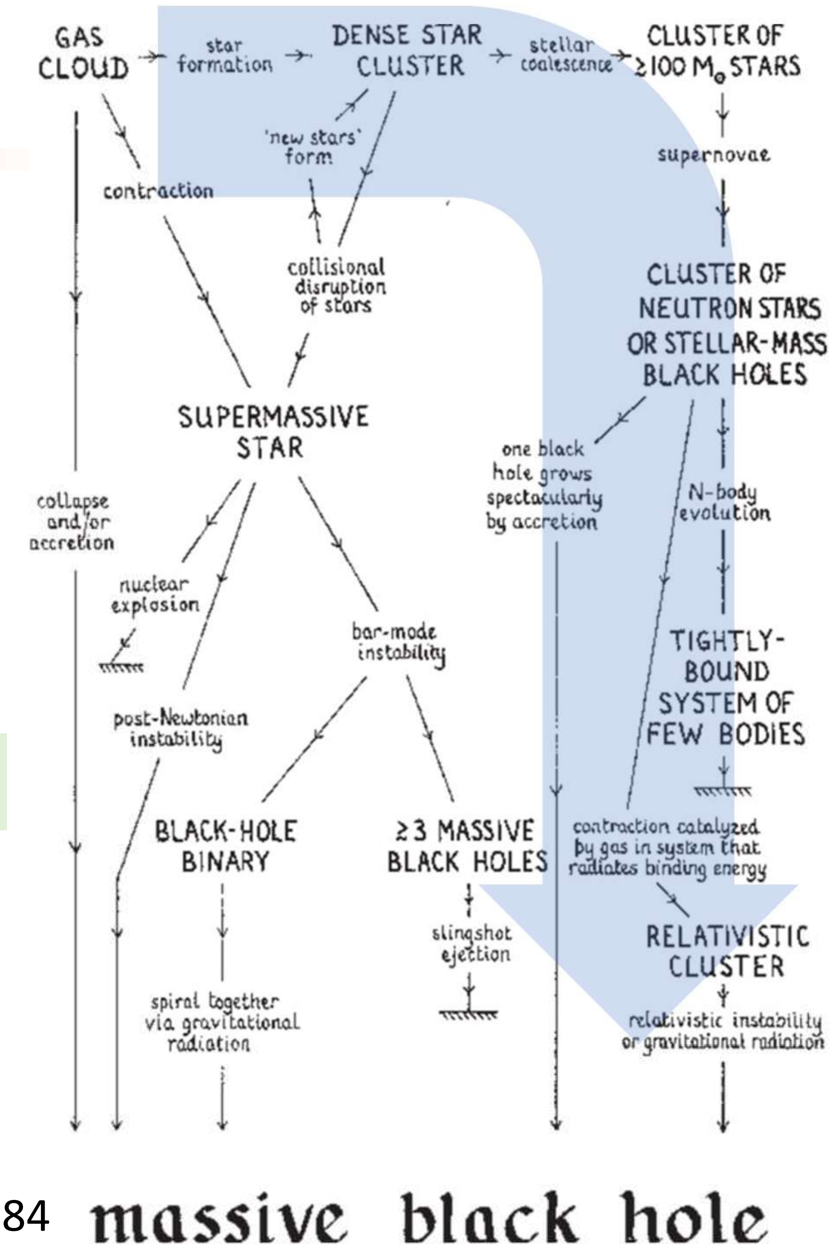
Central object of ULX?

- Intermediate-mass BH!?
  - Missing-link of the bottom-up SMBH formation scenario

Stellar mass BH w super-critical acc.

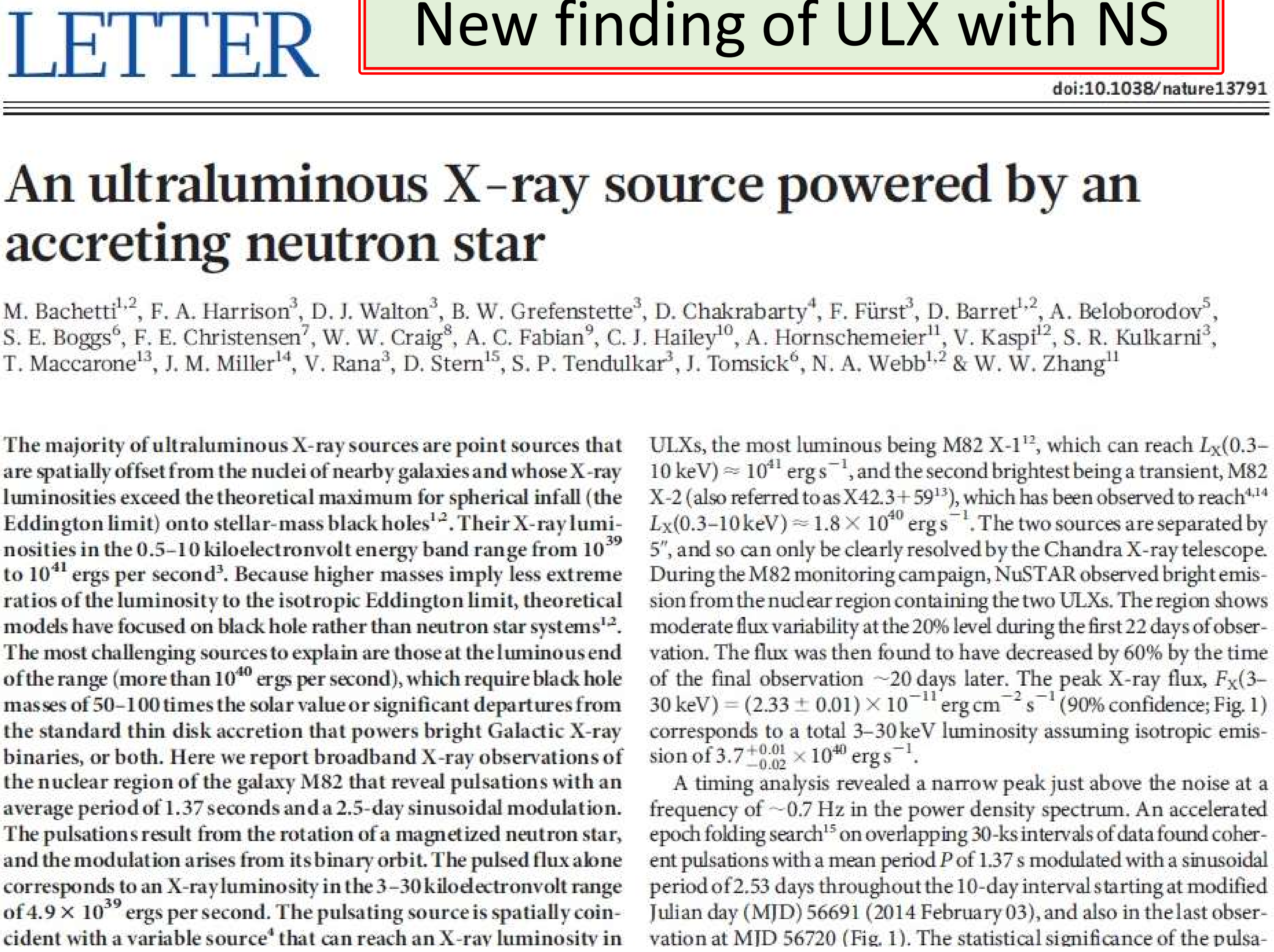
vs

Massive BH w sub-critical acc.



Rees 1984

New finding of ULX with NS



LETTER

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

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The majority of ultraluminous X-ray sources are point sources that are spatially offset from the nuclei of nearby galaxies and whose X-ray luminosities exceed the theoretical maximum for spherical infall (the Eddington limit) onto stellar-mass black holes[1,2]. Their X-ray luminosities in the 0.5–10 kiloelectronvolt energy band range from 10^{39} to 10^{41} ergs per second[3]. Because higher masses imply less extreme ratios of the luminosity to the isotropic Eddington limit, theoretical models have focused on black hole rather than neutron star systems[1,2]. The most challenging sources to explain are those at the luminous end of the range (more than 10^{40} ergs per second), which require black hole masses of 50–100 times the solar value or significant departures from the standard thin disk accretion that powers bright Galactic X-ray binaries, or both. Here we report broadband X-ray observations of the nuclear region of the galaxy M82 that reveal pulsations with an average period of 1.37 seconds and a 2.5-day sinusoidal modulation. The pulsations result from the rotation of a magnetized neutron star, and the modulation arises from its binary orbit. The pulsed flux alone corresponds to an X-ray luminosity in the 3–30 kiloelectronvolt range of 4.9×10^{39} ergs per second. The pulsating source is spatially coincident with a variable source[4] that can reach an X-ray luminosity in

ULXs, the most luminous being M82 X-1[12], which can reach L_X(0.3–10 keV) ≈ 10^{41} erg s^{-1}, and the second brightest being a transient, M82 X-2 (also referred to as X42.3+59[13]), which has been observed to reach[4,14] L_X(0.3–10 keV) ≈ 1.8×10^{40} erg s^{-1}. The two sources are separated by 5″, and so can only be clearly resolved by the Chandra X-ray telescope. During the M82 monitoring campaign, NuSTAR observed bright emission from the nuclear region containing the two ULXs. The region shows moderate flux variability at the 20% level during the first 22 days of observation. The flux was then found to have decreased by 60% by the time of the final observation ~20 days later. The peak X-ray flux, F_X(3–30 keV) = $(2.33 \pm 0.01) \times 10^{-11}$ erg cm^{-2} s^{-1} (90% confidence; Fig. 1) corresponds to a total 3–30 keV luminosity assuming isotropic emission of $3.7^{+0.01}_{-0.02} \times 10^{40}$ erg s^{-1}.

A timing analysis revealed a narrow peak just above the noise at a frequency of ~0.7 Hz in the power density spectrum. An accelerated epoch folding search[15] on overlapping 30-ks intervals of data found coherent pulsations with a mean period P of 1.37 s modulated with a sinusoidal period of 2.53 days throughout the 10-day interval starting at modified Julian day (MJD) 56691 (2014 February 03), and also in the last observation at MJD 56720 (Fig. 1). The statistical significance of the pulsa-

ULX M82 X-2

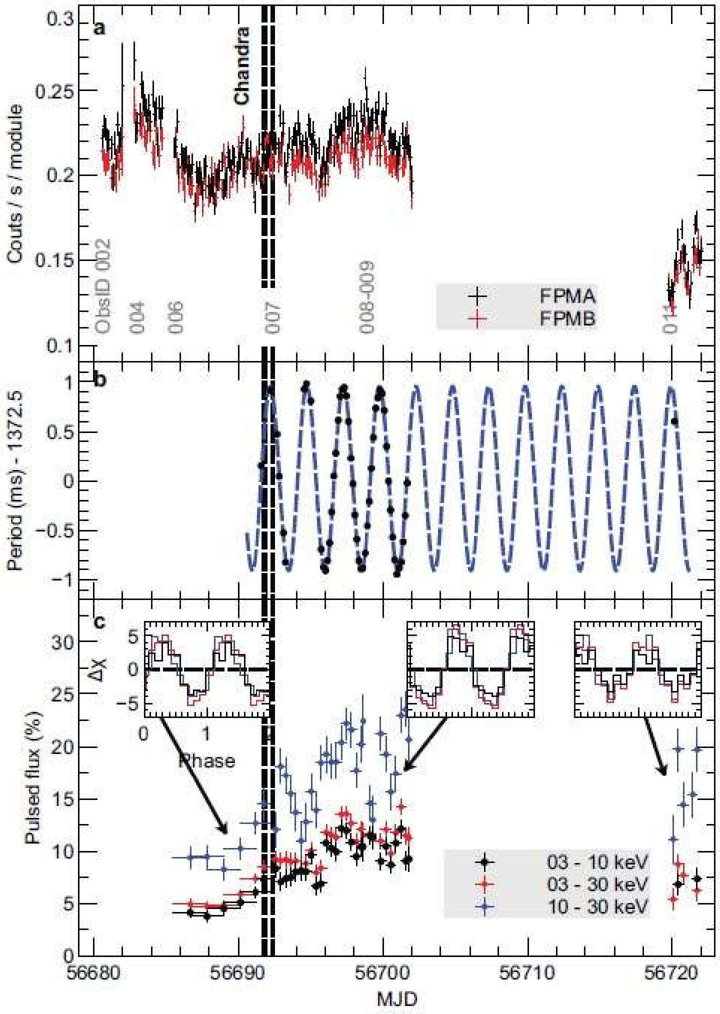


Figure 1 The X-ray lightcurve and pulsations from the region containing NuSTAR J095551+6940.8.

- Periodic X-ray pulsation from ULX M82 X-2 by NUSTAR
  - Bachetti et al. (2014)
- Rotating magnetized NS?

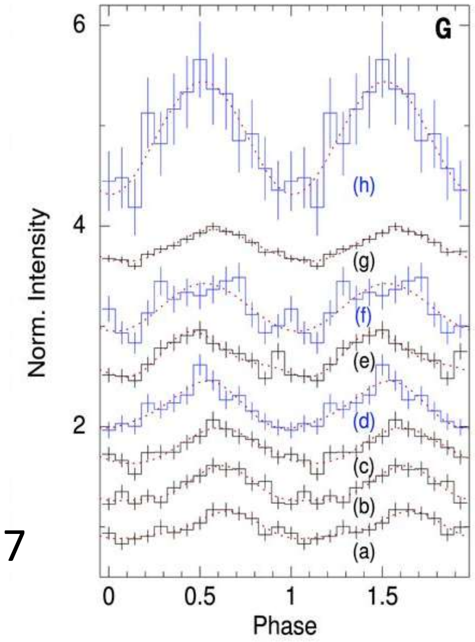
ULX M82 X-2

- Observed properties
  - Pulse period: 1.73s
  - Orbital period: 2.53d
  - Spin-up rate: $-2\times10^{-10}ss^{-1}$
  - Maximum X-ray pulse luminosity: 7×10^{39}erg/s
  - Maximum X-ray luminosity: 4×10^{40}erg/s
  - Orbital eccentricity: <0.02
  - Donor mass: $>5.2M_{sol}$

High-mass X-ray binary system with NS

NS ULXs found one after another

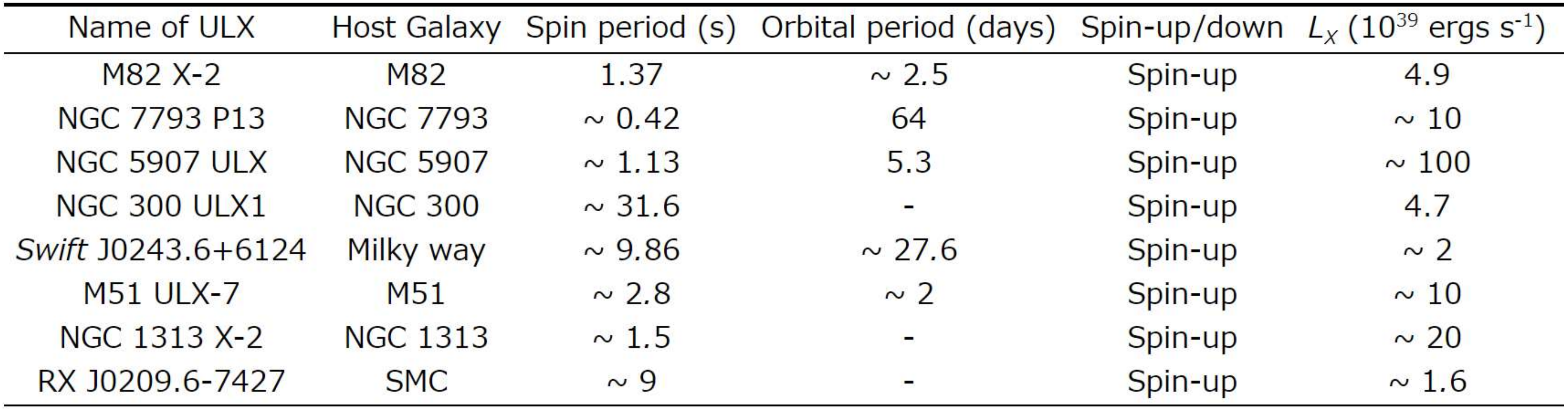
- Once it was discovered, a lot of groups try to detect pulsations from ULXs, and similar objects were discovered one after another
  - NGC7793 P13(Furst++2016)
  - NGC5907 ULX-1(Israel++2017)
  - NGC300 ULX-1(Carpano++2018)
  - …
  - Etc.



Israel++2017

NS ULX pulsar catalogue

- About 10 objects have been found
  - Chandra++ 2020

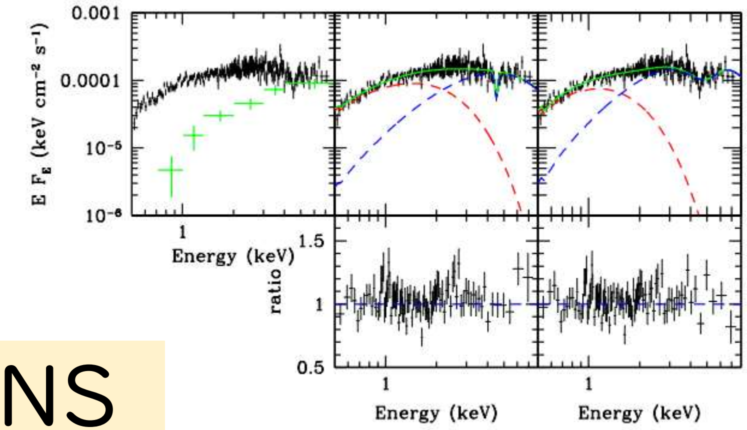


Name of ULX	Host Galaxy	Spin period (s)	Orbital period (days)	Spin-up/down	L_X (10^{39} ergs s^{-1})
M82 X-2	M82	1.37	~ 2.5	Spin-up	4.9
NGC 7793 P13	NGC 7793	~ 0.42	64	Spin-up	~ 10
NGC 5907 ULX	NGC 5907	~ 1.13	5.3	Spin-up	~ 100
NGC 300 ULX1	NGC 300	~ 31.6	-	Spin-up	4.7
Swift J0243.6+6124	Milky way	~ 9.86	~ 27.6	Spin-up	~ 2
M51 ULX-7	M51	~ 2.8	~ 2	Spin-up	~ 10
NGC 1313 X-2	NGC 1313	~ 1.5	-	Spin-up	~ 20
RX J0209.6-7427	SMC	~ 9	-	Spin-up	~ 1.6

  - Some of them are transients

NS ULX without pulsation

- Also, an NS ULX without pulsation has been found
  - M51 ULX-8
  - Most probably, magnetic field around 10^{12}G according to CRSF detection?



Middleton++2019

It seems that ULX with NS origin exists universally

Some issues of NS ULX

- Magnetic field?
- Accretion mechanism?
- Mass transfer process?
- Beaming?
- Population?

Strongly magnetized NS?

- Under the strong field, scattering cross-section significantly decreases
  - High luminosity (10^{40}erg/s) could be achieved
    - Eksi et al. (2014), Dall'Osso et al. (2014)
- Estimation of the field, under the spin equilibrium assumption (M82 X-2)

$$B_{NS} = 2^{-5/12}\pi^{-7/6}\zeta^{1/2}G^{5/6}M_{NS}^{5/6}R_{NS}^{-3}\dot{M}^{1/2}P_{spin}^{7/6}$$

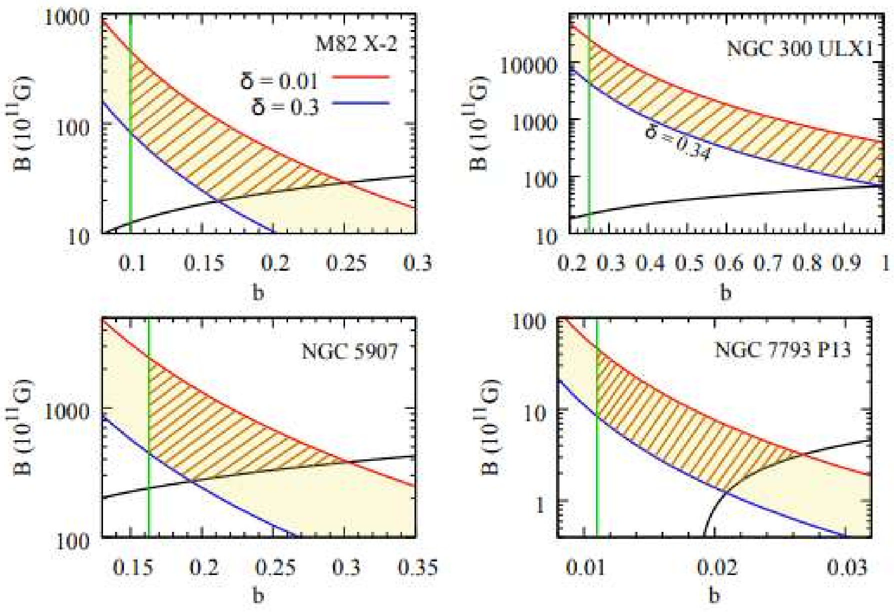
$$= \underline{\underline{4.46\times10^{13}\,G}}$$

$$\times\left(\frac{M_{NS}}{1.4M_{sol}}\right)^{5/6}\left(\frac{R_{NS}}{10\mathrm{km}}\right)^{-3}\left(\frac{P_{spin}}{1.37\mathrm{s}}\right)^{7/6}\left(\frac{\dot{M}}{2\times10^{20}\,\mathrm{g/s}}\right)^{1/2}\zeta^{1/2}$$

– Marginally strong (above quantum limit)

Is the strong field real?

- Rotational equilibrium may be NG✖
- Need to try other estimation method?
  - Spin equilibrium
  - Spin-up rate
  - Propeller effect
  - Critical luminosity etc.



Not necessarily need a magnetar -level strong field.
(but, still under discussions)

Erkut++2020

Accretion process

- Under progress with numerical simulations and theoretical modellings
  - Super-critical acc. may cause strong outflow driven by radiation pressure
  - Acc rate could be high, when magnetic radius and spherization radius are almost the same?
    - King++2017

Takahashi & Ohsuga 2017

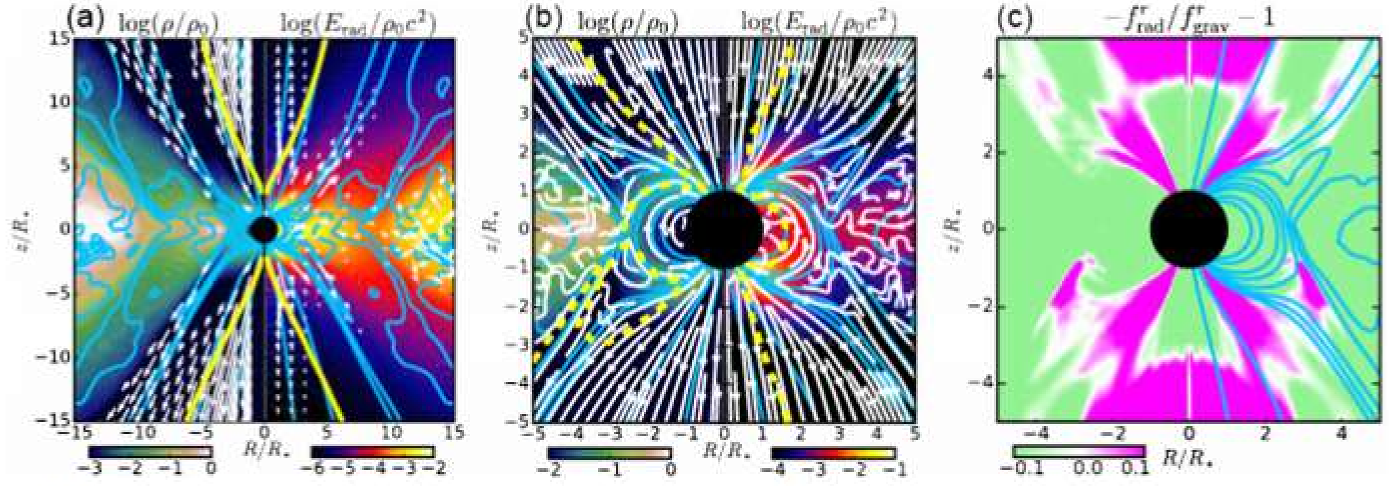


Figure 1. (a) Colors show ρ/ρ_0 (left) and $E_{\rm rad}/\rho_0 c^2$ (right), while vectors show four velocities (left) and radiation flux (right). Blue lines are magnetic field lines, and yellow lines show the photosphere measured from the poles. (b) Enlarged view of Figure 1(a), but the white curves show stream lines of four velocities (left) and radiation flux (right). The yellow dashed curves show $\beta = 1$ (left) and $\sigma = 1$ (right). (c) Colors show $-f^r_{\rm rad}/f^r_{\rm grav} - 1$.

Beaming

- If the beaming works efficiently, mass acc rate (intringic luminosity) could be smaller

$$L_{spherical} = \frac{1}{b} L$$

$$b \sim \left(\dot{M} / \dot{M}_{Edd} \right)^{-2}$$

King 2009

- Recent studies suggest moderate beaming?
    - Analysis from pulse-fruction and pulse-profile
        - Mushtukov++ 2020
    - Mass accretion rate could be really high?

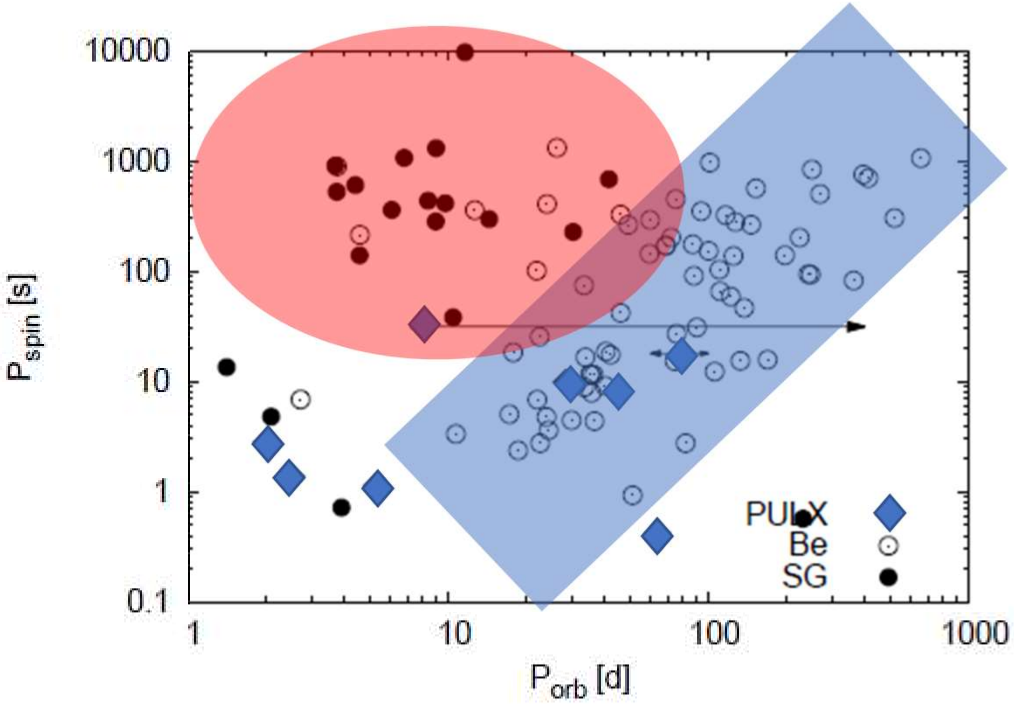
Population

- How much ULXs are NS origin?
  - How many IMBHs?
    - Some of ULXs are almost confirmed to be IMBH
- X-ray object in most of ULXs are unknown
  - Difficult to know from their spectra?

- ULXs can be observed even in far galaxies, since they are highly luminous
  - Can be used to estimate BH／NS ratio and to know star formation history in galaxies

Corbet diagram

- Orbital period vs spin period of NS in HMSBs
  - Corbet (1984)



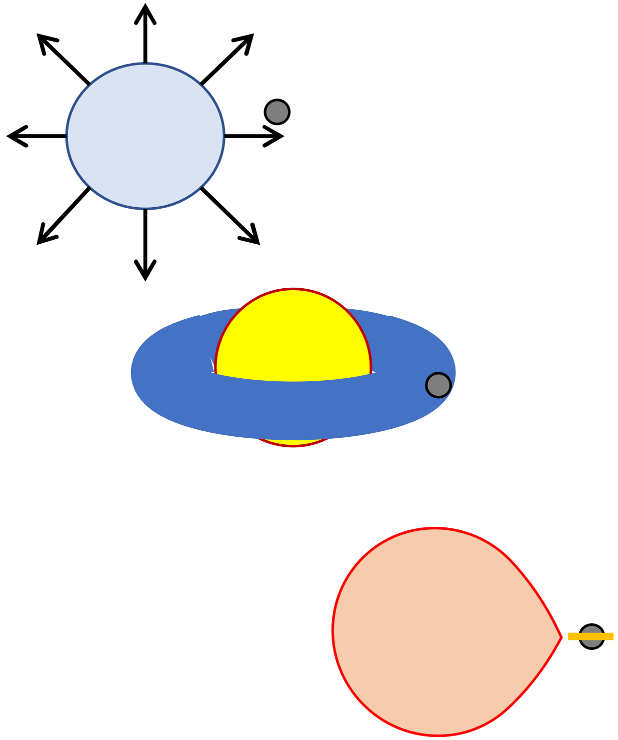
OB-type:
wind accretion

Be-type:
Accretion from
Be-disk

Mass transfer mode in NS ULX systems as HMXBs

$$\dot{M} = \frac{L_X R_{NS}}{G M_{NS}} = \boxed{2.0\times 10^{20}\,\mathrm{g/s}}$$

- How to realize high mass accretion rate: 2×10^{20}g/s
- MT mode in HMXBs
  - Wind accretion (OB-type)
    - <20%
  - Disk wind accretion (Be-type)
    - >80%
  - RLOF (OB/SG-type)
    - A few



BHL acc from donor wind?

- Stellar wind from massive stars
  - Line-accerelated wind (CAK process)

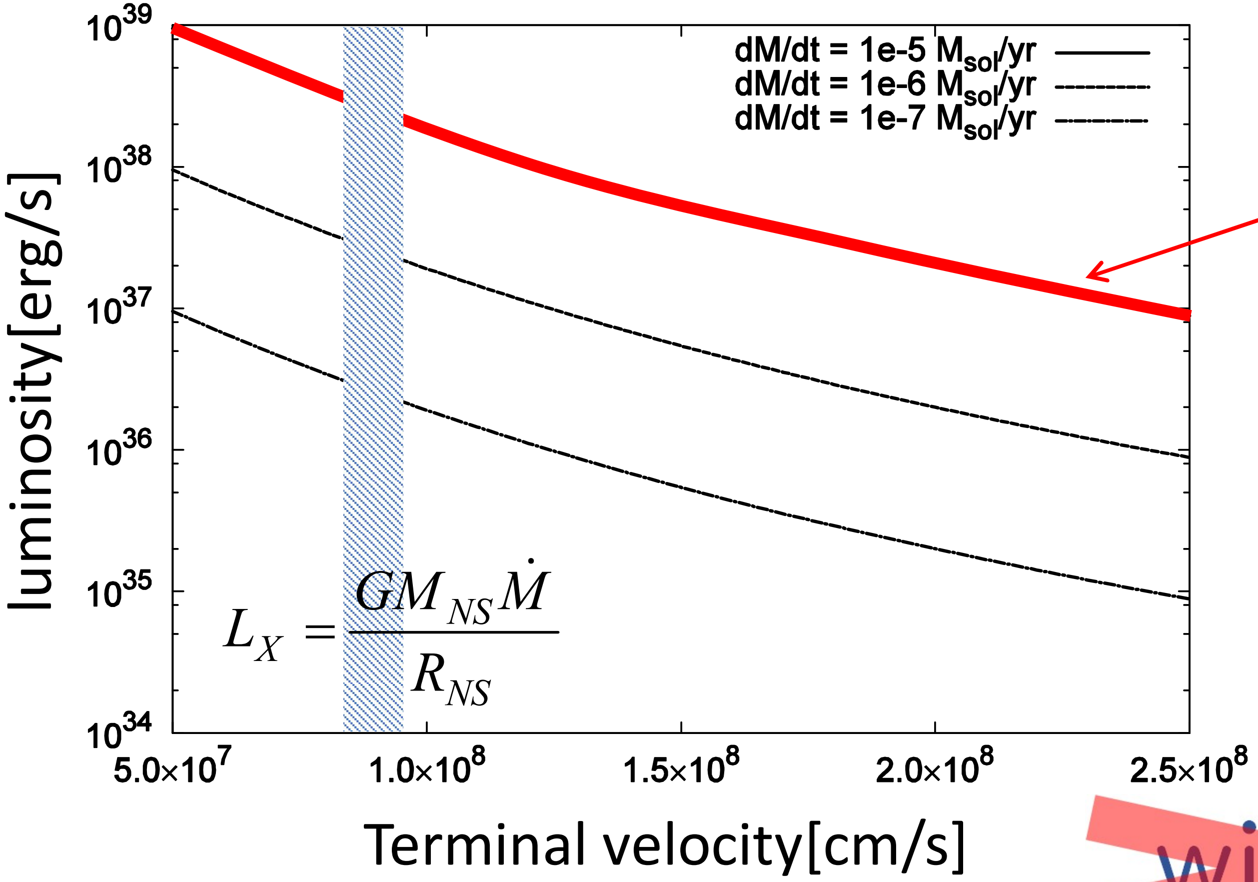
$$v_w(r) = v_\infty \left(1 - \frac{R_1}{r}\right)^\beta \qquad \rho_w(r) = \frac{\dot{M}_w}{4\pi r^2 v_w}$$

  - β is assumed to be 1
  - v_∞ is the terminal velocity ~1000km/s
- Consider BHL accretion
  - Mass acc rate

$$\dot{M} = \rho_w v_{rel} \pi R_{acc}^2$$

Possibility of the wind acc?

- No: BHL process cannot achieve $>10^{39}$erg/s



$$L_X = \frac{GM_{NS}\dot{M}}{R_{NS}}$$

Highest mass-loss rate of O-type stars observed in our Galaxy

~~wind acc.~~

Possibility of RLOF acc?

- Low mass donor
  - RLOF starts after HG phase
  - Suffer from Darwin instability and lose orbital stability
    - Darwin (1879)

- High mass donor
  - RLOF starts during MS phase
  - Donor expands in short time scale

Observable system has intermediate mass donor（10～20Msol）?

Possibility of RLOF acc?

- Mass acc. rate depends on the evolution stage of the donor
  - MS donor(radiative envelope)
    - Mass transfer proceeds in thermal time

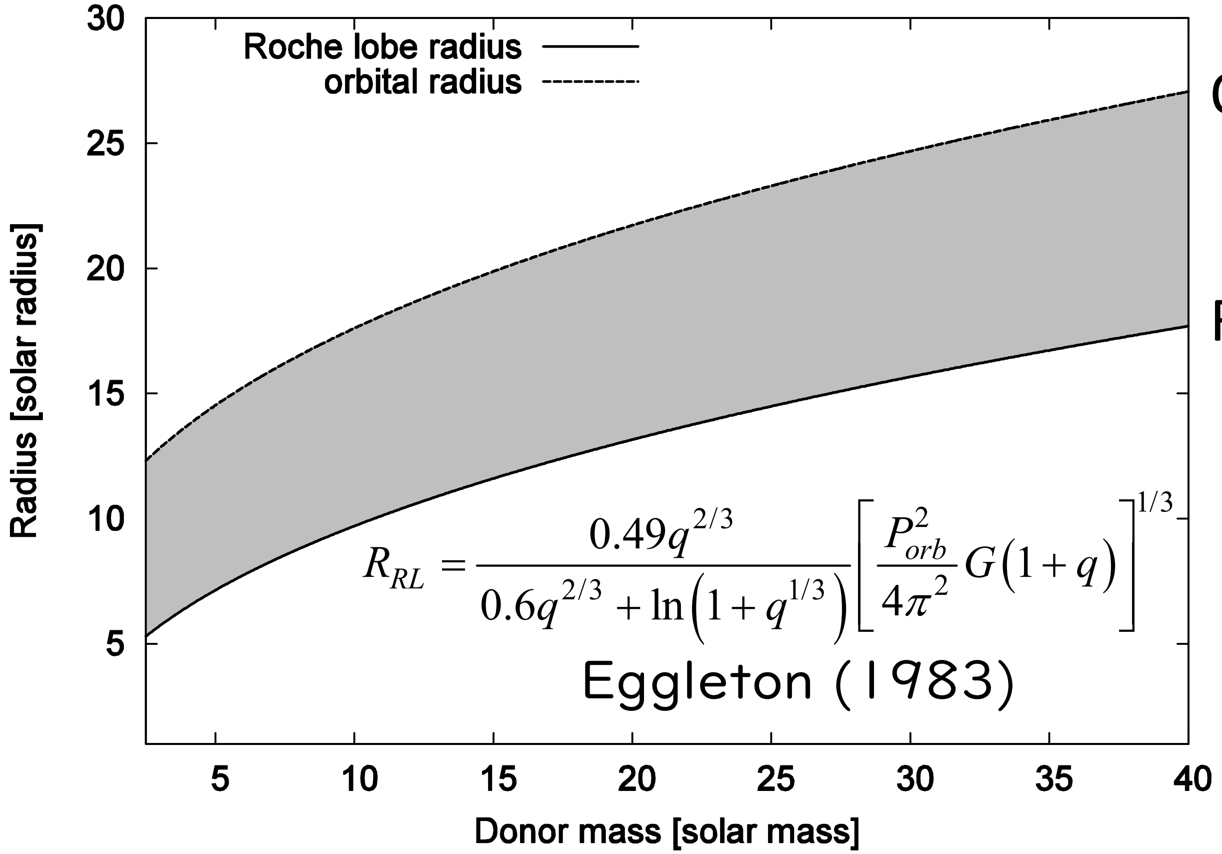
$$\tau_{th} \simeq \frac{GM_1^2}{R_1 L_1} \sim 10^6\,\mathrm{yr} \Rightarrow \dot{M} \simeq 10^{-5} M_{sol}/\mathrm{yr}$$

$$\Rightarrow L \simeq 10^{40}\,\mathrm{erg/s}$$

  - ~~Ginant donor(convective envelop)~~
    - ~~Mass transfer proceeds in dynamical time~~
    - ~~CE forms rapidly~~

RLOF condition

- Donor radius is larger than Roche radius
- Donor radius is smaller than orbital radius



$$R_{RL} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln\left(1 + q^{1/3}\right)} \left[\frac{P_{orb}^2}{4\pi^2} G\left(1 + q\right) \right]^{1/3}$$

Eggleton (1983)

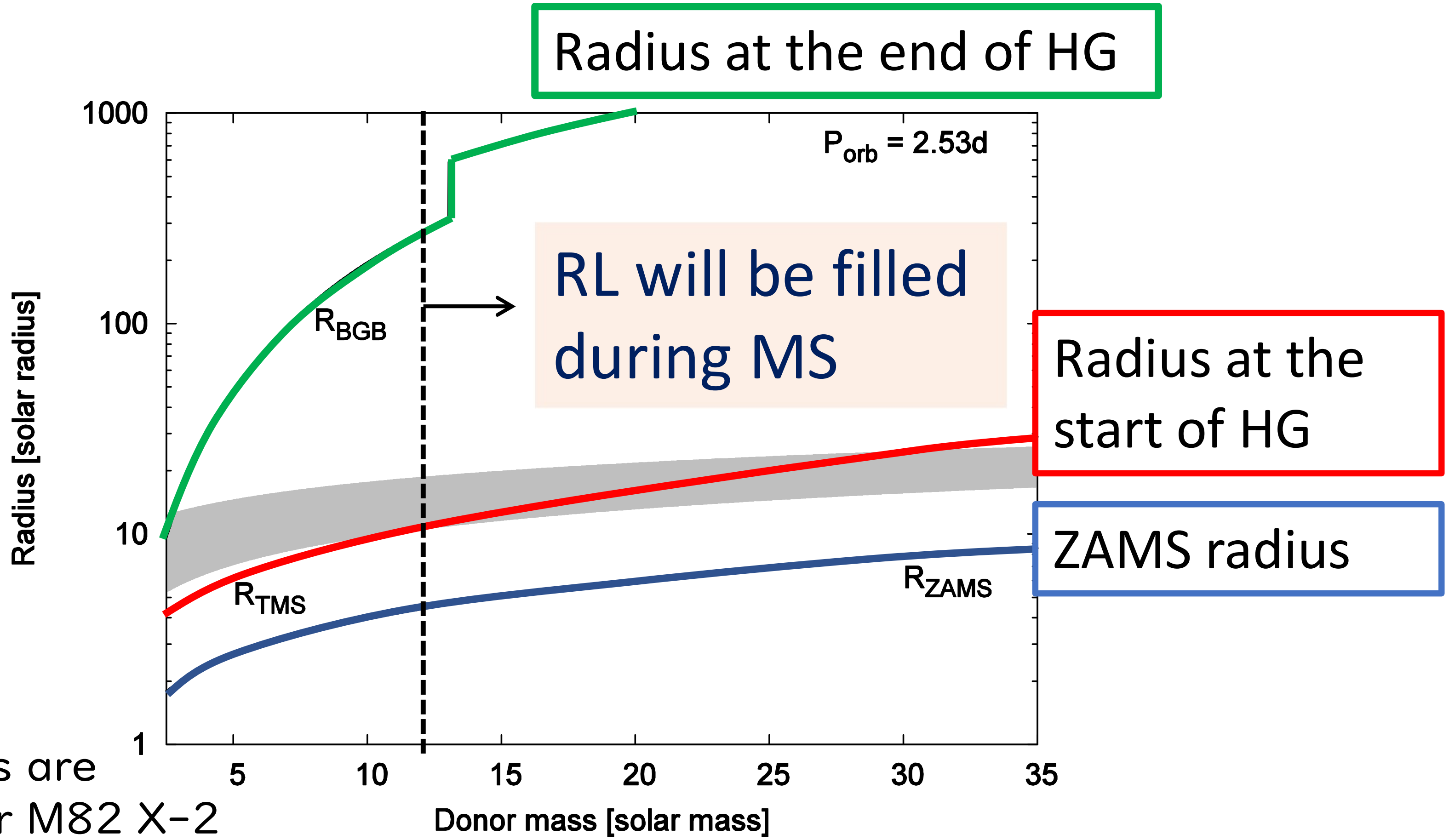
Orbital radius (e=0)

Roche radius

$M_{NS} = 1.4 M_{sol}$
$P_{orb} = 2.53\mathrm{d}$
$e = 0.0$

Evolution of donor

- Donor mass could be restricted from orbital parameters
  - Karino & Miller (2016)



Radius at the end of HG

RL will be filled during MS

Radius at the start of HG

ZAMS radius

Parameters are suitable for M82 X-2

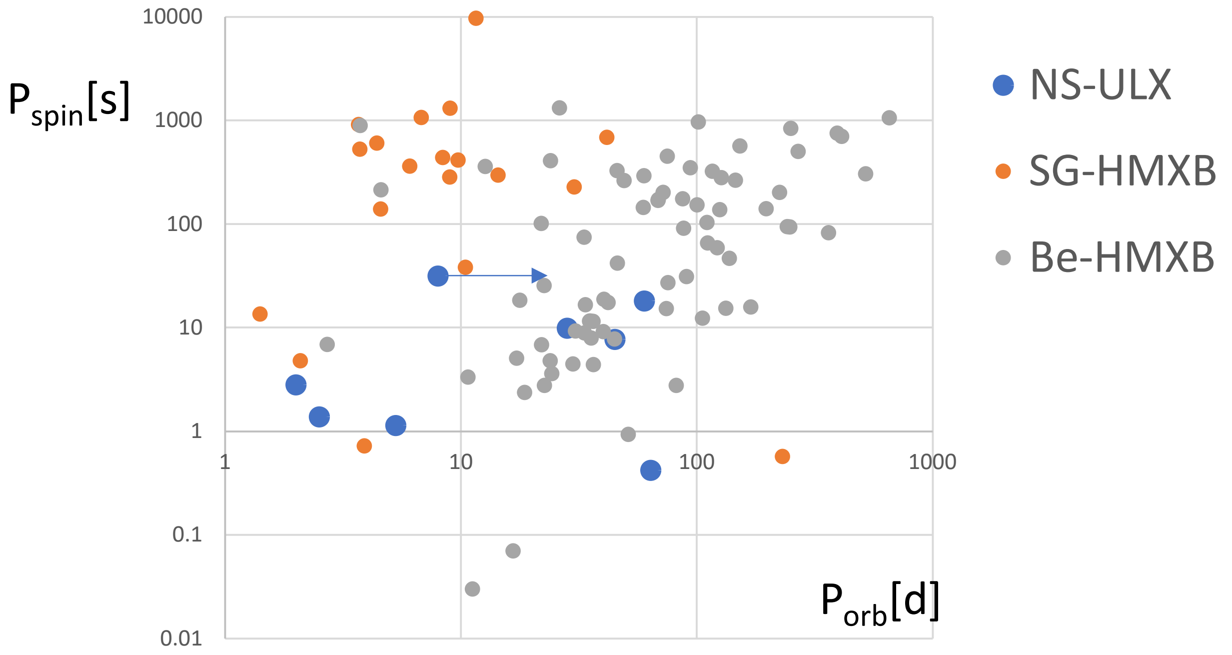
Possiblity of RLOF?

- Donor should be moderately massive
  - For M82 X-2, donor mass should be larger than $12M_{sol}$
    - If less than this mass, the life-time will be very short
  - If donor is too heavy, observable time scale becomes very short
- From orbital parameters, the donor mass could be estimated
  - Important information for population synthesis

BeHMXBs as ULXs

- Some of NS ULXs have Be donor
  - In the Corbet diagram, some NS ULXs locate the same region with BeHMXBs

Under what conditions does BeHMXB become a ULX?



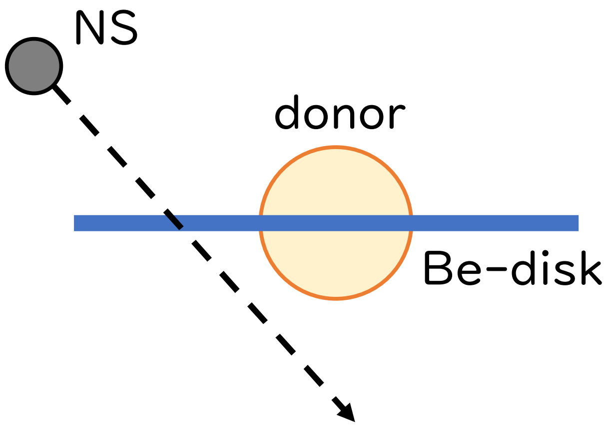
Conditions to be a ULX

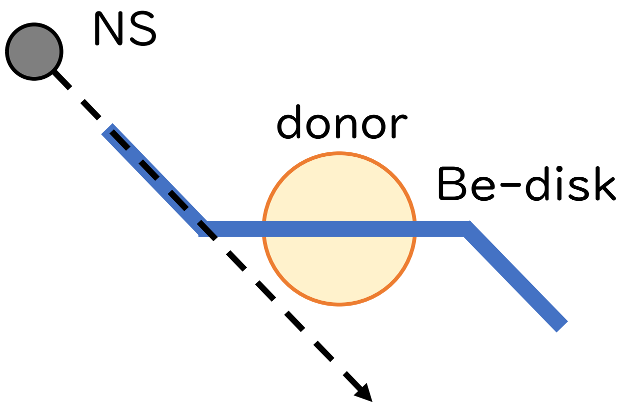
- Mass transfer rate from Be-disk to NS should be larger than Eddington rate
  - Consider the conditions of giant (typeII) bursts of BeHMXB (Okazaki++2013)
    - BHL accretion from warped Be-disk

- Transferred matter should accrete on NS with super-Eddington rate
  - Accretion disk will be a slim-disk
  - Acc matter will be captured by NS dipole field before lost due to strong out-flow (King++2017)

Warped Be-disk

- Warped disk is needed for large MT rate
  - Disk is warped due to NS tidal effect





MT rate from the Be-disk

- Warping condition of Be-disk

$$r_{\rm warp} < r_{\rm tr}$$

truncation radius of disk should be smaller than warping radius

$$r_{\rm tr} = 0.5a\left(1-e\right)$$

$$r_{\rm warp} = 4.9\times10^{11}\left(1-e^2\right)^{3/4}\alpha_2^{1/2}h\left(\frac{P_{orb}}{1d}\right)$$

$$\times\left(\frac{M_D}{M_\odot}\right)^{1/2}\left(\frac{M_{NS}}{M_\odot}\right)^{1/2}\left(\frac{M_D+M_{NS}}{M_\odot}\right)^{1/2}\left(\frac{R_D}{R_\odot}\right)^{-1/2}\ [\mathrm{cm}]$$

Cf: Paczynski 1979, Martin++2011

MT rate from Be-disk

- BHL accretion from Be-disk

$$\dot{M}_{\mathrm{T}} = \min\left(1, \frac{r_{\mathrm{RL}}}{r_{\mathrm{acc}}}\right) \times \dot{M}_{\mathrm{BHL}} > (\text{a few})\dot{M}_{\mathrm{Edd}}$$

$$\dot{M}_{\mathrm{BHL}} = \rho v_{\mathrm{rel}} \pi r_{\mathrm{acc}}^2$$

$$\rho = \rho_0 \left(D / R_d\right)^{-7/2}$$

$$r_{\mathrm{acc}} = \frac{2GM_{\mathrm{NS}}}{v_{\mathrm{rel}}^2}$$

$$v_{\mathrm{rel}} = v_{\mathrm{orb}}^2 + v_{\mathrm{Kep}}^2 - 2v_{\mathrm{orb}} v_{\mathrm{Kep}} \cos\delta$$

Bondi-Hoyle-Littleton theory

Cf:
Edgar 2004,
Okazaki++2013

Accretion rate onto NS

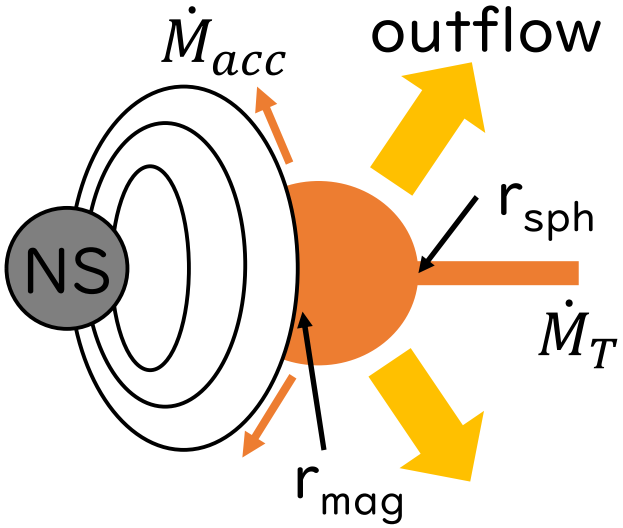
- Consider mass loss due to out-flow

$$\dot{M}_{\mathrm{acc}} = \frac{r_{\mathrm{mag}}}{r_{\mathrm{sph}}} \dot{M}_{\mathrm{T}} > \dot{M}_{\mathrm{Edd}}$$

$$r_{\mathrm{sph}} = \frac{27}{4} \frac{\dot{M}_{\mathrm{T}}}{\dot{M}_{\mathrm{Edd}}} \frac{GM_{\mathrm{NS}}}{c^2}$$

$$r_{\mathrm{mag}} = \left(\frac{\mu_{30}^4}{8k^2 GM_{\mathrm{NS}} \dot{M}_{\mathrm{acc}}^2} \right)^{1/7}$$

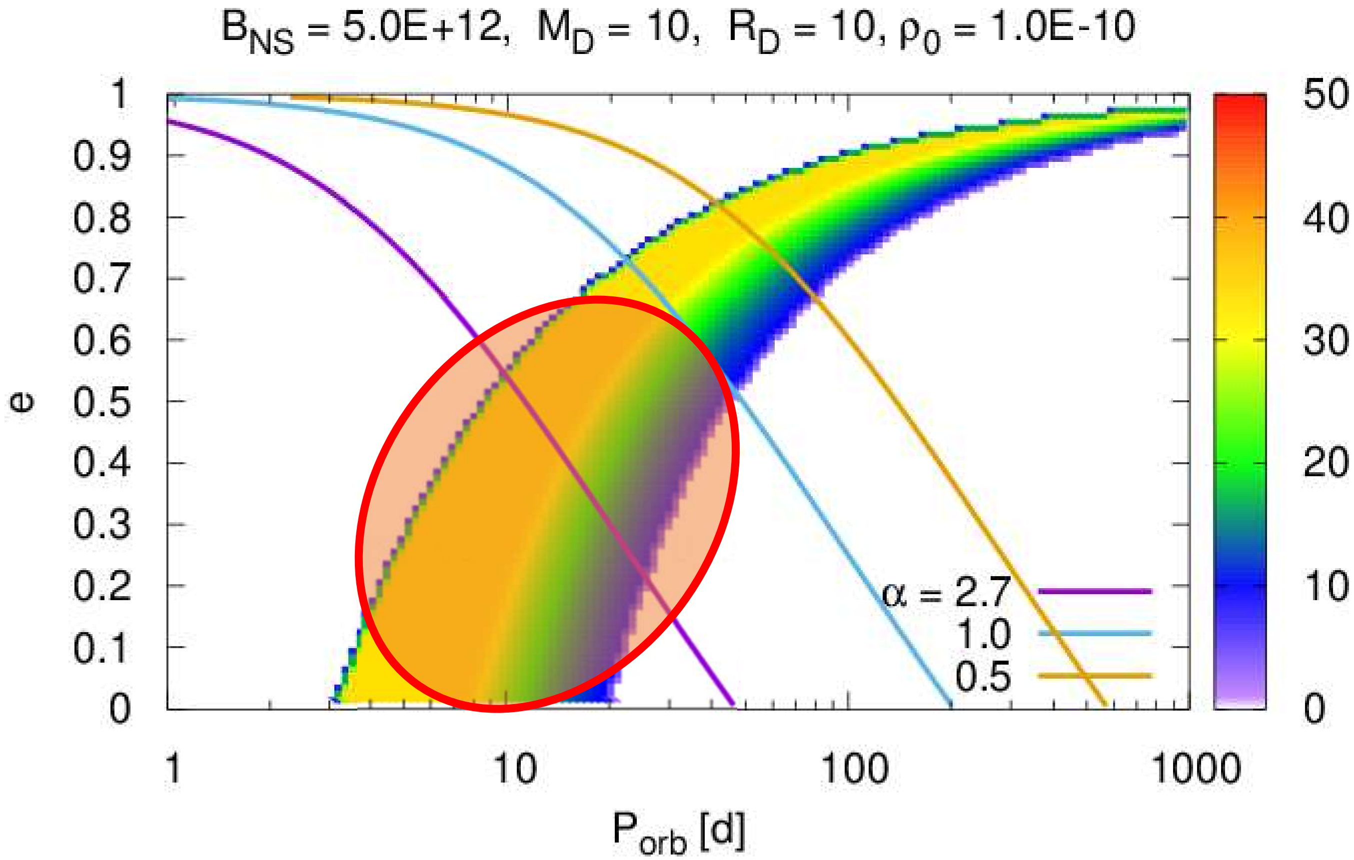
Mass accretion rate must still exceed Eddington rate even with outflow losses



Cf: King++2017, 2019

ULX region for BeHMXB

- On the orbital period-eccentricity plane
  - Curves indicate warped disk conditions

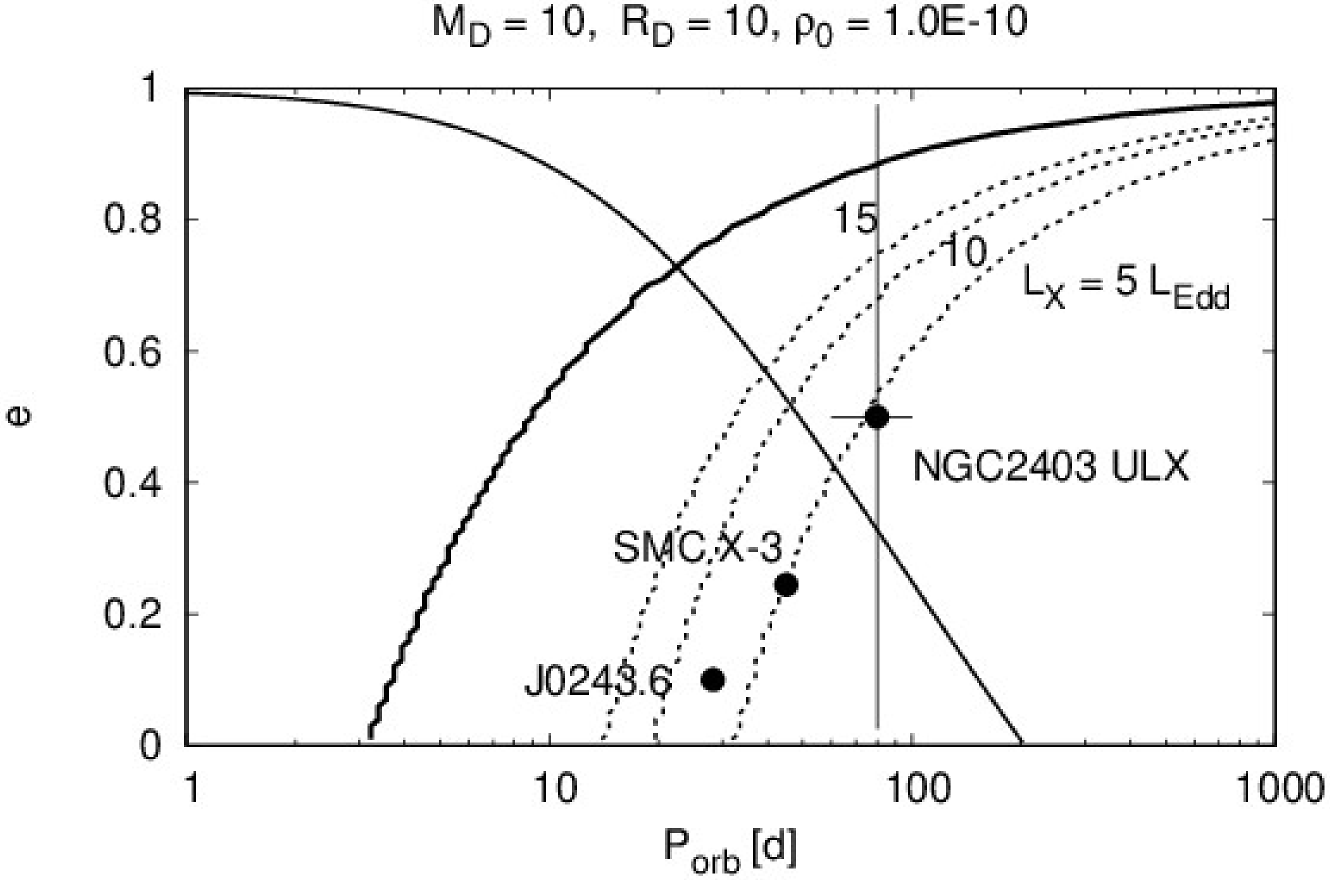


$$\frac{L_X}{L_{Edd}} = \frac{\dot{M}_{acc}}{\dot{M}_{Edd}}$$

Comparison to observations

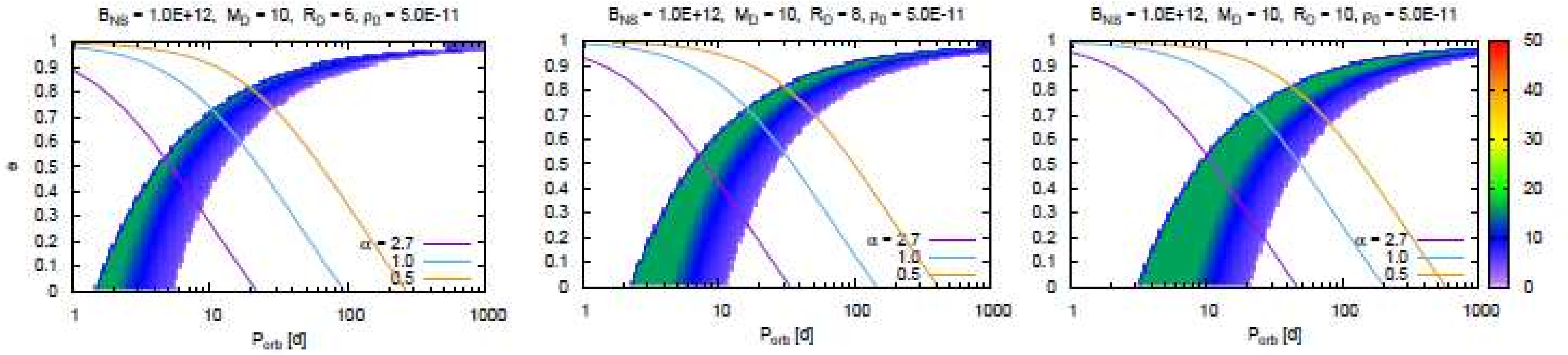
- Considering beaming, OK

$$L_{\mathrm{obs}} = \frac{L_{\mathrm{X}}}{b}$$



Donor radius

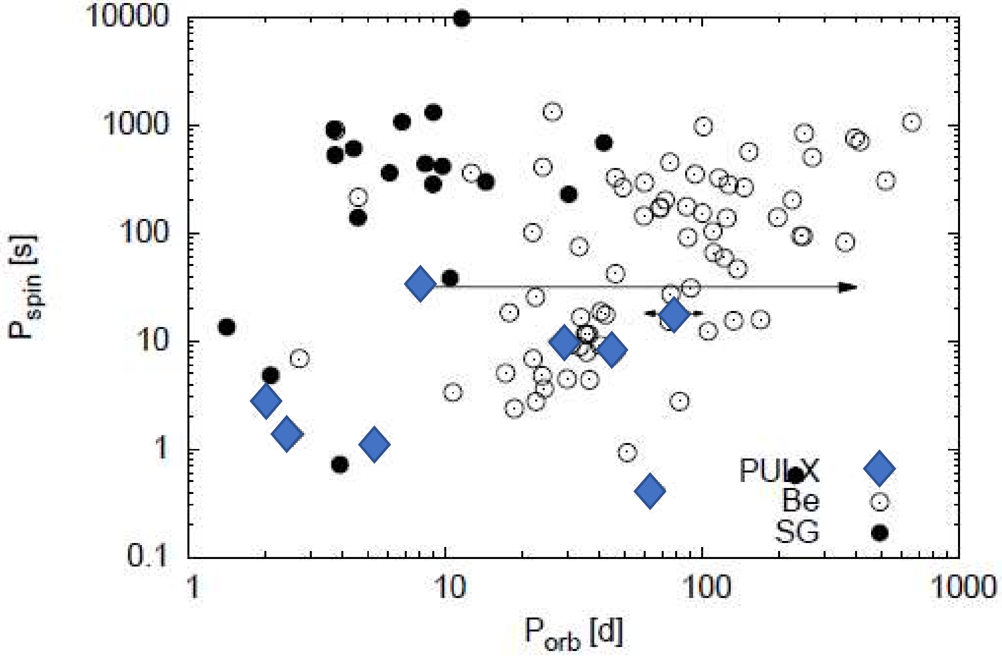
- When donor evolves and expands, the ULX condition will be relaxed
  - Some Be-HMXBs will become NS ULX, when the donor evolves and expands
  - Luminosity is less than 50 L_{edd} regardless of the model



Donor radius

ULX as a stage in the evolution of HMXB

- BeHMXB with an orbital period shorter than ˜50d potentially evolves to a ULX
- Population synthesis could give an NS ULX formation rate per galaxy



What I want to know

- How much of ULX has a NS?
  - There are few observable properties
  - Spectra, binary parameters, light curve, magnetic field, etc.

- Does ULX also have subclasses?
  - Continuity to classical HMXBs
  - ULX is only an evolutionally stage of HMXB?
  - Need donor information

Conclusion

- Under certain conditions, NS exceeds the Eddington luminosity and can be observed as ULX
  - RLOF or accretion from Be-disk
  - Some Be-HMXBs will evolve to ULX

Future work

- Pop. Synthesis in combination with binary evolution provides ULX abundance ratio, including unobserved ones.
  - Strong limit on the NS/BH ratio can be given