Science from the In Situ Exploration of the Proxima Centauri System: a summary

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This significant paper was submitted to arXiv.org on 22 April 2026. https://arxiv.org/abs/2604.20182 by T Marshall Eubanks (Space Initiatives Inc, USA) et al (including most of our i4is researchers). The paper has received considerable publicity in the scientific community, which is strong and heartening evidence of the surging interest in the subject. We wanted to showcase the content here as well as shine a spotlight on some of the insightful commentary recently posted by sources external to i4is.

Here's the abstract

In the future interstellar exploration at near-relativistic speeds will be possible using beamed energy laser propulsion. With this, spacecraft as small as gm mass picospacecraft become candidates for the exploration of deep-space, with a trade space of velocity and mission duration versus mass. Here, the authors examine the potential science return from interstellar expeditions with Coracle™ laser-sail picospacecraft swarms and show how even with fast flybys at near relativistic velocities, a picospacecraft swarm could deliver gigapixel resolution of the target exoplanets. The mission target is the planet Proxima b in the habitable zone of the red dwarf Proxima Centauri, the tertiary (and nearest) component of the nearest star system, Alpha Centauri. They explore science returns from such an expedition, both en route to Proxima and at the Proxima system, and conclude that initial small spacecraft expeditions would provide a substantial science return, including the ability to detect surface biology or a technological civilization, should either or both be established on the target planet.

Paper acknowledgments

The authors of the paper acknowledge that the work was supported in part by the NASA Innovative Advanced Concepts (NIAC) contract and also in part by a Breakthrough Starshot Foundation award.

Centauri Dreams

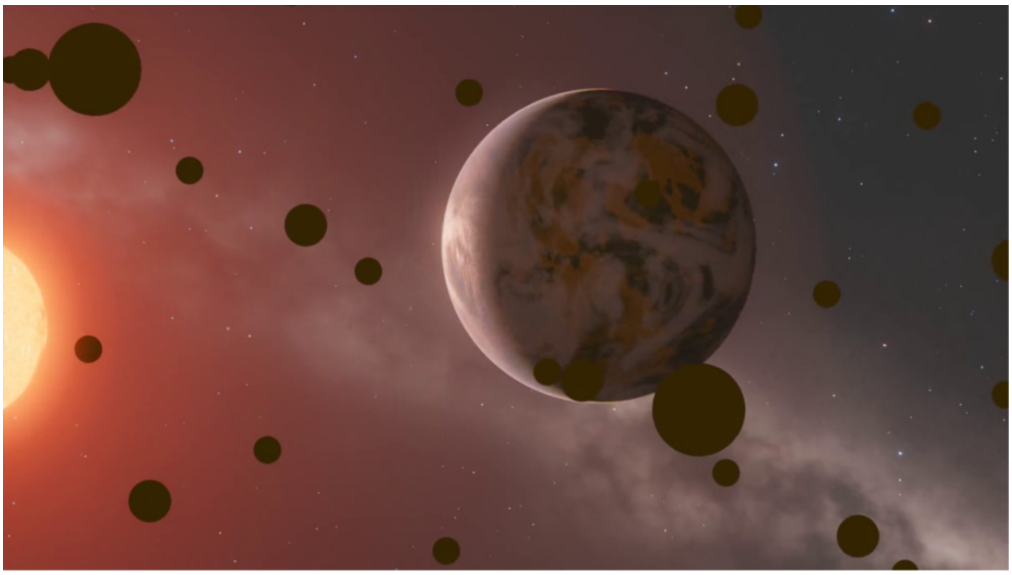
We were happy that our favourite interstellar blogger Paul Gilster penned a comprehensive review of the paper on 9 May 2026 in *A Deeper Dive into the Proxima Centauri Swarm*: https://www.centauri-dreams.org/2026/05/09/a-deeper-dive-into-the-proxima-centauri-swarm/. Discussing the communications problems of transmitting data back to Earth: "The concepts here are ingenious, even startling, and deserve further investigation". He concludes with the following words: "The kind of investigation mounted by this team is how we move the ball forward in interstellar studies. Drawing on recent work including the deep investigations of the Breakthrough Starshot scientists, Eubanks and colleagues have enlarged the speculative space especially in terms of communications and swarm computational options, all making an interstellar crossing in decades rather than centuries possible. This paper should be studied by anyone seriously following our increasingly refined strategies for making such a crossing happen".

Universe Today and Phys.Org

On 29 April 2026, Universe Today posted *Laser-Swarm Science at the Proxima Centauri System*: https://www.universetoday.com/articles/laser-swarm-science-at-the-proxima-centauri-system. Summarising: "Other stars are so far away that it will take bold initiatives to ever reach them. While other advanced propulsion technologies are always being pondered, we never know when they'll come to fruition. That's why the laser sail idea never goes away". Phys.Org also published the same article in their Space Exploration and Astrobiology sections: *Near-relativistic swarm could image Proxima b at 20-meter resolution and scan for biosignatures, paper says;* see https://phys.org/news/2026-04-relativistic-swarm-image-proxima-meter.html.

The art

I adore Dr Mark Garlick's artist's conception so much that I have to include this artwork again.



The Swarm approaches Proxima's planet b.
Image credit:
Dr Mark Garlick,
www.markgarlick.com

Some highlights of the paper

The authors investigate the potential scientific value and feasibility of sending a swam of picospacecraft to Proxima b, an exoplanet orbiting the red dwarf star Proxima Centauri. Proxima b is Earth-mass and orbits within the habitable zone of its star: the primary reasons for the intense scientific curiosity surrounding it. This paper is jam packed with science and my only caveat is that there are dozens of delightful rabbit holes to dive into!

We have previously published a few items on the design of the picospacecraft swarm so I've added those links at the end of this article for ease of reference.

The Coracle™ laser-sail picospacecraft are ultra-lightweight probes that use laser propulsion to achieve sufficiently high velocities that they reach the Proxima Centauri system within a few decades. They will execute a highly co-ordinated high-speed flyby to capture gigapixel-resolution data. The swarm of a thousand probes introduces redundancy to mitigate individual failures and maximise data collection.

Basic parameters of the proposed Coracle™ probe swarm. The aerographene metamaterial that forms the main probe body has a variable density, tailored for the particular mechanical requirements. A denser layer will support the drive-beam dielectric reflector while the middle layer will be very sparse. There would be thicker areas around the sensor/communications telescope array on the front face and around the betavoltaic, capacitor, and electronics layers to support them. There are 169 hexagon spaces for optical aperture, not all of which may be occupied depending on the mission profile and mass budget.
Credit (graphic and caption): Eubanks et al, Table 1

Swarm or Probe Parameter	Value [units]
Individual probe diameter [mm]	4000
Probe rim height [mm]	20
Main disk thickness [mm]	10
Mass budget: total sailcraft mass [mg]	3600
Mass budget: total sail mass [mg]	2600
Mass budget: total payload mass [mg]	1000
Mass budget: payload disk + apertures [mg]	330
Mass budget: betavoltaic battery and ultracapacitor pulsed storage [mg]	330
Mass budget: rim, intra-probe communications, computation and everything else [mg]	340
Overall input electrical power per probe, at flyby [mW]	6
Input electrical power to Swarm-Earth or intra-swarm lasers, at flyby [mW]	4
Optical output power per probe, at flyby [mW]	0.4
Swarm-Earth communications wavelength source / as received red-shifted [nm]	432 / 539
Maximum Number of probe multi-use optical apertures	169
Intra-swarm (rim) communications wavelength [nm]	12,000
Number of rim transceivers per probe	6
Transverse swarm diameter at flyby [km]	100,000
Number of probes at launch	1000
Number of surviving probes at flyby, after the Proxima encounter (assumed)	300
Average probe spacing within main swarm [km]	6100

Operational Considerations

Section 6 details the operational considerations of the mission in great depth, from power to communications and navigation.

Here's some teasers.

Swarm-to-Earth Communication

"We assume interstellar communications with 2-symbol Pulse Position Modulation (2-PPM), which is widely used in optical communications. 2-PPM uses synchronous time slots, with two adjacent time slots for each bit. A "0" value is sent with a pulse in slot 1 and no pulse in slot 2; and vice versa to send a "1" value. Symbols are transmitted at 1,000 Hz, with pulses nominally 1 ns in duration and the integration slots 10 ns in length. This technique also has the desirable effect of greatly lowering the unwanted background noise, since the integration time is very short...In conclusion, 0.9 kbps data transfers and a data return rate of 3.38 Gbytes/year, comparable to the data return of the New Horizons spacecraft after its Pluto flyby, should be possible with the main picospacecraft swarm at Proxima Centauri, and the two sub-swarms should each be able to return ~188 Mbytes/year back to Earth."

Establishing a Coherent Swarm

"A swarm of probes has a co-ordination problem after it is launched - at first, its members will not on their own know where the other probes are. As described in the Conops (Section 3), we have developed preliminary protocols to develop swarm coherency, defined as a set of probes with intra-swarm communication, positional knowledge, and the ability to position swarm members in a desired configuration. We find that a swarm with a diameter of ~100,000 km can, with assistance from Earth, gain "self-knowledge" and configure itself in deep-space (Eubanks et al 2023b [1]; Ding et al 2023 [2]; Dennison et al 2023 [3]). Establishment of coherence will occur in several distinct phases: Discovery, Probes as Beacons, Convergence."

Damage Reduction by Travelling Edge-On

"The VoT-Attitude Adjustment method could be initially be under control from Earth, but soon (due to communication latency), it has to become fully autonomous, ie, under the control of individual probes and eventually that of the swarm as a whole, which in effect would eventually create a "hive mind." With virtually no mass allowance for shielding, travelling edge-on is the only practical means to minimize the extreme radiation damage and erosion induced by travelling through the ISM at 0.2 c."

[1] *Swarming Proxima Centauri: Optical Communication Over Interstellar Distances* https://arxiv.org/abs/2309.07061
[2] *Distributed Machine Learning for UAV Swarms: Computing, Sensing, and Semantic* https://arxiv.org/abs/2301.00912
[3] *Autonomous Asteroid Characterization Through Nanosatellite Swarming* https://ieeexplore.ieee.org/document/10049738

Sheer volume of data

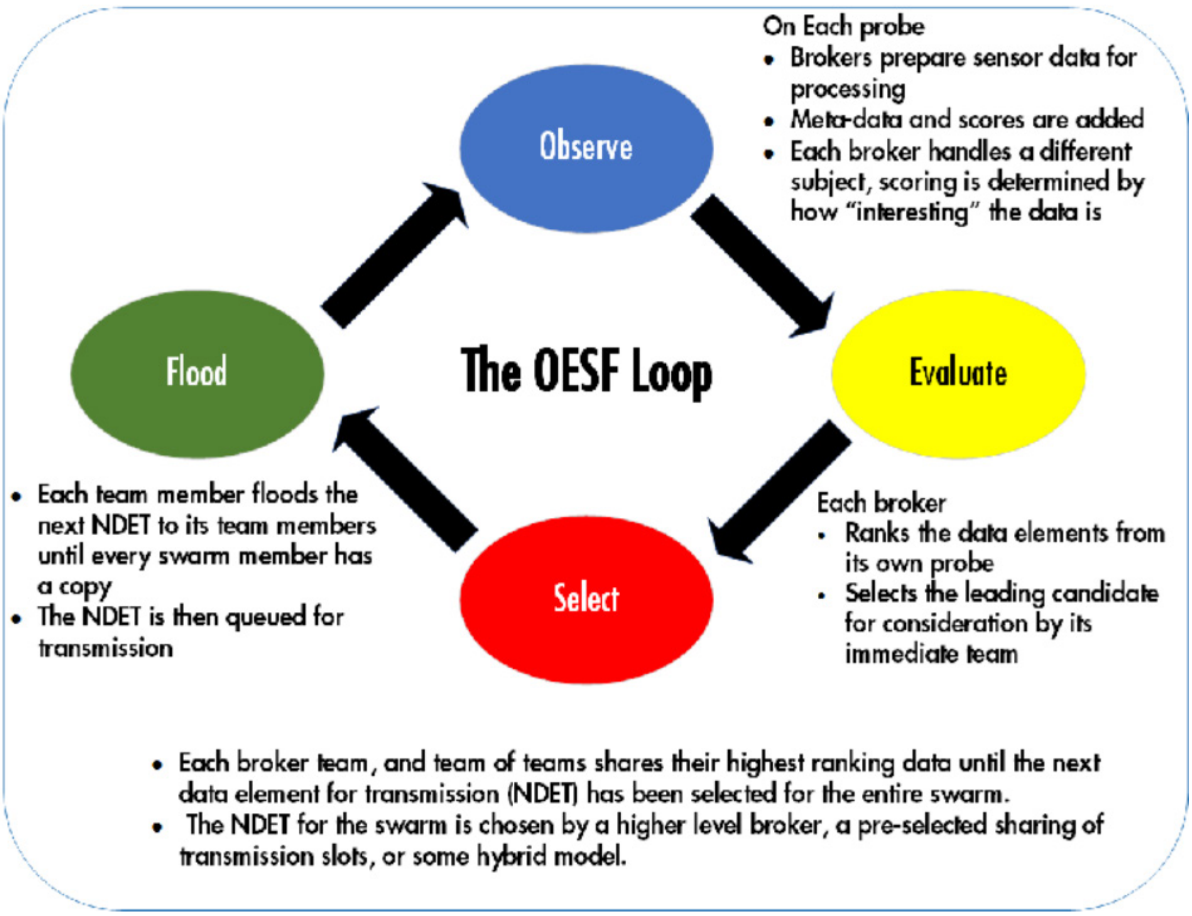
One significant problem is that the volume of data gathered will be simply too vast to send back to Earth in its entirety. Section 7 investigates some solutions.

"With the entire swarm co-ordinating the return of data to Earth, it should be possible to support a data rate of ~0.9 kbps, or ~3.4 gigabytes per year. The data selection process will thus demand new means of filtering and selecting data for return to Earth. Data-broker-agents (or agents) — automated software systems designed to support different scientific goals by sifting, characterizing and prioritizing swarm observations - will be critical tools for managing the floods of data from light-sail swarms."

OESF loops in Swarm data Selection

"There will be a mass of redundant data collected (nearly identical images of the target planet, for example), and having each probe flood all of its data to every other probe is not an efficient use of intra-swarm bandwidth. This can be solved through the use of Observe – Evaluate – Select – Flood (OESF) Loops, and the division of the swarm into nested sets of nearest-neighbour groups."

The basics of the OESF loop. To minimize bandwidth usage, this would be kept to small sets of neighbours, neighbours of neighbours, etc.
Credit (graphic and caption): Eubanks et al, Figure 10

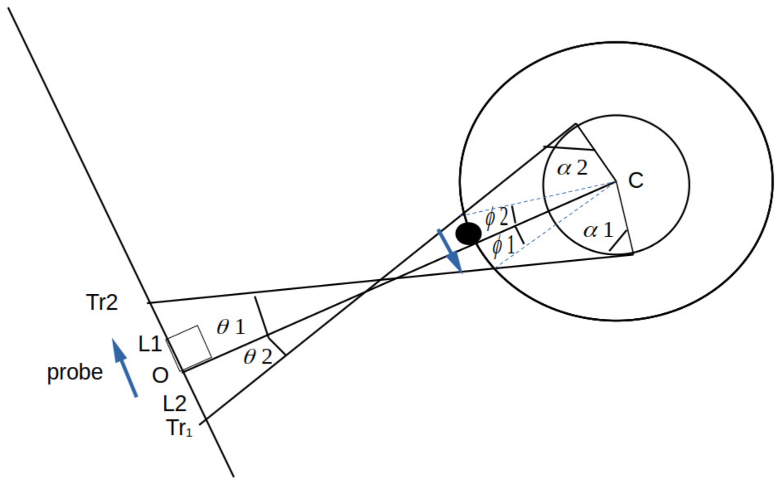


Science. science and more science

There are several scientific goals - both during transit and upon arrival - described in the paper. Some are summarised here.

En route science in section 8

1. Monitoring the Trailing Hemisphere: The orientation of the swarm will enable observation of objects and events in the swarm's trailing hemisphere during the 21-year voyage.
2. Stellar Occultations en route: During its two years voyage through the Solar System's Oort Cloud, the probes will observe stellar occultations by small bodies. Beyond the Oort Cloud, the probes will similarly observe stellar occultations by interstellar asteroids or rogue planets, if any, and then there will be a period when it is exposed to the shadows of bodies in the Oort cloud of the α Centauri system.
3. Detection of Nearby Bodies from Trajectory Deviations: We can investigate how the presence of a single body, with a gravitational mass may, through its gravitational influence, affect the trajectories of some probes as they fly past the object.
4. Exploring the Oort Cloud: The probability that at least one probe passes closer than 0.02 AU from a comet is 50%. Such close approach will allow direct imaging of Oort comets.
5. Astrometry: the probes can observe targets such as the nearby stars from a different perspective to the same stars as seen from the Solar System, possibility improving certain stellar data.
6. Observing Companion Transits en route: statistically, the probes can detect significantly more transits than are possible from Earth or a telescope in orbit.
7. Exploring the Interstellar Medium (ISM): in addition to remote observations, the probe will sample the ISM in situ.
8. Interstellar Dust: Recording the impact rate due to collisions with ISM "dust" (here, any particles bigger than single molecule) or other hazards will both inform this mission's operation and also provide the first high-fidelity map of the dust density all the way between Sol and Proxima.

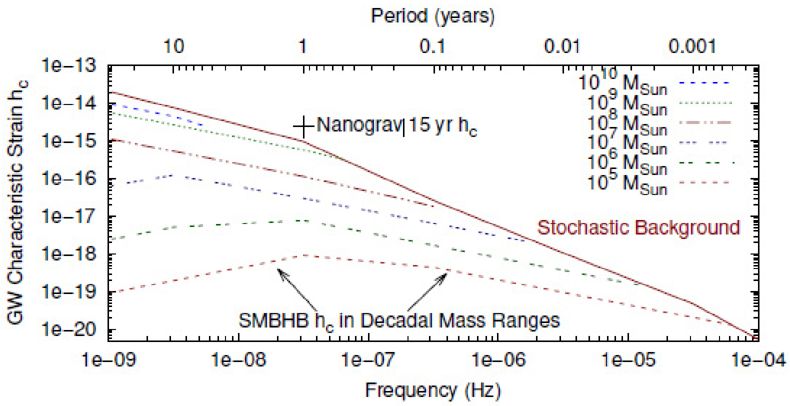


Geometry of the transit seen by the probe in direction antiparallel to the planet trajectory. Credit (graphic and caption): Eubanks et al, Figure 14

Science. science and more science...*continued*

Fundamental Physics in section 9

1. Tests of Gravity: MOND versus Newton. See Banik & Kroupa *Directly testing gravity with Proxima Centauri* [1].
2. Interstellar Gravitational Wave Detection: although unlikely from a single swarm, detection should become possible as multiple swarms are sent through the Proxima system over time.



Predicted gravitational wave characteristic strains based on statistical models of the SMBHB number density (Pesce et al 2022), here broken into decadal mass ranges. At a given mass, the number of sources declines going along the curve to the right (ie, towards higher frequencies); each curve stops at the frequency step where the expected number of sources in that mass decade falls below 1. These models agree reasonably well with the characteristic strain estimate, h_c, from the 15 year Nanograv pulsar timing analysis, shown here scaled to a nominal 1 year period (Agazie et al 2023).
Credit (graphic and caption): Eubanks et al, Figure 15

Arrival Science in section 10

Event	Distance	Time from Encounter	Assumed Abs. Mag. H
Detect Proxima b	~10,000 au	~300 days	-4.0
Detect Proxima d	~6000 au	~170 days	-1.6
Detect Proxima c	~1400 au	~40 days	-7.0
Resolve Proxima disk	~271 au	7.8 days	-
Detect 100 km Asteroid in Prox. b orbit	~27 au	18.5 hr	9.0
Resolve Proxima b disk	~21 au	14.6 hr	-4.0

Imaging possibilities before or after the Proxima encounter. The search for other planets in the system would be possible in the months around encounter, and in the few days around encounter an encounter video could be obtained monitoring atmospheric changes on all 3 planets. (Note that Proxima c, if it exists, is sufficiently far from its star to make it relatively dim, even though it would presumably be considerably larger than Proxima b.)
Credit (graphic and caption): Eubanks et al, Table 7

[1] https://academic.oup.com/mnras/article/487/2/1653/5491320 [2].
[2] Be mindful of rabbit holes mentioned in paragraph 1 on page 6 [3].
[3] Don't say I didn't warn you.

Science. science and more science...*continued*

Arrival Science in section 10...*continued*

1. Approach Imaging: Roughly 8 days before the encounter, the primary probe imaging apertures would be able to resolve the Proxima b Hill sphere and begin a search for Proxima b moons.
2. GigaPixel Imaging in the Proxima System: A single 200-mm aperture observing at optical wavelengths has a diffraction limited resolution of order 0.4 arc-seconds, providing a potential for gigapixel imagery in the Proxima system, revolutionizing the study of the Proxima planets.
3. Night-Side Imagery: As Proxima b is likely to be tidally locked - and the night-side could thus remain dark for all future missions - probes, trajectories and mission timing should all be developed to provide the best possible lowlight and IR imagery of the planet's night-side.
4. Bistatic Laser Ranging: The drive laser signal should be pulsed or modulated to allow for bistatic laser ranging (lidar) of objects in the Proxima system.
5. Transmission Spectroscopy: Transmission spectroscopy can be done at Proxima b using natural and artificial sources, and will, through the search for spectral lines of biomarkers and technosignatures, likely provide the best means of establishing the existence of a biology or even a technological society on Proxima b.
6. Proxima Helioscience: Proxima is a frequent flare star and the swarm should be able to provide valuable observations of the details of possibly a few dozen moderate intensity flares.
7. Impact Spectroscopy: it is possible that one or more Coracle™ probes would enter the Proxima b atmosphere, if it exists, or impact the surface, if it does not. The resulting flash would be potentially observable from the visible spectrum into the Gamma Ray bands by nearly the entire fleet and would yield important spectroscopic data about Proxima b's composition.
8. Proxima b geocorona: the Earth's geocorona - the planet's outermost neutral atmosphere - stretches well beyond the lunar orbit (Bertaux et al 1995). Any corresponding geocorona on Proxima b could be detected by probes, either by detecting any atoms in situ or by observing them via Proxima flare light.
9. Biosignatures and Technosignatures: the search for these will be intensive, aiming to image vegetation and detect biologically driven atmospheric lines.
10. Radio Science: Measurements of the intensity and frequency of radio emissions will provide information about the stellar and planetary magnetic fields in the Proxima system complementing direct measurements from magnetometers carried by the swarm.
11. Small Bodies: Beginning approximately 1 day before the Proxima b encounter, imaging of the Proxima system can be used to search for exterior planets, asteroid belts, and planetary moons and ring systems.

Conclusion

The authors conclude that initial, small-scale interstellar expeditions using laser-sail picospacecraft are highly viable and offer immense scientific returns. They serve as a foundational, practical first step for humanity's transition into in-situ interstellar exploration.

Some links to previous articles and milestones

The downlink from swarming micro-probes

Principium Issue 35 November 2021 page 66
https://i4is.org/wp-content/uploads/2021/11/The-downlink-from-swarming-micro-probes-Principium35-print-2111260906-opt-3.pdf

i4is delivers Communications Study to Breakthrough Starshot

Principium Issue 41 November May 2023 page 50
https://i4is.org/wp-content/uploads/2023/05/News-Feature-i4is-delivers-Communications-Study-to-Breakthrough-Starshot-Principium41-23052291003-1.pdf

NASA NIAC funds swarming study

Principium Issue 44 February 2024 page 14
https://i4is.org/wp-content/uploads/2024/02/NASA-NIAC-funds-swarming-study-Principium44-2402201033-comp.pdf

The Interstellar Coracle™ at the NIAC Symposium in Pasadena

Principium Issue 49 May 2025 page 27
https://i4is.org/wp-content/uploads/2025/06/coracle-pasadena-Principium49-2506041431.pdf

In **September 2018**, our Step A proposal #18-NIAC19A-0090 "*Swarming Proxima Centauri: Optical Communication over Interstellar Distances*" was submitted by i4is-US to NIAC.

On **5 December 2018** the Institute for Interstellar Studies submitted a Step B proposal #18-NIAC19A-0090 "*Swarming Proxima Centauri: Optical Communication over Interstellar Distances*".

On **24 April 2023**, after a year of preparation and a year-and-a-half of contracted work, Institute for Interstellar Studies-US delivered its final systems engineering analysis and conceptual design to the Breakthrough Starshot Foundation.

On **12 September 2024,** Marshall Eubanks (Space Initiatives) and the i4is team presented at NASA NIAC 2024 Pasadena on their proposal "*Swarming Proxima Centauri: Coherent Picospacecraft Swarms Over Interstellar Distances*".

The video was officially released by NASA Space Tech on YouTube in September 2025. See https://www.youtube.com/watch?v=XXW_keR5OIM.