Recipes for the **Cosmic Cocktail**

"Space is an enigma": Sadegh Khochfar wanted to be an astrophysicist for as long as he can recall.

Photo: Axel Griesch

A pile of astronomy books and a telescope in his childhood bedroom. Space cast its spell on **Sadegh Khochfar** at an early age – and he is still captivated today. The 37-year-old now heads a Max Planck research group at the Garching-based **Max Planck Institute for Extraterrestrial Physics**, where he is at least as successful at piecing together the components of the universe as he was at mixing cocktails as a student.

TEXT **ALEXANDER STIRN**

Sadegh Khochfar knows the secret to making a good caipirinha – if not the best. It's the ratio of limes to brown sugar. But not only does the quantity have to be right, but also the sequence: cut the limes, sprinkle the sugar on them, and only then do you mash them. Only in this way can the sugar bind with the essential oils in the peel, allowing the caipirinha to develop its full flavor.

The 37-year-old should know. For years, he financed his physics studies by mixing cocktails, spending his days at the university and his nights at the bar. Even today, he still gladly plays bartender for his friends. No one has ever complained. "I still make the best caipirinha east of Brazil," he says and laughs. "I am absolutely certain of that." And this despite the fact that Khochfar, a lively Hessian with Iranian roots, drinks no alcohol himself. He says he simply never felt the need to try an alcoholic drink – regardless of who mixed it, regardless of how good it is.

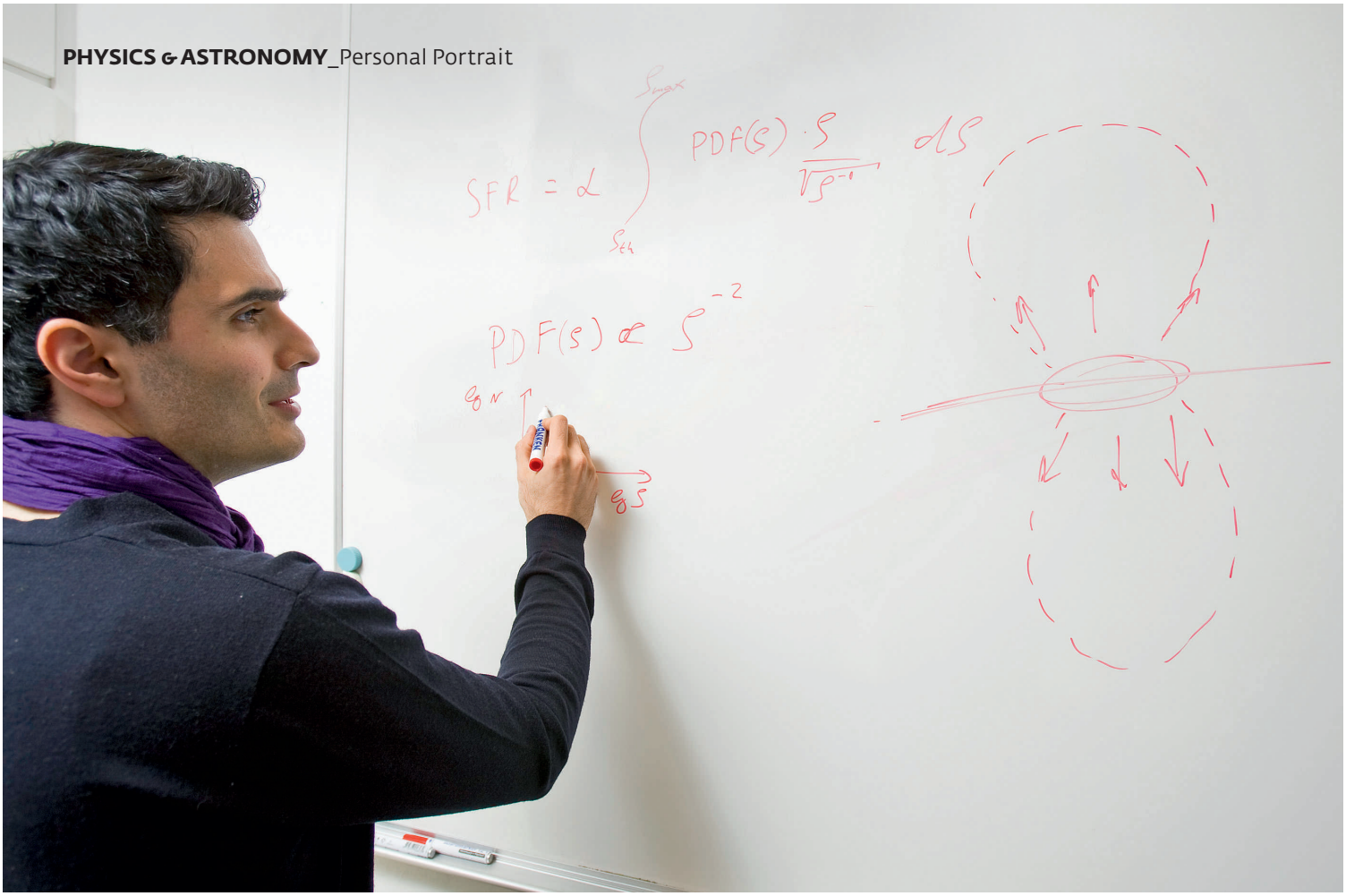
Sadegh Khochfar is a theoretician, not only behind the bar, but also in his professional life, at the Max Planck Institute for Extraterrestrial Physics in Garching. Since May 2008, he has headed an eight-member research group there that explores the emergence and development of galaxies. It deals with such questions as why the universe looks the way we see it today, how the supermassive black holes form that are found at the center of most galaxies, and which growth phases these structures go through on the path from baby galaxy to mature stellar system.

FREEDOM TO DREAM UP CRAZY THINGS

"The mere thought that we can understand something that is so large and so complex as space is simply fascinating," says Khochfar. "It's like an enigma, a great mystery that I can unveil a bit here and there with my science." It isn't quick. It takes effort. But Sadegh Khochfar is persistent.

For as long as he can recall, he wanted to be an astrophysicist – a theoretical astrophysicist, to be precise: "It simply gives one more freedom to think, to dream up new, sometimes also crazy, things, and to explore the consequences."

Crazy is not a word that describes Khochfar's career path. He followed the classical, perhaps even stereotypi-



cal astronomer career: His childhood bedroom was filled with stacks of pertinent books about the Sun, moon and stars. As a ten-year-old, he devoured Carl Sagan's masterpiece *Cosmos*. Of course he had a telescope, and of course he took advanced math and physics courses.

A TEATOTALLER WORKING AS A BARKEEPER

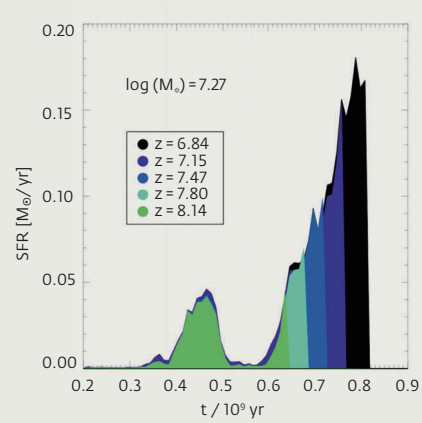
But Khochfar's career path also always had an unusual twist, a small kink, something exotic: normally, astronomy-crazed youth spend their nights gazing at the starry sky. Sadegh Khochfar, in contrast, preferred to read books. "Sure, it was nice to look at the individual constellations with the telescope, but it didn't give me the ultimate thrill," he recalls. "I always first wanted to know what I was seeing. And above all, where it comes from, and why it looks like it does."

The son of an immigrant, Khochfar would have preferred to study astrophysics straight away, but that isn't possible in Germany. So he studied physics – of course – in Frankfurt, his home town. Nevertheless, Khochfar moved out of his family home. He wanted to stand on his own two feet, wanted to finance his studies himself. But that also meant that he needed a part-time job.

While still in high school, Sadegh Khochfar had already met an experienced barkeeper who taught him how to mix cocktails. The two traveled through Germany with a mobile bar and put on a show like Tom Cruise in the movie *Cocktail*. However, the time pressures involved in his studies forced him to give this up.

Sadegh Khochfar, the non-drinker, heard that the hip Frankfurt club Café Cult was looking for a barman. He got the job – despite his rather theoretical knowledge of the subject matter, or perhaps precisely because of it: "Because I wasn't drinking any alcohol, I was probably the only one behind the bar they could trust with the cash register," says Khochfar with a laugh. But the quality of his cocktails left nothing to be desired, either. "As a barman, you have to look at the faces of your customers to see whether they like your drinks."

Wednesdays and Thursdays, Khochfar tended bar from 6:00 p.m. until 2:00 a.m., and weekends until 6:00 a.m. No wonder he didn't want to spend his nights also gazing at stars. Instead, he saw other stars: Silvester Stallone, for example. He didn't order a caipirinha, though, but rather a boring Jackie-Coke.



Growth: The diagram shows that the star formation rate of a galaxy increases with time.

Photo: Axel Griesch, graphic: MPI for Extraterrestrial Physics

The universe in three dimensions: The model above shows the distribution of galaxies in a galaxy cluster. The most massive galaxies in early times end, in all probability, in the center of such clusters. Before the scientists feed the data into their computers, they must incorporate in their calculations as many formulas from the physics patchwork family as possible (left).

Photo: Axel Griesch

Nor did Sadegh Khochfar give up his job at the bar when, after completing his intermediate exams, he switched to the University of Heidelberg. For three years, he commuted between the cities on the Main and Neckar rivers. "To be honest, it was hard, but despite everything, it was a good time," says Khochfar. He wrote his doctoral dissertation at – of course – the Max Planck Institute for Astronomy in Heidelberg. His working group dealt with elliptical galaxies, the most massive stellar systems in the universe.

Sadegh Khochfar wanted to do something cosmological, something relating to the formation of galaxies, a field with many unanswered questions. In his theoretical work, the young physicist was able to show that elliptical galaxies are not created – as previously supposed – by the merger of two spiral galaxies. Instead, there are already two ellipses involved in their birth. In addition, it turns out that these processes require much less gas than was thought. "What is interesting about this is that these findings have since become confirmed and accepted," says Sadegh Khochfar.

Advanced physics course, physics degree, Ph.D. in astrophysics, head of an astrophysics group. It sounds straightforward, even almost boring. Sadegh Khochfar shakes his head vehemently. "Astrophysics is a patchwork family. In order to understand what is happening in the sky, we have to make extensive use of physics."

ASTROPHYSICS – THE BIGGEST PUZZLE OF THEM ALL

If you want to fathom how and why galaxies form, you have to understand gravitation and the theory of relativity. But you also have to take radiative processes, turbulences and hydrodynamic equations into account. "It isn't easy to be an expert in all fields, but there's no way around understanding the fundamental laws of physics, extracting the core messages and correctly incorporating all that in our astrophysical models," says the researcher.

It's almost like being a barkeeper. He, too, must know the characteristic properties of the ingredients in order to find the right composition and mix a tasty cocktail. "Basically, astrophysics is the biggest puzzle one can imagine," says Sadegh Khochfar.

Of course he enjoyed doing puzzles as a child, no doubt about it. Today, however, the scientist tends toward chess – in its more athletic variant: Khochfar fences, his weapon a foil. "Fencing really is like chess. You have to try to find your opponent's weakness, and then outwit him at the crucial moment," he says. Size, physique and speed are secondary here; for Khochfar, fencing is more a battle of will. "If you are clever enough, you can also beat opponents who appear to be superior,"

he says. "On the other hand, there is no one you can blame for a loss. You have to take the responsibility. That's good, I like that."

Zorro and musketeer films are what first turned the young Frankfurt native on to fencing. During his final high school exams, university studies and Ph.D., however, he no longer had time for this unusual hobby. Khochfar didn't take it up again until, with his doctorate in hand, he moved to Oxford in 2003. Over time, Heidelberg had become a bit too small for him; he didn't want to go to the US, and there were no positions available in Cambridge. The offer he received from the "Heidelberg without mountains," as the astrophysicist jokingly refers to Oxford, couldn't have come at a more opportune time.

"It was a magical time," he says. Khochfar collaborated with Joe Silk, an authority in the field of cosmology. He continued to research elliptical galaxies, penetrating into ever more distant times. And he met his wife, who at the time was doing her Ph.D. in political science. The two now have an eight-month-old daughter, so his focus is no longer solely on the growth spurts of baby galaxies, but also on the development of his own child.

Primarily, however, Sadegh Khochfar began his time in Oxford with that which even now still dominates his day-to-day work: simulations. "Traditional theoretical models always assume a simplified, ideal system. Otherwise, it wouldn't be possible to calculate them," he says. But the universe is far more complex. If, like Sadegh Khochfar, we want to understand it in detail, we need numerical simulations.

BALANCING ACT WITH COMPUTER MODELS

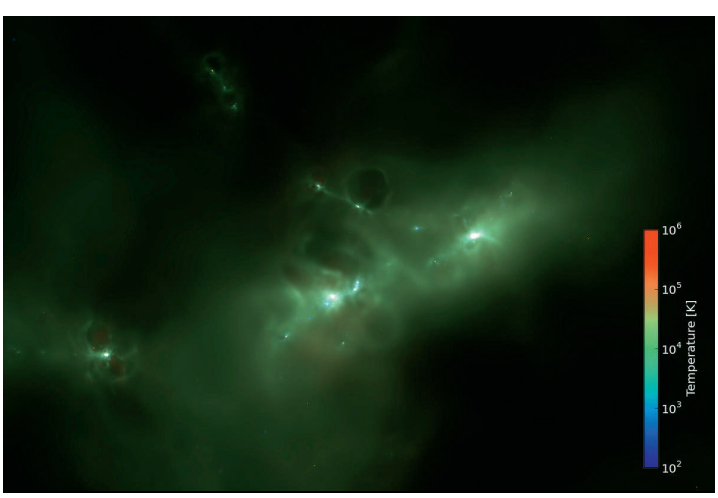
But numerical algorithms are, initially, also just an approximation of reality. The theoreticians try to incorporate, in their simulations, as many formulas from the physics patchwork family as possible, but eventually they fail due to the resolution and the computing time required. For galaxies with many billions of young stars, it is impossible, for example, to calculate, for each individual star, the nuclear fusion processes that ultimately lead to the ignition of the star. Instead, the astrophysicists resort to subgrid recipes, as Sadegh Khochfar puts it: they tell their models that the calculated clumps of gas should eventually turn into a star. It's a balancing act.

And sometimes it goes wrong. Then Khochfar's computer obtains different results than the telescopes of the observers who sit a few doors down. Then discussion, interpretation and the search for errors follow. "In such cases, we have to understand what went wrong, make appropriate changes to the simulation, and integrate the missing physics," says Khochfar.

But doesn't that pose the risk that the models are simply tweaked until they yield the desired result – in other words, that they plow through the algorithms with a saber rather than a foil? Sadegh Khochfar shakes his head. "We can't manipulate the simulations at will, because we are always bound by fundamental physical laws," he says. Energy and angular momentum must always be preserved, and the equations of hydrodynamics also apply to gas flows in galaxies.

"Basically, here, too, it's like with a puzzle," says the scientist. You start with one piece and try to attach the second piece to it. If it doesn't fit, it can be made to fit with a bit of force. With the third piece, it's more difficult, and with the fourth, nearly impossible. Eventually, the whole thing is so bad that nothing fits together anymore.

Cosmic birth: Sadegh Khochfar's simulation shows how baby galaxies could have formed in the early universe (left). Such systems presumably form elliptical galaxies in the course of 13 billion years, similar to M 87 (photo right), but with less mass. The researchers believe that many baby galaxies merge with one another during their development, thus forming larger galaxies.



First Billion Years Project: S. Khochfar and C. Della Vecchia (MPE); visualization: K. Reuter & M. Rampp (MPG RZG)

Teamwork: Simulating the cosmos on the computer is complex and time consuming. For the latest project, it took two years just to develop the algorithms, with 30 million megabytes of data having been collected. This makes it all the more important to continually discuss the results – as Claudio Dalla Vecchia, Alessandra Beifiori, Sadegh Khochfar and Jan-Pieter Paardekooper (left to right) are doing here.

Photo: Axel Griesch

The astrophysicist opens his laptop and proudly presents one of his group's most recent projects. It's one of the highest-resolution simulations of the early universe. It shows the emergence of the galaxies during the first billion years of the universe. From cold, greenish glowing clouds of gas and dust, the first stars form – hot yellow dots that eventually explode, pushing gas away and distributing heavy elements in their surroundings. New stars emerge, and galaxies form and merge together.

It's a mammoth project: it took nearly two years to develop and test the algorithms and, finally, run the simulation. The processors of various computing centers toiled for more than three million hours; billions of particles had to be taken into account, and 30 million megabytes of data accrued. "We will undoubtedly need another year to evaluate everything and exploit every last detail," says Sadegh Khochfar.

The real test will take even longer: at present, the best telescopes can look just far enough into the past of the 13.7-billion-year-old universe that they can recognize objects that formed a billion years after the Big Bang. But their images are weak and show few details. The next generation of telescopes, including the James Webb Space Observatory and the European Extremely Large Telescope, will change that. "We truly live in a fascinating time," says Sadegh Khochfar. "It doesn't happen often that one has the opportunity to predict things and then verify their existence a short time later."

A SENSE OF HOME AND BELONGING

That is precisely why Sadegh Khochfar came to the Max Planck Institute for Extraterrestrial Physics. In principle, he could just as well have moved a hundred meters further to the Max Planck Institute for Astrophysics – a purely theoretical institute. But Khochfar, who says that he is sometimes a bit too enthusiastic, wanted to face reality, the observers and their measurable results. "It was important to me to go to an institute where I can offer complementary expertise, even if it means that I am sometimes the exotic one," says Khochfar.

He even turned down an offer to take on a professorship in San Francisco at the time – in favor of northern Munich. "Garching is simply a fantastic place to do astrophysics," he says. "This is where cutting-edge research happens. Nowhere in Europe is the density of institutes and astronomers higher." Nearly 500 people work and conduct research at Khochfar's institute alone – a large, but above all international community. For him, the man with Iranian and German citizenship, that was also an important argument. "To be honest, it gives me a very good feeling, a sense of home and belonging."

It wasn't always like that: In the early 1970s, Khochfar's parents left their home in Iran and moved to Frankfurt. His father, a carpet weaver, earned a living repairing carpets, while his mother stayed at home. Two years later, little

A battle of will: Fencing, says Sadegh Khochfar, is like chess. "You have to try to find your opponent's weakness, and then outwit him at the crucial moment."

Sadegh was born. "I always enjoyed growing up in Frankfurt, because it was very multicultural there," he says. Among the ten or twelve kids who met on the playground, only two were German. Also at his high school, the proportion of students from immigrant families was a good 50 percent.

That changed abruptly when he went to Johann Wolfgang Goethe University. "In the beginning, we were a handful of foreign students who, funnily enough, met right away and always sat in the last row," says Khochfar. He was the only one who stayed. "Things didn't go quite as smoothly at the university as they had gone in high school. As a foreigner, I had a bit of trouble from time to time."

Once, after completing his practical electronics course, the anonymous results lists showed that only one student didn't pass the associated test. An assistant matter-of-factly approached Khochfar and asked: "You didn't make it, did you?" Of course he had passed. "I found this reaction a bit strange," he says today.

In the end, though, the astrophysicist-in-training didn't let such things lead him astray. He simply enjoyed his studies too much. He saw it through, just like his two siblings. His brother became a doctor, his sister is close to finishing her law degree – and that despite the fact that their parents never went to university. "In Iran, people traditionally set great store by education," says Sadegh Khochfar, "so my parents always made sure that we did well in school and that we received a good education."

They never told their son what he should study. On the contrary: When ever more astronomy books began piling up in his room, when he expressed his desire to have a telescope, when he finally said, "I want to become a theoretical astrophysicist," their question was rather: "And what do you plan to do with that?" But maybe his parents were just thinking of an old Persian saying: "Those who live only from day to day become either poets or astronomers." Sadegh Khochfar occasionally still gets teased about this today – even if it doesn't fit him at all. ◂

GLOSSARY

Elliptical galaxy
In principle, one distinguishes between irregular, spiral-shaped and elliptical galaxies. The latter are among the oldest systems in space. The largest elliptical galaxies have masses of several billion solar masses.

Extremely Large Telescope
A project of the European Southern Observatory (ESO) for a new, next-generation optical telescope. Its main mirror will have a diameter of 39.3 meters and consist of nearly 1,000 hexagonal mirror elements. According to the present plans, the construction of the Extremely Large Telescope is expected to be completed in 2018.

Black hole
A black hole possesses such a large gravitational pull that not even light can escape from it. The region where the escape velocity is greater than the speed of light is called the event horizon. Supermassive black holes are found at the center of most galaxies and play an important role in cosmic evolution.

Photo: Axel Griesch