



*THE  
ZOOMABLE  
UNIVERSE*

*AN EPIC TOUR THROUGH COSMIC SCALE,  
FROM ALMOST EVERYTHING TO NEARLY NOTHING*

*CALEB SCHARF*

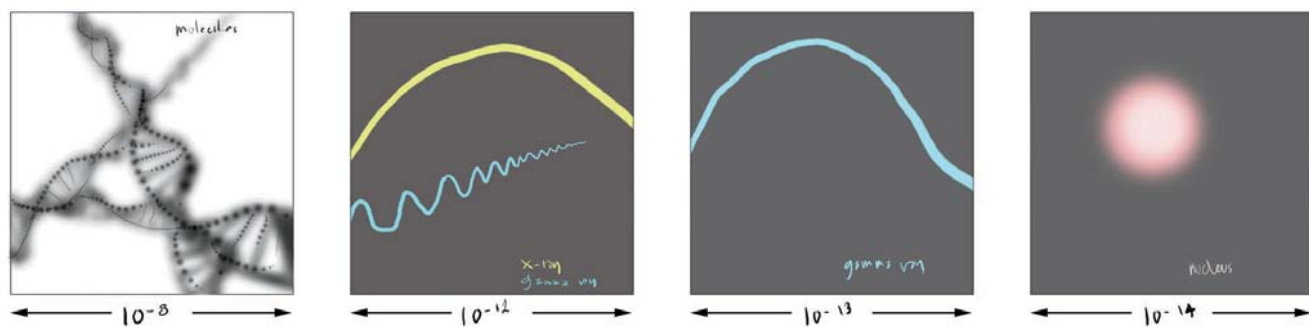
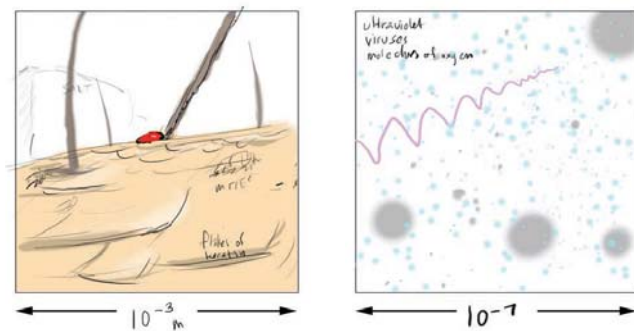
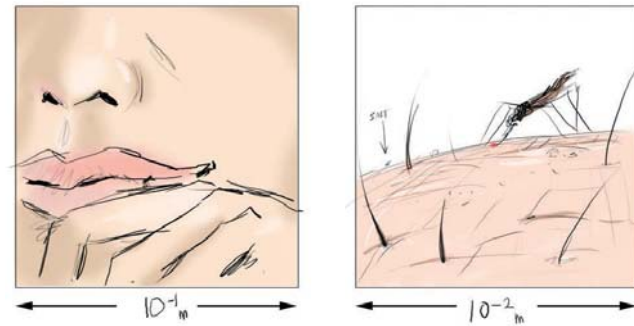
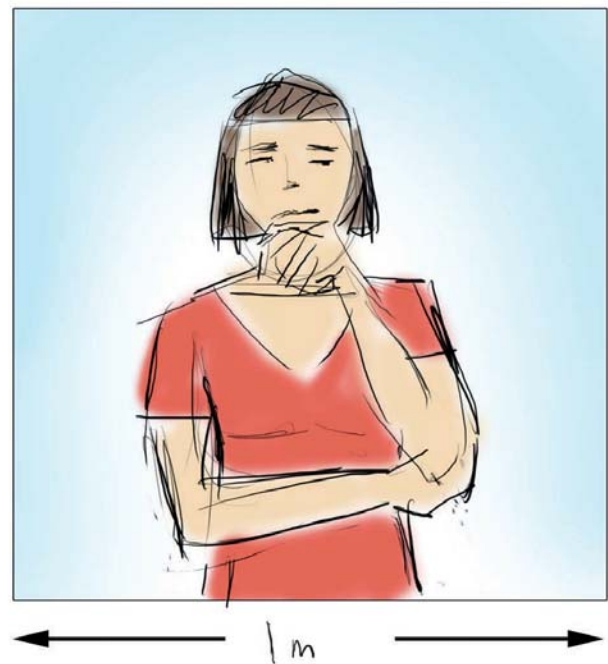
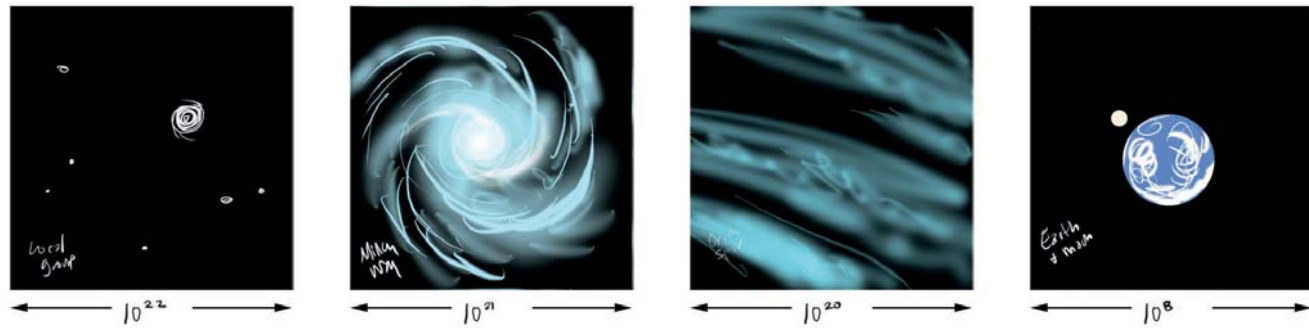
*ILLUSTRATIONS BY RON MILLER*

*AND 5W INFOGRAPHICS*



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## **PREFACE**

Do you want to hear the most epic story ever?

A long time ago the atoms in your body were spread across trillions of kilometers of otherwise empty space. Billions of years in the past there was no hint that they would eventually come to be configured as your eyes, your skin, your hair, your bones, or the eighty-six billion neurons of your brain.

Many of these atoms came from deep inside a star—perhaps several stars, themselves separated by many trillions of kilometers. As these stars exploded, they hurled matter outward in a flood of scorching gas that filled a small part of one galaxy out of hundreds of billions of other galaxies, arrayed throughout a gaping maw of space and time almost a trillion trillion kilometers across.

Despite being scattered in the cosmos, these atoms eventually became part of a world, our world, Earth. They cooled and condensed together, drawn by gravity, becoming new stuff, a billion trillion times denser than when they were just floating in space. For four and a half billion more years they shape-shifted into lots of different guises.

Some of these atoms were part of the very first microscopic bubbles of living complexity in otherwise empty oceans and continents. And many of the very same atoms have been discarded and picked up a billion or more times as they've traveled through Earth's environment.

They've been in the shell of a trilobite, perhaps thousands of trilobites. They've been in tentacles, roots, feet, wings, blood, and trillions, quadrillions of bacteria in between. Some have floated in the eyes of creatures that once looked out across the landscapes of a hundred million years ago. Yet others have nestled in the yolks of dinosaur eggs, or hung in the exhaled breath of a panting creature in the depths of an ice age. For other atoms this is their first time settling into a living organism, having drifted through eons in oceans and clouds, part of a trillion raindrops or a billion snowflakes. Now, at this instant, they are all here, making you.

Each atom is itself a composite that's about a tenth of a billionth of a meter across—sitting on the precipitous edge of a universe between our perceived reality and the quantum world. Electrons hazily occupy much of the atom's empty space. Protons and neutrons cluster in a nucleus, a hundred thousand times smaller than its atom, and are themselves composed of other stupendously small things, quarks and gluons. An electron may have no meaningful property of size but can be thought of as ten million times smaller than the nucleus. And, at some point, 13.8 billion years ago, all these components of all the atoms in the universe were squeezed into a far smaller, hugely energetic origin of space and time. Although that origin is now vastly expanded, we're still inside its envelope, along with any being that may exist a billion light-years from here. We're not truly disconnected, even now.

It's quite a tall tale. Except this is not fiction. It's our current best shot at recounting what has really happened in the past 13.8 billion years.

The purpose of *The Zoomable Universe* is to try to capture more of this story, to lead you through what we know (and what we don't) about the entirety of nature. To do that we've turned to a tried-and-true approach: the simple premise of a tenfold zooming view to tour the universe, from the edge of the observable cosmos to the innermost knots of reality.

The conceit of a journey through the scales of nature is not new, and doing it scientifically goes back at least as far as *Micrographia*, published by Robert Hooke in 1665. Works like the seminal 1957 book *Cosmic View: The Universe in 40 Jumps*, by Kees Boeke, and the short films *Cosmic Zoom*, by the National Film Board of Canada (1968), and *Powers of Ten*, by Charles and Ray Eames (1977), as well as many derivatives in subsequent years, demonstrate our universal love of cosmic journeys.

It seemed that the time was ripe to make a contribution that not only brought the core material fully up to date but added focus on the intricate connectivity of the universe. Atoms

here in my hand are related to atoms over there, or on the next planet, or halfway across the cosmos. The physics that operates inside us is the same that operates on other scales, and at other cosmic times. And the patterns and emergent phenomena that infuse our day-to-day experiences share rules and properties in countless surprising ways throughout nature.

From fingers and toes to modern mathematics and measurements, we can all grasp the notion of powers of ten, sizes that shift by ten times or by a tenth. Chain these sliding scales together and we have a language for expressing the continuities and relationships of nature that extend far outside our ordinary everyday experience. The powers of ten let us zoom from almost everything to nearly nothing.

This book is a synopsis, a cheat sheet if you will. It can't recount every exact detail of the contents and history of the universe. Instead, it treats the reality we know as a zoomable map with a preset path to follow. In video-game parlance, it's a "rail shooter." That rail follows the physical scales of the cosmos—starting at the top and zooming on down.

As we wrote and illustrated this journey, we agonized over how to build this rail. The cosmos has three dimensions of space, and that tricky thing we call time. There are also trillions of interesting things to take a look at along the way. We've tried to balance the idea of a "grand overview" with making sure we visited some very, very cool places en route.

Some of the waypoints are intellectually challenging—even in Chapter 1 you'll have to contend with the strange concept of dark matter, an expanding universe, and even stranger things like multiple universes and multiple versions of you. In Chapter 3 you'll have to grapple with the majestic origins of the solar system. By Chapter 6 you'll be puzzling over the nature of consciousness, and by Chapter 9 you'll be tackling interpretations of quantum mechanics. Don't worry—the beautiful illustrations and infographics will help delight and inform you along the way.

We hope you enjoy finding your own connections among the gloriously varied pieces of data and knowledge that bring our vision of reality together. Remember, it's your universe as much as anyone else's.



1

## ALMOST EVERYTHING

$10^{27}$ ,  $10^{26}$ ,  $10^{25}$ ,  $10^{24}$ ,  $10^{23}$  meters

From about 93 billion light-years to 10 million light-years

From the diameter of the cosmic horizon to the size of the Local Group of galaxies

It's a summer morning. You're sitting in a sunlit room holding this book, reading this page, and about to start a journey through cosmic scale.

Looking up, you notice that tiny specks of glowing dust are caught in the beams of light streaming through the windows. These bright pinpoints loft and swirl in the air currents, like a swarm of mysterious creatures.

The specks are microscopic, yet if the whole room were to represent the size of the observable universe, each of these dusty motes would be the size of an entire galaxy of stars.

Now follow a single sunlit speck. This is our galaxy, the Milky Way. It is home to more than 200 *billion* stars, and at least that number of planets. These stars and planets span a structure that is a hundred thousand light-years across—a distance of more than nine hundred thousand *trillion* kilometers. At a walking pace, it would take you twenty trillion years to cross this object.

Packed deep inside, hidden among these billions of other worlds, is one particular planet we call Earth. This world is a modest rocky orb with a thin coating of crystallized mineral crust atop a hot interior, lightly painted with water and atmosphere. It orbits a lonesome star that we call the Sun—one star, only 4.5 billion years old in a 10-billion-year-old galaxy.

Now think about all the things that you know and experience in your life. Your family,

friends, dogs, cats, small furry rodents, horses, houses, couches, beds, pizza, apples, oranges, trees, flowers, insects, dirt, clouds, water, snow, rain, mud, sunshine, and starry nights.

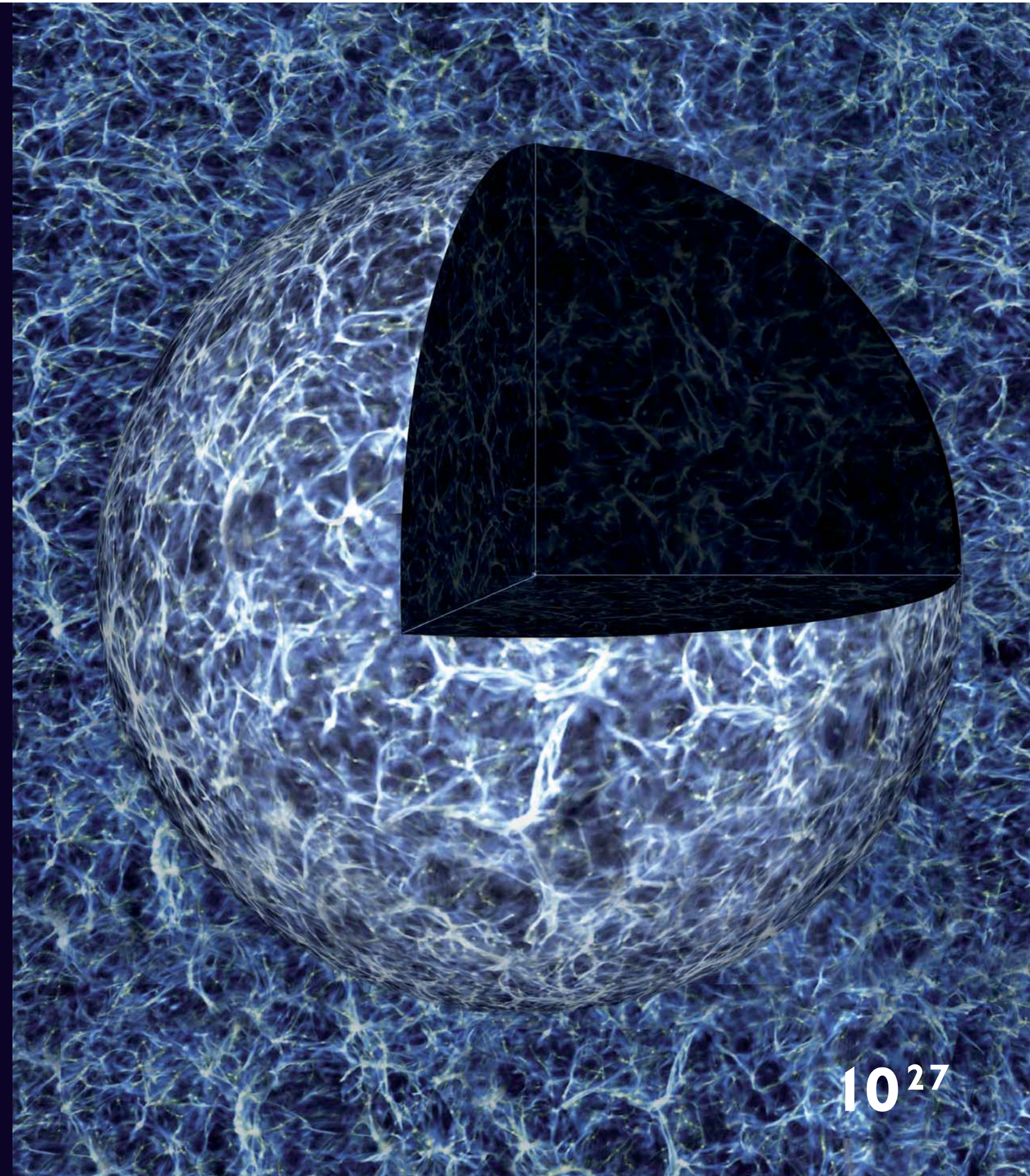
Then think about all the people who have ever lived (a total of around 110 billion individual, biologically modern humans) and all that *they* knew in their lives. All these people, billions upon billions of them, experiencing their surroundings for centuries, decades, years, months, days, hours, seconds, and the blink of an eye.

That's a lot of special moments for human beings. But for 3.5 billion years before we came along, living things swarmed the Earth, from bacteria and archaea to multi-cellular clumps, from trilobites to insects, dinosaurs to cephalopods. Trillions of living entities slithered around every conceivable niche, compelled into existence by varying potentials of chemical energy and chance. During every passing moment of those many years, all these organisms were being sculpted and battered by natural selection, and driven by the restless engines of molecular mechanics.

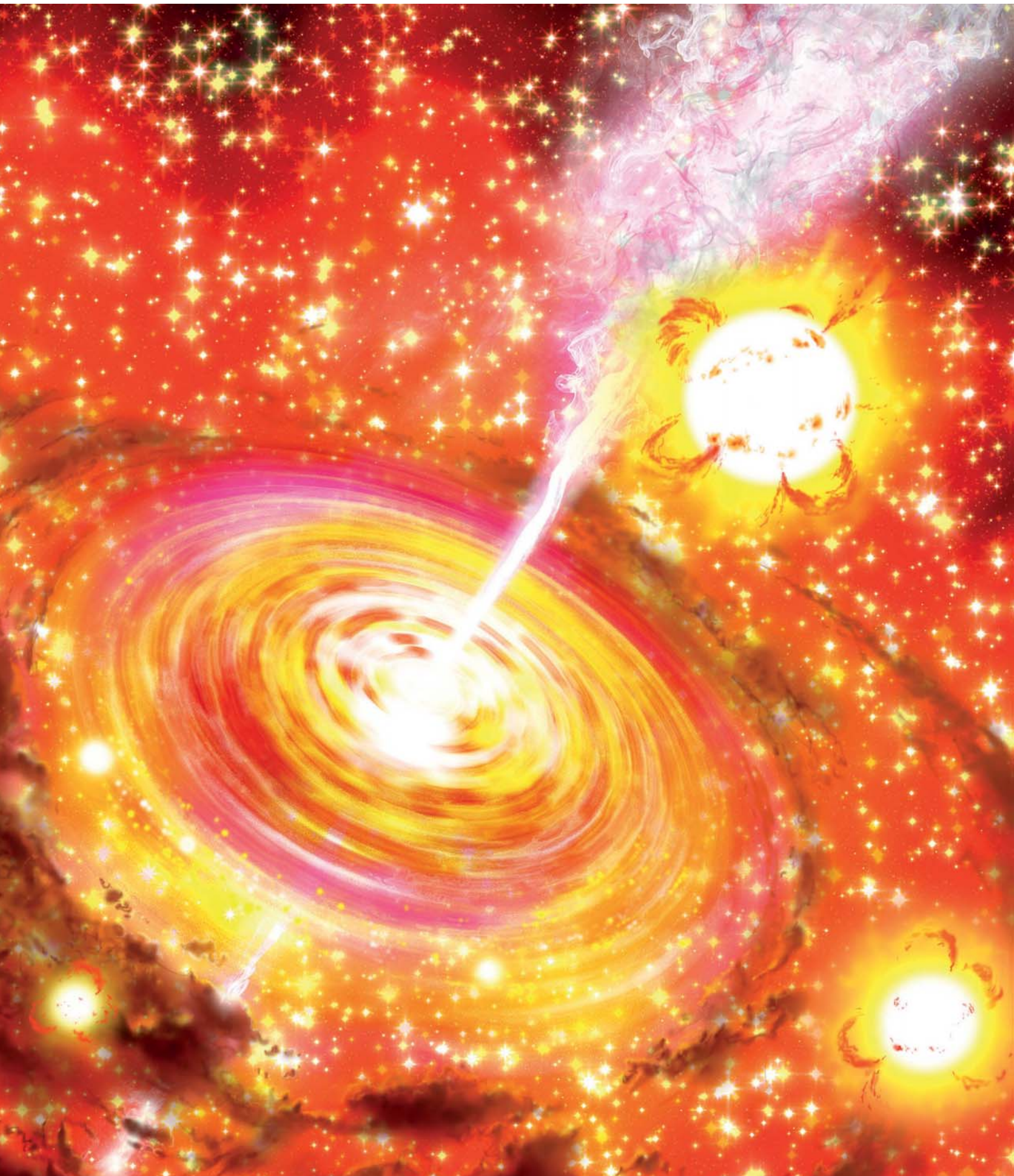
The sum total of that, every single last bit of it, has existed on this one world—a vanishingly small mineral dot among billions of mineral dots, all held within a single dust mote that you watch floating through a sunny room that is the universe as we know it.

This one-mote galaxy that we call the Milky Way is a microscopic part of a wrinkly, web-like ocean of matter. That ocean sustains more than 200 billion *other* galaxies. These galaxies range from small to enormous, some isolated, some in the midst of messy collisions. And these are merely the galaxies from which light has had time to reach us in about thirteen billion years—they're within our "horizon," the horizon of light travel time, like the walls of your room.

This cosmic sprawl is also awash in electromagnetic radiation, energy that exhibits both wave- and particle-like behavior, packaged as massless units called photons racing to and fro across space. Some of this radiation is the product of the early and hot history of the place that we generally call the universe. Other photons are from specific, individual sources: stars, supernovas, warmly glowing young planets, cosmic crashes and shock waves, possibly even plaintive missives hurled between technological civilizations—or not.



$10^{27}$



**2**

## ***DARKNESS AND LIGHT***

**$10^{22}$ ,  $10^{21}$ ,  $10^{20}$ ,  $10^{19}$ ,  $10^{18}$  meters**

**From about 1.06 million light-years to 106 light-years**

**From about 8 to 10 Milky Way diameters to the size of a giant molecular cloud**

Imagine that you are an all-powerful alien being who decides to scrunch up all the stars in the Milky Way so that they are packed next to one another. By getting rid of all the space in between, you can fit these stars into a cube only about 8 billion kilometers (or fifty-four times the radius of Earth's orbit) on each side. That cube, containing some 200 *billion* stars, fits neatly within the orbital diameter of Neptune in our solar system. In other words, the galaxy has plenty of surplus room between its stars.

Of course, physics wouldn't actually let you do this, at least not without making a lot of mess. The problem with putting this much mass in one place is that you'd wind up making a black hole. Why? Because the gravitational pull of all those stars on one another would be irresistible. Weirdly, though, the size of the black hole containing the mass of the 200 billion or more stars of the Milky Way would be much bigger than our imaginary cube of stars by a factor of about 146.

That's because very massive black holes are actually rather low density if you treat their outermost extent as the measure of their size. This may feel counterintuitive, but the size of a black hole—the event horizon (the point of no return, the radius surrounding the hole's mass from within which nothing can escape)—increases in lockstep with the hole's mass. In other words, if you double the black hole mass, you double the radius of the event horizon.

That's very different from what happens with regular objects. For example, add two



Compact matter in black holes strongly warps space and time.

identical balls of dough together, and the new radius of the combined ball is not twice what it was; it's only about 26 percent larger. Why? Because for ordinary materials in a sphere the radius grows as the cube root of the mass—double the mass and you only increase the size by 26 percent. So if we treat the event horizon of a black hole as a measure of its physical size, the *average* density of matter within its bounds can end up being very low. A black hole with a mass three billion times that of the Sun would appear to be only as dense as the air we breathe! But this is a bit of cosmic misdirection, because our formal understanding of these objects tells us that all of a black hole's mass is actually concentrated in a tiny, hidden, infinitely dense region at its center.

Where such giant singularities exist, in the cores of most large galaxies, they also often look like the precise opposite of what we might expect. Yes, black holes are black, but you might not think so, because they can generate enormous amounts of light. Gas, dust, stars, planets, and who knows what else gets accelerated, shredded to bits, and heated if close enough to a black hole. In the process, energy spews outward, from above the event horizon and before the point of no return. With enough infalling matter, a spinning black hole can convert mass to energy with higher efficiency than even nuclear fusion. The most luminous cases across the universe shine with the power of hundreds of trillions of suns.

Matter at its most compact, like in a black hole, can surprise even the most scientific among us. At the other extreme, all that empty space in a galaxy like the Milky Way is also surprising.

### **NECESSARY EMPTINESS**

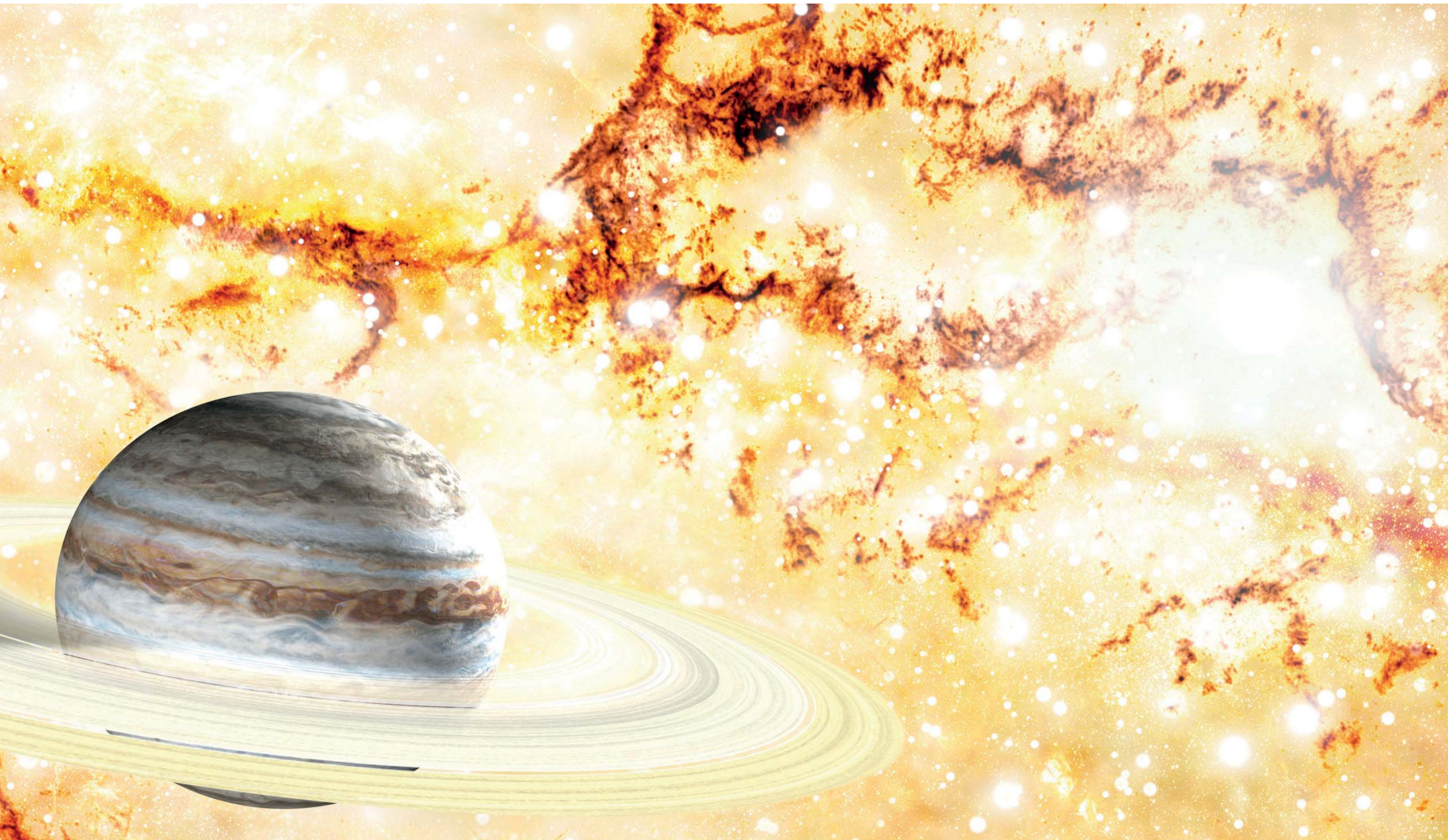
Most of us experience physical loneliness at some point in our lives: lost in an unfamiliar city, alone in a house, or abandoned in a deep, dark wood by scheming relatives. But intergalactic space and interstellar space—between the galaxies or between the stars in the typical parts of a galaxy—are actually the two loneliest places you might ever wind up in. In these “inter-zone” environments it can be a very, very long distance between safe havens, devoid of much of anything at all.

If you were a hapless cosmic hitchhiker stranded between the stars of the Milky Way, your body would represent a concentration of matter a *hundred million trillion* times greater than the





Inside the Local Group of galaxies

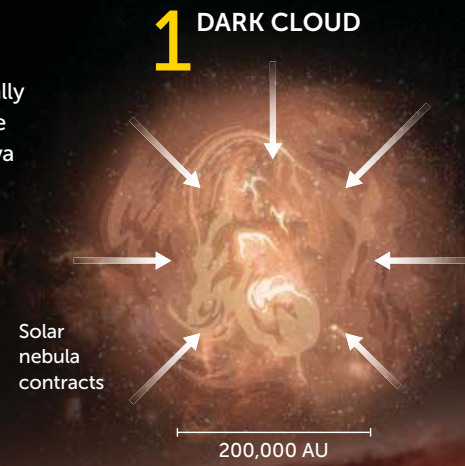


# Birth of a Solar System

Stars and planets condense out of interstellar space—when material collects and compacts itself. It's not an easy process. Gravity is pitted against thermal energy and electromagnetic energy, and no two systems are identical.

## The Trigger

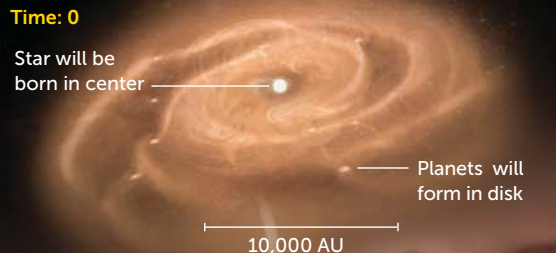
Part of a great nebula becomes gravitationally unstable, possibly due to a passing supernova shock wave, and falls in on itself to form a disk of matter.



## 2 GRAVITATIONAL COLLAPSE

Time: 0

Star will be born in center



**Proto-stellar jet** High-speed outflow of hot, accelerated matter

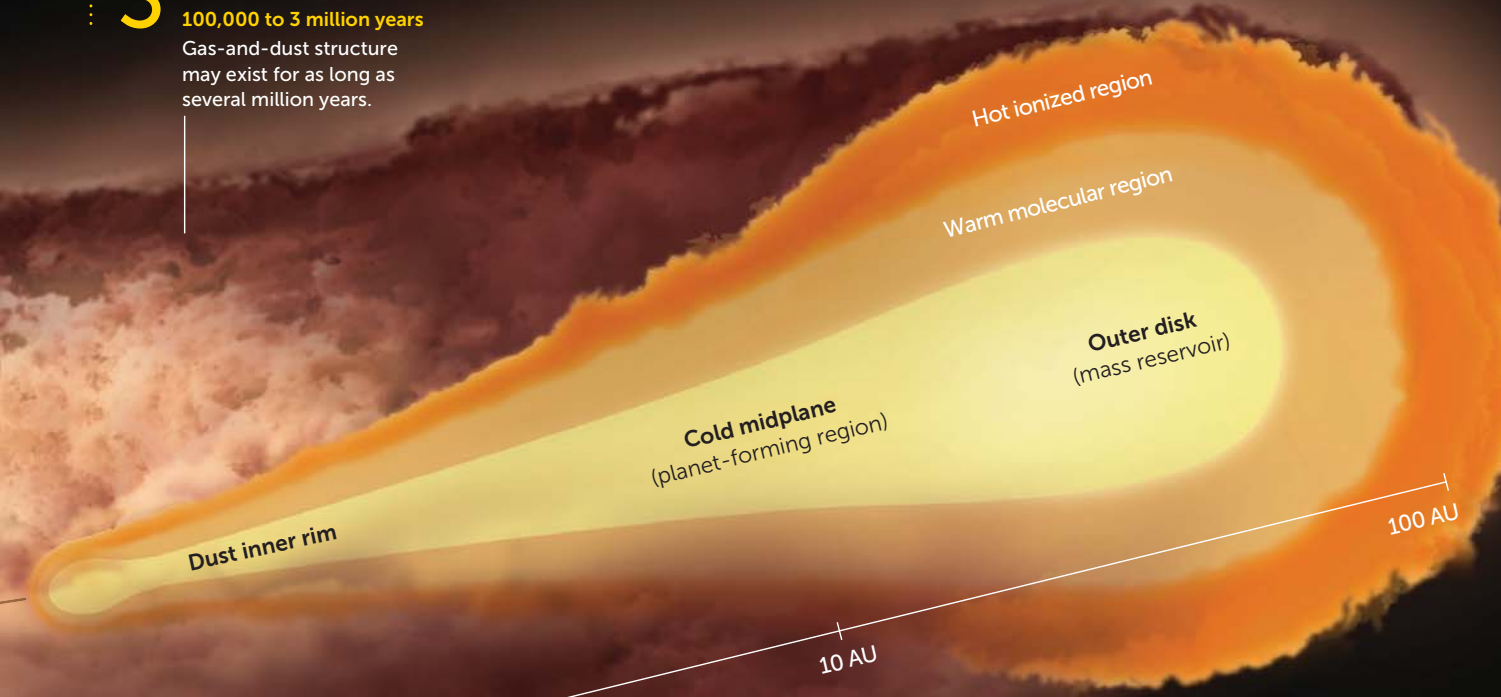
## Maker of Suns and Worlds

A proto-planetary disk is full of structure, flow, and activity. Its flared shape and luminous central star create zones of temperature, evaporation, and chemistry that influence composition and the growth of planetary building blocks.

## 3 PROTO-PLANETARY DISK

100,000 to 3 million years

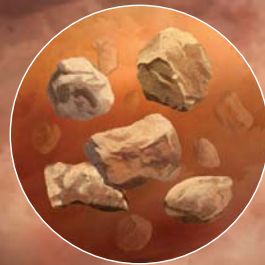
Gas-and-dust structure may exist for as long as several million years.



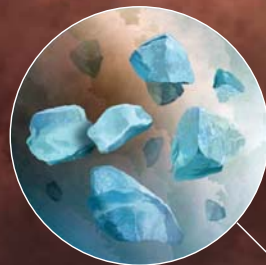
**Proto-star** Gas and dust concentrate in a growing spherical region at the center.

Pure gas disk

Warm temperatures allow only metal/rock material to condense in the inner system.



Cold temperatures allow water ice, carbon dioxide ice, and more to form in outer system.



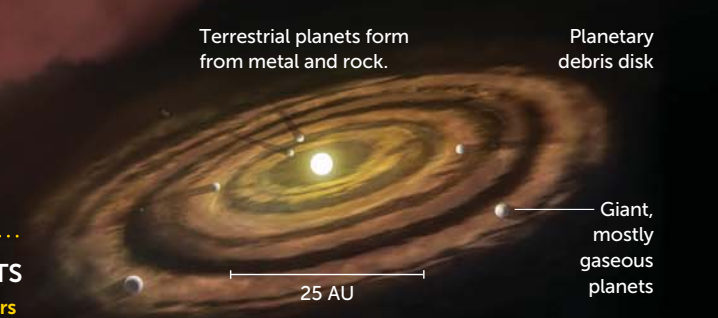
Distance to star (AU\*)  
0 AU 0.03 AU

## Our Planetary System

Most gas is either evaporated or condensed into planets. Orbiting dust and solid chunks keep merging, colliding, and perturbing one another's motions. Planetary systems are always a work in progress.

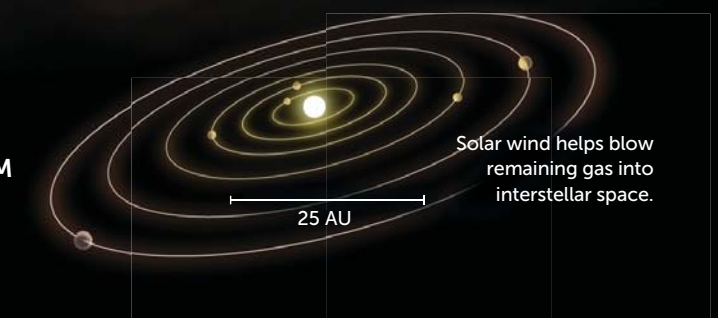
## 4 GIANT PLANETS

3 to 50 million years



## 5 YOUNG SOLAR SYSTEM

50 million years



\*AU = Astronomical Unit: the distance from Earth to the Sun (roughly 150 million kilometers).



These creatures show complicated, and apparently altruistic, social behavior. They are almost certainly conscious. They are clearly intelligent, even if their smarts are not exactly like ours.

At the same time, the elephant's feathery symbiotic companion has a different lineage, one that had a last common ancestor with mammals 300 million years ago. The oxpecker, like all modern birds, is a descendant of a particular group of "great lizards"—the egg-laying dinosaurs. Between 65 million and 260 million years ago, the oxpecker's raptor ancestors scooted about this very same continental landscape. It was a world where dinosaurs had the evolutionary upper hand, or at least hogged the evolutionary limelight.

The oxpecker is certainly aware and intelligent by standards that we recognize. Many birds show signs of self-awareness, numeracy, and tool use. Yet a bird's brain is physically much smaller

than that of either the elephant or a human, and contains (only) about 100 million neurons.

The parasitic louse in the bird's beak has an ancestry that goes even further into the past. It is part of the group of wingless insects, at least 480 million years old, that evolved from a group of invertebrates. In that sense the louse is the most alien organism in the picture, and also the most successful, despite its present predicament.

Is the louse conscious or intelligent? Some insects, like bees, show behaviors that can be construed as signs of cognition, of intelligence, and can have upwards of a million neural cells. The louse is no bee, but we don't know what's really going on in its nervous system.

This one brief slice of life (a snapshot out of hundreds of millions of years of photo opportunities) contains another critical story.

A mammal hosts a bird and an insect. The bird consumes the parasitic insect, helping the



**Role reversal: Once, some dinosaurs succeeded as apex species, while mammals did not.**



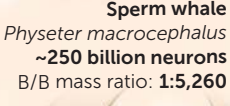
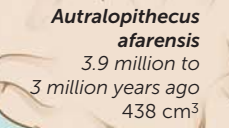
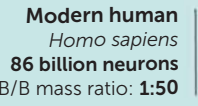
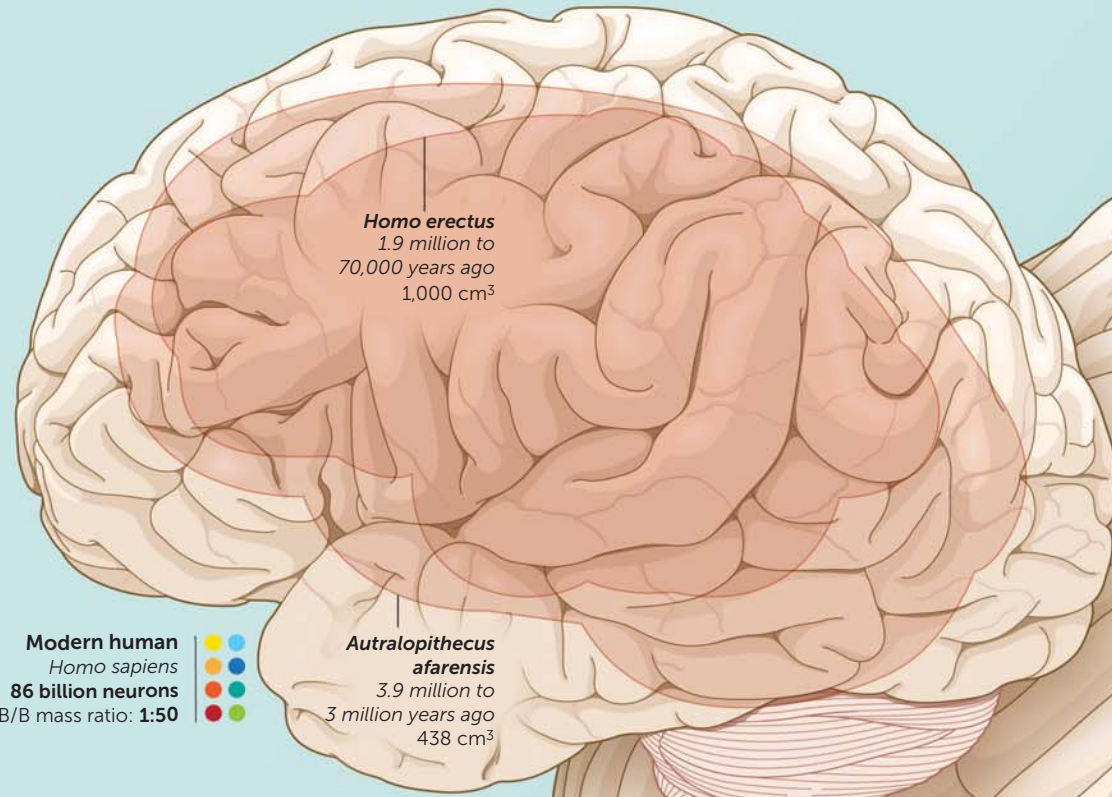
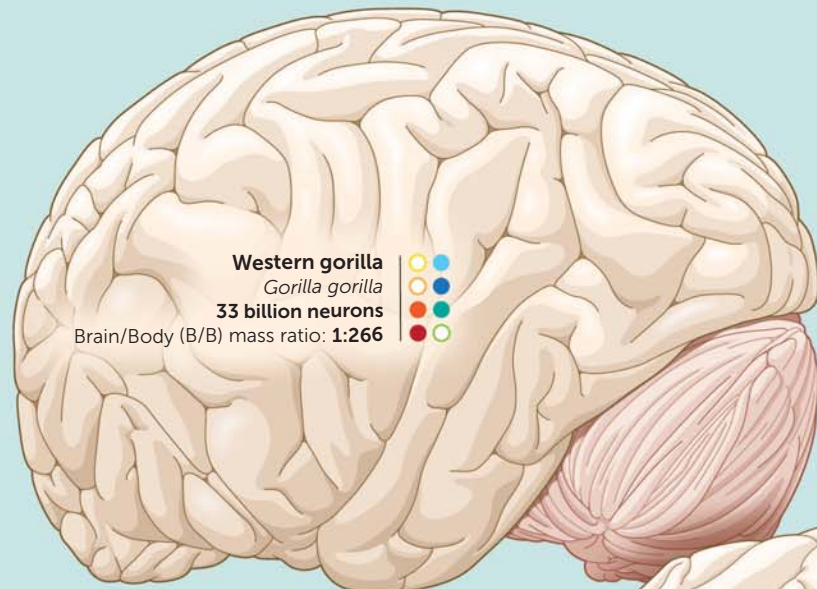
# Brains of the World

Brains are built out of neurons—specialized cells that form electrically sensitive networks capable of receiving, processing, and transmitting electrochemical signals. Brains are the most complex biological structures we know of.

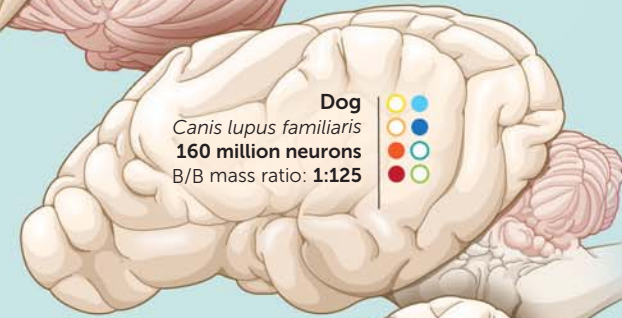
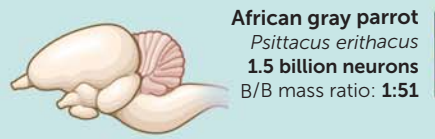
## Brain capabilities

Much is still a mystery about the inner workings of brains.

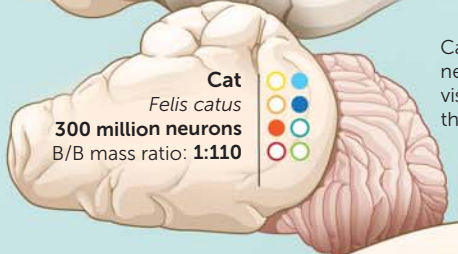
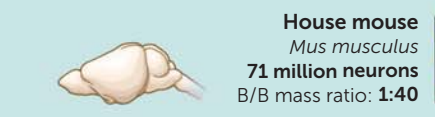
- YES / UNKNOWN
- Abstraction
  - Invention/creativity
  - Social behavior
  - Altruism
  - Associative learning
  - Fear/pain
  - Language
  - Consciousness



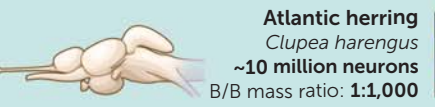
A sperm whale's cerebral cortex is far more convoluted than a human's.



Modern human brains have 16 billion neurons in the cerebral cortex—a number exceeded only by the long-finned pilot whale.



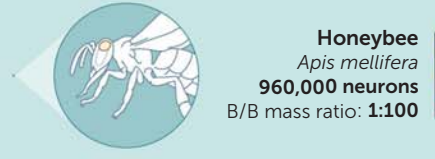
Cats have more neurons devoted to visual processing than humans.



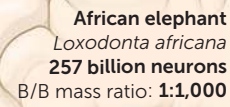
Fish brains can generate new neurons after damage.



Crocodile brain mass grows with body mass, but more slowly.



Neurons in a bee brain are 10 times more densely packed than in a human brain.



97.5% of elephant neurons are in the cerebellum. Only 5.6 billion neurons are in the cerebral cortex.



$10^{-2}$

7

## FROM MANY TO ONE

$10^{-2}$ ,  $10^{-3}$ ,  $10^{-4}$ ,  $10^{-5}$  meters

From 1 centimeter to 10 micrometers

From the size of a human fingertip to the size of a cloud-water droplet or an animal cell

The planet we call home is fading into the background as we zoom ever further down the cosmic scale. All of Earth's color and drama is now just a blur that's a billion times larger than the scope of our new waypoint. But this scale and the next few orders of magnitude within it are far from boring. You're going to be challenged here by concepts that are both beautiful and strange. The first of these is what we call complexity.

Complexity is a central part of the currency of the universe. We've already encountered it out among the galaxies and nebulas, but it infuses our daily existence too. The very structure of our bodies and the multilayered populations of species that we live with are proof of that. Although we seldom notice, we live in a world of complicated biological granularity.

The built-in limitations of our senses don't let us quite see this world for what it really is. If we hold two tiny objects at a comfortable distance from our faces, our eyes can only distinguish, or resolve, the pair if they're separated by at least the width of a human hair. Cut that separation in half, and even the most eagle-eyed of us can't tell whether we're looking at one or two objects.

Because of this limitation, we've spent most of the past hundred thousand years painfully unaware of the universe beneath our noses, under our fingernails, in our blood, drool, and skin. We've mostly thought about our physical selves, and other creatures, as tightly wrapped packages. Everything from great beasts to lowly bugs appears equally solid and self-contained.

A mouse and a whale contemplate each other  
across two orders of magnitude in scale.





**Prochlorococcus** is possibly the most plentiful species on Earth: a single milliliter of surface seawater may contain **100,000** cells or more. Worldwide, there are estimated to be **several octillion ( $\sim 10^{27}$ )** individuals.

Bacterial biomass could be **350 to 550 BILLION\*** tons of carbon. That equals **1/3 to 1/2** of the total global biomass.

**Prokaryotes** may have a global biomass of **550 BILLION TONS** of the Earth's dry biomass.

**COPEPODS** may form the largest biomass of any animal species group.

THERE ARE TYPICALLY **1,000,000,000 TO 10,000,000,000 BACTERIAL CELLS** IN A GRAM OF SOIL.

Antarctic krill form one of the largest biomasses of any individual animal species: **500 MILLION TONS**.

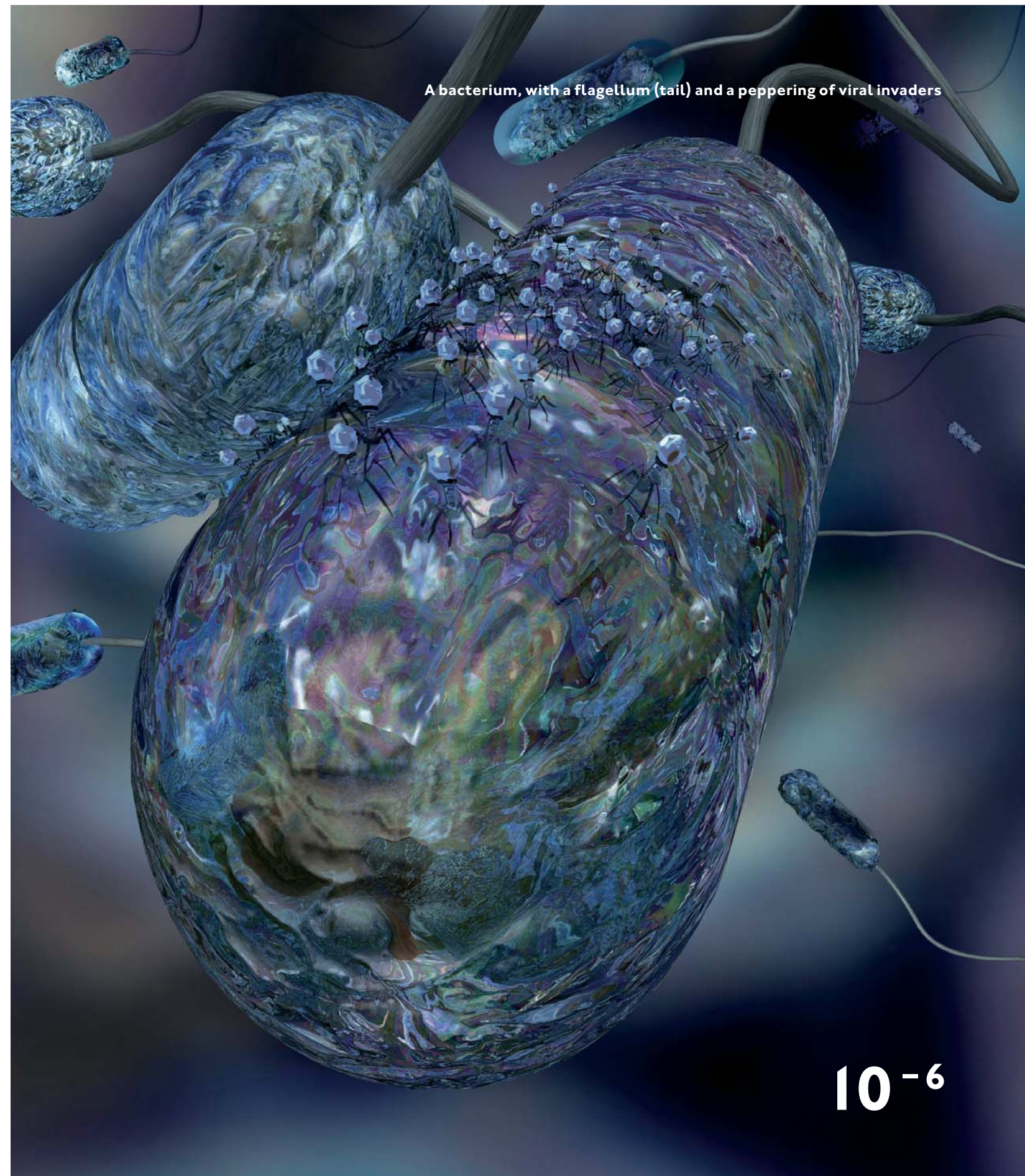
The length of all DNA in your body's cells is **74 billion kilometers** (OR **193,000 TIMES** THE DISTANCE FROM THE EARTH TO THE MOON).

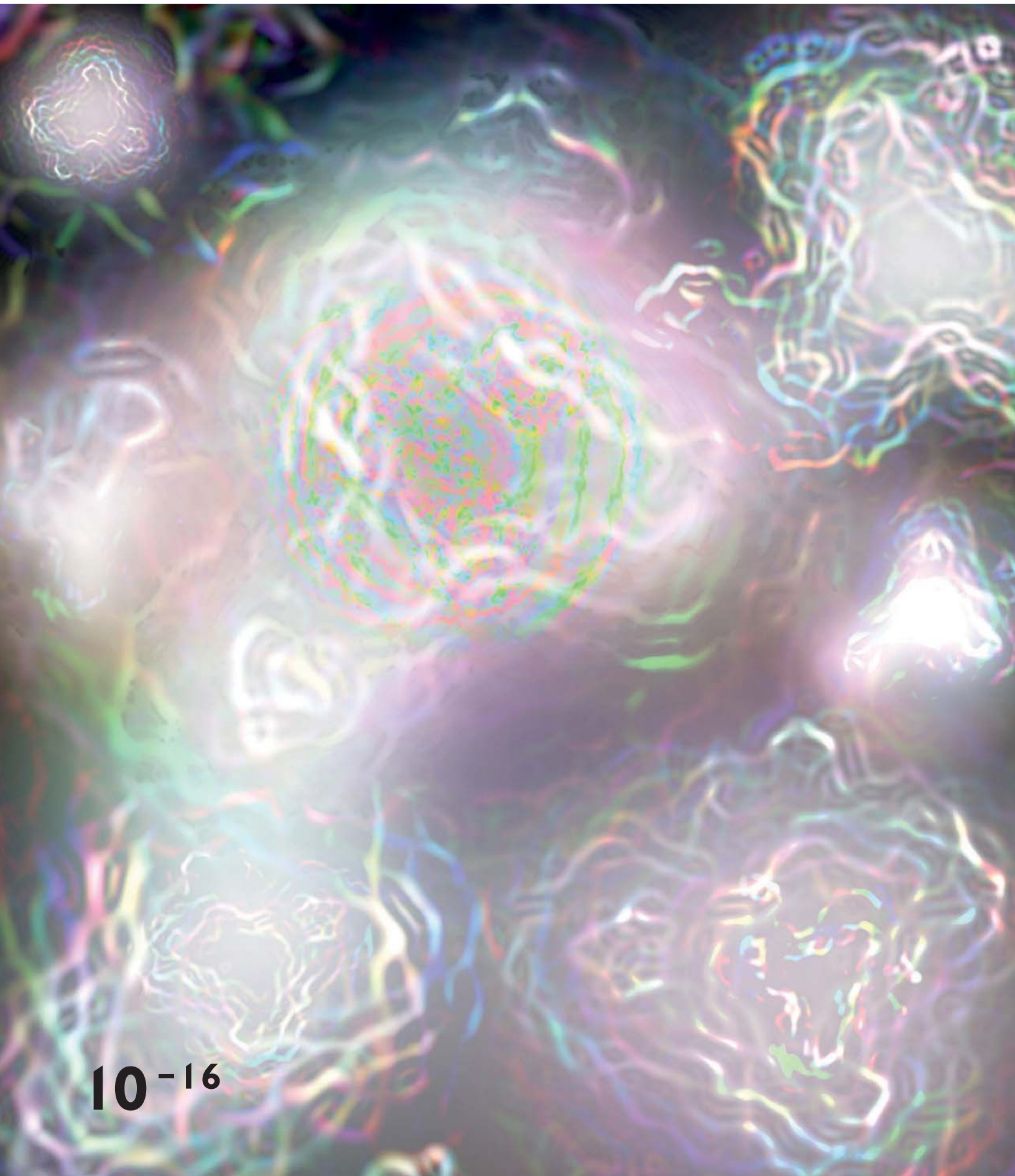
The length of all human DNA on planet Earth is **58 million light-years**.

\* Some studies indicate this biomass may be a smaller 50 billion to 250 billion tons of carbon.

extensions called pili. Inside the capsule is a mess of genetic material: a lengthy DNA strand, small loops of double-strand DNA known as plasmids, and a crowd of smaller compounds and molecular structures.

This bacterium is a fully fledged biological entity. It's a busy chemical factory, with compounds endlessly filtering in and out of its membrane covering. As alien as it appears, the bac-





10

## IT'S FULL OF . . . FIELDS

$10^{-16}$ ,  $10^{-17}$ ,  $10^{-18}$ , and . . .  $10^{-35}$  meters

From a tenth of a femtometer to the Planck length

From approximate proton radius to nearly nothing

This is our final descent. Starting at  $10^{-16}$  meters, or the approximate scale of a proton, we hop onto a trajectory that is going to take us all the way down to the very bottom of the rabbit hole.

Our ultimate destination is an astonishing *nineteen* orders of magnitude away. That's a journey equivalent to our earlier passage from the scale of the entire observable universe to the parochial familiarity of the Earth-Moon system. And it's all *inside* a single proton.

The innards of that proton are far more messy and inelegant than we might have expected. Although this composite object is experienced by the outside world as if it simply contains two up quarks and one down quark, that is only part of the story.

Look closer and we find that the structure of this composite particle is a stew of gluons and virtual quark and anti-quark pairs—popping in and out of existence within the allowances of the uncertainty principle. Energy and time are borrowed and balanced; stuff appears and disappears before the universal bookkeepers can get angry.

If, for an instant, you could set aside all the virtual quarks and anti-quarks that complement one another, the two up quarks and one down quark would be all that remain. These three are what the outside world senses—the asymmetry in the stew.

At these scales, and in such an alien environment, it makes sense to modify our earlier ideas about a reality composed of “particles” and “waves” (although the mathematics of waves is still a

Farther into the composite proton