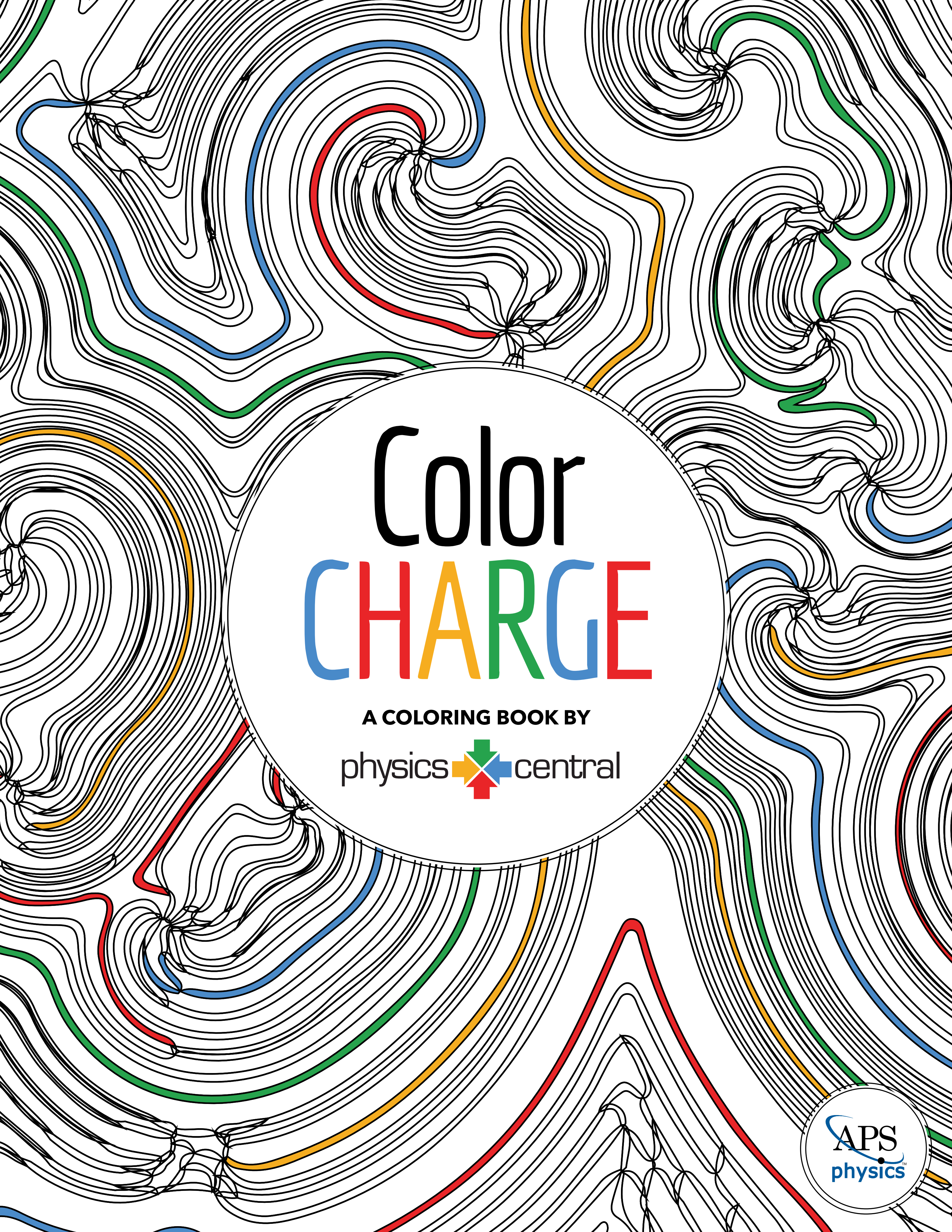

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Thank you for picking up ***Color Charge***, a new coloring book from the from the American Physical Society and PhysicsCentral! While previous coloring books we've released have been aimed at a young audience, *Color Charge's* designs and content are a little more advanced. On each page, you'll find an intricate, colorable, physics-related image, along with a short explanation of what you're seeing—all intended to entertain, educate, and inspire.

ABOUT THE TITLE

You probably know that all the visible matter in the universe is composed of infinitesimal particles known as atoms, a hundred million times smaller than the head of a pin. As small as an atom is, every atom is composed of particles ten thousand times smaller than that—protons and neutrons. And inside those protons and neutrons, there's *yet another* level of even smaller structure: quarks!

Electrons and protons have an electric charge that governs how they move and interact, and quarks have electric charge, too—but they also have another kind of charge: *color charge*. While there are only two kinds of electric charge, positive and negative, there are three kinds of color charge: red, green, and blue. These don't correspond to actual colors, though; they refer to the fact that a proton or neutron must contain all three kinds. Red, green, and blue quarks add together to create a stable particle, just as red, green, and blue light can add together to produce white. While the rules that govern these interactions—called *quantum chromodynamics*—are a little too involved for us to go into here, we couldn't pass up a perfect name like *Color Charge*. We hope you have as much fun coloring it as we did putting it together!

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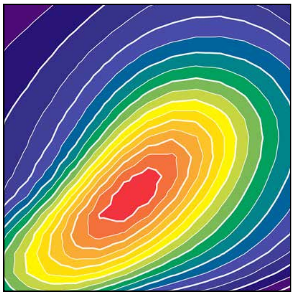
Text by Stephen Skolnick
Images adapted by Ashley Mumford

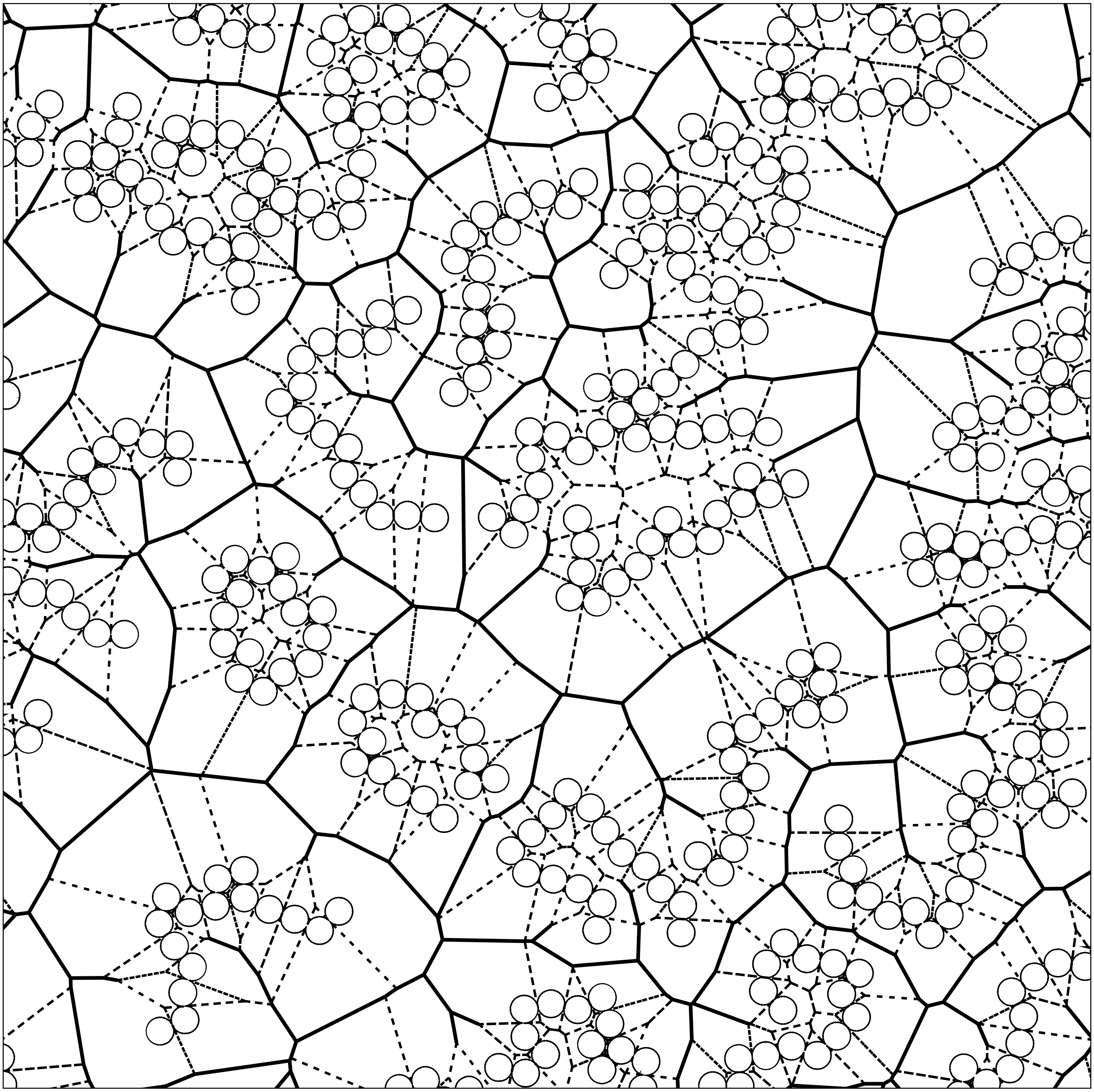


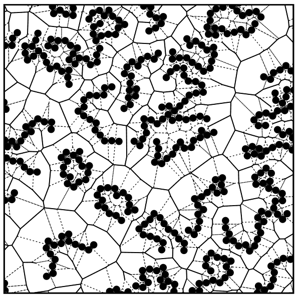
Spontaneous oscillations, signal amplification, and synchronization in a model of active hair bundle mechanics

Lijuan Han and Alexander B. Neiman, Phys. Rev. E **81**, 041913 (2010)

When a sound wave hits your inner ear, it rustles thousands of tiny brush-like structures called *hair bundles* that protrude into the fluid that sits behind your eardrum. These vibrations cause special pores in the hair bundles to open up, letting in positively charged calcium ions. This flow of charges creates an electrical signal, which can then be transmitted along your neurons to the brain, where it will be processed and interpreted.

This image is taken from a graph showing how the responsiveness of hair bundles, represented by the color, depends on a sound's frequency (x-axis), as well as on the surrounding fluid's concentration of calcium ions (y-axis). The complex, variable properties of these hair bundles are responsible for their ability not only to detect sound waves, but also to amplify them, and even to generate sounds of their own—a process called *otoacoustic emission*.



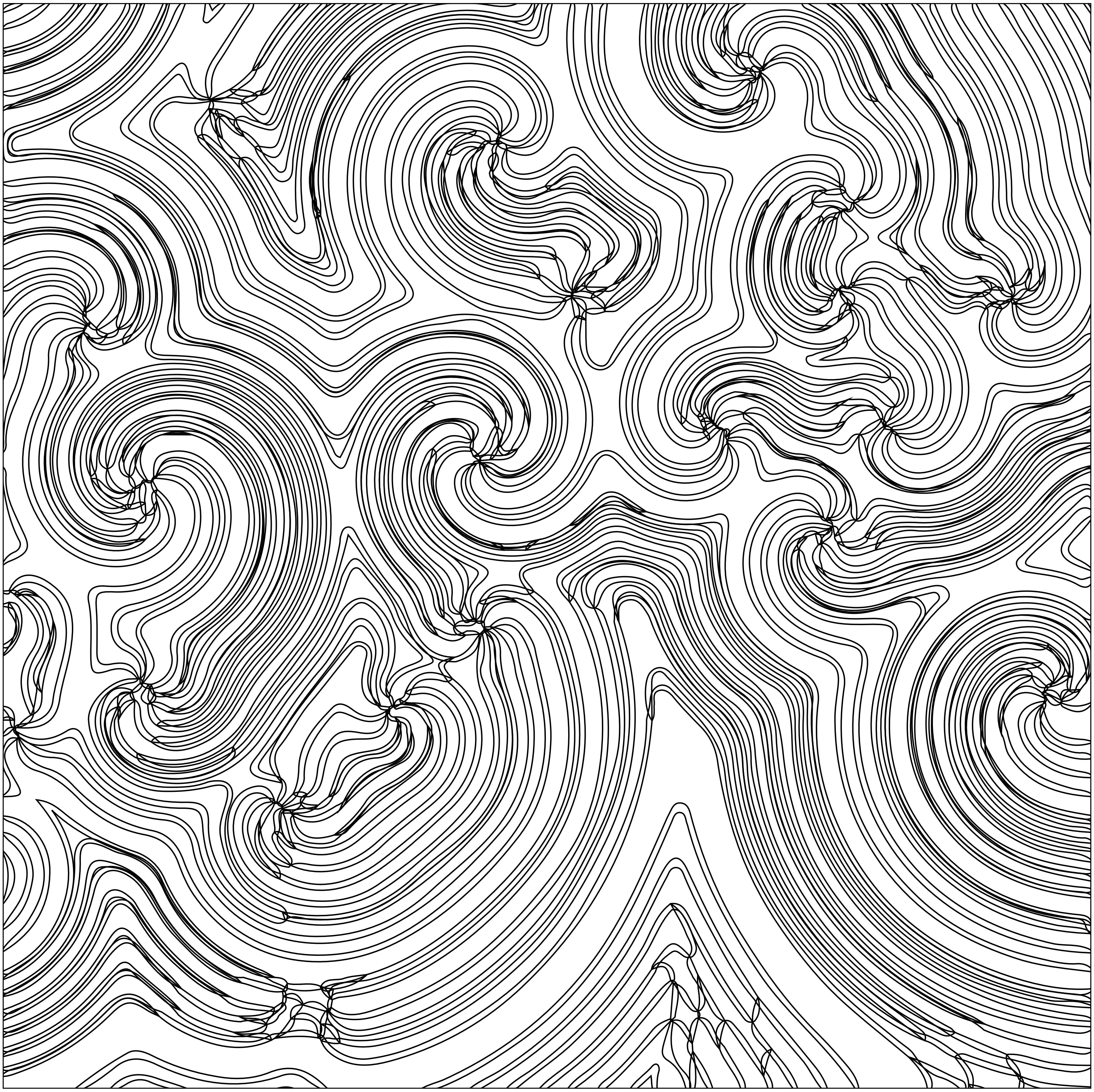


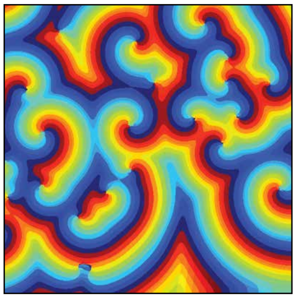
Structure of void space in polymer solutions

Bong June Sung and Arun Yethiraj, Phys. Rev. E **81**, 031801 (2010)

Any time a chain of identical molecules are linked together into a larger molecule, it's called a *polymer*. Plastics are composed of polymers—although not all the molecules in a plastic cup are linked together. The polymer chains, sometimes hundreds of molecules long, get tangled up and interwoven to form a solid, sort of like a clump of cat fur.

This figure, called a *Voronoi diagram*, was created to examine the gaps among chains in a polymer material. This can help us predict a material's properties, like how airtight or heat-stable a plastic will be. Each of the circles is a *monomer*—a component of a polymer chain—and around each monomer is a *cell*: the space that's closer to that monomer than to any other. Voronoi diagrams are useful in all sorts of contexts, but this one helps us analyze how freely molecules can shift around. Solid lines indicate a path that a free monomer could take, while dashed lines are ones where it's too tight for the particle to squeeze through.

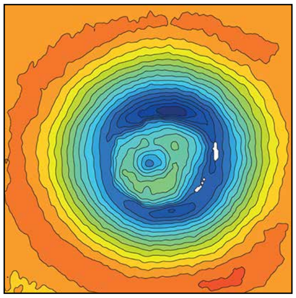




Weakly and strongly coupled Belousov-Zhabotinsky patterns

Stephan Weiss and Robert D. Deegan, Phys. Rev. E **95**, 022215 (2017)

A Belousov-Zhabotinsky (BZ) reaction is a complex bit of chemistry that involves atoms losing electrons, gaining them back, and losing them again. In the right conditions, certain atoms look different depending on how many electrons they've got in their outer shell, so the BZ reaction creates visible concentric rings that slowly spread out from a central point—at least when the reaction takes place in calm circumstances. In a more chaotic environment, like one where there are multiple origin points that these waves radiate out from, patterns like the image above can form when wave fronts run up against one another and interfere.

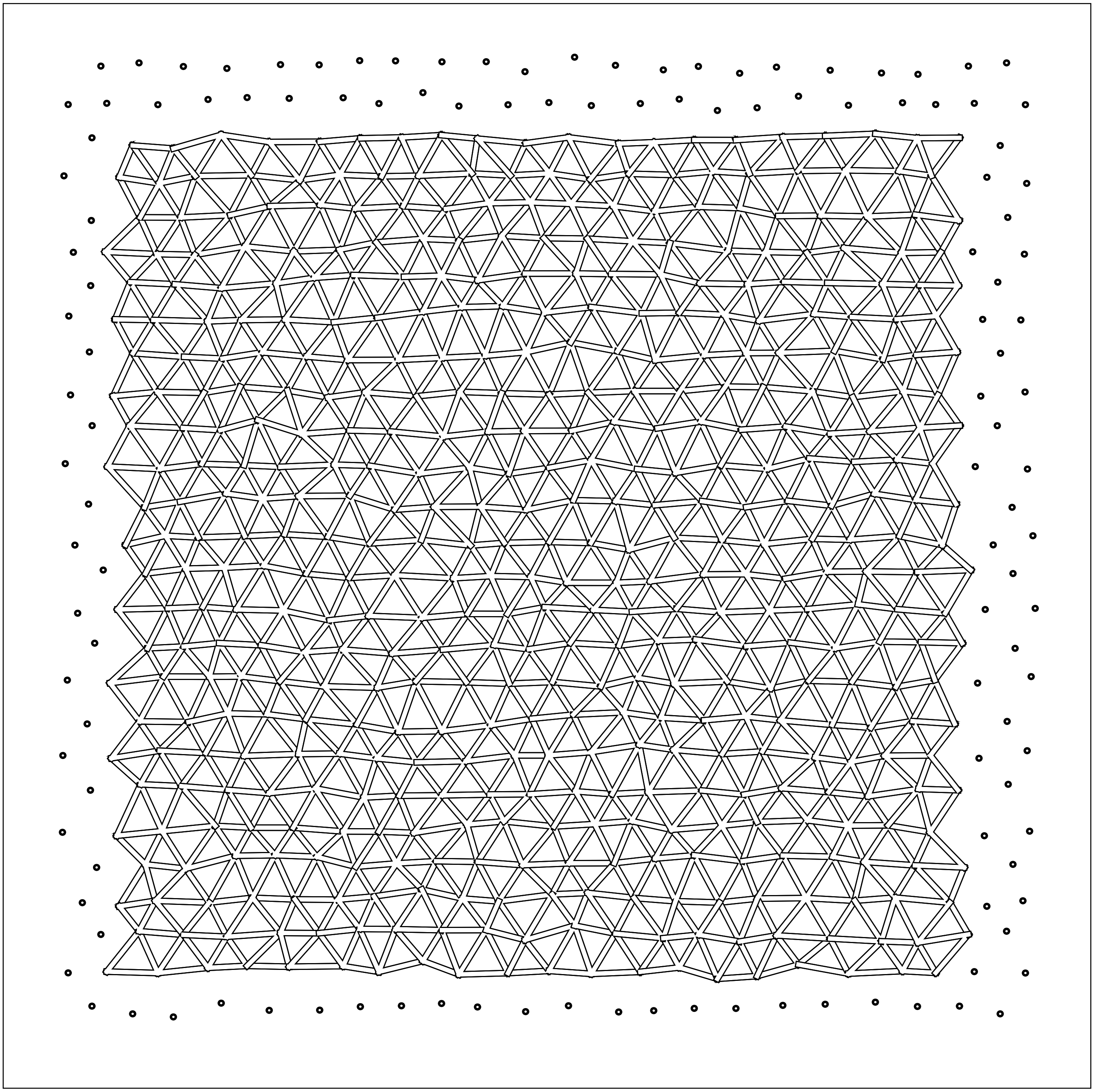


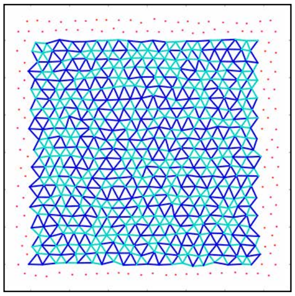
Crater formation during raindrop impact on sand

Rianne de Jong, Song-Chuan Zhao (赵松川), and Devaraj van der Meer, Phys. Rev. E **95**, 042901 (2017)

When we think of craters, it's usually the pockmarked surface of the moon that jumps to mind, or else the giant basins left by impacts on ancient Earth. But similar physics governs the behavior of sand and soil when they're hit by a simple water drop, with important implications for things like agriculture—if you want to create an efficient watering system, you need to know how the drips are going to affect your soil.

The image here is a topographical map, which uses different colors to indicate the changing elevation of the landscape…although in this case the landscape is only about a centimeter across, scanned with a laser beam. At the center, starting at the green rings, the sand is saturated by a water droplet, forming a donut-like raised shape with a dent in the middle.

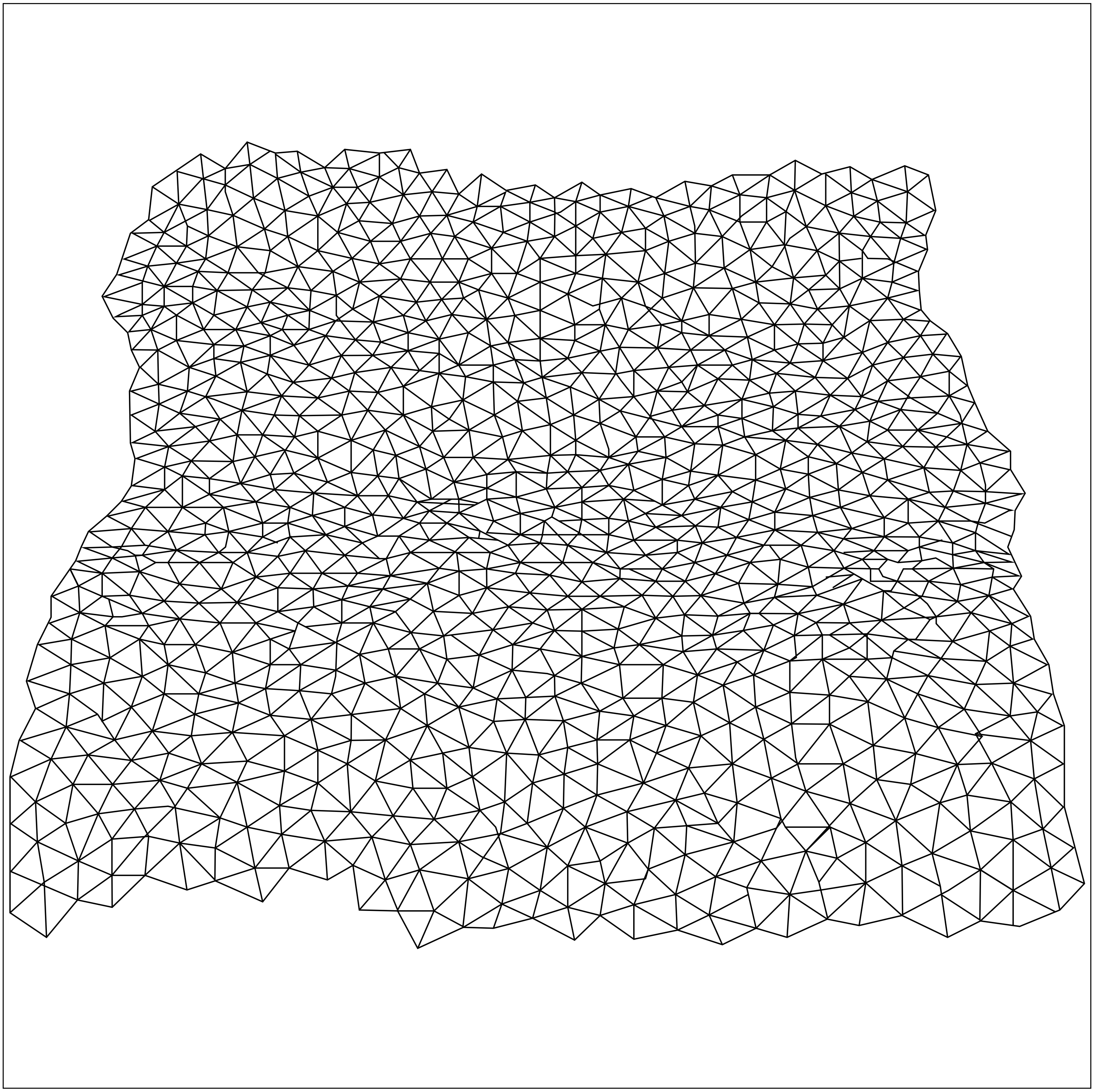


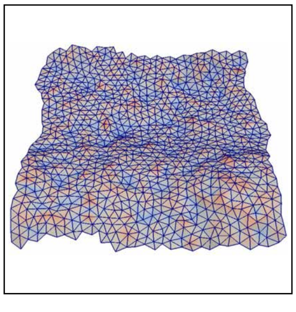


Effects of disorder and chain stiffening on the elasticity of flexible polymer networks

Christiane Caroli and Anaël Lemaître, Phys. Rev. E **95**, 032501 (2017)

Polymers, like the ones discussed on page 2, can have a wide range of properties. Some polymer-based substances are hard solids, while others are flexible—both the plastic body of a mechanical pencil and the rubber of its eraser are made of polymers. The difference has to do with the connections among their molecules, and how strongly they influence one another: you can't move one molecule in the pencil without moving the rest, but the eraser can be stretched or twisted without breaking. To design materials with specific features, we need to understand how the length of a polymer chain determines the properties of the material that it's a part of, and how interactions between chains factor in. The image above is a simulation of a polymer, representing it as a 2D network of short and long chains linked at various points. Using a simplified model like this lets us make predictions based on well-known physics principles, which can then be linked to results from the real world.



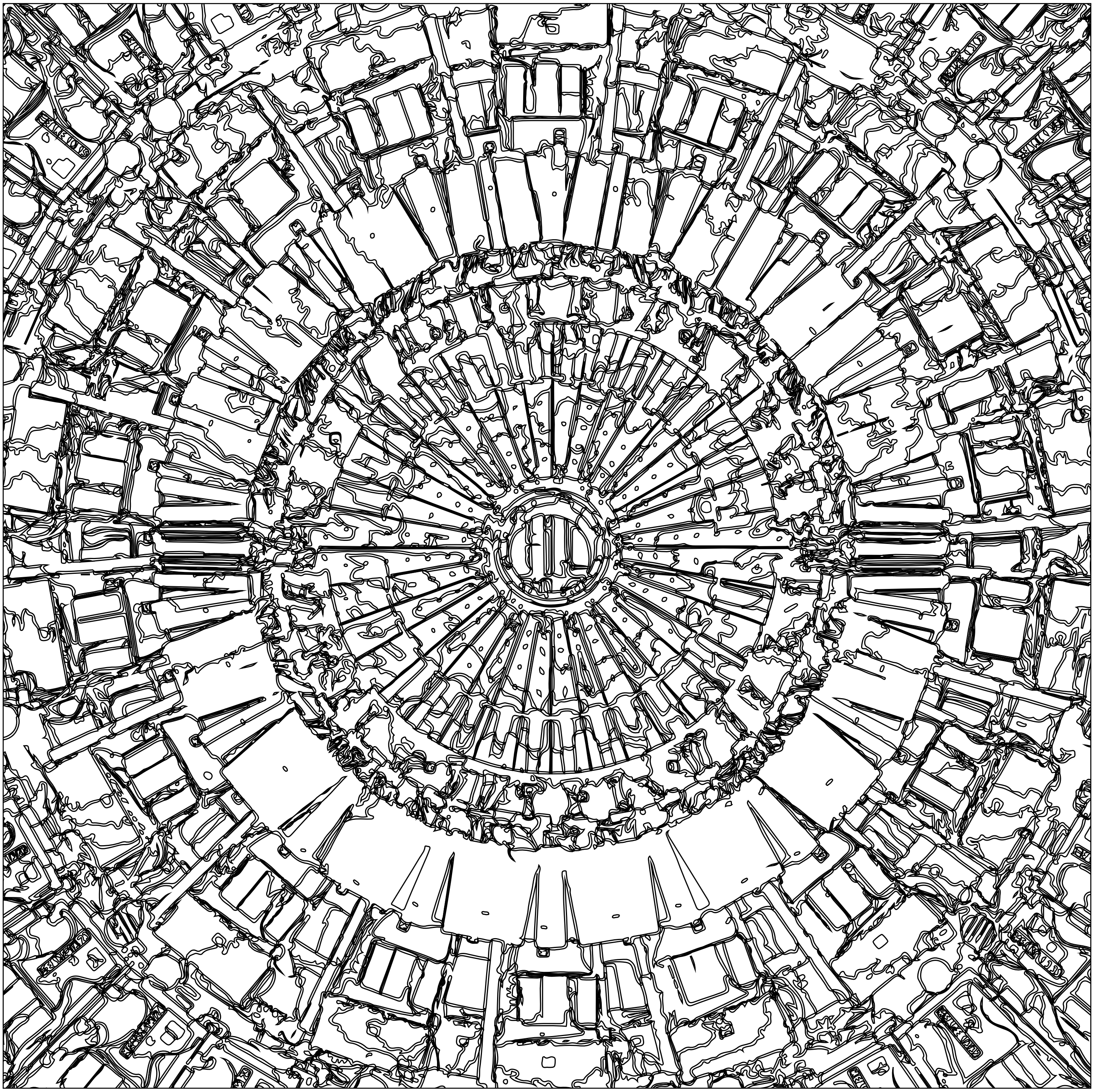


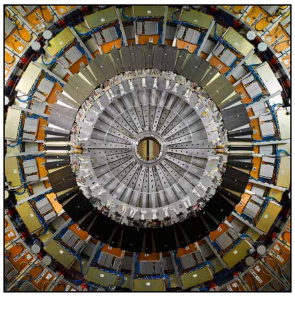
Defining the free-energy landscape of curvature-inducing proteins on membrane bilayers

Richard W. Tourdot, N. Ramakrishnan, and Ravi Radhakrishnan, Phys. Rev. E **90**, 022717 (2014)

Proteins, long chains of amino acids folded up into various shapes, are the molecular machines that drive most life as we know it. Some sit on a cell's surface and pull in chemicals from the environment, while others act as flags to help your immune system tell the difference between your body's cells and a pathogen's. Anything a living thing does, you can bet there are proteins involved.

The proteins in this study are *curvature-inducing* proteins; they help give a cell shape, and let it change that shape to do things like perform cell division. But any machine requires energy to run, and there's no gas tank here—curvature-inducing proteins get their energy from the membrane they're embedded in. To understand them, we need to model the interaction between the proteins and that cell membrane. In the image above, scientists have simulated the kind of texture you'd see on the membrane of a real cell, allowing for a realistic study of curvature-inducing proteins' functions.



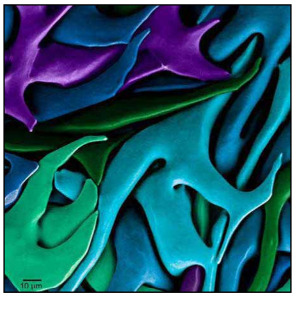


Compact Muon Solenoid (CMS) particle detector inside the Large Hadron Collider

Getty Images

In a particle accelerator, bits of matter like protons and neutrons are ramped up to extraordinary speeds—so fast that time passes hundreds of times slower for them than it does for us, thanks to a strange quirk of relativity. These particles are smashed into one another, producing a spray of subatomic shrapnel that helps us understand what gives these particles their unique properties. All this action is too small and too fast to catch on a camera, of course, so particle detectors like the Compact Muon Solenoid have been built to lend a hand.

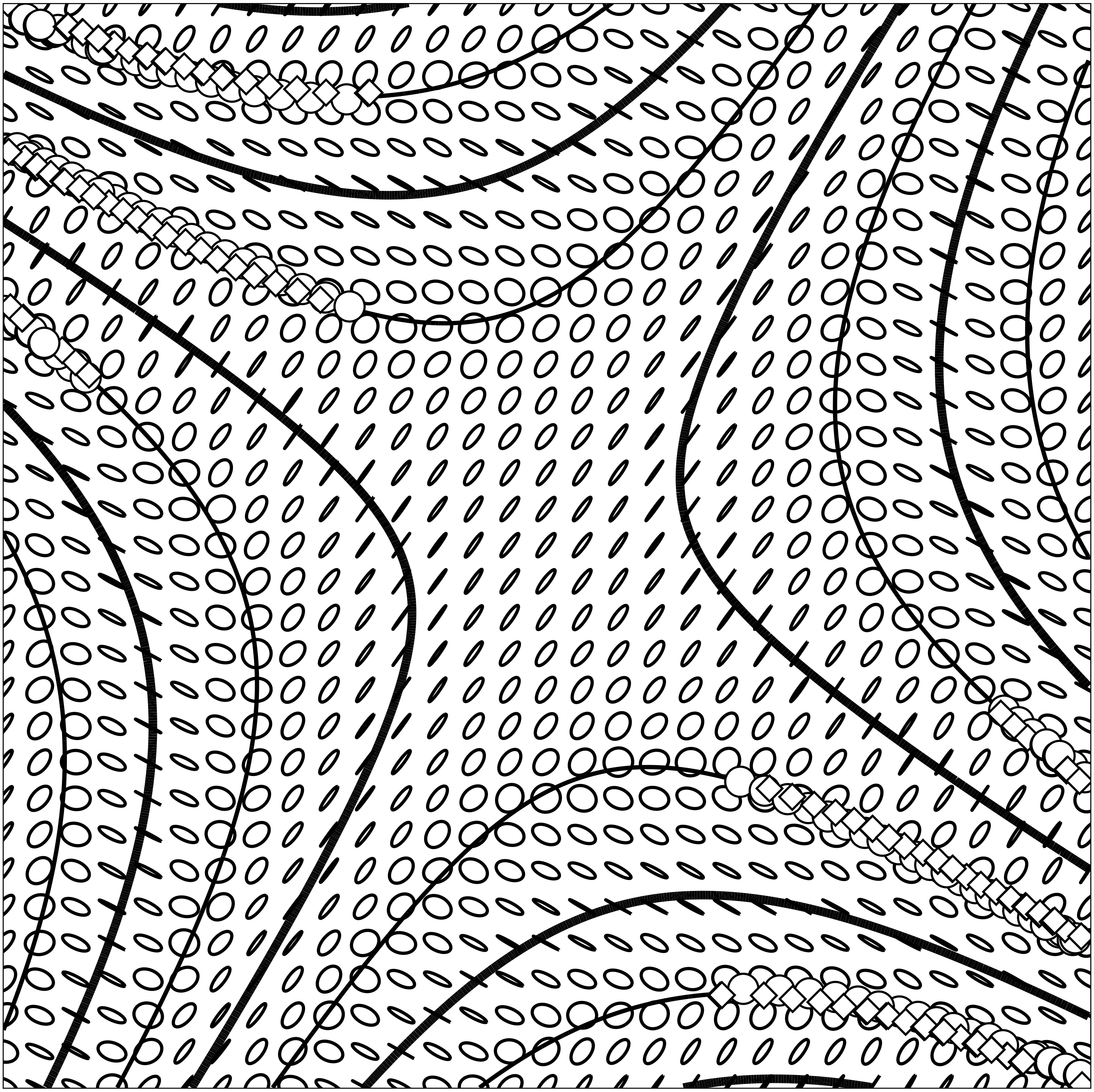
The CMS detector uses high-strength magnetic fields to steer particles that enter it, guiding them into chunks of materials that produce light or electric currents when they're struck by the high-energy byproducts of a particle collision. After analyzing the data that comes from the multiple different detectors incorporated into CMS, scientists can reconstruct the particle's path, learning about its momentum, charge, and other properties.

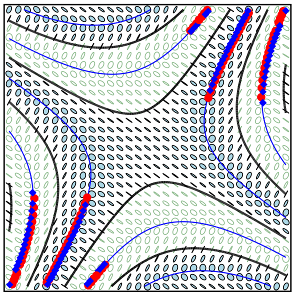


Structure of Calcite Crystals in Sea Urchin Teeth

Pupa Gilbert, University of Wisconsin-Madison (2011)

When we think of crystals, the image that springs to mind is usually a translucent prism, like a gemstone. But a crystal is any material made of a repeating pattern of atoms, linked together in a characteristic way—so everything from seashells to metal fits the bill. In this image, taken with a microscope that bounces electrons off its target (rather than photons, as with an ordinary microscope), we can see the intertwined plates of calcium carbonate crystal that make up a sea urchin's teeth. This puzzle-piece-like arrangement provides integrity and versatility—when bits break off, they do so in such a way that the tooth gets sharper.



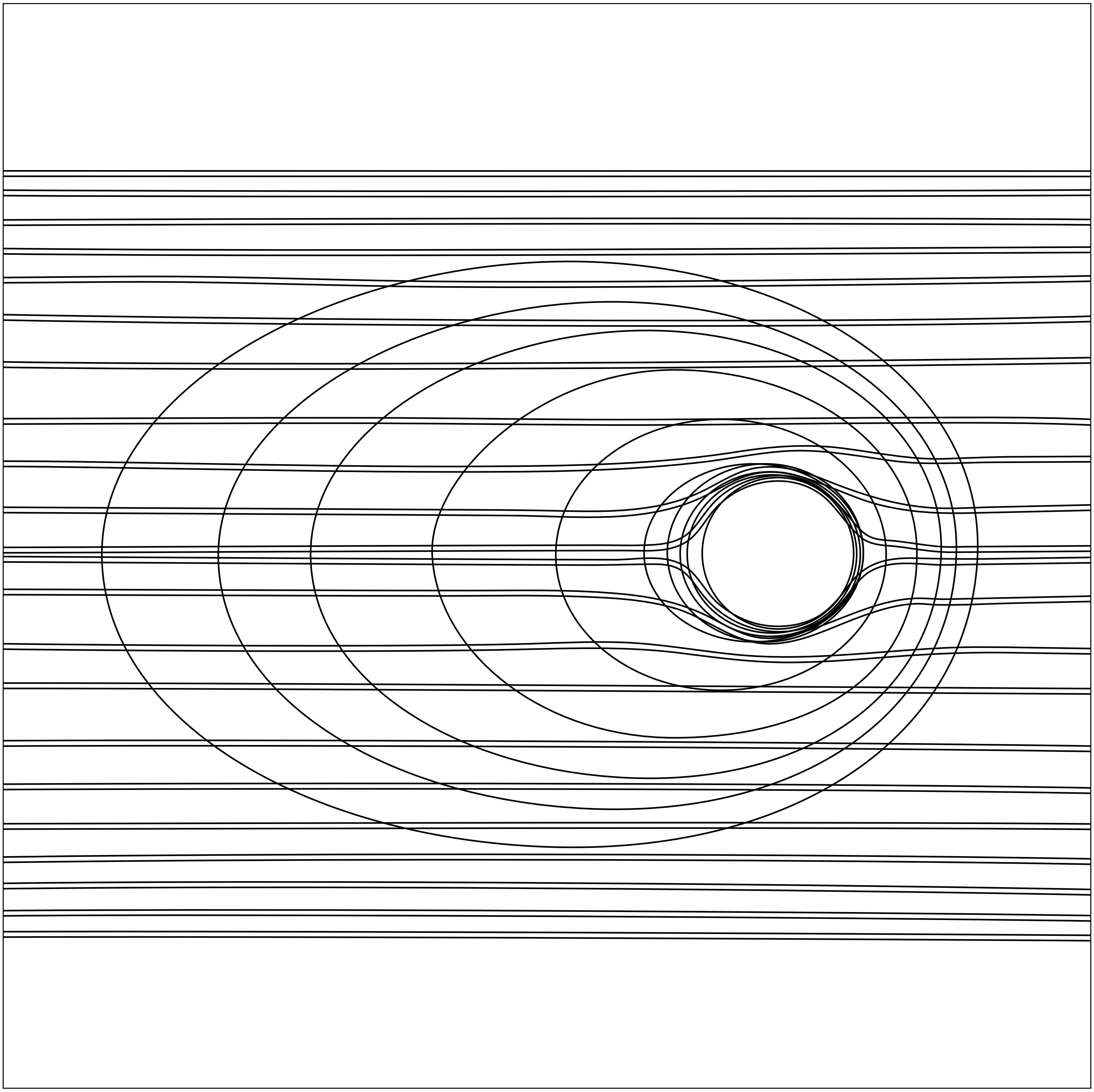


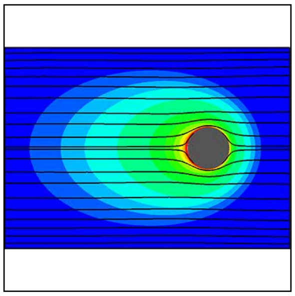
Optics of short-pitch deformed-helix ferroelectric liquid crystals: Symmetries, exceptional points, and polarization-resolved angular patterns

Alexei D. Kiselev and Vladimir G. Chigrinov, Phys. Rev. E **90**, 042504 (2014)

Liquid crystals are an interesting state of matter somewhere between a liquid and a solid. They can flow like a liquid, but have repeating structure like a crystal. There are a number of uses for liquid crystals, such as in calculators, computer displays, and televisions. Liquid crystals can have many different structures, or phases, and by using the polarization of light it's possible to see what type of phase a particular liquid crystal has. Some types of liquid crystals will respond to strong electric fields, flipping around based on the magnitude and direction of the field. One orientation of liquid crystals is a helix, like a twisted rope ladder with long liquid crystal molecules in place of the bars.

This paper looked at a theoretical way to predict the orientation of the crystals based on an electric field being applied. The image shown here is a computer-generated picture of how crystals might line up in the presence of a specific electric field.



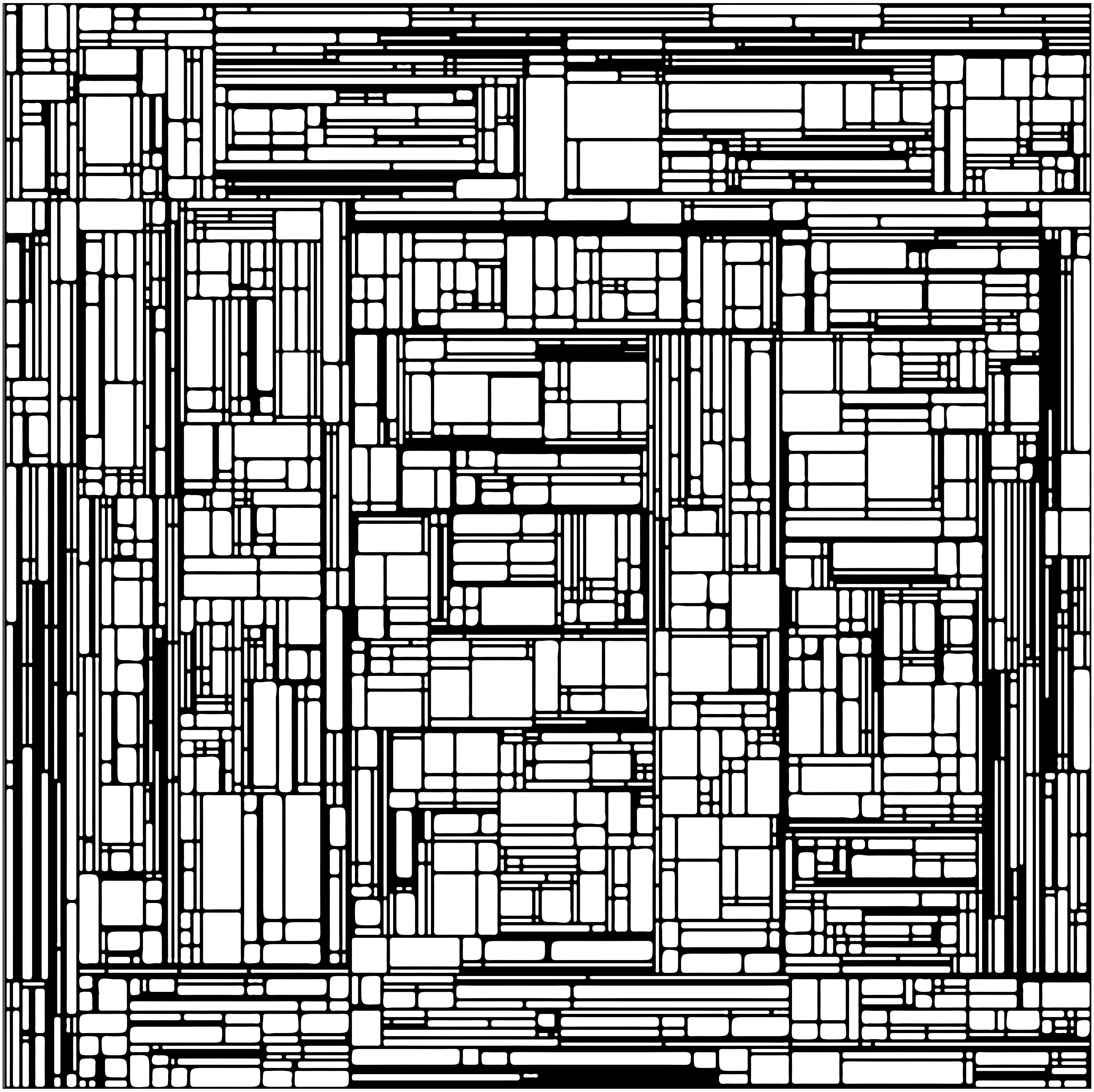


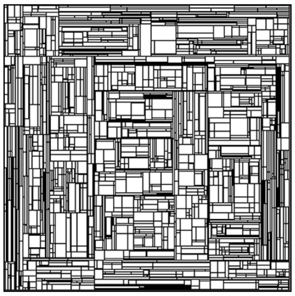
Electrophoresis of a polarizable charged colloid with hydrophobic surface: A numerical study

Somnath Bhattacharyya and Partha Sarathi Majee, Phys. Rev. E **95**, 042605 (2017)

When a *polarizable* particle is placed near a strong negative charge, some of the positive charges in the particle are attracted to the external negative charge, while the particle's negative charges are repelled to the far end. As a result, the particle is attracted to the source of the electric field. By putting something in the way that impedes these particles' motion, like a thick fluid or gel, particles can be separated by size in a process called *electrophoresis*; small particles have an easier time making their way through the gel. Forensic scientists, for example, use electrophoresis to process and compare DNA samples.

In this image, researchers are looking at how the surface properties of a particle affect its motion during electrophoresis—if a particle is water-repellent, or *hydrophobic*, it flows through materials differently than a non-hydrophobic one, thanks in part to the distribution of charges around it—represented by the oval rings around the particle in this image.



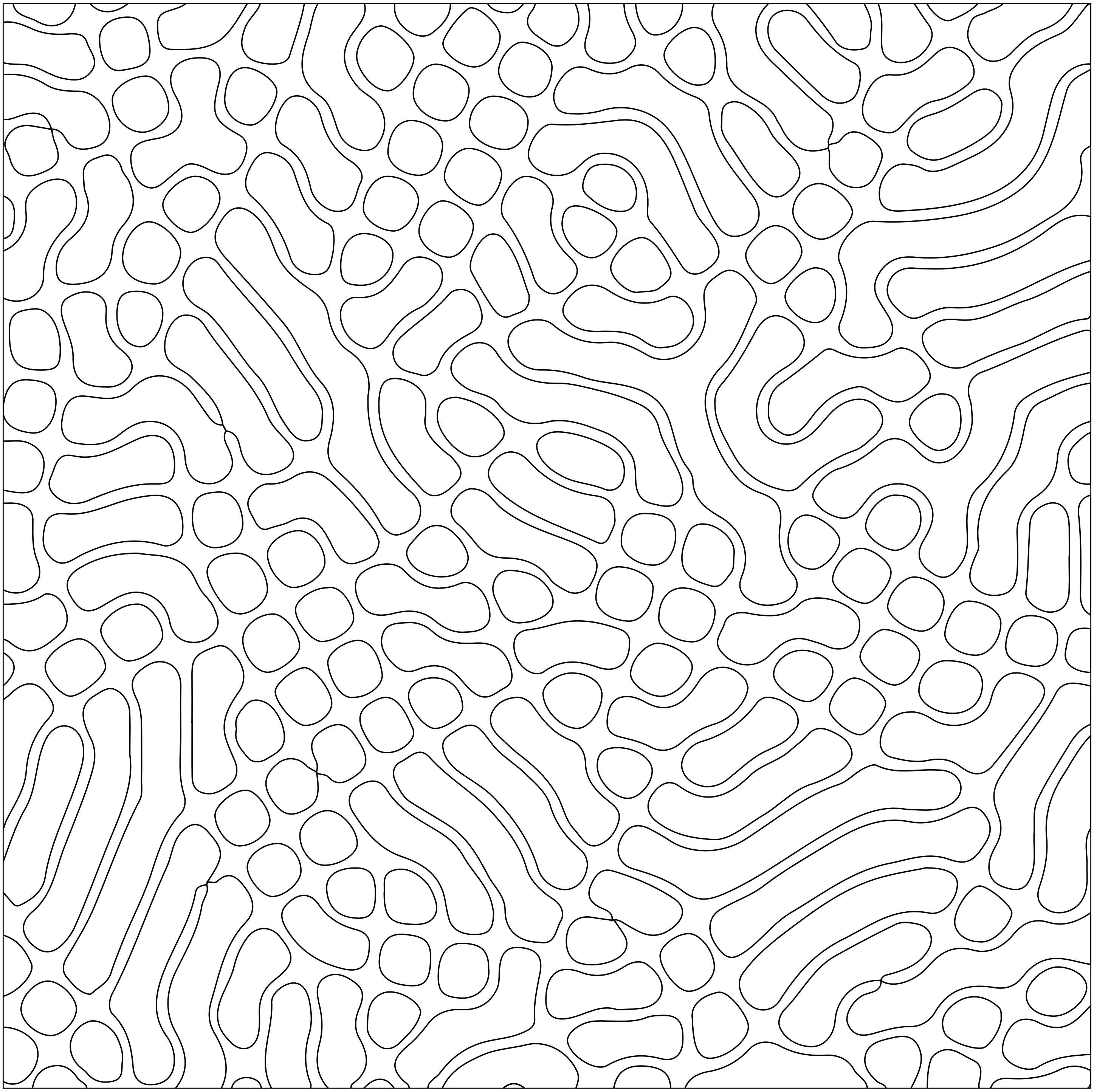


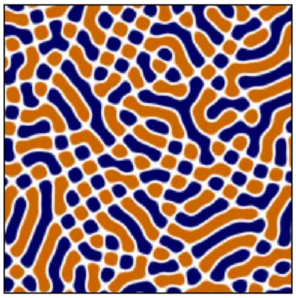
Explosive percolation on a scale-free multifractal weighted planar stochastic lattice

M. M. Rahman and M. K. Hassan, Phys. Rev. E **95**, 042133 (2017)

Percolation theory uses math to describe how things flow through a connected network, like water working its way through the pockets of air in your coffee grounds or a news story making the rounds on social media. In *explosive percolation*, a small change in the network's interconnectedness can create startlingly large changes in the whole system—like grinding your coffee slightly finer than usual and finding that the water takes twice as long to drip through, leaving you with a much stronger cup.

To study this, we need to simulate different kinds of networks, like the one in this image—called a *stochastic lattice*. This image was constructed by dividing a square into four rectangles of random size, picking a point in the square at random, and dividing the rectangle where that point is found into four more rectangles of random size. Repeating the process until there are enough blocks creates a lattice with unusual properties that make it useful for modeling explosive percolation.

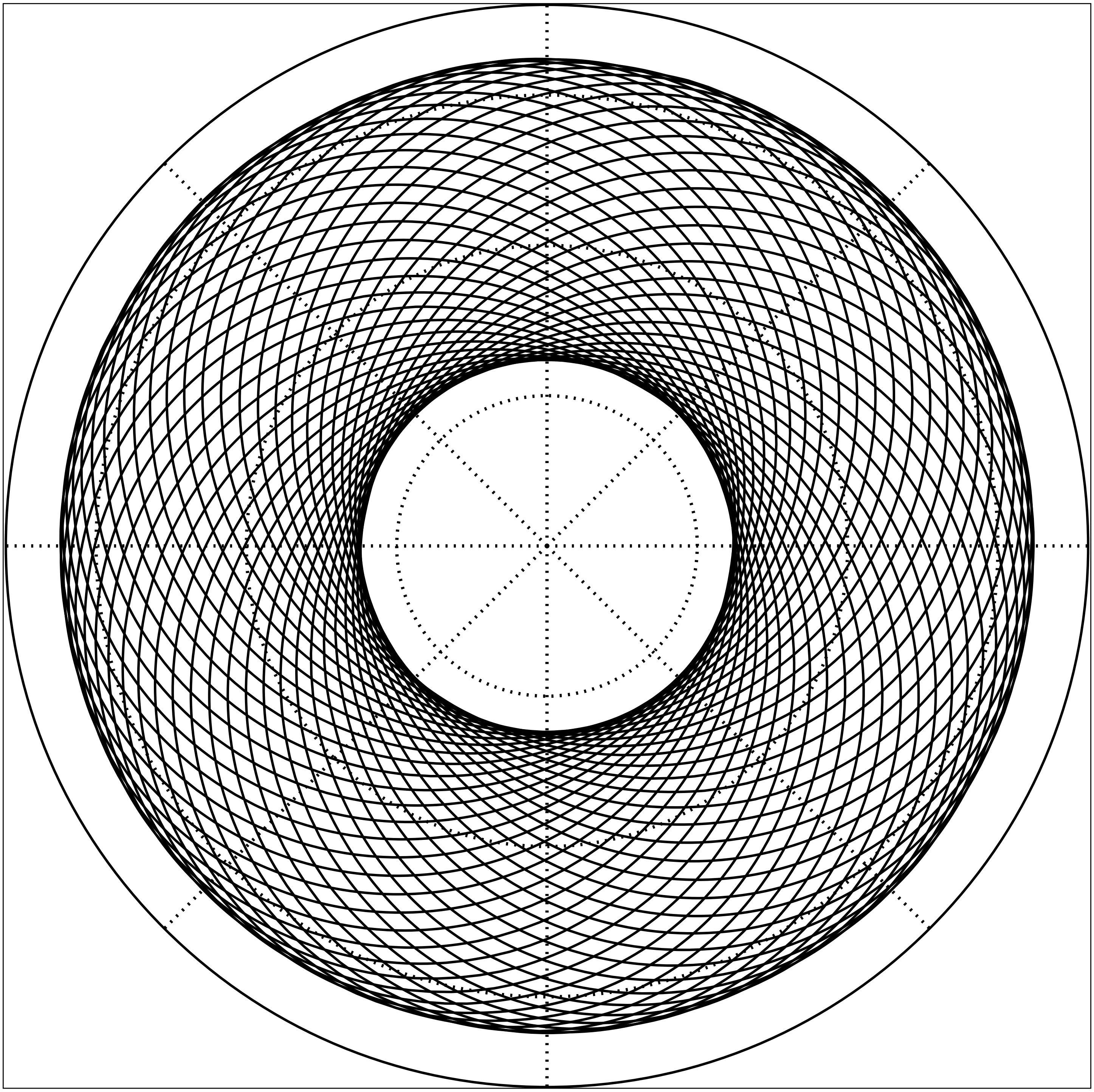


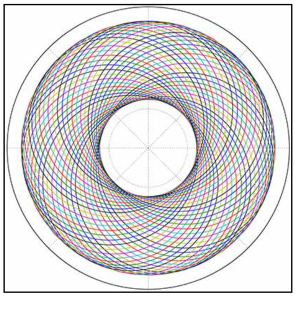


Modeling the structure of liquids and crystals using one- and two-component modified phase-field crystal models

M. J. Robbins, A. J. Archer, U. Thiele, and E. Knobloch, Phys. Rev. E **85**, 061408 (2012)

Predicting how a substance is going to behave, like the temperature at which a liquid will freeze into a solid, is no easy task. One way to do it involves simulating thousands of particles and watching them interact, but this approach involves too much calculation to be feasible in most cases. Instead, scientists can sometimes use equations to model the material's properties and interactions as a whole. Sometimes, this method works well, producing a density distribution that's smooth and homogeneous—like a liquid—in some conditions, and highly ordered in a repeating structure—like a solid—for others. For certain parameters, though, strange stripes like the ones seen here can arise, which don't seem to correspond to any known state of matter; researchers describe diagrams featuring these stripes as being "unphysical".

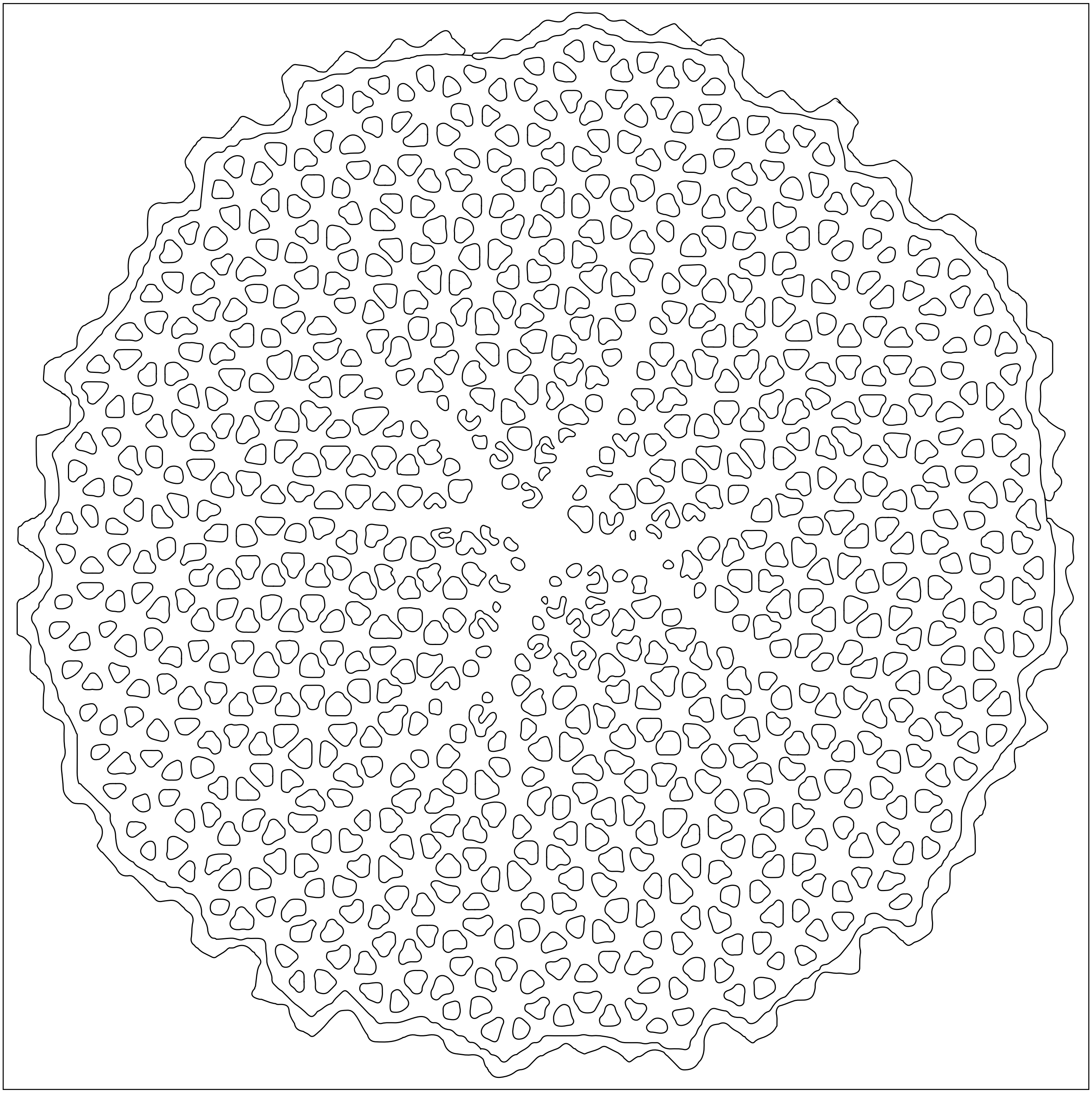


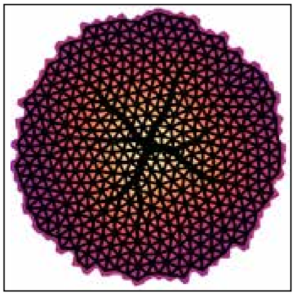


Dirac states of an electron in a circular intense magnetic field

Guillaume Voisin, Silvano Bonazzola, and Fabrice Mottez, Phys. Rev. D **95**, 085002 (2017)

When a charged particle like a proton or electron moves through a uniform magnetic field, the interaction between the two causes the particle's trajectory to curve. Although the particle isn't speeding up or slowing down, the change in direction is still classified as an acceleration—and when charged particles accelerate, radiation is released. In the vicinity of astronomical objects like rotating neutron stars, magnetic fields trillions of times stronger than those found on Earth can arise, making these objects exciting space-based "laboratories" for exploring extreme conditions and the phenomena they cause—like intense radiation resulting from particles experiencing extraordinary accelerations. In this image, possible trajectories are plotted for an electron caught around a strong magnetic field line, like those found near fast-rotating neutron stars.

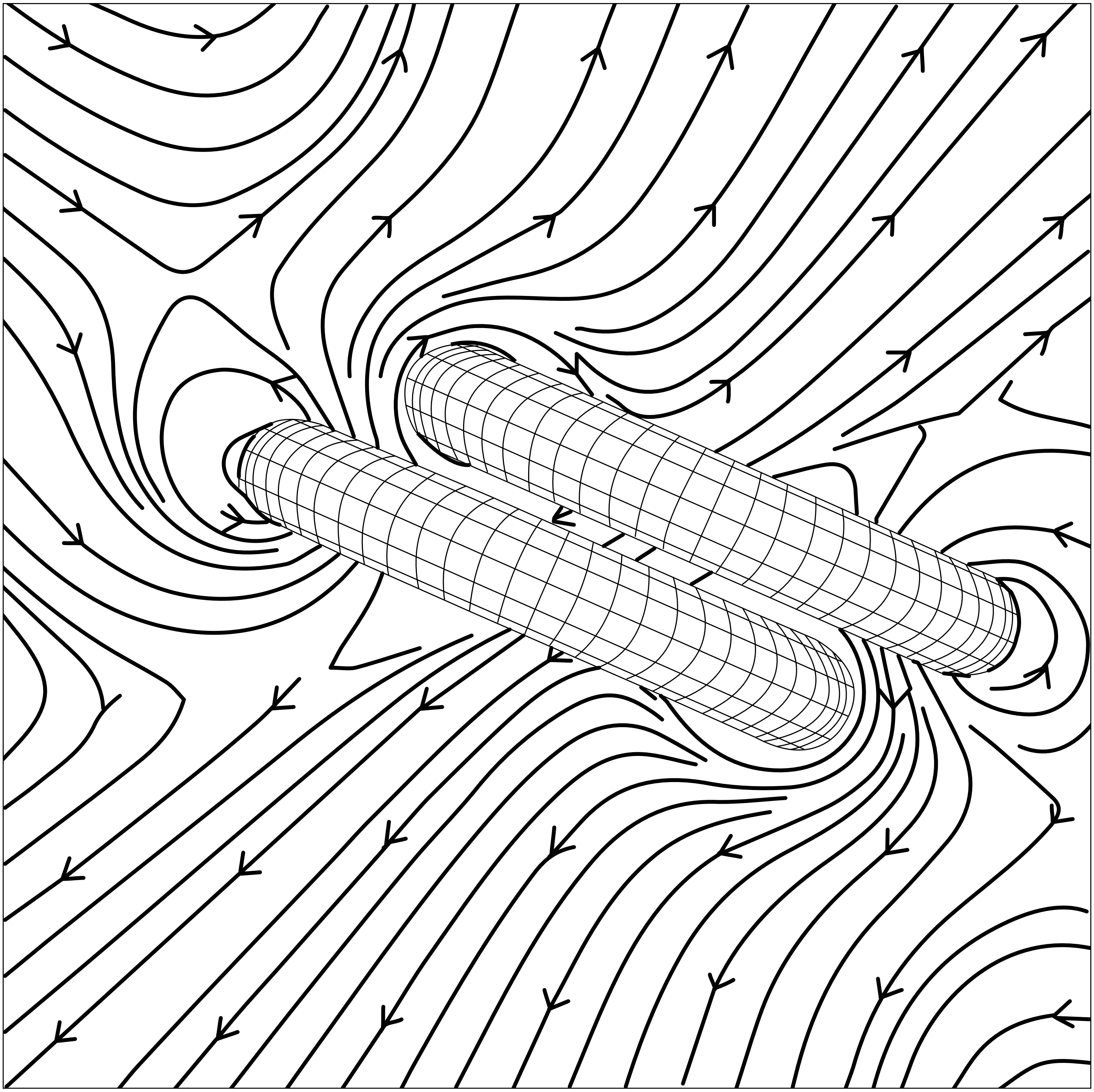


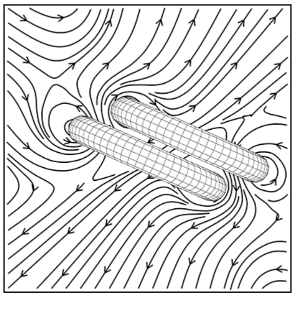


Global Optimization, Local Adaptation, and the Role of Growth in Distribution Networks

Henrik Ronellenfitsch and Eleni Katifori, Phys. Rev. Lett. **117**, 138301 – (2016)

Figuring out the optimal way to set up a transportation network—whether that's water pipes or a train system—is a difficult task that even the best computer algorithms have trouble with. But biological systems, like the veins of a leaf or the blood vessels in your body, accomplish it with ease—and seemingly without relying on detailed blueprints. In the paper that this image is from, scientists discovered the secret to creating a highly efficient transport network with relatively simple formulas: growth—not just growth of the network itself, but of the system that it's embedded in. As a leaf grows, a hormone produced in its cells encourages the formation of veins, which transport it out—leading under-vascularized areas to develop the necessary channels, and over-vascularized ones to "prune" the unnecessary veins. While this image is from an intermediate stage in the group's simulations, the end result is a branching structure that has all the fractal elegance of a leaf's underside.

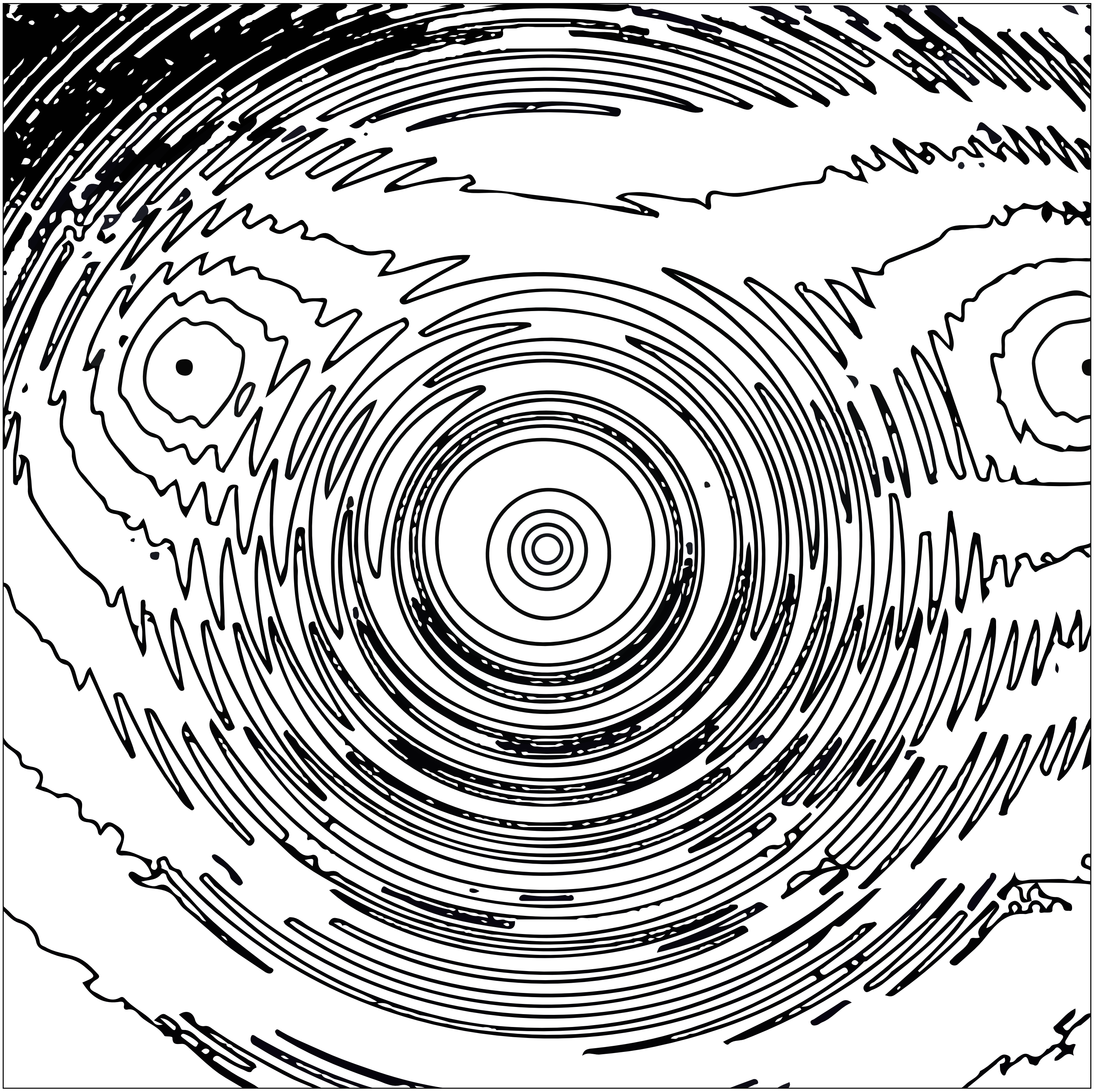


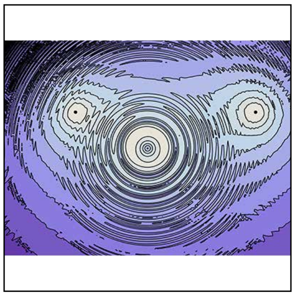


Interaction of toroidal swimmers in Stokes flow

Jianjun Huang and Lisa Fauci, Phys. Rev. E **95**, 043102 (2017)

Designing on a microscopic scale holds enormous promise—hospitals of the future might dispatch a swarm of tiny swimming machines to deliver chemotherapy drugs precisely to the location of a tumor. Before that can happen, though, we need to understand how such tiny motors interact with the fluid around them…and with each other. One design might yield swimmers that work best on their own, while another design could produce ones that swim well together, like a school of fish. Here, researchers are looking at interactions between two tiny swimmers with a simple design: a rotating toroid that travels through fluid like a smoke ring. These toroids work well together when rotating in the same direction, but if one gets turned around, they can run into problems—bumping into one another and getting stuck there—as researchers discovered by modeling their behavior in this work.

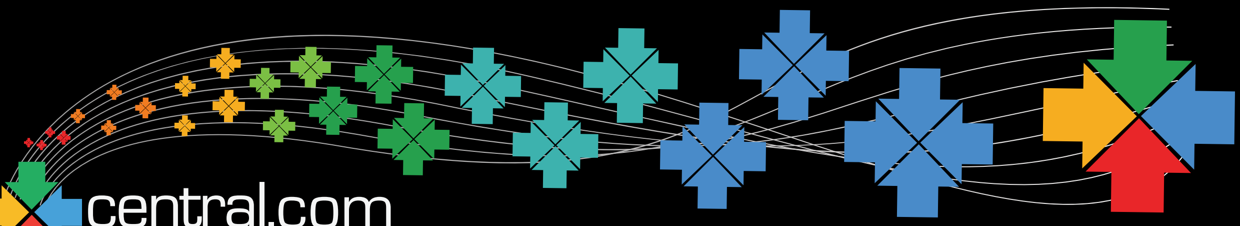




Interference in spectrum of radiation from doubly scattered charged particle

M.V. Bondarenco and N.F. Shul'ga, Phys. Rev. D **95**, 056003 (2017)

Thanks to light's wavelike nature, photons can add together in intensity if they're in-sync, or cancel out if the crests of one wave match up to the troughs of another. This *interference* is responsible for everything from the rainbows on a soap bubble to the metallic sheen of peacock feathers. But it's not just visible light that produces interference like this; it happens at every energy, from the microwaves that cook your food to the *bremsstrahlung*—or "braking radiation"—produced when a high-energy charged particle is deflected by an electromagnetic field. Here, we're seeing the interference pattern of light that results from a stream of electrons being fired through a pair of thin foil sheets, one after the other. The atoms in the sheets scatter the electrons, and the resulting bremsstrahlung adds together in some places and cancels out in others, producing a ripple-like pattern that depends on both the energy of the electrons and the spacing of the sheets.



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