The enduring mystery of ultra-diffuse galaxies!

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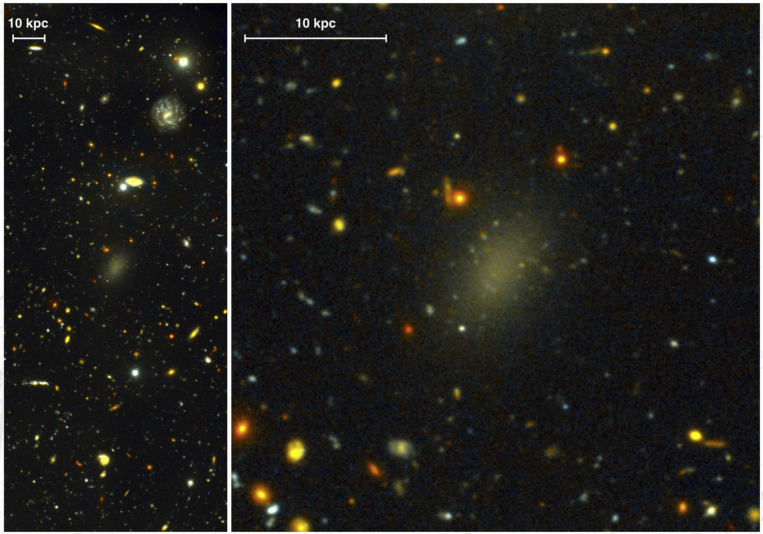
Astrophysics

The Dragonfly 44 galaxy

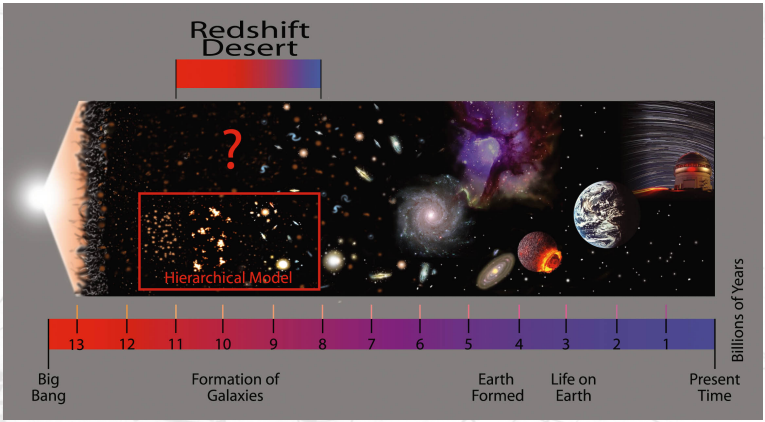
- In a shocking report released in 2016, astronomers claimed to have found a galaxy that is so faint but also so large and heavy that it must be almost completely undetectable.
- They calculated that the Dragonfly 44 galaxy is 99.99% dark matter.

Pieter van Dokkum, Roberto Abraham, Jean Brodie, Charlie Conroy, Shany Danieli, Allison Merritt, Lamiya Mowla, Aaron Romanowsky, Jielai Zhang
"A High Stellar Velocity Dispersion and 100 Globular Clusters for the Ultra Diffuse Galaxy Dragonfly 44",
The Astrophysical Journal Letters, **828***:L6, 6pp (2016),*
arXiv:1606.06291,
doi:10.3847/2041-8205/828/1/L6

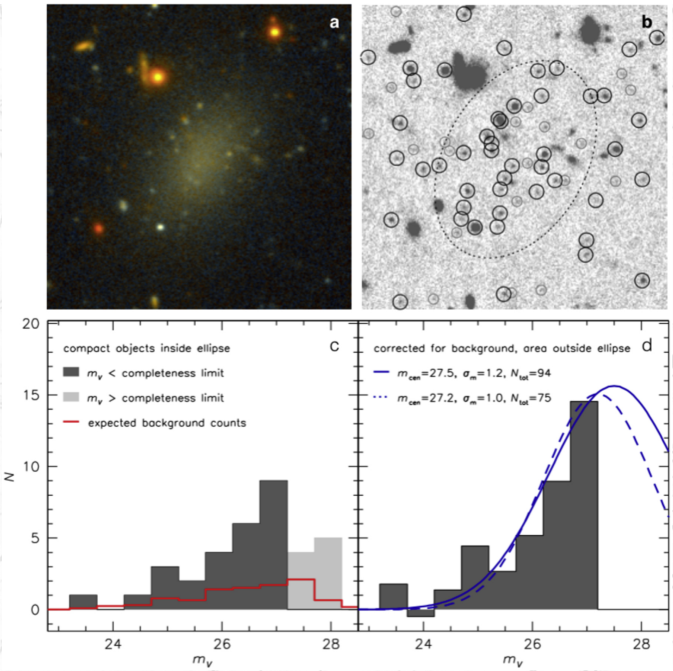


To produce a color image of Dragonfly 44 and its environs, Deep Gemini g and i photos were merged. The galaxy has an unusual look; it is a spheroidal object with low surface brightness that is dotted with dim, compact sources.

Two of the world's premier observation locations are home to the twin 8.1-meter optical/infrared telescopes that make up the Gemini Observatory. The telescopes at Gemini Observatory have access to the entire sky from their sites on Maunakea in Hawaii and Cerro Pachón in Chile. The NSF's NOIRLab runs the global Gemini Observatory.



The Gemini Deep Field Survey Offers a New Perspective on the Galaxy Assembly's Distance Universe. Several hundred far-off, elusive galaxies' ultra-deep spectra were recorded using the Gemini Multi-Object Spectrograph and a complex technique known as Nod & Shuffle. These findings from the Frederick C. Gillett Gemini North Telescope contribute to a fresh understanding of the characteristics and development of galaxies between 7 and 10 billion years ago.


a
b
c
compact objects inside ellipse
m_v < completeness limit
m_v > completeness limit
expected background counts
N
m_v
d
corrected for background, area outside ellipse
m_{cen}=27.5, σ_m=1.2, N_{tot}=94
m_{cen}=27.2, σ_m=1.0, N_{tot}=75
m_v

Preliminaries!

- The characteristics of Dragonfly 44 sparked an argument that hasn't been settled.
- Meanwhile, more than a thousand other large but weak galaxies have been discovered.

In recent years, more than 1,000 ultra-diffuse galaxies have been found, including Dragonfly 44, NGC 1052-DF2, and a pair of nearby galaxies known as NGC 1052-DF4 and NGC 1052-DF5.

Preliminaries!

- We call Dragonfly 44 and similar galaxies ultra-diffuse galaxies (UDGs).
- Although they can reach sizes comparable to the largest regular galaxies, UDGs are incredibly dark.
- Because of this, it can be difficult to remove background noise from telescopic surveys of the sky without inadvertently removing these galaxies.
- In UDGs, the luminous star-forming gas that is common in other galaxies appears to have disappeared, leaving just an old star's skeleton.

Preliminaries!

- They were not predicted by galactic evolutionary theory, which has caused a commotion over their presence. They were absent from the simulations.
- A galaxy needs to be created in a unique way if it is to be so large and dim.
- To explain the origins of Dragonfly 44 and other UDGs, fascinating new theories have surfaced.
- And these enormous blobs of light might be offering brand-new proof of the mysterious influence of dark matter.

A surplus of dark matter!

- As clusters of gas and stars are drawn together by gravity, their combined energy and momentum force the mixture to expand and rotate. A galaxy finally appears.
- There is only one issue: galaxies should split apart as they revolve. They don't seem to have enough mass or gravitational attraction to cling to one another. To fill in the gap left by the absence of gravity, dark matter was proposed. A galaxy can be seen inside a larger collection of nonluminous particles. The spinning galaxy is held together by this dark matter "halo".

A surplus of dark matter!

- The number of spherical star clusters in a galaxy can be used to calculate its rotational velocity and, consequently, its dark matter composition. From a theoretical perspective, we are unsure of why there are more of these "globular clusters", which are closely correlated with the harder to quantify features.
- It was discovered that Dragonfly 44 contains 94 globular clusters in this 2016 study, which shows the galaxy having very little visible matter.
- This finding showed that Dragonfly 44 contains an incredibly huge dark matter halo.
- Nothing like that has ever been witnessed before. It's possible that Dragonfly 44 is a "failed Milky Way" — a galaxy with a dark matter halo the size of the Milky Way that experienced an early unknown catastrophe that robbed it of its star-forming gas, leaving it with nothing but aged stars and a massive halo.

Or just no dark matter!

- Modifying Newton's equation of gravity, often known as modified Newtonian dynamics (MOND), allows us to claim that dark matter, the missing gravity in galaxies, does not actually exist.
- According to MOND, the mass-to-light ratio of each galaxy's stars, i.e., their total mass divided by their luminosity, is used to determine the modified gravitational force for each galaxy.
- The ad hoc formula, on the other hand, matches the observed speeds of the vast majority of galaxies without the need for dark matter.
- The MOND theory states that it does not hypothesize why it would depend on this ratio.

Or just no dark matter!

- In 2016, MOND determined that Dragonfly 44 should rotate more slowly than the initial estimate suggested based on its mass-to-light ratio. The data didn't seem to suit the MOND computation.
- But in 2019, when Dragonfly 44's rotation speed was downgraded using improved data, MOND was vindicated. Dragonfly 44 is an example of how these data evolve to agree with MOND.

Pieter van Dokkum, Asher Wasserman, Shany Danieli, Roberto Abraham, Jean Brodie, Charlie Conroy, Duncan A. Forbes, Christopher Martin, Matt Matuszewski, Aaron J. Romanowsky, Alexa Villaume
"Spatially Resolved Stellar Kinematics of the Ultra-diffuse Galaxy Dragonfly 44. I. Observations, Kinematics, and Cold Dark Matter Halo Fits",
The Astrophysical Journal, **880***:91, 26pp (2019),*
arXiv:1904.04838,
doi:10.3847/1538-4357/ab2914

May be again dark matter!

- However, according to dark matter theory, the slower rotation just indicated that Dragonfly 44's halo is smaller than first anticipated.
- By counting far fewer globular clusters in 2020, an independent group further reduced the size of the halo, but this finding is debatable.
- The extent of the halo is still unknown, although it might be smaller than first thought, indicating that Dragonfly 44 isn't a failed Milky Way after all.

Teymoor Saifollahi, Ignacio Trujillo, Michael A. Beasley, Reynier F. Peletier, Johan H. Knapen
"The number of globular clusters around the iconic UDG DF44 is as expected for dwarf galaxies",
Monthly Notices of the Royal Astronomical Society, **502**, *5921–5934 (2021),*
arXiv:2006.14630,
doi:10.1093/mnras/staa3016

May be again dark matter!

- Recent research has revealed that Dragonfly 44 is incredibly old, having evolved between 10 and 13 billion years ago.
- However, a galaxy that old shouldn't be as big as Dragonfly 44.
- Because they were created before the universe's fast expansion, early-universe objects have a tendency to be more compact.

Kristi A. Webb, Alexa Villaume, Seppo Laine, Aaron J. Romanowsky, Michael Balogh, Pieter van Dokkum, Duncan A. Forbes, Jean Brodie, Christopher Martin, Matt Matuszewski
"Still at odds with conventional galaxy evolution: the star formation history of ultradiffuse galaxy Dragonfly 44",
Monthly Notices of the Royal Astronomical Society, **516**, *3318–3341 (2022),*
arXiv:2208.11038,
doi:10.1093/mnras/stac2417

May be again dark matter!

- Furthermore, such an ancient, worn-out galaxy ought to have been utterly destroyed by now.
- The fact that Dragonfly 44 has survived suggests that it has a substantial dark matter halo after all, which could revive the “failed Milky Way” idea.

Another explanation: “high spin” hypothesis!

- If two dwarf galaxies combined while rotating in the same direction, Dragonfly 44 would inherit the angular momentum of both.
- It puffs out and blows out its star-forming material as a result of its faster rotation.

Stunningly Different UDGs!

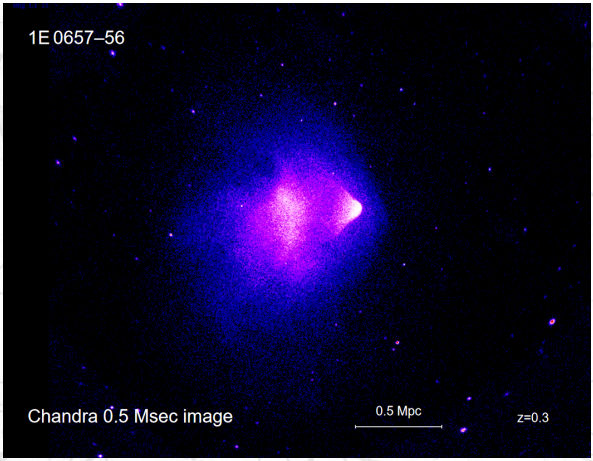
- Astronomers have compiled a huge and varied array of other ultra-diffuse galaxies while studying Dragonfly 44.
- They are being forced by the findings to draw the conclusion that galaxies originate in more diverse ways than they previously realized.
- Some newly discovered UDGs appear to have no dark matter at all.

Pieter van Dokkum, Shany Danieli, Yotam Cohen, Allison Merritt, Aaron J. Romanowsky, Roberto Abraham, Jean Brodie, Charlie Conroy, Deborah Lokhorst, Lamiya Mowla, Ewan O'Sullivan, Jielai Zhang
"A galaxy lacking dark matter",
Nature, **555**, *629–632 (2018)*,
arXiv:1803.10237,
doi:10.1038/nature25767

Stunningly Different UDGs!

- This galaxy has a trail of other galaxies nearby. Two galaxies collided in the past, creating the trail.
- The galaxies' gas flow was slowed down by the collision, but their dark matter continued to move as if nothing had happened.
- The gas subsequently condensed into star clusters, eventually generating a chain of galaxies devoid of dark matter.

Pieter van Dokkum, Zili Shen, Michael A. Keim, Sebastian Trujillo-Gomez, Shany Danieli, Dhruba Dutta Chowdhury, Roberto Abraham, Charlie Conroy, J. M. Diederik Kruijssen, Daisuke Nagai, Aaron Romanowsky
"A trail of dark-matter-free galaxies from a bullet-dwarf collision",
Nature, **605**, *435–439 (2022),*
arXiv:2205.08552,
doi:10.1038/s41586-022-04665-6



Example: X-ray photo by Chandra X-ray Observatory of the Bullet Cluster (1E0657-56). This provides support for the idea that most of the gravitation in the cluster pair is in the form of two regions of dark matter that bypassed the gas regions during the collision. This is consistent with predictions of dark matter being only gravitationally interacting, as opposed to weakly interacting. Distance: 1.141 Gpc (3.7 billion light-years).

Stunningly Different UDGs!

- In the UDG, there have been reports of recent star formation, debunking the notion that only old stars can be found there.
- A variety of UDGs that have an external appearance but differ within could support dark matter theory over MOND.
- For those other ideas, it would be extremely problematic if stars were traveling very quickly in one galaxy and very slowly in the other.

Steven R. Janssens, Aaron J. Romanowsky, Roberto Abraham, Jean P. Brodie, Warrick J. Couch, Duncan A. Forbes, Seppo Laine, David Martínez-Delgado, Pieter G. van Dokkum
"The globular clusters and star formation history of the isolated, quiescent ultra-diffuse galaxy DGSAT I",
Monthly Notices of the Royal Astronomical Society, **517**, *858–871 (2022),*
arXiv:2209.09910,
doi:10.1093/mnras/stac2717

Stunningly Different UDGs!

- There are actual outliers in the UDG population, which presents challenges for MOND.
- But that doesn't always mean that dark matter is a more accurate explanation.
- The recently launched James Webb Space Telescope has already observed far-off galaxies as they appeared when they were developing in the early cosmos, which will assist in testing and improving the initial hypotheses.
- We are still unaware of what is out there. Even after all these years of examining the sky, there may be galaxies that we haven't seen that are very large, very nearby, and have strange characteristics. These galaxies are not in our existing catalogs.