



## **Computational astrophysics related to black holes and dark matter**

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### **ABSTRACT**

This paper gives a brief analysis on computational astrophysics, how it is related to black holes and dark matter, experimental evidence on the same and their theory. Computational astrophysics is a very important topic in astrophysics, because in the near future we will rely a lot on simulations using the laws of physics and maths to find out what will happen in the unknown places of the universe. Knowing about black holes and dark matter will help by understanding the connections of general relativity and quantum mechanics which helps understand the universe's behaviour. This paper's research was conducted through looking at other papers and many other sites related to this topic. While researching on this topic I found out the connections between black holes, dark matter and computational astrophysics. I further looked into the evidence of black holes and dark matter to understand their connections. My understanding is that these are the future of astrophysics so it deserves more time and attention as these topics are going to be extremely helpful to learn about.

**Keywords:** Computational Astrophysics, supernovas, Observable universe, accretion disk, baryonic matter, galactic, cosmological scales, dark matter, dark energy

### **INTRODUCTION**

Computational astrophysics is a branch of astrophysics which focuses on discovering problems by using math and computers to discover places of the universe we can't directly see because it is too far, and due to dark energy, the universe is drifting apart. Scientists simulate events that have taken place in totally unknown areas of the universe through universal laws. It combines the three fields, mathematics, physics & computer science. Scientists use this field to find out the formation of galaxies, stages of a black hole, early universe explosions, etc. This field was invented over a long period of time during 1940 - 1960 and since then it has gained power and importance because of the realization of its benefits. Its main benefits are that it can find out things that are impossible to directly test because we cannot create black holes or dark matter in laboratories. It also predicts cosmic events such as supernovas, birth of galaxies and other phenomena which we can't use simple math to find out. Some of the most important discoveries that have taken place in this field are our cosmic webs, better understanding of dark matter, black hole behaviour and understanding of the universe's early formation.

### **BLACK HOLES & DARK MATTER AND HOW ARE THEY RELATED TO COMPUTATIONAL ASTROPHYSICS**

The two most intriguing and vast fields of astronomy in my opinion are black holes and dark matter because they truly have no end to them as you can never know it all in these fields specifically. Black holes are the most mysterious field in all of science because it is a region in space which is impossible to escape from even the fastest known object in the universe light can't escape its gravity, it has several parts to it such as the event horizon a point where



the fundamental laws of physics don't make sense anymore which is why light cannot escape, another important part of the black holes are the singularities are the most dense parts of a black hole as it break anything that enters it down to infinite. An accretion disk is a rotating disk of hot gas, plasma, or the light of stars falling into the black hole and it is what gives colour or light to detect the black hole through gravitational lensing. Dark matter is an invisible form of matter, it makes up 85% of the observable universe, scientists believe it exists because of its gravitational effects on galaxies, stars and planets. Scientists also know it exists because normal visible matter cannot explain how galaxies rotate at such high speeds and why galaxy clusters stay compact with each other. And now I will explain how black holes and dark matter are connected to computational astrophysics. As mentioned earlier in this paper I covered that computational astrophysics is a branch of astrophysics which focuses on discovering problems by using math and computers to discover places of the universe we can't directly see because it is too far and that perfectly relates to black holes and dark matter as they are fields that which need a lot of calculations and computer back up, so thus they correlate smoothly.

#### **FUTURE SCOPE OF COMPUTATIONAL ASTROPHYSICS IN BLACK HOLES AND DARK MATTER**

The future scope of computational astrophysics in black holes and dark matter is very important as astrophysics in the near future will rely more on simulations, Artificial intelligence and supercomputers because there are theories that the universe will start drifting away from each other slowly and no matter how good the telescopes are then we will not be able to see many things at that time so simulations will be our best hope at that time. Now computational astrophysics will start to play a huge role in black hole studies as the computers will start to make more accurate simulations of accretion disk, a better picture of singularities, and a better understanding of the space time curvature near the event horizons. As for dark matter, computers are even more important because dark matter is invisible and we need it to look at dark matter's effects on celestial bodies. They simulate billions of particles which are of dark matter to find how galaxy clusters, the cosmic Webb formed over time which help scientists know about warm dark matter, cold dark matter, axion and sterile neutrinos and more dark matter theories. There is a very bright future ahead for computational astrophysics in black holes and dark matter to make new discoveries.

#### **LITERATURE REVIEW**

Theoretical and Computational astrophysics in the study of Black Holes and Dark Matter by Judah Liew Rion published in December 2025 his paper gave me a brief understanding on what computational astrophysics is and how it relates to black holes and dark matter further inspiring me to write on this topic, this paper is The understanding of black holes and dark matter remains central to resolving some of the most fundamental questions in cosmology and high-energy astrophysics. Theoretical and computational astrophysics have emerged as indispensable tools in exploring these enigmatic phenomena, offering detailed insights into their formation, structure, and interactions at both galactic and cosmological scales. This paper surveys the contemporary approaches in modeling black holes and dark matter using relativistic hydrodynamics, N-body simulations, and numerical relativity. Further, it highlights the synergy between theory, simulation, and observations in current research, and



identifies gaps where future efforts should be concentrated. A comprehensive literature review contextualizes the work in the research landscape, and visual aids are included to elucidate key concepts and model workflows.

Community paper Computational Astrophysics by T. Naab, R. S. Klessen, W. Kelly, F. Röpke, with input from the computational astrophysics community this paper talks about How does the large-scale structure of the Universe emerge? Which astrophysical processes govern the dynamics of the interstellar medium, and how do stars form and evolve in galaxies? What determines when and where planets build up, and how can we explain the large diversity of the planetary systems observed today? What happens when black holes accrete matter? How do black holes merge and emit gravitational waves? High-performance supercomputer simulations have become the primary theoretical tool to answer essential astrophysical questions. Using about 25% - 30% of the German supercomputing time, computational astrophysics is 12th exemplary for high-performance computing, technical excellence and technology transfer driven by fundamental science. With access to world-class computing facilities many strong research groups in Germany have reached world-leading excellence over the past decade. However, the field will face unprecedented challenges in the next decade. Progress in our theoretical understanding of the Universe requires more complex and computationally demanding simulations. This challenge - in a highly competitive international environment - requires new research, and funding strategies. The rapidly increasing effort for the sustained and innovative development of parallel simulation codes, which can make efficient use of upcoming supercomputers, is beyond the scope of typical astrophysical research projects. Efficient simulation codes are the basis for excellence in the field. They serve the same purpose and should be treated and funded similarly to observational instruments for telescopes. New and innovative funding schemes can provide the necessary support for the development, validation, and dissemination of astrophysical simulation tools. It is also essential for the field that German funding agencies continue their high-level support for upgrading the German tier-0 supercomputing facilities at a world leading level.

### **THEORY**

Dark matter remains one of the greatest mysteries in the universe because of its unusual nature and behavior. Unlike ordinary matter, dark matter does not emit, absorb, or reflect light, making it impossible to observe directly using conventional telescopes. Despite this challenge, scientists are confident that dark matter exists because of the powerful gravitational effects it has on galaxies, galaxy clusters, and the large-scale structure of the universe.

What makes dark matter especially unique is that it primarily interacts through gravity, unlike baryonic matter—the ordinary matter that forms stars, planets, and living organisms—which also interacts through electromagnetic radiation. Researchers estimate that dark matter constitutes about 27% of the observable universe, while baryonic matter accounts for only 5%. The remaining portion of the universe is believed to consist of dark energy, which is responsible for the accelerated expansion of the universe. The idea of dark matter was initially pondered upon by Fritz Zwicky in 1930 because he wondered why there was an empty chunk of nothingness in the galaxy cluster. Later in the early 1970s Dr. Vera Rubin

added on to this rare field at the time by discovering how galaxies move at unimaginable speeds and that is what sparked curiosity in young scientists to work further on this field. People believed her theory because stars, planets, and other cosmic objects not close to the supermassive black hole in the galaxy are not expected to move at such high speed because they have less gravity pulling on them from the core of the galaxy. Dark matter is especially important as it helps explain the galaxy structure, gravitational lensing, and the picture of the universe as a whole.

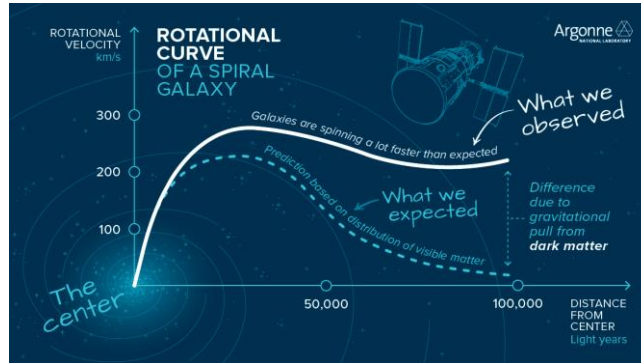


Figure 1: Rotational Curve of a Spiral Galaxy

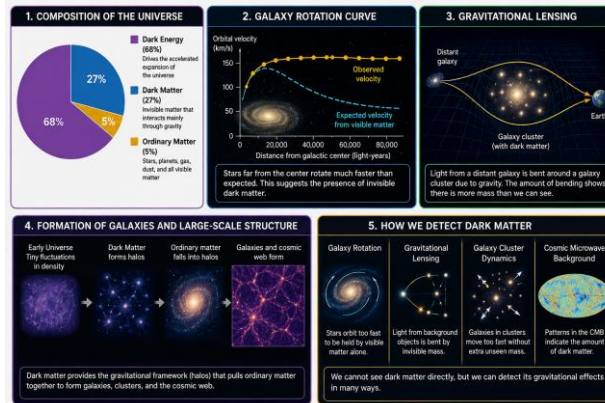


Figure 2: Composition of the universe

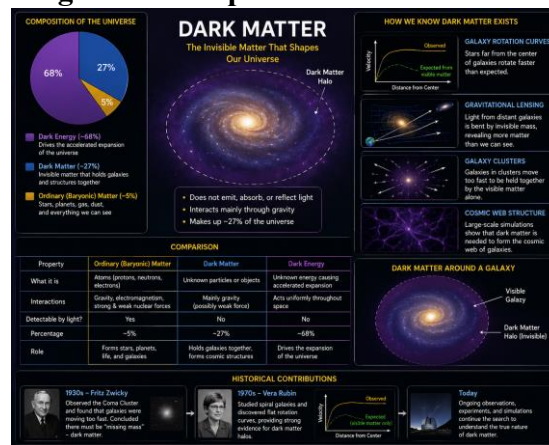


Figure 3: Dark Matter

Black holes in my opinion is the most destructive and mysterious field in the whole of astrophysics because it has many unique properties, such as how it is formed. Black holes are



formed by the death of extremely large stars. They live a life of approximately a couple of million years for big stars and trillions of years for smaller stars changing based on size, because bigger stars use more energy by glowing initially and smaller stars use their energy over a long period of time. After the star's life span gets over its core becomes unstable and suddenly breaks down under its own gravity and the rest of its layers explode. The explosion is called a supernova. If the remaining core is large enough the star turns into a black hole. Now how do we determine if the star turns into a black hole or a white dwarf followed by a black dwarf? A scientist named Subrahmanyan Chandrashekhar discovered that a white dwarf that exceeds 1.4 solar masses becomes black hole or neutron star. This law is called the Chandrashekhar Limit. A very important name in the field of black holes is Albert Einstein who discovered general relativity. It means larger objects curve space time and black hole singularities are extremely dense so they curve space time infinitely.

### EXPERIMENTAL REVIEW

Back in 2015 LIGO detected gravitational waves and confirmed the existence of black holes and showed that it can orbit and merge with other black holes. A tool called event horizon telescope is used to take photos of the shadows of black holes, and it first took a photo of a black hole called Messier 87\* in 2019, it was no coincidence as it was predicted by the math of general relativity. Black holes are also detected by a method called X - ray observations. It is used by detecting the hot accretion disk of the black hole to conform the properties about that specific black hole and its type. Some examples of this tool are the NASA Chandra X - ray Observatory and the European Space Agency XMM Newton.

The experimental evidence of why we believe dark matter exists is

- Vera Rubin's theory of stars moving very fast even without them being near the black hole in the middle of their galaxy and visible matter cannot explain this phenomena.
- Light bends a lot as compared to what we expect near galaxies and galaxy clusters. It indicates the large amount of invisible mass.
- When two galaxy clusters collide with each other a major gravitational part of the visible gas, these are called the bullet cluster observations.
- Cosmic microwave background data observed by Planck collaboration and WMAP found out about how ordinary matter cannot be responsible for structure, size, shape and expansion of the universe
- Computer simulations like 'millennium simulation' show how dark matter forms the cosmic web and galaxy halos.

### CONCLUSION

This research paper focused on the connection of black holes and dark matter to computational astrophysics as in the near future the world will rely majorly on simulations, because of dark energy the universe is drifting apart so it will become much tougher to detect objects in space. It also focuses on black holes and dark matter as they are also some of the most mysterious objects in the universe. Black holes have such strong gravity that even the fastest object in the universe, light cannot escape its gravity. Dark matter on the other hand explains how planets, stars and other celestial bodies travel so fast without being near the central black hole of the galaxy which was never predicted by scientists earlier. Some proof that black holes exist are the images taken of Messier 87\*, even LIGO detected gravitational



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waves and much more evidence. Proof that dark matter is real is the fast movement of objects even without them being in the centre of the galaxy. In my opinion, computational astrophysics related to black holes and dark matter should be a very well-studied field because it has a really big and bright future.

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