Indirect evidence for dark matter density spikes around stellar-mass black holes

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Reference paper: M. H. Chan & C. M. Lee, Indirect evidence for dark matter density spikes around stellar-mass black holes, *The Astrophysical Journal Letters* 943, L11 (2023).

Press release

- SciNews

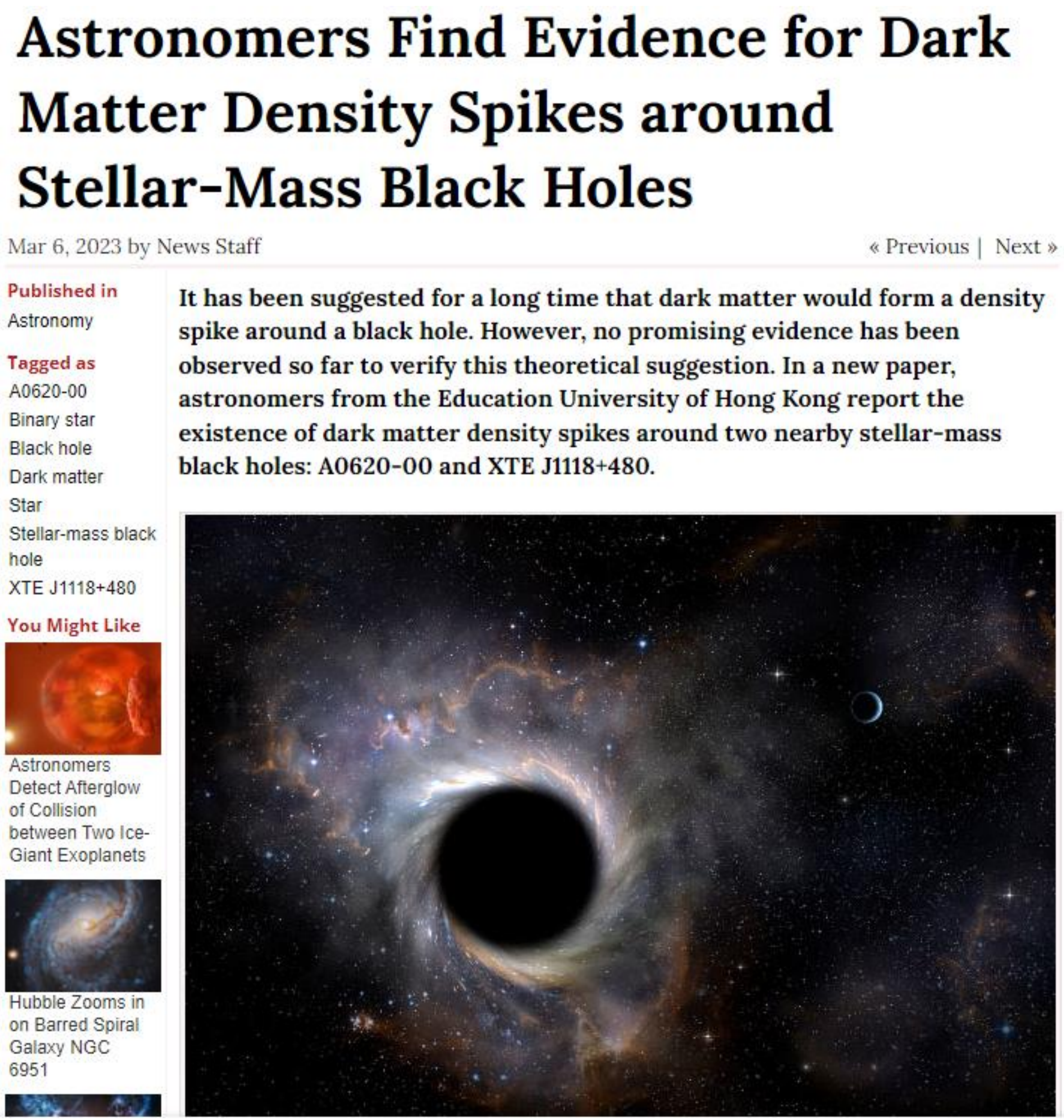
https://www.sci.news/astronomy/dark-matter-density-spikes-stellar-mass-black-holes-11716.html

- Phys.org

https://phys.org/news/2023-03-team-indirect-evidence-dark-black.html

- Live science

https://www.livescience.com/black-holes-may-be-swallowing-invisible-matter-that-slows-the-movement-of-stars



Astronomers Find Evidence for Dark Matter Density Spikes around Stellar-Mass Black Holes

Mar 6, 2023 by News Staff

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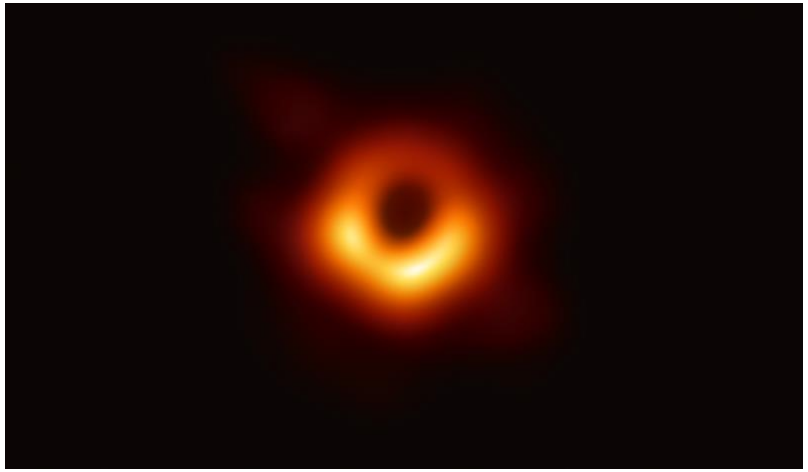
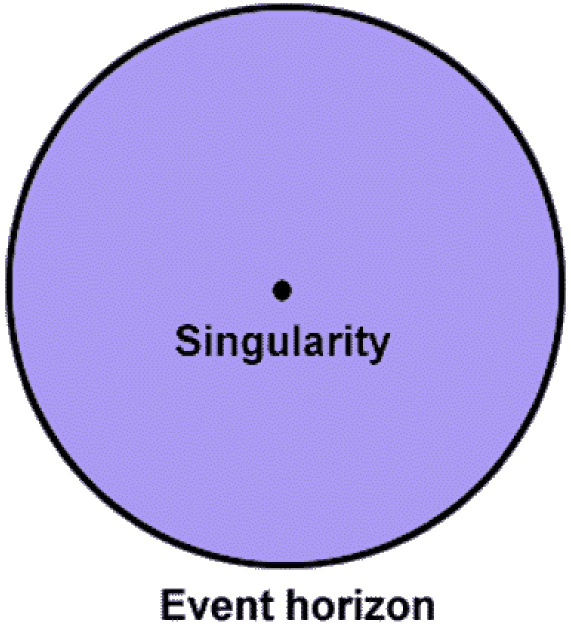
It has been suggested for a long time that dark matter would form a density spike around a black hole. However, no promising evidence has been observed so far to verify this theoretical suggestion. In a new paper, astronomers from the Education University of Hong Kong report the existence of dark matter density spikes around two nearby stellar-mass black holes: A0620-00 and XTE J1118+480.

Black hole

- Nothing can escape from the event horizon of a black hole, even light
- Can attract the surrounding matter gravitationally
- Origin:

1. Death of a star
2. Primordial
3. Others





Dark matter

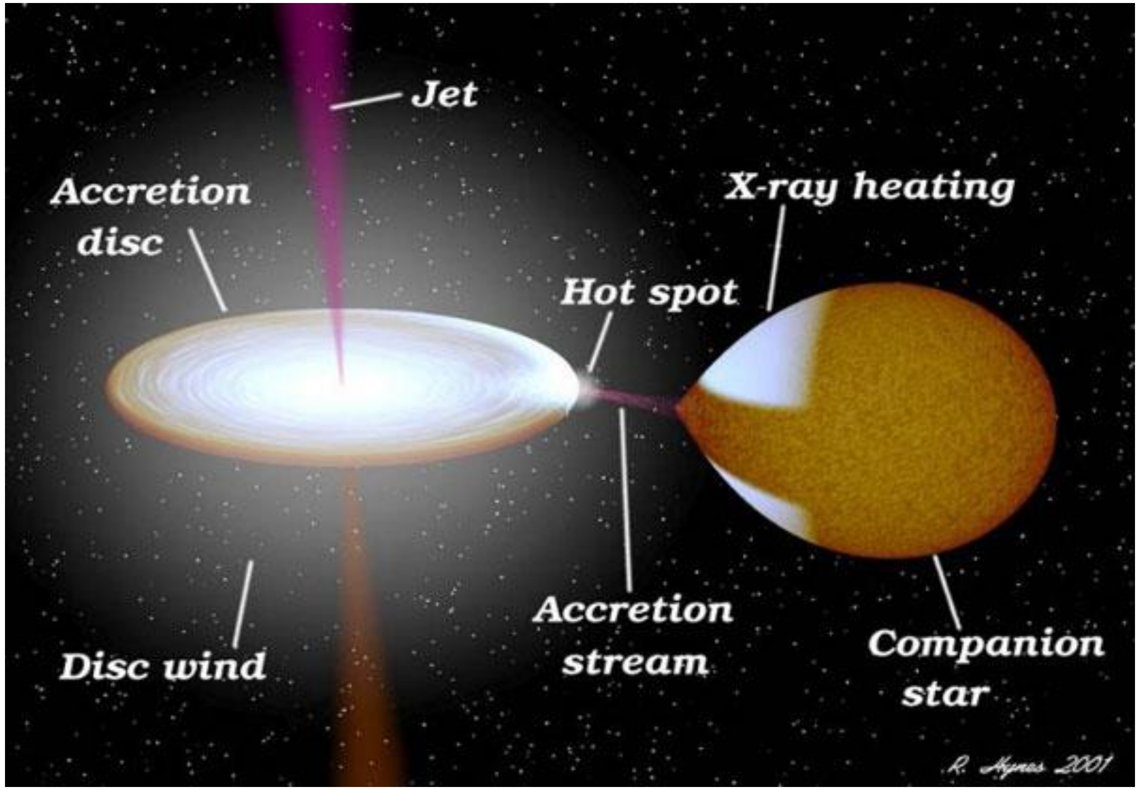
- Observations reveal dark matter exists (some missing mass in galaxies, galaxy clusters, etc.)
- Around 90% of matter is dark matter in our universe
- Dark matter may be unknown particles
- Dark matter almost does not interact with ordinary matter
- We can see the effect of dark matter via gravitational interaction

Dark matter surrounding a black hole

- Dark matter is distributed throughout a galaxy
- Therefore, any black holes inside a galaxy should be surrounded by dark matter
- A black hole would swallow some dark matter surrounding it
- Then the remaining dark matter would re-distribute to form a density spike around the black hole (a very high density near the black hole event horizon)
- The dark matter density spike might produce some observable events
- We target on the black hole binary systems

A black hole binary system

- For a black hole binary system, there is a companion star orbiting the central black hole
- Some of the gas from the companion star would be first heated up and then swallowed by the black hole
- The heated gas would emit X-ray
- By detecting the X-ray signals, we can measure the details of the system



Two target systems: A0620-00 and XTE J1118+480

- A0620-00: a K-type main-sequence star (0.35 solar mass) orbiting a black hole with mass 5.86 solar mass (period: 0.32301415 day)

- XTE J1118+480: a star with mass 0.18 solar mass orbiting a black hole with mass 7.46 solar mass (period: 0.16993404 day)

The dark matter density spike model

- The spike model originates from the Galactic supermassive black hole physics
- Theoretical calculations predicted that dark matter density distribution would be altered by a massive black hole (Gondolo & Silk 1999; Merritt 2003; Gnedin & Primack 2004)
- The conservation of angular momentum and energy would naturally force dark matter to form a dense spike (a cusp-like density profile)

$$\rho_{DM} \propto r^{-\gamma}$$

Dark matter density spike model

- The spike index γ depends on the outer dark matter density distribution
- The benchmark model suggests

$$\gamma = \frac{9 - 2\gamma_c}{4 - \gamma_c}$$

where γ_c is the power index of the outer dark matter density distribution. For the NFW profile, we have $\gamma_c = 1$ and we can get $\gamma = 7/3$

Searching for the dark matter density spike

- Since the spike index is large (>2), this can trigger a much higher rate of dark matter annihilation because the rate is proportional to ρ_{DM}^2
- Therefore, there are various studies proposing the detection of dark matter spike by gamma-ray detection. However, no signal has been observed so far
- One possible reason might be the annihilation cross section is too small to give a large observable annihilation rate
- Besides gamma-ray detection, gravitational wave detection is also looking for the signal of dark matter density spike (merger of black holes)

The dark matter density spike model

- In fact, the same model can also be applied in the stellar-mass black holes (most other studies have not considered this, but focused on intermediate-mass black holes)

$$\rho_{\mathrm{DM}} = \begin{cases} 0 & \text{for} \quad r \leqslant 2R_s \\ \rho_0 \left(\dfrac{r}{r_{\mathrm{sp}}} \right)^{-\gamma} & \text{for} \quad 2R_s < r \leqslant r_{\mathrm{sp}}, \\ \rho_0 & \text{for} \quad r > r_{\mathrm{sp}}, \end{cases}$$

The spike model predicts $\gamma = 1.5 - 2.5$

$$R_s = \frac{2GM_{BH}}{c^2}$$

The dark matter density spike model

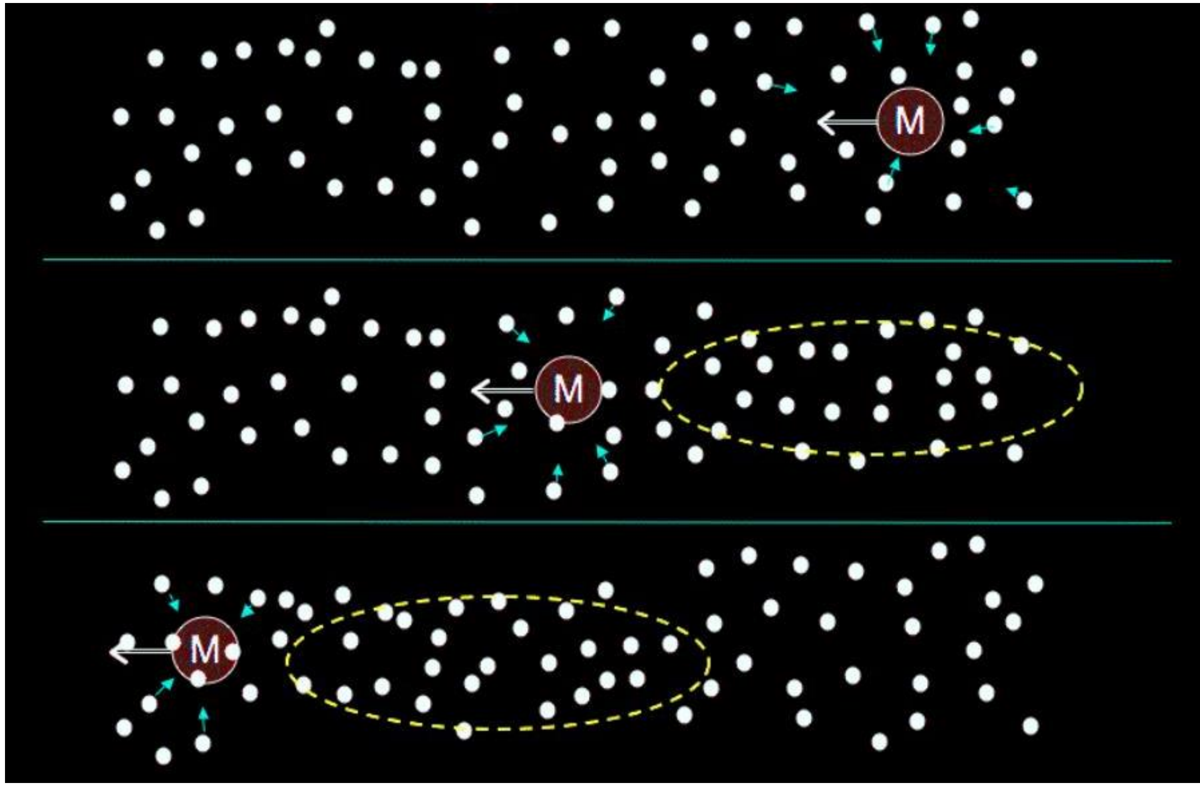
- Here, the spike radius r_p is usually connect with the radius of black hole's sphere of influence r_{in} as $r_{sp} = 0.2r_{in}$ (Fields et al., 2014)
- Outside r_{sp}, the dark matter density would follow the local dark matter density ρ_0
- The radius of influence can be determined by (Merritt 2003)

$$M_{DM}(r \leq r_{in}) = \int_0^{r_{in}} 4\pi r^2 \, \rho_{DM} dr = 2M_{BH}$$

- Therefore, the black hole mass determines the spike radius

Dynamical friction

- Consider a mass M passing through a background bath of dark matter particles
- Along the direction of the movement of M, the dark matter particles would be slightly redistributed and accumulate at the back of the movement
- A slightly higher density of dark matter particles would give a gravitational force to decelerate the movement of M



Dynamical friction in the BH binary system

- One can imagine that the companion star orbiting a black hole would be slowed down via dynamical friction due to the dark matter distributed near the black hole
- This process is well known. But the key question is: how large is the dynamical friction?
- The energy loss due to dynamical friction is given by

$$\dot{E} \approx -\frac{4\pi G^2 m^2 \rho_{DM} \ln \Lambda}{v}$$

- The effect can be manifested by the orbital decay rate:

$$\dot{P} = -\frac{12\pi q G P \ln \Lambda}{(1+q)^2 \left(\frac{K}{\sin i}\right)} \left[\frac{G M_{BH} (1+q) P^2}{4\pi^2}\right]^{\frac{1}{3}} \rho_{DM}$$

Two binary systems: A0620-00 and XTE J1118+480

	A0620-00	XTE J1118+480
$M_{\rm BH}$	$5.86 \pm 0.24 M_{\odot}$ (Van Grunsven et al. 2017)	$7.46^{+0.34}_{-0.69} M_{\odot}$ (Gonzalez Hernandez et al. 2014)
q	0.060 ± 0.004 (Van Grunsven et al. 2017)	0.024 ± 0.009 (Khargharia et al. 2013)
K (km s^{-1})	435.4 ± 0.5 (Neilsen et al. 2008)	708.8 ± 1.4 (Khargharia et al. 2013)
i	$54\overset{\circ}{.}1 \pm 1\overset{\circ}{.}1$ (Van Grunsven et al. 2017)	$73\overset{\circ}{.}5 \pm 5\overset{\circ}{.}5$ (Khargharia et al. 2013)
P (day)	0.32301415(7) (Gonzalez Hernandez et al. 2014)	0.16993404(5) (Gonzalez Hernandez et al. 2014)
$\dot{P}$ (ms yr^{-1})	-0.60 ± 0.08 (Gonzalez Hernandez et al. 2014)	-1.90 ± 0.57 (Gonzalez Hernandez et al. 2014)
d (kpc)	1.06 ± 0.12 (Gonzalez Hernandez et al. 2011)	1.70 ± 0.10 (Gonzalez Hernandez et al. 2011)

Surprising large orbital decay of BHs

- For the two closest black hole low-mass X-ray binaries (BH-LMXBs), A0620-00 and XTE J1118+480, we can measure their orbital periods P precisely
- Observations found that there exist abnormally fast orbital decays in these two BH-LMXBs:

- A0620-00: $\dot{P} = -0.60 \pm 0.08$ ms/yr
- XTE J1118+480: $\dot{P} = -1.90 \pm 0.57$ ms/yr

- Theory of gravitational-wave radiation only predicts $\dot{P} \sim -0.02$ ms/yr

Surprising large orbital decay of BHs

- Some proposals have been suggested:

1. Magnetic braking of the companion star: the surface magnetic field of the companion star is very strong (e.g. > 10^4 G), the coupling between the magnetic field and the winds from the companion star driven by X-ray irradiation from the black hole would decrease the orbital period through tidal torques (Justhan et al. 2006; Chen & Li 2015)
2. The tidal torque between the circumbinary disk and the binary can efficiently extract the orbital angular momentum from the binary to cause the orbital decay (Chen & Li 2015)

Surprising large orbital decay of BHs

- However, recent simulations show that the predicted mass transfer rate and the circumbinary disk mass are much greater than the inferred values from observations (Chen & Li 2015)
- Also, the calculated initial mass and effective temperature of the companion stars do not match the observations somewhat (Chen & Podsiadlowski 2019)
- Therefore, the abnormally fast orbital decays in the two BH-LMXBs are still a mystery

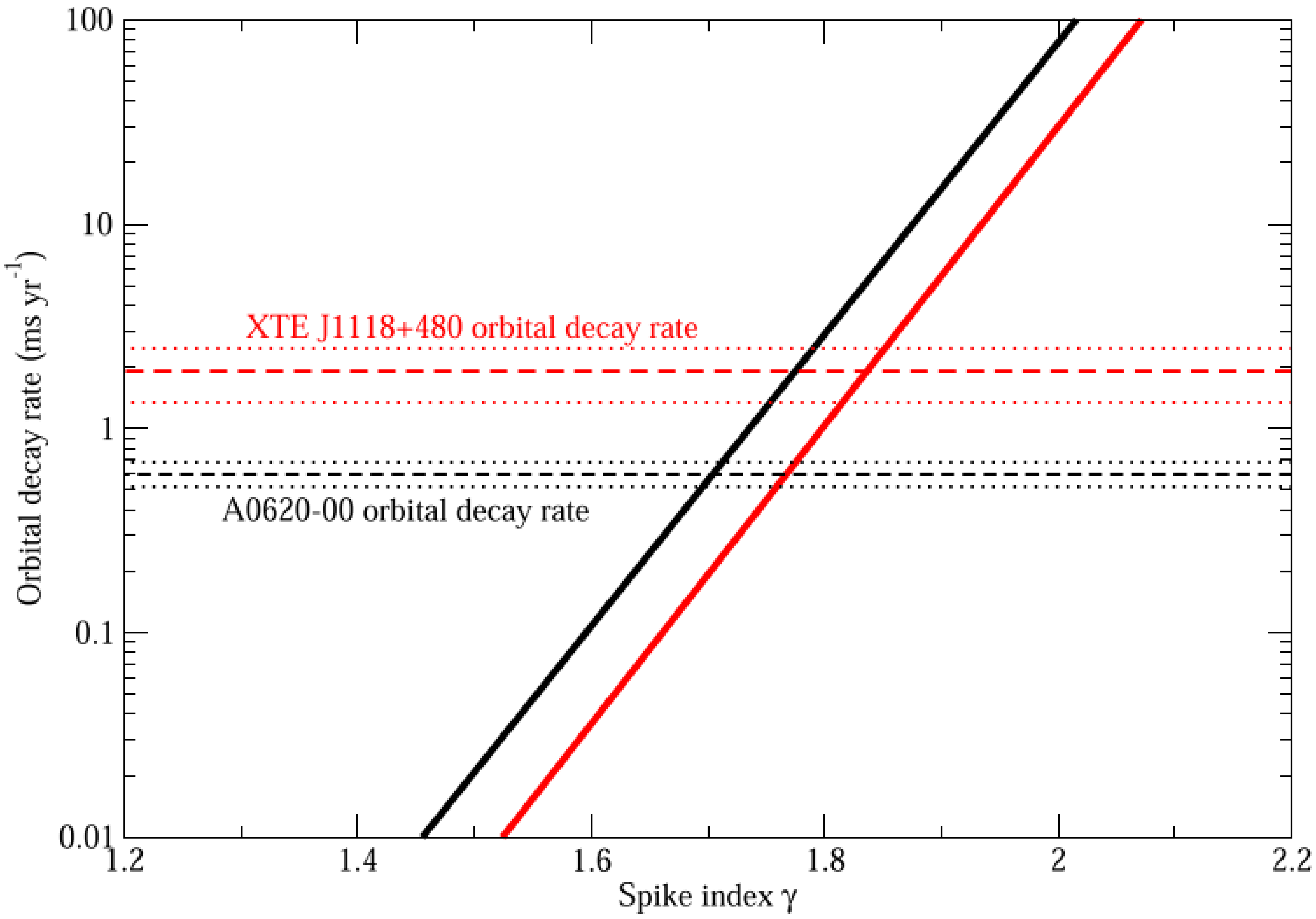
The Model

- We applied the dark matter density spike model to the two target BH-LMXBs to constrain the spike index
- Assuming the orbital decays of the two BH-LMXBs originate from the dynamical friction of dark matter
- We get

- A0620-00: $\gamma = 1.71^{+0.01}_{-0.02}$
- XTE J1118+480: $\gamma = 1.85^{+0.04}_{-0.04}$

- The values of the spike index are consistent with the spike model

Results



XTE J1118+480 orbital decay rate
A0620-00 orbital decay rate
Orbital decay rate (ms yr^{-1})
Spike index γ
100
10
1
0.1
0.01
1.2
1.4
1.6
1.8
2
2.2

The dark matter density spike model

- The spike index γ is the only unknown free parameter
- Generally, it can be ranging from 1.5 to 2.5
- If the gravitational scattering of stars is important, the stellar heating effect would drive the value down to 1.5 (Gnedin & Primack 2004)
- The heating time scale is

$$t_{\rm heat} = \frac{\sqrt{3\pi}\,\Gamma(0.5) M_{\rm BH}}{18 m \ln\Lambda}\left(\frac{G M_{\rm BH}}{r_{\rm in}^3}\right)^{-1/2}$$
$$= 1.2 \times 10^{15}\ {\rm s} \times \left(\frac{M_{\rm BH}}{5 M_\odot}\right)^{1/2}\left(\frac{r_{\rm in}}{5\ {\rm pc}}\right)^{3/2}\left(\frac{m}{M_\odot}\right)^{-1}\left(\frac{\ln\Lambda}{3}\right)^{-1}$$

The dark matter density spike model

- Therefore, we expect that if the age of the black hole $t_{BH} \geq t_{heat}$, the spike index would be more likely approach $\gamma = 1.5$
- The heating time scales for the two BH-LMXBs are

- A0620-00: $t_{heat} = 3.5 \times 10^{15}$ s
- XTE J1118+480: $t_{heat} = 6.1 \times 10^{15}$ s

- Although we don't know the age of the black holes, we can assume $t_{BH} \leq P/\dot{P}$:

- A0620-00: $t_{BH} \leq 1.7 \times 10^{15}$ s
- XTE J1118+480: $t_{BH} \leq 3.5 \times 10^{14}$ s

- Therefore, we can get a consistent picture for the dark matter density spike model and provide a good explanation for the orbital decay rates observed

The fitted parameters

	A0620-00	XTE J1118+480
a (AU)	$0.0169^{+0.0003}_{-0.0002}$	$0.0118^{+0.0002}_{-0.0004}$
$\rho_{DM}(a)$ (g cm^{-3})	$7.65^{+1.62}_{-1.43} \times 10^{-13}$	$1.60^{+1.51}_{-0.73} \times 10^{-11}$
γ	$1.71^{+0.01}_{-0.02}$	$1.85^{+0.04}_{-0.04}$
r_{in} (pc)	$5.41^{+0.10}_{-0.09}$	$5.34^{+0.02}_{-0.06}$
t_{heat} (s)	3.5×10^{15}	6.1×10^{15}
t_{BH} (s)	$\leqslant 1.7 \times 10^{15}$	$\leqslant 3.5 \times 10^{14}$

The effect of dark matter annihilation

- If dark matter annihilation rate is large enough, the spike structure might be destroyed and the central dark matter density would approach the constant saturation density $\rho_{sat} = m_{DM}/(\sigma v t_{BH})$ when $\rho_0 \left(\frac{r}{r_{in}}\right)^{-\gamma} > \rho_{sat}$ (Lacroix 2018)
- If the saturation density already achieved, we can determine the upper limits of dark matter mass for this case.
- Taking the standard annihilation rate $\sigma v = 2.2 \times 10^{-26}$ cm^3/s predicted by standard cosmology (Steigman et al. 2012), we can get $m_{DM} \leq 14$ GeV for A0620-00 and $m_{DM} \leq 48$ GeV for XTE J1118+480

The effect of dark matter annihilation

- Since many recent stringent constraints of thermal annihilating dark matter indicate $m_{DM} \geq 100$ GeV (Ackermann et al. 2015; Regis et al. 2021), the effect of dark matter annihilation is not significant in our study
- Therefore, omitting the effect of dark matter annihilation can be justified

Discussion

- The results are consistent with the dark matter density spike model surrounding black holes
- The high density of dark matter distributed near the black holes can exert dynamical friction to slow down the companion stars
- There is no satisfactory explanation for the observed decay in orbital periods for A0620-00 and XTE J1118+480 before this study
- Now, this model provides a satisfactory explanation
- This also provides the first evidence for a high density of dark matter around a stellar-mass black hole (with spike index > 1.5)

Further work

- There is another known black hole binary Nova Muscae which shows an abnormally fast orbital decay -20 ms/yr
- If there is a high density of dark matter around a black hole, we can investigate these similar systems in order to constrain the properties of dark matter
- There are at least 18 black hole binaries in our galaxy which can give rich information to study dark matter → a new research direction on dark matter

Q & A

Thanks