THE POWER OF **COLLABORATION**

Growing research collaboration at the Chinese Academy of Sciences

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CONTENTS

EXECUTIVE SUMMARY

As the old saying goes, "two heads are better than one". And certainly when it comes to scientific research, it is all about collaboration. The Chinese Academy of Sciences (CAS), as with most other leading research institutions in the world, is growing strongly in both domestic and international collaboration in the recent decade. This increase coincides with CAS's seminal growth in research output, and its emphasis on collaboration as part of its strategic development plan.

Here are some key findings about collaboration trends based on analysis of journal publications from 2008 to 2018, as tracked in Digital Science's Dimensions database:

- For CAS's total research output from 2008 to 2018, around 83% are outcome of collaboration, including around 14% of intra-CAS collaboration, 40% of domestic collaboration with non-CAS institutions, and 29% of international collaboration.

- Collaborative publications have been increasing, from accounting for 75% of CAS's total publications in 2008 to 91% in 2018. While this is mostly contributed by domestic collaboration, international collaboration has also increased, 26% of output in 2008 to 31% in 2018.

- In global comparisons, European institutions typically have larger proportions of publications collaborated internationally, while only CAS has a significant amount of internally authored papers involving researchers from more than one CAS institutes.

- CAS tends to have more domestic collaboration in its strong research fields, particularly, chemical sciences and engineering; while its Earth science has the most international papers, at just over 40%, followed by physical and environmental sciences.

- In high-quality work, international collaboration plays a dominant role, accounting for more than 48% of CAS's papers in Nature Index journals. CAS also has the largest absolute rise in high-quality output of international collaboration among its peers.

- By region, CAS seems to be diversifying its collaborators. While most of its international collaborations are with North American researchers, collaborations with North African researchers are growing the fastest.

- By institution, half of CAS's top 10 international collaborators in high-quality papers are from Russia, and most of the collaborations are in physical sciences, likely to be multi-national collaborations involving several institutions.

- Domestic collaboration at CAS, particularly in high-quality research, is primarily with leading universities, with the top ones being Peking, Tsinghua, and Nanjing Universities.

Of course, collaboration also drives outcomes beyond joint publications. CAS is also actively enhancing its collaboration network to establish joint training programmes, construct big science facilities, or set ethics or guidelines for the development of a specific field, with the goal to achieve the best science possible.

A COLLABORATIVE LANDSCAPE

The Chinese Academy of Sciences (CAS) emphasizes collaboration in its strategic development plan. We analyse the data around CAS's domestic and international collaborations, and how they shape scientific output.

The benefits of science collaboration extend beyond accelerating discovery.

Science requires collaboration. More people means a greater exchange of knowledge, ideas, technology and resources. Many of the greatest scientific discoveries were the result of collaboration. Johannes Kepler's laws of planetary motion were based on data collected by Danish astronomer Tycho Brahe. James Watson and Francis Crick discovered the double helical structure of DNA, enabled with the help, albeit unwittingly, of the superb X-ray crystallography of Rosalind Franklin and Raymond Gosling.

Today, teams are increasingly dominant in research, and the sizes of those teams are likewise increasing[1]. Papers produced by teams are more frequently cited than those written by an individual, and teams are increasingly responsible for the highest impact research.

Most strikingly, the past couple of decades have seen a rise in 'big science' tackling complex research challenges. The mapping of the human genome, the validation of the Higgs boson and the exploration of Mars all involved hundreds if not thousands of collaborators.

Scientific cooperation has benefits beyond accelerating discovery. As China was opening up in the 1980s and 1990s, its most prestigious research institution, the Chinese Academy of Sciences (CAS), encouraged collaboration, especially with international researchers. By working with scientists from other countries, CAS researchers improved their own skills and knowledge, growing China's research capacity.

The emphasis on international collaboration, with developed and developing countries, has continued. In 2007, CAS presented the first Award for International Scientific Cooperation[2], intended to encourage overseas researchers to work with Chinese researchers. It has established various funding schemes to sponsor individual exchanges or institution-level cooperation. In recent years, CAS has also initiated several big-science projects of its own, which further foster international collaboration.

What role does collaboration play in CAS's current research output, and how has the pattern of collaboration changed? This report evaluates those questions through the analysis of scientific publications. It reviews CAS's collaborations over the past 10 years, for both overall and high-quality research, and compares the trends with those of other leading research institutions. The report also assesses collaboration by broad research field, and identifies some of CAS's top collaborators. These analyses are accompanied by case studies that explore different real-world collaborations at CAS.

Scientific collaborations will continue to grow. By examining CAS's collaborations over the past decade, it could be possible to strategically guide joint efforts in the future, raising the quality of research within China and internationally. ■

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A DECADE OF GROWING COLLABORATIONS

As with many other top-flight global research institutions, the Chinese Academy of Sciences (CAS) is undertaking more international research collaborations.

Global collaborations are increasing in the top levels of science.

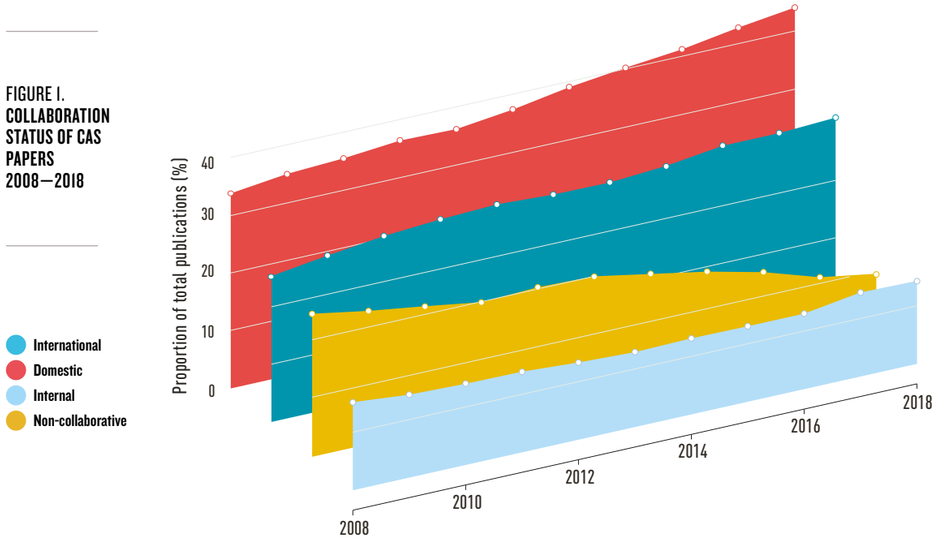
For leading research institutions around the world, the majority of their research output is the result of collaborations, either domestic or international. CAS is no exception.

Of CAS's nearly 320,000 papers from 2008 to 2018, as tracked in Digital Science's Dimensions database, 83% are collaborative. The largest category is domestic collaboration, or papers written by CAS with other China-based researchers. This category represents 40% of the total output. International collaboration represents 29% of CAS's total output, while 14% is classified as internal collaboration, which is work produced by more than one institute of CAS.

As in other parts of the world, collaborative papers at CAS are a growing trend. In 2018, more than 90% of CAS's output involved teamwork, whether with another CAS institute, another university or institution in China, or an international one. That is up from 75% in 2008. Domestic collaborations have increased the most, rising from 34% in 2008 to 45% in 2018 (**FIGURE 1**). Collaborations with overseas researchers have also increased considerably, from 26% in 2008 to 31% in 2018. Not only has collaboration become more important to CAS, it has also come to include a more diverse range of authors.

This growth coincides with measures to enhance domestic and international collaboration as part of CAS's 'Pioneer Initiative', a strategic plan that establishes a blueprint for development from 2015 to 2030. In line with its open innovation strategy, CAS plans to develop a national science and technology service network, establish regional innovation systems, build national science platforms and implement an internationalization strategy[1]. Its construction of 'feature institutes' and 'mega-science research centres' will also increase collaborative research, in terms of journal publications and other outputs not assessed here. The aim of feature institutes is to boost regional development by building partnerships with local institutions. Mega-science research centres, such as particle accelerators, synchrotron light sources and magnetic facilities, which enable innovative research on key problems, provide open research platforms for the entire scientific community. For instance, the Shanghai Synchrotron Radiation Facility has provided bright X-ray beams to domestic and international researchers from various fields, enabling many collaborative works.

FIGURE I.
COLLABORATION STATUS OF CAS PAPERS 2008—2018



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A GLOBAL TREND OF COLLABORATION

Similar, albeit less pronounced, trends are seen for the majority of CAS's global peers. All the international research institutions assessed in this report have seen increases in the absolute number of collaborative papers, as well as in the proportion of collaborative publications.

For all the institutions, the majority of their papers are produced in collaboration with authors from other institutions, whether domestic or international (**FIGURE 2**). The Max Planck Society leads, with 84% of its total output produced through collaborations. It is just ahead of the Helmholtz Association and CAS, both of which attribute 83% of their total research output to collaborative publications.

The European institutions tend to collaborate the most internationally. More than half of their collective papers are published with researchers from other countries, with the Max Planck Society leading at 67%. This is possibly related to the smaller size of European countries and their geographic proximity, particularly compared with China and the United States (US). The many collaborative initiatives by the European Union, and its internal economic ties, also support this trend.

FIGURE 2.
GLOBAL COMPARISON OF COLLABORATION FOR 2008—2018 RESEARCH OUTPUT

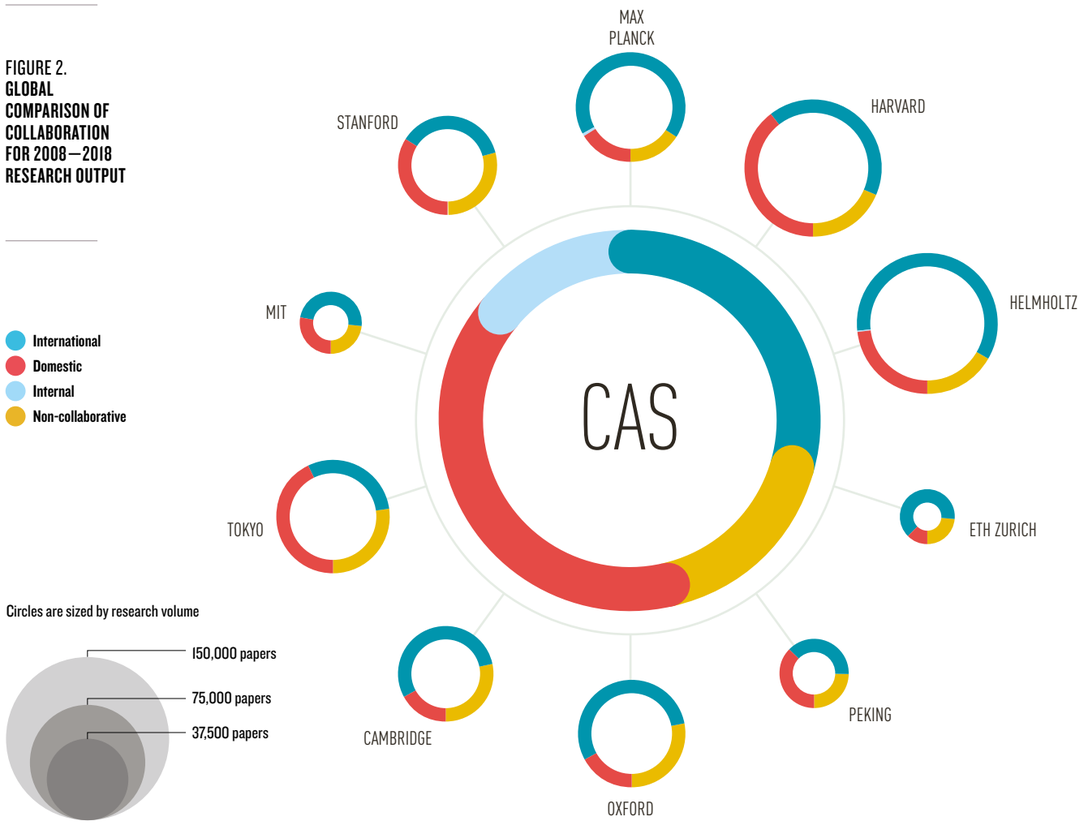
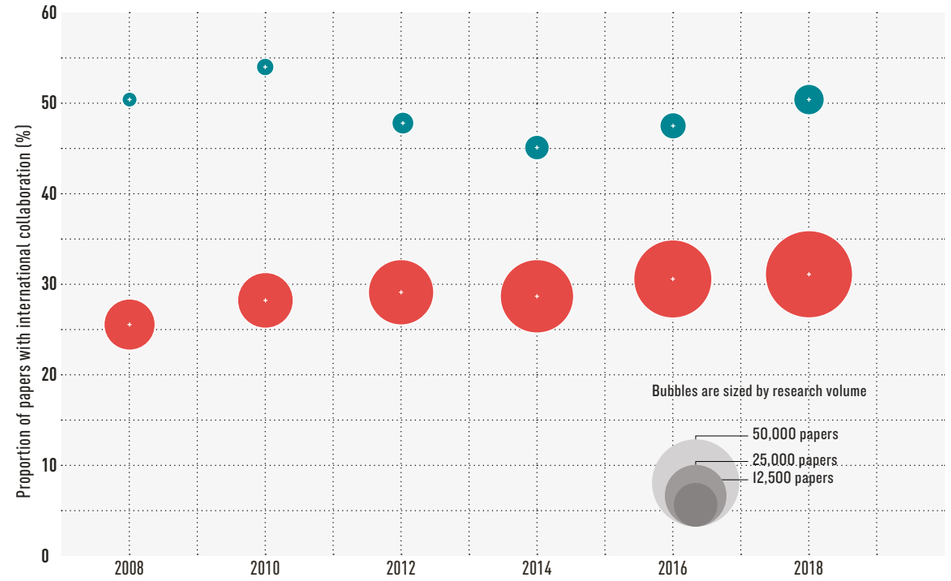


FIGURE 3.
INTERNATIONAL COLLABORATION FOR TOTAL VERSUS HIGH-QUALITY OUTPUT



HIGH-QUALITY COLLABORATIONS

When it comes to papers published in the 82 journals in the Nature Index, a proxy for high-quality research in this report, there is a marked shift towards international collaboration for CAS. Of all the high-quality papers published by CAS from 2008 to 2018, 48% have overseas researchers as co-authors, nearly 20 percentage points more than in CAS's overall output (**FIGURE 3**). This demonstrates the importance of international collaboration when it comes to producing high-quality science.

This trend is set to continue: CAS is publishing more high-quality papers with international co-authors, growing at a compound annual growth rate (CAGR) of 18% from 2008 to 2018. CAS's growth rate is second only to Peking University (22%). Although all the institutions studied increased their high-quality international output over the past 10 years, CAS has the largest absolute rise. This rise is likely to be associated with CAS's strong growth in high-quality research, as the proportion of its high-quality international papers has changed little in the past 10 years.

Domestic papers are the second most common among CAS's high-quality publications, at 29% of high-quality research output. Both the number and proportion of domestically authored papers increased substantially for CAS, at a CAGR of 23% from 2008 to 2018, the highest among the institutions studied. Other institutions have a much flatter domestic output, the exception being Peking University, where domestic papers are rising at a CAGR of 20%. Taken together, the high growth rates of high-quality domestic collaborations at these two Chinese institutions indicate that the quality of scientific output across China is steadily increasing. ■

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VARIED COLLABORATION PATTERNS

The Chinese Academy of Sciences (CAS) has different patterns when it comes to domestic versus international collaboration across the scientific disciplines.

As collaborations cross scientific disciplines, they exhibit diverse and, at times, unexpected patterns.

In CAS's case, the chemical sciences, CAS's strongest subject, have the lowest percentage of papers produced by international collaboration, at only 20%. Domestic collaboration, by contrast, accounts for 45% of CAS's chemical sciences publications (**FIGURE 4**). Likewise, in engineering science, another strong area for CAS, only 23% of papers are produced with overseas authors.

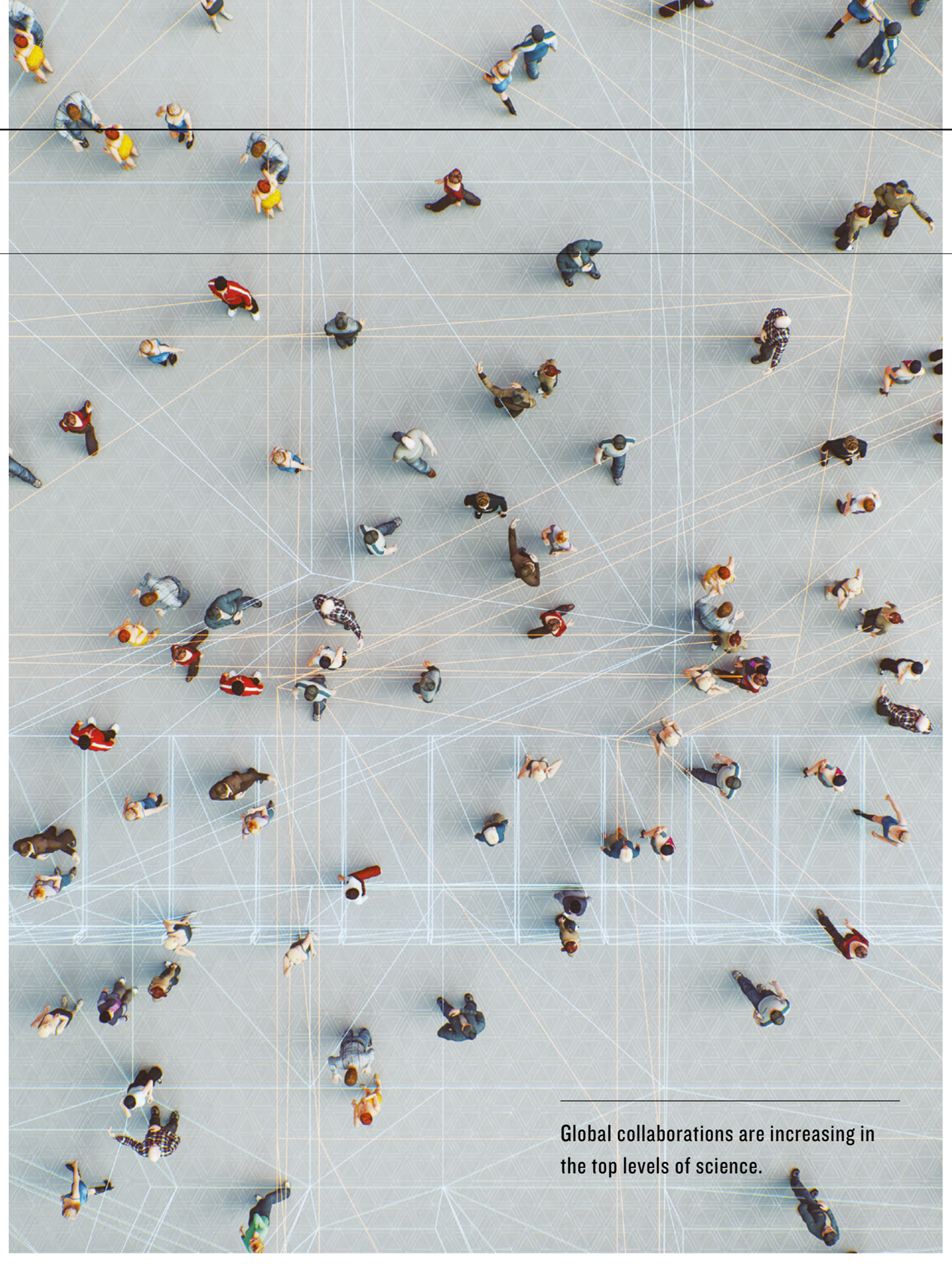
One explanation for such variation is that China does not need collaboration to the same degree in these fields. As China is historically strong in these fields, and many of its chemical and engineering research projects address national development needs, CAS researchers may be more likely to collaborate domestically. They may also apply for joint research grants from the government. Indeed, Peking University has a similar collaboration pattern to CAS, with low percentages for international collaboration in chemical sciences and engineering.

The pattern is reversed in the Earth sciences, where 40% of CAS's publications are the result of an international collaboration, compared to 34% for domestic. Co-authorship with overseas researchers is also more common for physical and environmental sciences, with each having 38% of papers produced via international collaboration.

CAS's international peers also collaborate most in Earth, physical and environmental sciences. This is not surprising, given the many large-scale international projects in physics, such as supercolliders to study fundamental particles and astronomical observatories to peer deep into space. CAS is involved in many big-science projects, including the International Thermonuclear Experimental Reactor (ITER) and the China-based Daya Bay Neutrino Experiment, a multinational collaboration that discovered a new type of neutrino oscillation.

"In particle physics research, almost every experiment is international," says Yifang Wang, director of CAS's Institute of High Energy Physics and lead for the Daya Bay experiment. "This kind of collaboration will help you get all the experience, and all the intelligent people to one experiment. It helps you to have high-quality research." International collaboration also provides the necessary funding for these kinds of megaproject, which typically require costly equipment and facilities, according to Wang.

For Earth and environmental sciences, many research topics naturally lend themselves to international collaboration, because of their relevance to all humans and the need for field trips and satellite data across country boundaries.



Global collaborations are increasing in the top levels of science.

Case study I: Joint effort for common goods

Collaborations in high-energy physics are often driven by a need to share resource costs. Joint ventures in Earth science, by contrast, are motivated by a shared interest.

"Collaboration in Earth science is essential given that humanity shares one planet," says Lonnie Thompson, a paleoclimatologist from the Byrd Polar and Climate Research Center at Ohio State University (OSU). "Scientists studying Earth's environment and global climate change must collaborate to produce global-scale, comprehensive observations and develop a shared knowledge base."

For decades, Thompson has maintained a collaboration with CAS's Institute of Tibetan Plateau Research (ITPCAS). The relationship started more than 40 years ago at an academic conference, and turned into a working collaboration after Thompson's first field trip to China in 1984, when he met glaciologist Tandong Yao, now the honorary director of ITPCAS.

Over the years, joint interests led Yao to OSU for his postdoctoral studies and on several subsequent occasions as a visiting scholar, while Thompson became the deputy director of the academic advisory committee of ITPCAS. Today, Thompson says they have, "a win–win relationship, based on the joint commitment to conduct the very best science possible."

Working with CAS, especially Yao's team, Thompson's group has drilled ice cores from glaciers in some of the region's most remote mountain areas. By documenting the global melting of land ice, Thompson was one of the first scientists to discover the problem of global warming. A comprehensive survey of the Tibetan Plateau by Yao and Thompson has uncovered rapid glacial retreat, and identified atmospheric patterns driving this change[1]. Thompson also promoted the ITPCAS-led Third Pole Environment programme in the US, which is now an international network.

Thanks largely to Thompson's and Yao's efforts, the relationship between OSU and CAS has grown to encompass research and training. Other OSU Earth scientists also collaborate with CAS in areas including atmospheric modelling and geodetics. Such projects have received funding from both CAS and the US National Science Foundation.

"Many countries that are politically or economically at odds are nevertheless collaborating on issues such as global climate change," Thompson says. "I am optimistic that the global Earth science community will intensify its efforts to work together to address the causes of ongoing anthropogenic climate change and thereby mitigate its worst impacts."

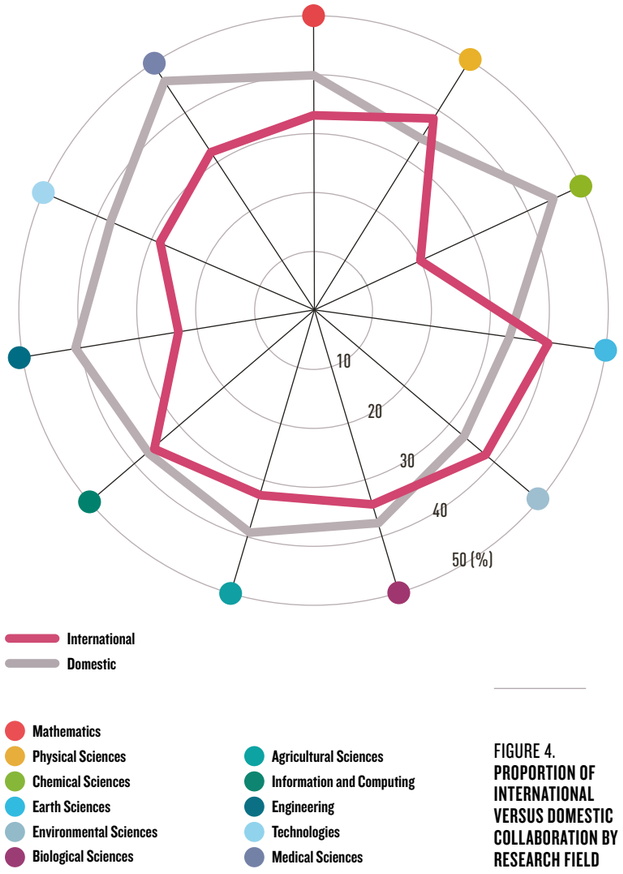


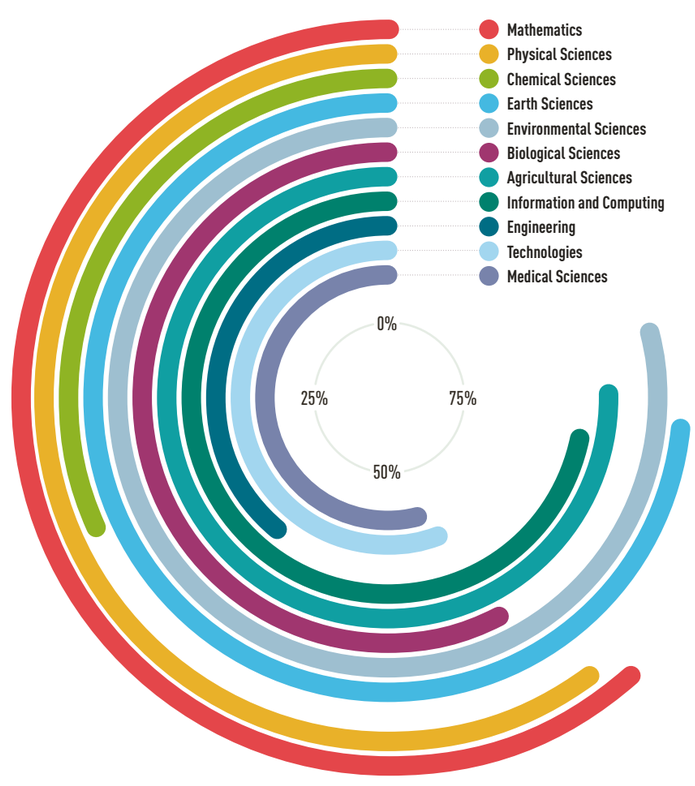
FIGURE 4. PROPORTION OF INTERNATIONAL VERSUS DOMESTIC COLLABORATION BY RESEARCH FIELD

HIGH-QUALITY COLLABORATION BY RESEARCH FIELD

In nearly every broad research field, the majority of CAS's high-quality research stems from international collaborations (**FIGURE 5**). The only two exceptions are, again, the chemical sciences and engineering, with each field having similar numbers of domestically and internationally authored high-quality papers. These are also the two fields where CAS has the most internally authored papers, accounting for more than 10% of high-quality output in each. As CAS is strong in these two fields, it is not surprising that when one institute is seeking quality collaborators, it tends to look first within CAS.

The research fields where CAS has the largest proportion of international collaboration for high-quality output are environmental sciences (79%), agricultural sciences (75%) and Earth sciences (73%). All of these fields relate to global challenges, covering areas such as food security, water availability, climate change and the health of ecosystems. With such important goals, it appears that international collaboration is essential to ensure the highest quality work. ■

FIGURE 5. PROPORTION OF INTERNATIONAL COLLABORATION FOR HIGH-QUALITY RESEARCH



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BROADENING COLLABORATION NETWORKS

On a global scale, the Chinese Academy of Sciences (CAS) collaborates with other world-leading institutions. But dig down to the regional level, there is growing diversity in its collaborators.

CAS is collaborating widely with research institutions worldwide.

When looking at CAS's collaborators, a trend towards diversification emerges. As well as emphasizing collaborations in general, CAS is also broadening its network, starting partnerships in previously under-reached regions and growing multinational partnerships.

Collaborators of CAS are concentrated in the developed regions of the world. Half of CAS's international papers involve at least one researcher in North America, while more than one-third are co-authored with Europe-based researchers, primarily in western or northern Europe (**FIGURE 6**). Researchers in Asia — mainly eastern Asia, including Japan and South Korea — contribute to one-quarter of international papers. Over the past 10 years, less than 4% of CAS's international papers have involved researchers from Africa, split fairly evenly between northern and sub-Saharan regions.

However, patterns of collaboration have changed over the past decade. Co-authorship with researchers based in northern Africa is increasing at a CAGR of 56%, the fastest growth rate for any region. This is possibly because of its low base value. If the growth rate continues, within five years, CAS will be producing more papers with researchers from northern Africa than from Latin America, and potentially even from eastern Europe (which includes Russia). These changes are probably intentional. In line with China's Belt and Road initiative, CAS has launched several projects to connect countries that lack good research infrastructure and to improve cooperation, in the hope to increase their contribution to scientific research[1].

In every research field, co-authors on CAS's international papers were based in the greatest proportion in North America, amounting to more than 40% in all cases. Co-authors from this region, particularly the US, appeared on roughly the same proportion of CAS's papers across the broad research fields. Often, collaborations are driven by personal relationships. Many CAS researchers have experience in the US, so co-authorship with former colleagues or supervisors is probably a strong driver of these results.

The influence of the US is most evident for medical science papers, where the majority of CAS's international output involves at least one US-based researcher. This is not surprising given the US's leading position in the medical sciences. Most of the other regions' collaborations with CAS focus on the physical sciences.

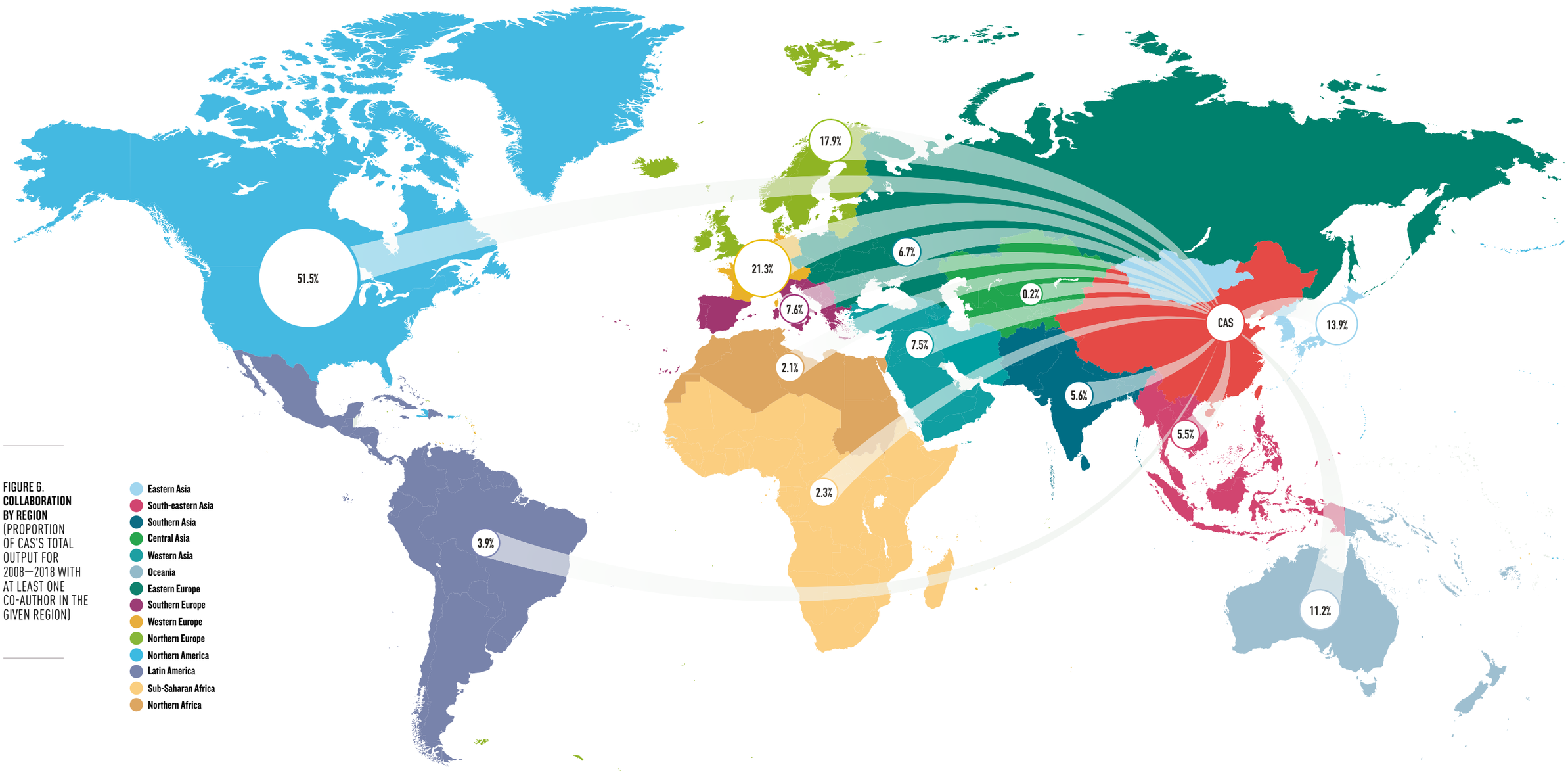


FIGURE 6.
COLLABORATION BY REGION
(PROPORTION OF CAS'S TOTAL OUTPUT FOR 2008—2018 WITH AT LEAST ONE CO-AUTHOR IN THE GIVEN REGION)

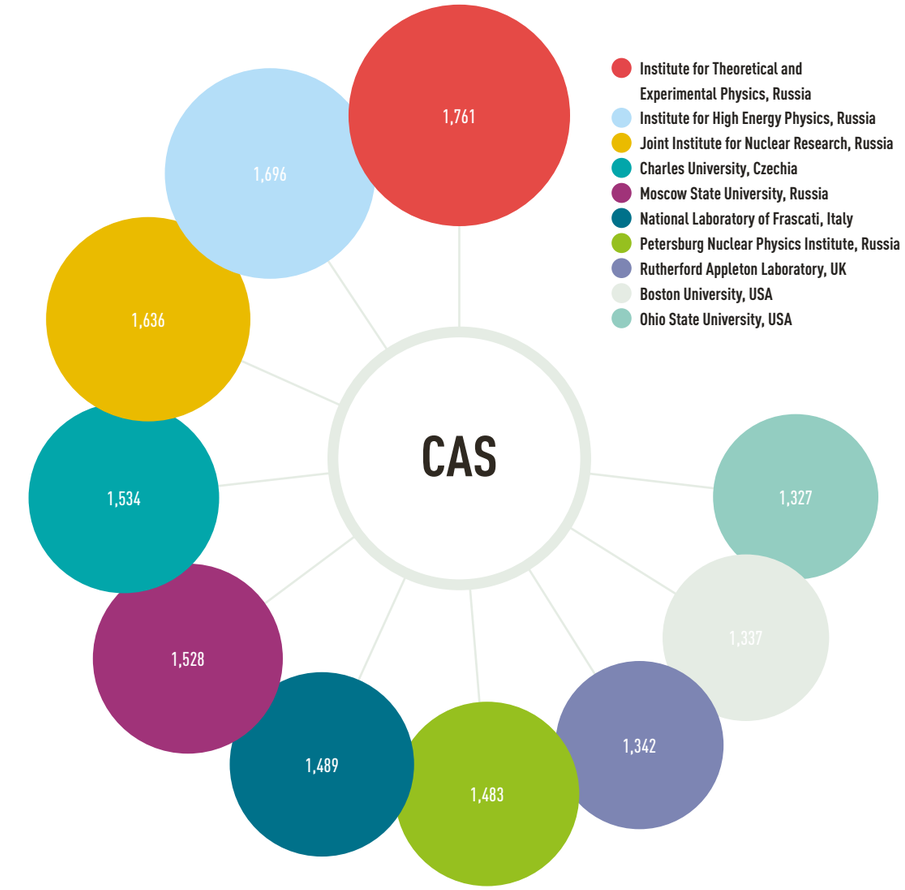
TOP INTERNATIONAL COLLABORATORS IN HIGH-QUALITY RESEARCH

When it comes to high-quality research over the past 10 years, half of the institutes that make up CAS's top 10 international collaborators are Russian, with only two in the US. Institutions in Czechia, Italy and the UK round out the top 10 (**FIGURE 7**). For all these institutions, collaborations are almost exclusively in the physical sciences, followed by mathematical sciences, part of an overlap with theoretical physics. Only the two US institutions have any collaborative papers in other fields, in this case, Earth and biological sciences.

The fact that these top international collaborators are not primarily from North America, despite the outsized influence of researchers from that region, is to do with distribution. CAS has a variety of collaborations with US-based researchers, who are not concentrated in only a handful of leading institutions. Given the large number of US institutions collaborating with CAS, many driven by personal ties, as in the case of OSU, the number of co-authored papers for one particular institution may be less than that for a non-US institution.

It is also interesting that the majority of the papers produced in collaboration with the top 10 international partners involve several collaborators, suggesting that these collaborations are multilateral or even multinational. International megaprojects are likely to have had a role here.

FIGURE 7.
TOP 10 INTERNATIONAL COLLABORATORS FOR CAS
(BASED ON 10-YEAR TOTAL HIGH-QUALITY OUTPUT)



Case study 2: Larger teams for grander goals

Among the many international institutions that contribute to CAS's high-quality research, the top three collaborators are from Russia. Russia has collaborated on almost 4,500 papers with CAS in the past 10 years, the majority being in the physical sciences. Many of these are the output of multinational big-science research projects, such as CMS and ATLAS at CERN.

ITER, the world's largest fusion experiment, is another example. It currently involves 35 countries, including China, Russia and the US, and CAS's Institute of Plasma Physics (IPP) is a major contributor[2]. ITER aims to build the world's largest tokamak, a doughnut-shaped, magnetic confinement reactor, to produce controlled thermonuclear fusion power.

Russian scientists first proposed using a magnetic field to confine plasma, and developed the concept of the tokamak in the 1950s. Physics has come a long way since then, and ITER aims to eventually produce 500 MW of fusion power, 10 times of the input power. ITER will be twice the size of the European tokamak JET, the largest in operation today, with 10 times the plasma chamber volume. When finished, it will establish a basis for safe, clean and virtually limitless energy.

No single country could afford such a multi-billion-dollar project. With ITER, each member country manufactures certain components, which are then assembled on-site in southern France. China is responsible for 9% of these components[3].

Since participating in ITER, China's technical fusion capabilities have advanced rapidly. As part of ITER, IPP and CAS's University of Science and Technology of China have built the world's first fully superconducting tokamak, the Experimental Advanced Superconducting Tokamak (EAST). It can reach an electron temperature of over 100 million degrees Celsius and an ion temperature of 50 million degrees Celsius, around seven times hotter than the interior of the Sun[4]. It has also achieved the longest sustained reaction in a tokamak.

The EAST experiment was carried out in collaboration with international colleagues, including those from Russia. Specifically, CAS and its counterparts in Russia have collaborated on tokamak design and construction, relevant superconductivity and particle accelerator technologies. They are also establishing institutional agreements to apply the research results, turning them into products that benefit economic development and potentially produce clean energy for all.

CHINESE NETWORKS

On the domestic front, CAS's most common collaborators in high-quality research are Peking University and Tsinghua University, two of the most prestigious institutions in China. Third is Nanjing University (**FIGURE 8**).

For all of the top 10 domestic institutions, the majority of their collaborative papers with CAS are in the physical sciences. Shandong University, CAS's fourth most common collaborator, has more than 84% of its shared papers with CAS in the physical sciences. The next most common research field is chemical sciences, a strength of many Chinese institutions. Most of the top 10 collaborators do not share any papers with CAS in information and computing sciences, partly owing to the low coverage of papers in this field in Nature Index.

Evidently, most of CAS's domestic collaborators in high-quality research are China's leading universities. This is possibly because research capacity is usually a priority when seeking collaborators. As two or more strong forces joining together tends to enhance the quality of research, many institutional partnerships are established to facilitate this.

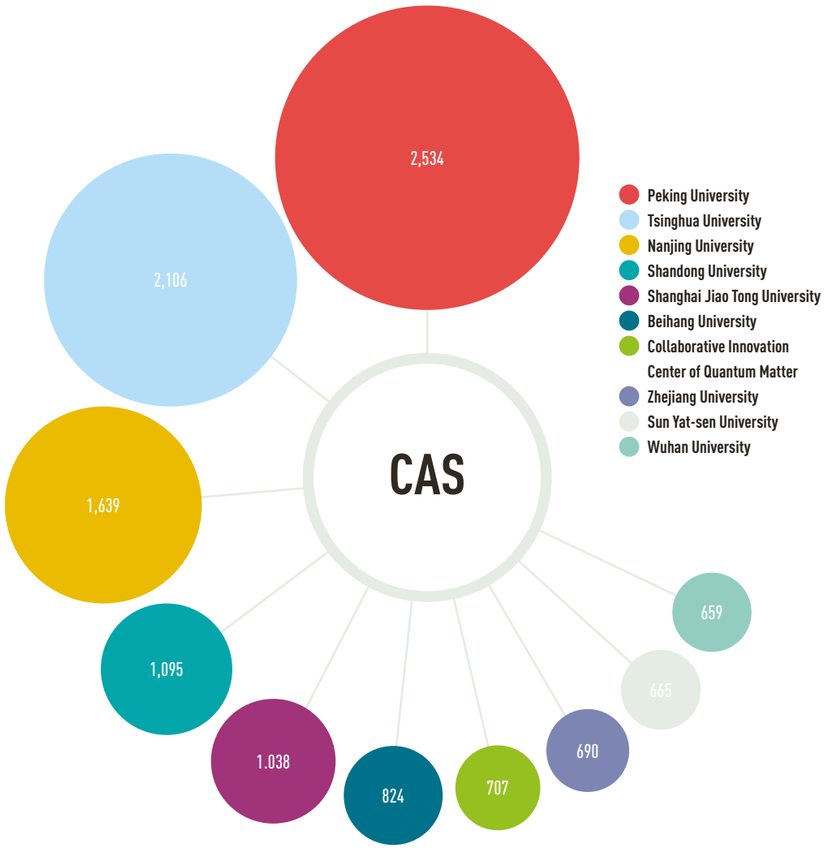


FIGURE 8.
TOP 10 DOMESTIC COLLABORATORS FOR CAS
(BASED ON 10-YEAR TOTAL HIGH-QUALITY OUTPUT)

Case study 3: Joining forces for mutual benefit

CAS's two largest domestic collaborators in high-quality research are China's top two universities — Peking (PKU) and Tsinghua. Over the past 10 years, each has shared authorship with CAS on more than 2,000 papers in the Nature Index journals, representing 7% and 6% of CAS's domestic publications, respectively.

PKU is CAS's co-author on roughly 400 more papers than is Tsinghua across the research areas. However, Tsinghua collaborates more in four fields: biological sciences, information and computing, engineering and medical sciences.

Tsinghua is renowned for its strengths in engineering science and information technologies. The Institute of Computing Technology at CAS established its strategic partnership with Tsinghua in 2005, with the aim of boosting China's technological capacity in computer science through basic research and training[5]. The two parties also committed to reforming the researcher evaluation criteria that emphasized first authorship, so as to encourage joint research[6].

CAS also collaborates with Tsinghua in life sciences, a growing field for the institution. Recently, researchers from Tsinghua's School of Life Sciences and CAS's Institute of Botany revealed the 3D structure of photosystem II, a pigment–protein supercomplex in a type of alga, shedding light on how these algae harvest light and turn it into chemical energy[7]. Tsinghua's cryo-electron microscopy platform enabled this structural analysis, which has implications for artificial photosynthesis.

CAS has many partnerships with PKU as well. For instance, CAS's Institute of Chemistry and PKU's College of Chemistry and Molecular Engineering established a partnership in 2001 to enhance China's chemical industry and research. The Beijing National Laboratory for Molecular Sciences grew out of this partnership, in 2017, to promote interdisciplinary innovation in molecular research, spanning energy, materials, life and environmental sciences. Recently, researchers from this laboratory analysed the electronic structures of a new 2D semiconductor, Bi_2O_2Se, demonstrating its potential as a material for next-generation electronics[8].

CAS, PKU and Tsinghua also collaborate together. The Collaborative Innovation Center of Quantum Matter, established in 2012, is one such example. It aims to address national strategic needs in energy and information technologies. Part of a national endeavour to promote science and technology innovation, the centre also explores new ways to collaborate to improve research, a shared goal for CAS and its domestic collaborators. ■

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TOWARDS THE NEXT LEVEL OF COLLABORATION

Shared interests and the strongest scientific ideals will continue to drive collaboration. But there are some challenges to overcome if the Chinese Academy of Sciences (CAS) is to grow team work further.

As science grows in complexity and scope, collaboration will grow with it. The image of the lone scientist toiling away in the laboratory is in the past. Teams working in parallel in laboratories across nations or across the globe will be the future. To ensure that it makes the most of the future, CAS needs to examine its past trends in collaboration.

As with most other leading research institutions, CAS is growing strongly in both domestic and international research, alongside its general growth in research output, based on publication data over the past 10 years. Although there is a larger proportion of domestic collaboration in overall research, CAS's high-quality research is dominated by international collaboration. Evidently, collaborating with researchers overseas is associated with higher-quality science.

Collaboration patterns by research fields show that CAS is an active player in large international physics projects. It is also collaborating broadly with international researchers in Earth and environmental sciences, committed to enhancing global sustainability for all.

CAS's collaborators and patterns of collaboration are also changing, expanding bilateral partnerships to multilateral ones. Although its collaborating institutions are still primarily leading research institutions, CAS is also broadening its international network to collaborate more with the less-developed regions.

While it is important to enhance team work, doing so is not necessarily easy. In domestic collaboration, a hurdle can be the competition for first authorship. A reform of the research evaluation system is needed, not just for CAS, but for all Chinese science, to put less emphasis on the number of publications and first authorship, or 'first responsible institution'. After all, the purpose of joining forces is to enhance the quality of science for all.

For international collaboration, while political tension may create administrative barriers, research may circumvent such tension. Take this year's fight against the COVID-19 pandemic as an example. While there is a global race for coronavirus vaccines, scientists quickly mobilized to investigate the structures of leading agents responsible for the infection. They shared their findings in publications, accelerating the discovery of the coronavirus protein structures, which is the result of collaborated efforts by a network of researchers around the world. Their findings are essential for developing potential drugs and vaccines.

As the case of solving coronavirus protein structures shows, when institutional-level partnerships are difficult, personal ties will facilitate collaboration, which is already taking effects at CAS, and should be encouraged. CAS will also need to enhance its ability to manage large, multinational teams to improve efficiency if it plans to lead complicated big-science projects.

Collaboration drives outcomes beyond joint publications. These could be joint training programmes, the construction of big-science facilities, or setting ethics or guidelines for the development of a specific field. CAS is promoting these other aspects of collaboration by launching fellowship and award programmes to encourage researcher exchange, by building overseas research centres, and by establishing joint training programmes to enhance the research capacity of less-developed countries.

The benefits will be mutual. After all, collaboration is about building a win-win relationship to achieve the best science possible. If administrative barriers are cleared to keep the communication channels open, collaboration will come organically, and is a trend for science that shows no signs of slowing. The results, just like the case of the COVID-19 research, are to benefit the mankind, as after all, science is borderless. ■

APPENDIX

Data and Methodology

This report uses journal publication data tracked by Digital Science's Dimensions database to assess research collaboration at CAS.

Based on the identified authors on articles, the following exclusive typology is used to classify the collaboration status of each paper, such that it falls into only one category:

- Single author
- Intra: more than one author, all from the same institute
- Internal: more than one author, from more than one institute of the same umbrella group
- Domestic: more than one author, all affiliated in the same country
- International: more than one author, affiliated in different countries.

A paper is generally considered non-collaborative, when it is authored by a single author or more than one author from the same institute (the first two categories above).

For each institution, there are papers where it had not been possible to determine the affiliation of all the authors. These undetermined papers represent only a small fraction of the total research output (<4%), and thus, have been excluded from the analyses. When multiple institutions are identified for an author, the first institute is used to categorize the collaboration status of the paper.

For the analysis on CAS's collaboration by region, the United Nations' coding for sub-region is adopted to categorize countries. And a list of countries by sub-region can be found on the United Nations Statistics Division website: https://unstats.un.org/unsd/methodology/m49/overview

As with the first report on CAS's research strengths (seehttps://www.nature.com/collections/befgajibgf), Field of Research (FOR) codes are used to categorize journal publications by research fields. And while there are 22 broad research fields with 2-digit FOR codes, the focus of the analysis is on FOR codes 1-11, which are primarily natural and applied science subjects and account for approximately 98% of CAS's total output.

High-quality research output, again, is represented by publications in Nature Index journals. These data are taken from Dimensions using the list of 82 Nature Index journals as the source.

Note that Dimensions also tracks reviews, perspectives and sometimes news, which are all included in the analysis, but the majority of publications assessed are primary research articles.

The same set of institutions is used in the global comparison as in the first report, and again, they are selected from the top performers in Nature Index's annual tables.