New study uses self-interacting dark matter to solve the final parsec problem

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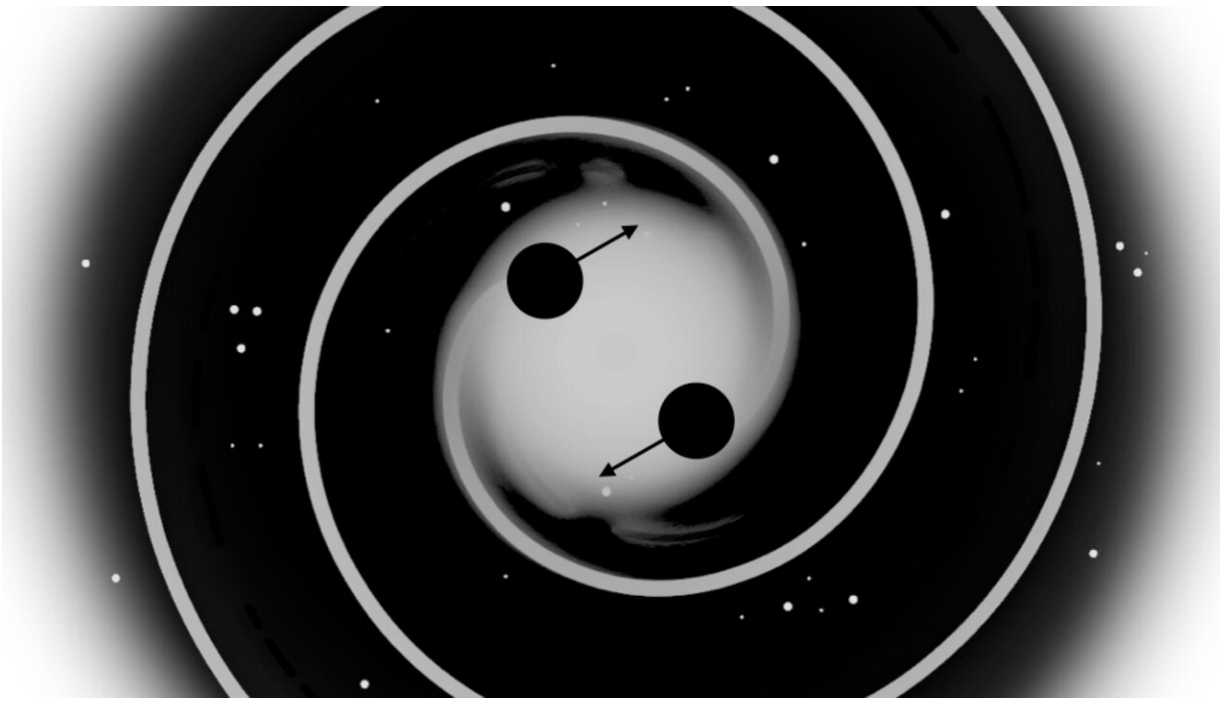

Illustrative representation of a black hole binary immersed in a dark matter spike at the center of a galaxy. Credit: Original image: NASA science.nasa.gov/resource/spiral-galaxy-blue/. Modified by Alvarez, Cline, and Dewar.

In a new study, scientists from Canada have proposed a solution to the final parsec problem of supermassive black hole (SMBH) mergers using self-interacting dark matter.

When two galaxies merge, gas and dust collide, leading to star formation. However, the stars themselves don't collide due to their vast distances. The SMBHs at the center of the two galaxies also begin to merge.

However, the merger of the black holes stalls when they are 1 parsec (or 30.9 trillion kilometers) apart. This problem is known as the final parsec problem in astronomy and astrophysics.

The study, published in *Physical Review Letters (PRL)*, attempts to solve this problem and explain the gravitational wave spectrum observed in 2021 by the Pulsar Timing Array collaborations.

Phys.org spoke to the first author of the study, Dr. Gonzalo Alonso Alvarez, a postdoc at the University of Toronto.

Speaking of the motivation behind the team's work, he said, "What struck us the most when Pulsar Timing Array collaborations announced evidence for a gravitational wave spectrum is that there was room to test new particle physics scenarios, specifically dark matter self-interactions, even within the standard astrophysical explanation of supermassive black hole mergers."

Why stop at 1 parsec?

When SMBHs from two merging galaxies are separated by 1 parsec, two counteracting things are at play.

Firstly, large objects like an SMBH cause ripples in spacetime, leading to the formation of gravitational waves that travel throughout spacetime. These gravitational waves carry energy away from the source. When two SMBHs merge, the gravitational waves carry energy away from the merger, causing the black holes to spiral inwards more rapidly.

The second is a frictional force called dynamical friction. When massive objects like black holes travel through a medium (like dust and stars), they have a trail of disturbed fluid called the wake. For example, when a ship moves through water, it leaves a turbulent trail of water behind it; this is its wake.

The particles attracted to the SMBH via gravity can cause a drag force, which is dynamical friction. This friction opposes the motion of the massive object, forcing it to slow down. In the case of two SMBHs merging, this can cause them to stop moving towards each other.

"Previous calculations have found that this process stalls when the black holes are around 1 parsec away from each other, a situation sometimes referred to as the final parsec problem," explained Dr. Alvarez.

This is where dynamical friction comes into play. This can either oppose or assist with the merging of the two SMBHs.

Self-interacting dark matter

The researchers propose that a form of dark matter might be the solution to this problem.

"In this paper, we show that including the previously overlooked effect of dark matter can help black holes overcome this final parsec of separation and merge, thus emitting a gravitational wave signal that matches the one observed by Pulsar Timing Arrays," said Dr. Alvarez.

In a galaxy, dark matter is predominantly present in the galactic halo, the region surrounding the visible galaxy. But, it is also present near the galactic core, where the SMBH is present. Therefore, the nature of dark matter could play a crucial role in the merger of SMBHs.

Self-interacting dark matter (SIDM) is a hypothetical form of dark matter in which dark matter particles interact with each other via a new unknown force.

In galaxies containing SIDM, the interactions between the dark matter particles can affect the density (distribution) and velocity of the dark matter, leading to a more efficient funneling of matter and energy toward the SMBH, which could potentially overcome the dynamical friction.

A delicate balance

To explore the role of SIDM in the SMBH merger, the researchers performed detailed calculations of dark matter density profiles around SMBHs for SIDM and cold dark matter (less interacting).

They also modeled dynamical friction effects on SMBH orbits, calculated energy transfer between the SMBH and dark matter, and conducted simulations of gravitational wave spectra under different dark matter scenarios.

They then compared these results with observational data from the pulsar timing arrays.

The researchers found that the interaction cross-section of dark matter particles must be within an optimal range. A larger cross-sectional area, which means more frequent interactions, causes dark matter particles to interact and scatter, flattening the density profile near the SMBHs.

This reduction in density decreases the dynamical friction necessary for the SMBHs to merge.

"On the other hand, sufficiently frequent dark matter self-interactions are needed to prevent this profile from being dispersed by the black hole motion," explained Dr. Alvarez.

The ideal cross-section range allows enough interactions to influence the SMBHs' movement without dispersing the dark matter too much, thereby maintaining sufficient dynamical friction to aid the merging process.

The researchers found this value to be between 2.5 and 25 cm^2/g. This means that for every gram of dark matter, the effective area over which the particles interact should be between 2.5 and 25 square centimeters.

Velocity-dependent interactions

The researchers also found that the velocity of the SIDM particles must be optimal. This velocity is in turn influenced by the unknown force carrier or mediator's mass, which facilitates the interaction between SIDM particles.

If the mediator is heavy, it could mean that dark matter particles only interact significantly when they are moving slowly relative to each other. Conversely, if the mediator is light, interactions could occur at higher velocities.

"Interestingly, this velocity dependence is theoretically well-motivated. It is precisely what one finds if the particle that acts as the force carrier for the dark matter self-interactions has a mass that is roughly 1 percent of the dark matter particle mass," said Dr. Alvarez.

The researchers estimated this value to be between 300 and 600 km/s.

"These velocity-dependent self-interactions leave an imprint on the gravitational wave spectrum because when the black holes are a fraction of a parsec away from each other, a significant fraction of the orbital energy is lost to dark matter friction rather than gravitational wave emission, thus relatively suppressing the gravitational wave signal at some frequencies compared to others," added Dr. Alvarez.

Implications and future work

The researchers' model of SIDM particles predicted that the gravitational waves would be weaker or less intense at low frequencies. This prediction matched what has been observed in actual data.

They also showed that SIDM with a velocity-dependent cross-section can solve the final parsec problem and survive the merger process.

Speaking of the impact of their work, Dr. Alvarez said, "We find the evolution of the black hole's orbit to be very sensitive to the microphysics of dark matter, meaning that we can use the gravitational wave emission of SMBH binaries to constrain dark matter models. This offers a new window for probing the dark matter nature in the innermost regions of galaxies that were previously not observationally accessible."

The team is also refining their model and developing numerical simulations to confirm the results found in this paper. These simulations will provide a better understanding of how dark matter profiles react to the energy injected by merging black holes.

More information: Gonzalo Alonso-Álvarez et al, Self-Interacting Dark Matter Solves the Final Parsec Problem of Supermassive Black Hole Mergers, *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.133.021401.