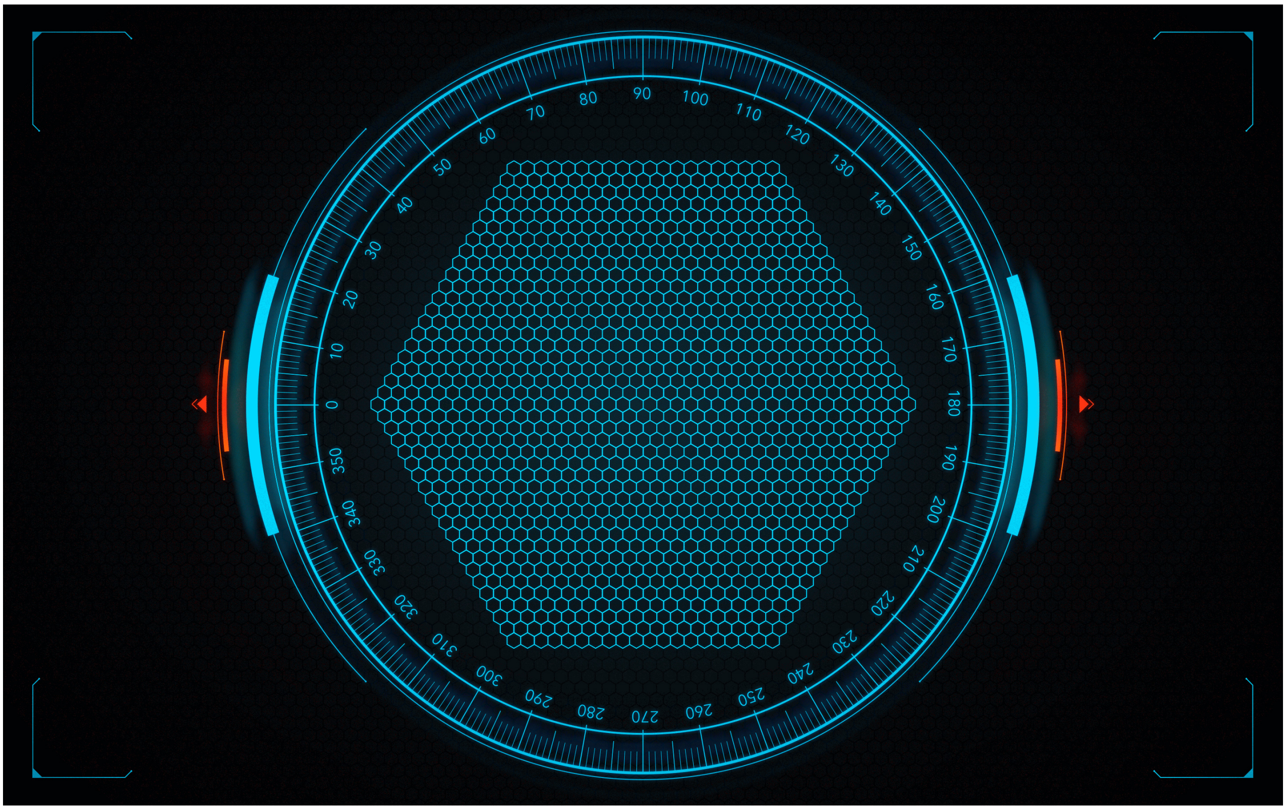
Quanta magazine

With a Simple Twist, a ‘Magic’ Material Is Now the Big Thing in Physics

***By* [David H. Freedman]**

April 30, 2019

The stunning emergence of a new type of superconductivity with the mere twist of a carbon sheet has left physicists giddy, and its discoverer nearly overwhelmed.



It’s exceptionally difficult to twist two sheets of graphene exactly 1.1 degrees out of alignment. But this “magic angle” leads to extraordinary effects. “I couldn’t believe it,” said one scientist. “I mean I actually found it beyond belief.”

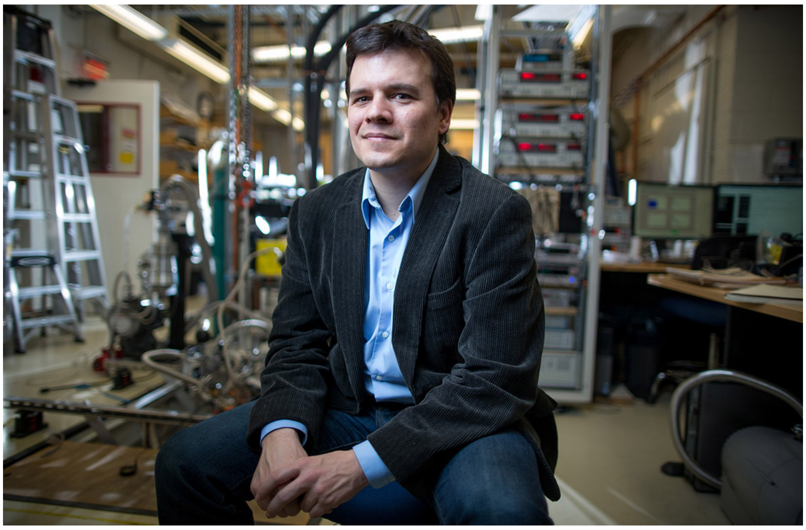
Olena Shmahalo/Quanta Magazine

[Pablo Jarillo-Herrero] is channeling some of his copious energy into a morning run, dodging startled pedestrians as he zips along, gradually disappearing into the distance. He’d doubtlessly be moving even faster if he weren’t dressed in a sports coat, slacks and dress shoes, and confined to one of the many weirdly long corridors that crisscross the campus of the Massachusetts Institute of Technology. But what he lacks in gear and roadway he makes up for in determination, driven by the knowledge that a packed auditorium is waiting for him to take the podium.

Jarillo-Herrero has never been a slacker, but his activity has jumped several levels since his dramatic announcement in March 2018 that his lab at MIT had [found superconductivity in twisted bilayer graphene] — a one-atom-thick sheet of carbon crystal dropped on another one, and then rotated to leave the two layers slightly askew.

The discovery has been the biggest surprise to hit the solid-state physics field since the 2004 discovery that an intact sheet of carbon atoms — graphene — could be lifted off a block of graphite with a piece of Scotch tape, work that was later awarded the Nobel Prize. And it has ignited a frenzied race among condensed-matter physicists to explore, explain and extend the MIT results, which have since been duplicated in several labs.

The observation of superconductivity has created an unexpected playground for physicists. The practical goals are obvious: to illuminate a path to higher-temperature superconductivity, to inspire new types of devices that might revolutionize electronics, or perhaps even to hasten the arrival of quantum computers. But more subtly, and perhaps more important, the discovery has given scientists a relatively simple platform for exploring exotic quantum effects. “There’s an almost frustrating abundance of riches for studying novel physics in the magic-angle platform,” said Cory Dean, a physicist at Columbia University who was among the first to duplicate the research.



Pablo Jarillo-Herrero’s work on twisted bilayer graphene has colleagues openly speculating about a Nobel Prize. “We try to be adventurous in this lab, and we have a good sense of smell,” he said. “This felt right.”

Bryce Vickmark

All this has left Jarillo-Herrero struggling to keep up with the demands of suddenly being out in front of a red-hot field that has already garnered its own name — “twistronics.” “Probably more than 30 groups are starting to work on it,” he said. “In three years it will be a hundred. The field is literally exploding.” Well, maybe not literally, but in every other way, it seems. He’s so swamped with requests to share his techniques and give talks that nearly tripling his speaking schedule has barely made a dent in the flow of invites. Even his students are turning down speaking offers. At the American Physical Society annual meeting in March it was standing room only at his session, leaving a crowd outside the doors hoping to catch snatches of the talk.

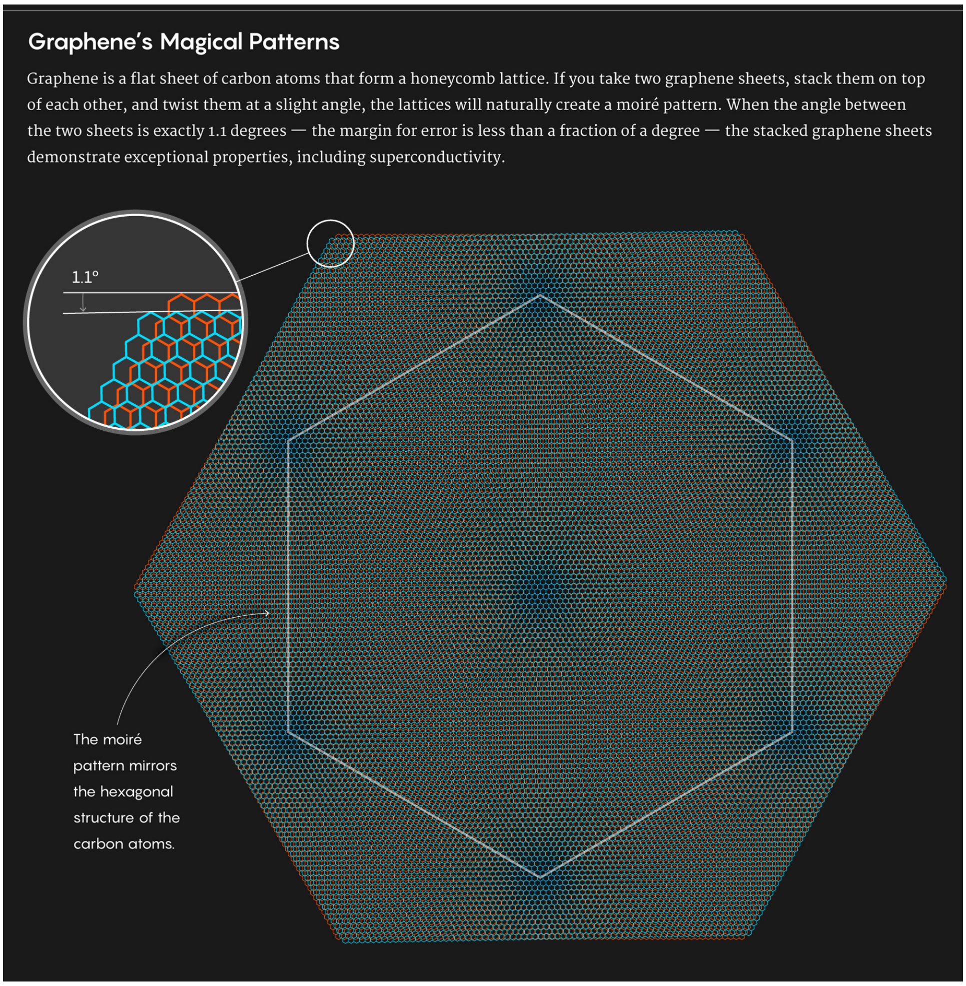
To tease out the startling observation, his group had to nail down a precise and dauntingly elusive twist in the layers of almost exactly 1.1 degrees. That “magic” angle had long been suspected to be of special interest in twisted bilayer graphene. But no one had predicted it would be *that* interesting. “It would have been crazy to predict superconductivity based on what we knew,” said Antonio Castro Neto, a physicist at the National University of Singapore. “But science moves forward not when we understand something, it’s when something totally unexpected happens in experiment.”

Beyond Belief

Castro Neto would know. In 2007 he suggested that pressing two misaligned graphene sheets together might produce some novel properties. (He later suggested that graphene might conceivably become superconducting under some specific conditions. “I just never put the two ideas together,” he said, wistfully.)

Several groups in the U.S. and Europe were soon studying the properties of twisted bilayer graphene, and in 2011, Allan MacDonald, a theoretical physicist at the University of Texas, Austin, urged his colleagues to hunt for interesting behavior at a particular “magic angle.” Like other theorists, MacDonald had focused on how the misalignment of the two sheets creates an angle-dependent moiré pattern — that is, a periodic grid of relatively giant cells, each of which is composed of thousands of graphene crystal cells in the two sheets. But where others had been struggling with the enormous computational complexity of determining how an electron would be affected by the thousands of atoms in a moiré cell, MacDonald hit on a simplifying concept.

He reckoned the moiré cell itself would have one property that varied strictly with rotation angle, more or less independently of the details of the atoms that made it up. That property was a critical one: the amount of energy a free electron in the cell would have to gain or shed to tunnel between the two graphene sheets. That energy difference was usually enough to serve as a barrier to intersheet tunneling. But MacDonald calculated that as the rotation angle narrowed from a larger one, the tunneling energy would shrink, finally disappearing altogether at exactly 1.1 degrees.



5W Infographics for Quanta Magazine

As that tunneling energy became small, the electrons in the sheets would slow down and become strongly correlated with one another. MacDonald didn't know exactly what would happen then. Perhaps the highly conductive graphene sheets would turn into insulators, he speculated, or the twist would evoke magnetic properties. "I frankly didn't have the tools to really say for sure what would happen in this sort of strongly correlated system," said MacDonald. "Certainly superconducting is the thing you most hope to see, but I didn't have the nerve to predict it."

MacDonald's ideas largely fell flat. When he submitted his paper for publication, reviewers dinged his simplifying assumptions as implausible, and the paper was rejected by several journals before landing in the *Proceedings of the National Academy of Sciences*. Then after it did come out, few experimentalists went after it. "I wasn't sure what we'd get from it," said Dean. "It felt like conjecture, so we put it aside."

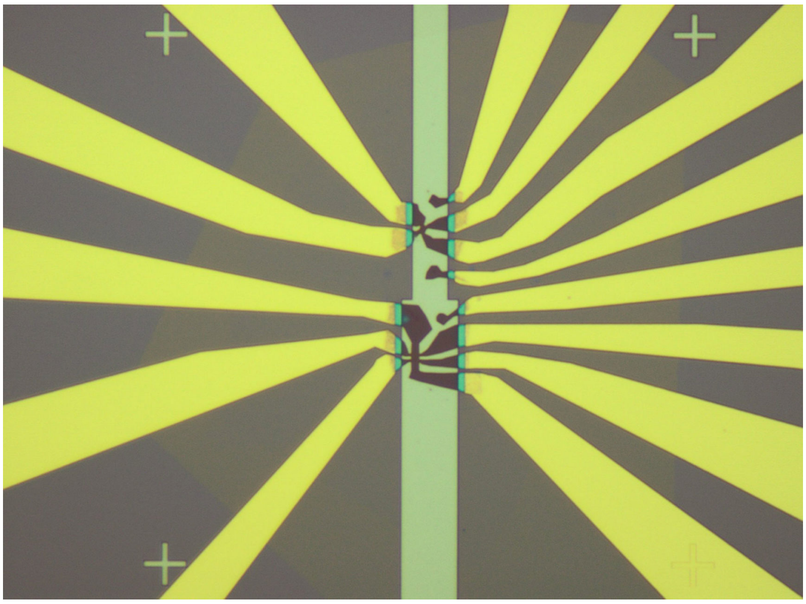
Also slow to pursue the magic angle was Philip Kim, a physicist at Harvard University and a kind of dean of the experimental twisted bilayer graphene field. (Both Dean and Jarillo-Herrero were postdocs in his lab.) "I thought Allan's theory was too simple," he said. "And like most experimenters, I thought it probably wasn't possible to control the angle well enough. People started to forget about it." In fact, said Kim, he and many others in the field were just about ready to move on from twisted bilayer graphene altogether, feeling other novel materials might present more exciting opportunities.

Not Jarillo-Herrero. He had already been working on twisted bilayer graphene for a year when MacDonald's prediction was published in 2011, and he was convinced there was something to it — even after a colleague tried to warn him off it as a likely waste of time. "We try to be adventurous in this lab, and we have a good sense of smell," said Jarillo-Herrero. "This felt right."

The challenge, he knew, would be to create an ultraclean, highly homogeneous pair of graphene sheets that overcome the material's natural opposition to holding a 1.1-degree angle. Graphene sheets show a strong tendency to pull into alignment with each other. And when forced into an offset position, the superflexible sheets tend to deform.

Jarillo-Herrero's group went about polishing every aspect of the fabrication process: from creating and cleaning the sheets, to lining them up at just the right angle, to pressing them into place. The measurements had to be done in near vacuum to prevent contamination, and the results had to be cooled to within a few degrees of absolute zero to have a good chance of seeing correlated electron behavior — at higher temperatures the electrons move too energetically to have a chance to strongly interact.

The lab produced dozens of twisted bilayer graphene "devices," as researchers call them, but none of them showed significant evidence of electron correlation. Then, in 2014, one of his students brought him a device that when exposed to an electric field showed signs of distinctly ungraphene-like insulating properties. Jarillo-Herrero simply put the device aside and continued making new ones. "Our devices are complicated. You can have flipped edges and other flaws that give weird results that have nothing to do with new physics," he explains. "If you see something interesting once, you don't pay attention to it. If you see it again, you pay attention."



A twisted bilayer graphene "device" consists of stacked graphene sheets (the dark material in the center of the image) connected to various electrodes (yellow). By varying the voltage in the electrodes, researchers can control the electrical properties of the bilayer graphene.

Jarillo-Herrero Lab

In the summer of 2017, doctoral student Yuan Cao, who at the age of 21 was already in his third year of graduate school at MIT, brought Jarillo-Herrero a new device that gave him reason to pay attention. As before, an electric field switched the device into an insulator. But this time they tried cranking up the field higher, and it suddenly switched again — into a superconductor.

The lab spent the next six months duplicating the results and nailing down measurements. The work was done in strict secrecy, a break from the typically highly open and collaborative culture of the twisted bilayer graphene field. "I had no way of knowing who else might be close to superconductivity," said Jarillo-Herrero. "We share ideas and data all the time in this field, but we're also very competitive."

In January 2018, with a paper prepared, he called an editor at *Nature*, explained what he had, and made his submission contingent on the journal agreeing to a one-week review process — a friend had told him one of the seminal CRISPR papers had received that extraordinary treatment. The journal agreed, and the paper flew through the rush review.

Jarillo-Herrero sent a prepublication email heads-up to MacDonald, who hadn't even known that Jarillo-Herrero had been doggedly pursuing the magic angle. "I couldn't believe it," said MacDonald. "I mean I actually found it beyond belief." Dean learned about it along with the rest of the physics community at a conference in March 2018, right around the time that the *Nature* paper came out. "The results proved me spectacularly wrong," Dean said.

The Perfect Playground

Physicists are excited about magic-angle twisted bilayer graphene not because it's likely to be a practical superconductor but because they're convinced it can illuminate the mysterious properties of superconductivity itself. For one thing, the material seems to act suspiciously like a cuprate, a type of exotic ceramic in which superconductivity can occur at temperatures up to about 140 kelvin, or halfway between absolute zero and room temperature. In addition, the sudden jumps in twisted bilayer graphene — from conducting to insulating to superconducting — with just a tweak of an external electric field indicate that free electrons are slowing to a virtual halt, notes physicist Dmitri Efetov of the Institute of Photonic Sciences (ICFO) in Barcelona, Spain. "When they stop, [the electrons] interact all the more strongly," he said. "Then they can pair up and form a superfluid." That fluidlike electron state is considered a core feature of all superconductors.

The main reason 30 years of studying cuprates has shed relatively little light on the phenomenon is that cuprates are complex, multi-element crystals. "They're poorly understood materials," said Efetov, noting that they superconduct only when precisely doped with impurities during their demanding fabrication in order to add free electrons. Twisted bilayer graphene, on the other hand, is nothing but carbon, and "doping" it with more electrons merely requires applying a readily varied electric field. "If there's any system where we can hope to understand strongly correlated electrons, it's this one," said Jarillo-Herrero. "Instead of having to grow different crystals, we just turn a voltage knob, or apply more pressure with the stamps, or change the rotation angle." A student can try to change the doping in an hour at virtually no cost, he notes, versus the months and tens of thousands of dollars it might take to try out a slightly different doping scheme on a cuprate.

Also unique, said MacDonald, is the small number of electrons that seem to be doing the heavy lifting in magic-angle twisted bilayer graphene — about one for every 100,000 carbon atoms. "It's unprecedented to see superconducting at such a low density of electrons," he said. "It's lower than anything else we've seen by at least an order of magnitude." Over 100 papers have popped up on the scientific preprint server arxiv.org that offer theories to explain what might be going on in magic-angle twisted bilayer graphene. Andrei Bernevig, a theoretical physicist at Princeton University, calls it "a perfect playground" for exploring correlated physics.

Physicists seem eager to play on it. Besides being able to flip between extremes in conductivity with a literal push of a button, notes Rebeca Ribeiro-Palau, a physicist at the Center for Nanoscience and Nanotechnology near Paris, there's already good evidence that twisted bilayer graphene's magnetic, thermal and optical properties can be nudged into exotic behaviors as easily as its electronic properties can. "In principle you can switch any property of matter on and off," she said. MacDonald points out, for example, that some of the insulating states in twisted bilayer graphene appear to be accompanied by magnetism that arises not from the quantum spin states of the electrons, as is typically the case, but entirely from their orbital angular momentum — a theorized but never-before-observed type of magnetism.

The Coming Age of Twistronics

Now that Jarillo-Herrero's group has proven that magic angles are a thing, physicists are trying to apply the twistronics approach to other configurations of graphene. Kim's group has been experimenting with twisting two double-layers of graphene and has already found evidence of superconductivity and correlated physics. Others are stacking up three or more layers of graphene in the hopes of gaining superconductivity at other magic angles, or perhaps even when they are aligned. Bernevig posits that as the layers stack up higher and higher, physicists may be able to get the superconductivity temperature to climb along with it. Other magic angles may play a role, too. Some groups are squeezing the sheets more tightly together in order to increase the magic angle, making it easier to achieve, while MacDonald suggests even richer physics may emerge at smaller, if much harder to target, magic angles.

Meanwhile, other materials are coming into the twistronics picture. Semiconductors and transitional metals can be deposited in twisted layers and are seen as good candidates for correlated physics — perhaps better than twisted bilayer graphene. "People are thinking of hundreds of materials than can be manipulated this way," said Efetov. "Pandora's box has been opened."

Dean and Efetov are among those sticking with what might already be called classic twistronics, in the hopes of boosting correlated effects in magic-angle twisted bilayer graphene devices by literally smoothing out the wrinkles in their fabrication. Because there's no chemical bonding to speak of between the two layers, and because the slightly offset layers try to settle into alignment, forcing them to hold a magic-angle twist creates stresses that lead to submicroscopic hills, valleys and bends. Those local distortions mean that some regions of the device might be within the magic range of twist angles, while other regions are not. "I've tried gluing the edges of the layers, but there are still local variations," he complained. "Now I'm trying to figure out ways to minimize the initial strain when the layers are pressed together." Efetov has recently reported progress in doing just that, and the results have already paid off in new superconducting states at temperatures of about 3 degrees kelvin, or twice as high as previously observed.

Having burst far out into the lead of the twisted bilayer graphene field in stunning fashion, Jarillo-Herrero isn't sitting back and waiting for others to catch up. His lab's main focus remains trying to coax ever more exotic behavior out of twisted bilayer graphene, taking advantage of the fact that through long trial and error he's boosted his yield of superconducting samples to nearly 50 percent. Most other groups are struggling with yields a tenth of that or less. Given that it takes about two weeks to fabricate and test a device, that's an enormous productivity edge. "We think we're just beginning to see all the fascinating states that will come out of these magic-angle graphene systems," he said. "There's a vast phase space to explore." But to cover his bases, he's pulled his lab into also exploring twistronics in other materials.

The stakes in the race to come up with easier to make, better performing, higher-temperature superconductors are huge. Aside from the oft-evoked vision of levitating trains, reducing the energy loss in electric power transmission would boost economies and sharply cut harmful emissions around the world. Qubit fabrication could suddenly become practical, perhaps ushering in the rise of quantum computers. Even without superconductivity, ordinary computers and other electronics could get a huge boost in performance versus cost from twistronics, due to the fact that entire complex electronic circuits could in theory be built into a few sheets of pure carbon, without needing a dozen or more complexly etched layers of challenging materials common to today's chips. "You could integrate wildly different properties of matter into these circuits right next to one another, and vary them with local electric fields," said Dean. "I can't find words to describe how profound that is. I'd have to make something up. Maybe dynamic material engineering?"

However such hopes ultimately pan out, for now the excitement in twisted bilayer graphene seems only to be building. "Some may be shy to say it, but I'm not," said Castro Neto. "If the field keeps going the way it is now, somebody is going to get a Nobel Prize out of this." That sort of talk is probably premature, but even without it there's plenty of pressure on Jarillo-Herrero. "What my lab did creates unrealistic expectations," he admits. "Everyone seems to think we're going to produce a new breakthrough every year." He's certainly determined to make further important contributions, he said, but he predicts that whatever the next electrifying discovery is, it's as likely come out of a different lab as it is his. "I've already accepted that as a fact, and I'm fine with it," he said. "It would be boring to be in a field where you're the only one advancing it."

Clarification March 9, 2019: An earlier version of this article referred to the "2004 Nobel Prize–winning discovery" of graphene. The discovery was made in 2004, but the Nobel Prize came later. The sentence has been revised to make this clear.