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One of the most ancient forms of life dating to ~3.5 bi
abundant organisms that convert light into energy an

different orientations, an active-matter analog of the Kibble-Zurek mechanism[45–47]. The possibility of forming light-induced active nematic

F . 3 43D t t t t v 2 t . Image of a 3D Geitlerinema sp. community induced by projecting a pattern of light with intensity gradients, obtained by projecting an inverse intensity pattern corresponding to the Mona Lisa painting by Leonardo da Vinci. Zoomed in 3D nematic gel ordering of trichomes captured by multiphoton imaging. 3D schematic of nematically arranged filaments embedded

displacements upon the transition from the nematic fluid to a gel state (Fig. 5c, d). The average value of d_{rev} for these 3D nematic states is ~8 μm (Fig. 5e), interestingly, being even shorter than ~22 μm for its thin 2D counterpart of the same age. The filamentous velocity in the 3D nematic fluid, which is ~0.84 μm/s under illumination conditions of our experiments, eventually decreases down to 0.13 μm/s upon the contiguous formation of the gel state as time elapses (Fig. 5g). Photobleaching of both 3D fluids and gels reveals that the recovery to uniform states typically occurs within 30 min in the former case (Supplementary Fig. 5c) and only after more than 1 h (Supplementary Fig. 5d) in the latter case, consistent with the observed slower filament propulsion within the gel revealed by videomicroscopy (Supplementary Movies 5 and 6).

Emergence and behavior of defects in phototactic active nematics

Collective trichome migration to lit areas often prompts merging of smaller nematiclike cyanobacterial colonies with misaligned local director orientations (Supplementary Figs. 6 and 7), which yields topological defects, singular points in the 2D ( ) where director cannot be defined and S_{2D} vanishes[6] (Fig. 6d–j, Fig. 7d–i and Supplementary Movies 7 and 8). We observed defect formation for both Geitlerinema sp. (Fig. 6d–j, Fig. 7d–i and Supplementary Fig. 6) and O. brevis (Supplementary Fig. 7) species studied here. This defect formation out of the misaligned active nematic domains can be thought of as an active matter analog of the Kibble-Zurek mechanism[45–47], where nematic domains having different director orientations merge to form the topological defects (Supplementary Fig. 6). The probabilities of having defects versus larger uniform domains formed in this process depends on the misalignment angles between multiple interacting smaller domains. The observed defects are characterized by a winding number m, defined as the number of times the director rotates by 2π when one circumnavigates the defect once, with the sign determined by the ( ) rotation relative to the circumnav

diagonal direction of the cyanobacterial filament orientations and motions emerges spontaneously (alignment along the other diagonal can occur with the same probability). Corners of the region impose perturbations of the alignment and motion directionalities (bottom left and top right corners in Fig. 10a) or cause locally reduced number density of bacteria (top left and bottom right corners, Fig. 10a). The cyanobacterial filament orientations slightly depart from the orientation in the bulk along the other fragments of the perimeter of the illuminated square-shaped region (Fig. 10a

moving "in an orderly manner"[38,41,44] were also active nematics, the "living liquid crystals" described in the scientific literature, long before the recent renewed interest in such systems[9–11]. Our work systematically shows how gradients of ambient-level light intensity trigger isotropic-nematic transformations and orderly phototactic motions within the dense cyanobacterial communities, which could be potentially related to van Leeuwenhoek's observations, even though his description of findings could also have other explanations[38,41,44]. Furthermore, we showed how the phototaxis drives a transition from initially polar motions of semiflexible long filaments along complex curved spatiotemporal trajectories confined within illuminated areas to their bipolar motility in the e

The active nematic state of motile Geitlerinema sp. filaments at the water-air i

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