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Evidence for dark matter spikes surrounding 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).

M. H. Chan & C. M. Lee, The first robust evidence showing a dark matter density spike around the supermassive black hole in OJ 287, *The Astrophysical Journal Letters* 962, L40 (2024).

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

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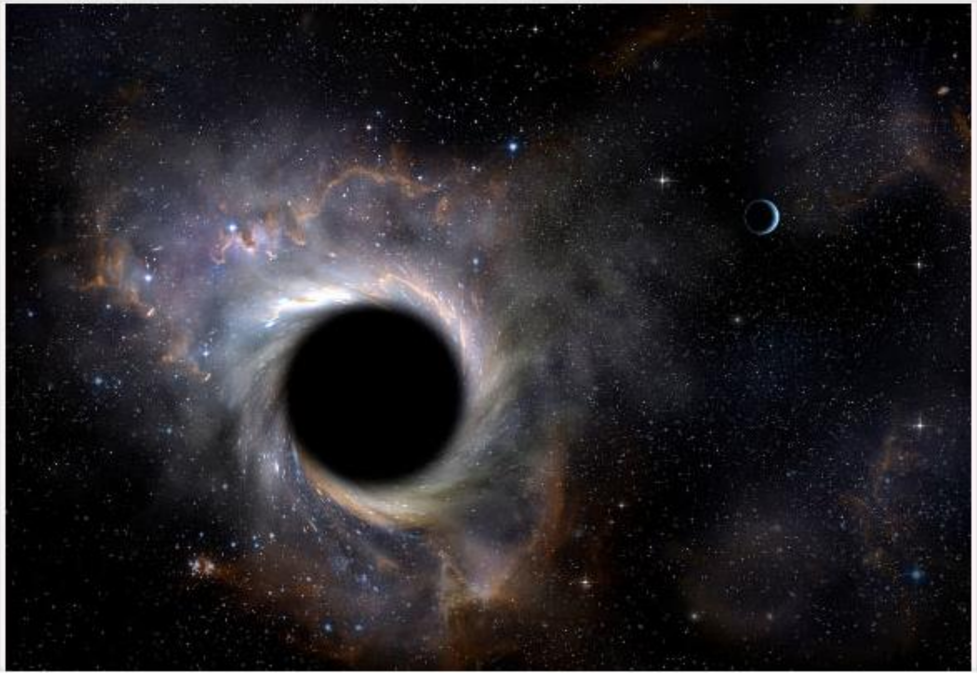
It has been suggested for a long time that dark matter would form a density spike around a black hole. However, no promising evidence has been observed so far to verify this theoretical suggestion. In a new paper, astronomers from the Education University of Hong Kong report the existence of dark matter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



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

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 radial action would naturally force dark matter to form a dense spike (a cusp-like density profile)

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

The dark matter density spike model

- The density spike model (Gondolo & Silk 1999):

$$\rho_{\rm DM} = \begin{cases} 0 & \text{for} \quad r \leqslant 2R_s \\ \rho_{\rm sp}\left(1 - \dfrac{2R_s}{r}\right)^3 \left(\dfrac{r}{r_{\rm sp}}\right)^{-\gamma_{\rm sp}} & \text{for} \quad 2R_s < r \leqslant r_{\rm sp} \\ \dfrac{\rho_s r_s}{r} & \text{for} \quad r_{\rm sp} < r \ll r_s \end{cases}$$

- The spike radius (Merritt 2003):

$$r_{\rm sp} = \left[\frac{(3 - \gamma_{\rm sp}) 0.2^{3-\gamma_{\rm sp}} M_{\rm BH}}{2\pi\rho_{\rm sp}}\right]^{1/3}$$

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

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

Dark matter density spike model

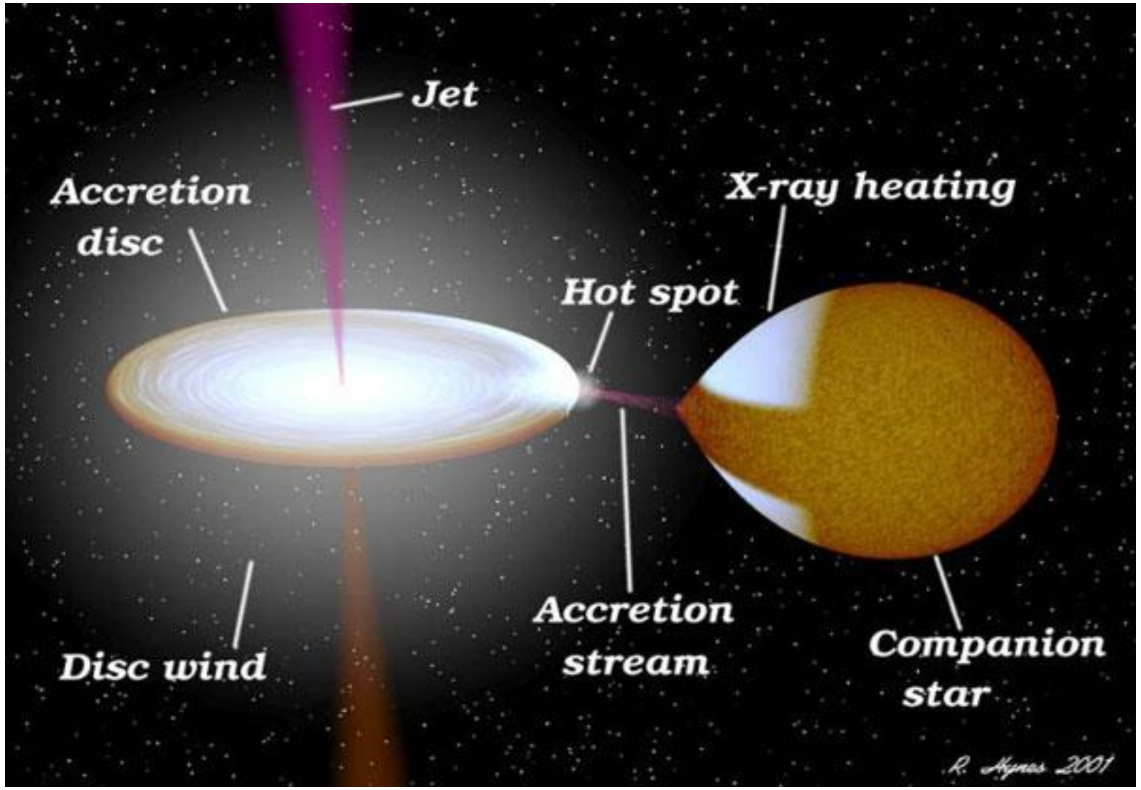
- The spike index γ depends on the outer dark matter density distribution
- The benchmark model suggests

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

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 $\gamma = 7/3$

Dark matter spike model in a black hole binary?

- 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)

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)

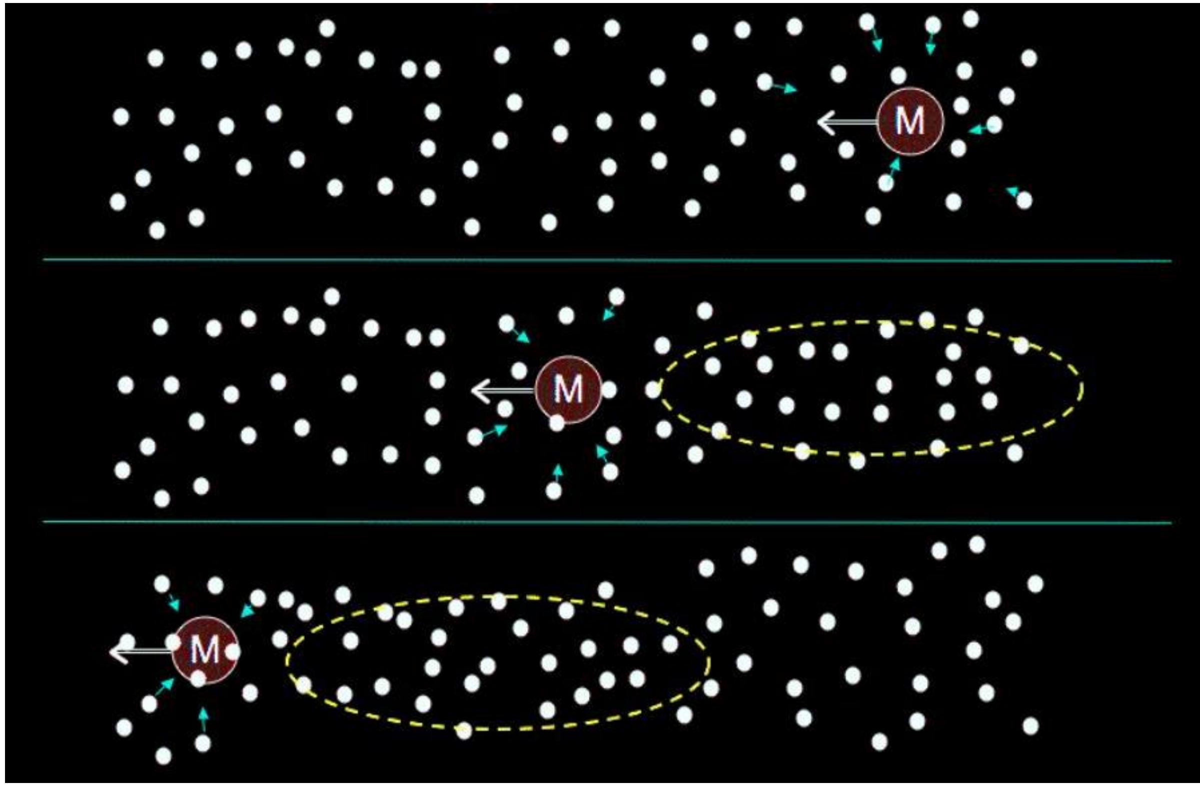
Surprising large orbital decay of BHs

- 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

Can the existence of dark matter explain the large orbital decay?

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)

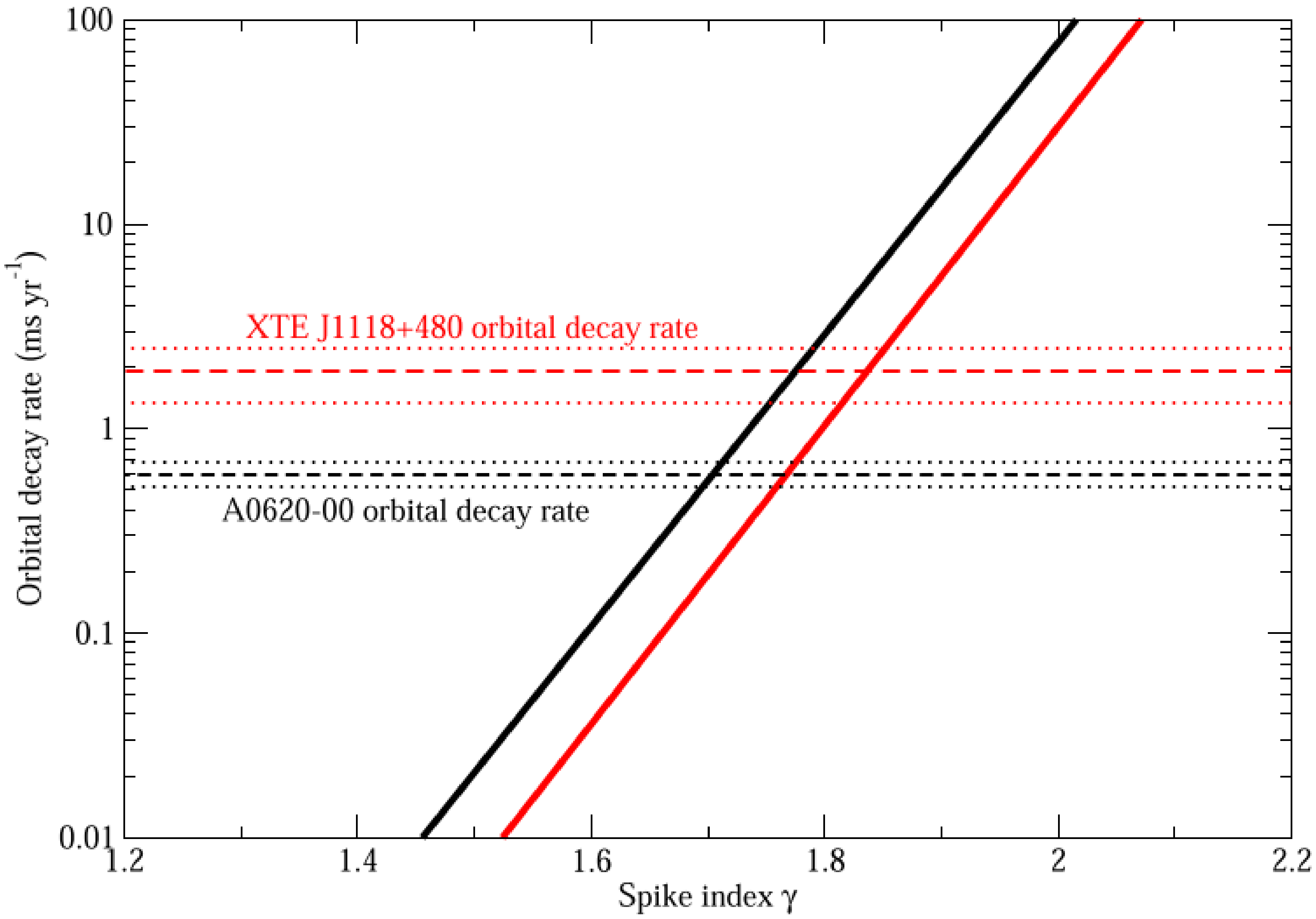
The Model

- 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

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

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 $t_{BH} \leq P/\dot{P}$:

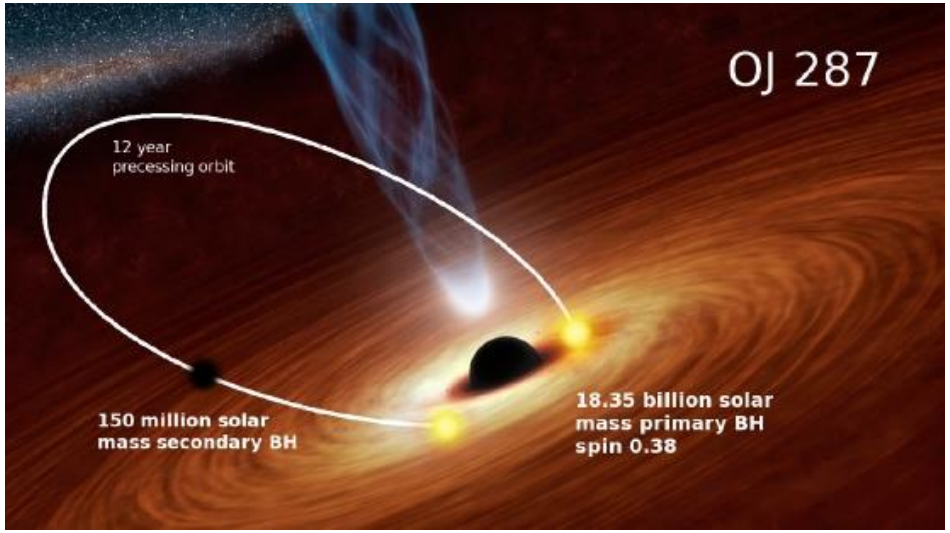
- A0620-00: $t_{BH} \leq 1.7 \times 10^{15}$ s
- XTE J1118+480: $t_{BH} \leq 3.5 \times 10^{14}$ s

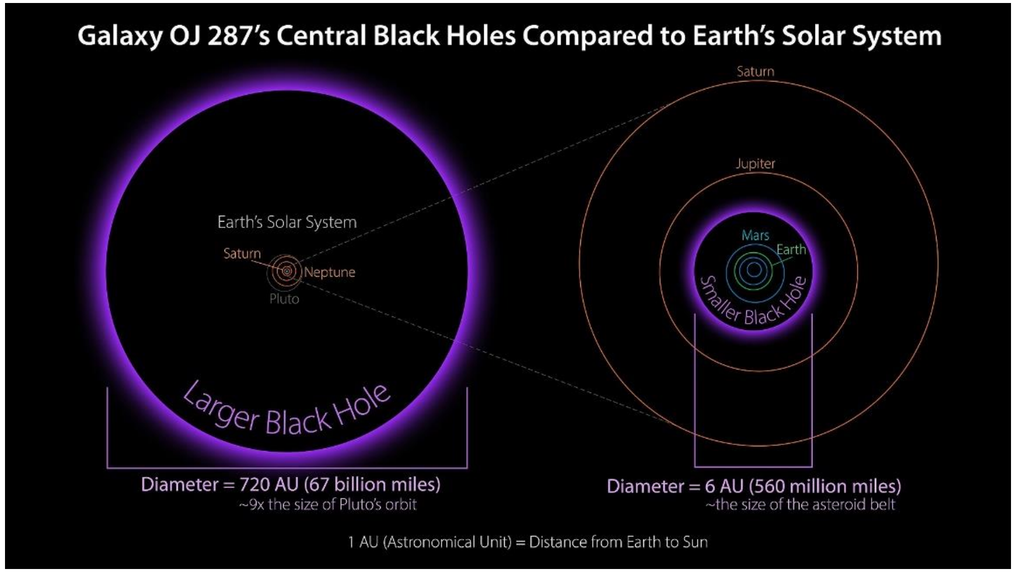
- Therefore, we can get a consistent picture for the dark matter density spike model and provide a good explanation for the orbital decay rates observed

Dark matter density spike in OJ 287

- We apply the same idea to the supermassive black hole binary OJ 287
- In OJ 287, a supermassive black hole with 150 million solar mass is orbiting another supermassive black hole with 18.35 billion solar mass
- Orbital period decay = -0.00099

  (will merge after 12000 yr)





The dark matter density spike model

- We include the energy loss due to GW and DF:

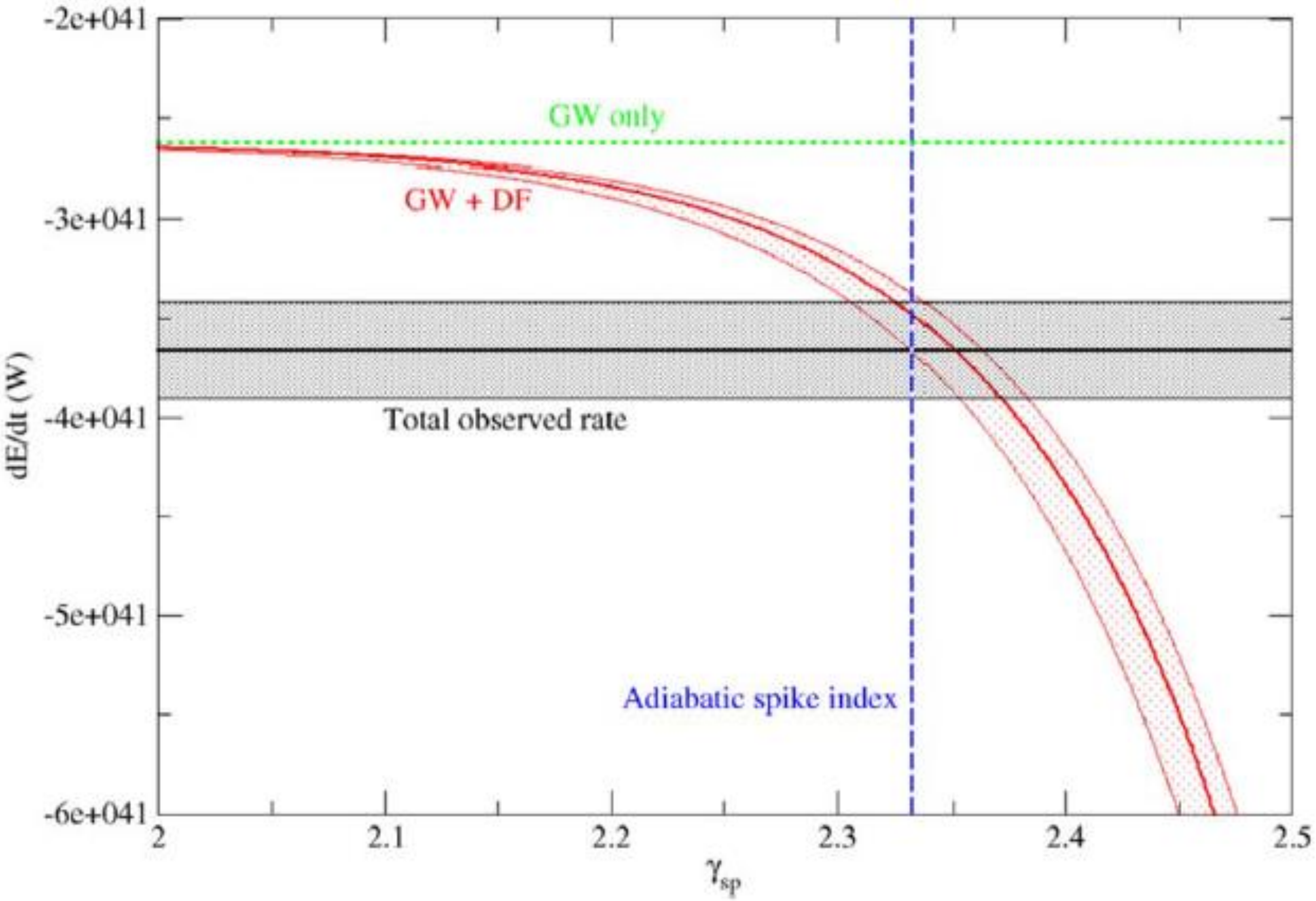
$$\dot{E}_{\rm GW} = -\frac{32G^4\mu^2M^3}{5c^5a^5}(1 - e^2)^{-7/2}\left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)$$

$$\dot{E}_{\rm DF} = -2G^{\frac{3}{2}}\mu^2\rho_{\rm sp}r_{\rm sp}^{\gamma_{\rm sp}}(1 - e^2)^{\frac{3}{2}}\ln\Lambda \times \int_0^{2\pi}\frac{[1 + e\cos(1 - \alpha)\phi]^{\gamma_{\rm sp}-2}[p - 2R_s(1 + e\cos(1 - \alpha)\phi)]^3}{p^{\gamma_{\rm sp}+\frac{5}{2}}M_{\rm BH}^{\frac{1}{2}}[1 + 2e\cos(1 - \alpha)\phi + e^2]^{\frac{1}{2}}}d\phi$$

- The dark matter density profile can be modeled based on the empirical relation (assumed NFW profile):

$$\log_{10}(M_{\rm BH}/M_\odot) = (8.18 \pm 0.11) + (1.55 \pm 0.31) \times [\log_{10}(M_{\rm tot}/M_\odot) - 13.0].$$

The dark matter density spike model



- GW cannot explain the period decay
- The constrained spike index is $\gamma_{sp} = 2.351^{+0.032}_{-0.045}$, which gives excellent agreement with the benchmark value 2.333 based on the adiabatic growing model

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 objects
- The dark matter density spike model provides satisfactory explanations for the orbital period decay
- These results provide the first evidence for the dark matter density spikes surrounding black holes

References

- 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).
- M. H. Chan & C. M. Lee, The first robust evidence showing a dark matter density spike around the supermassive black hole in OJ 287, *The Astrophysical Journal Letters* 962, L40 (2024).

Q & A

Thanks