My idea was always to conduct research on a broad basis, with motivated co-workers who love their work, with goals and projects to be newly set every few years. And to dare the adventure of applying **new methods** to old questions, sometimes just for the novelty. I hold for true that research should be adventure, not to become routine; the physicist in research should be an adventurer. One of my early Berlin co-workers who was travelling a lot once put it so: "In former times daring people have gone for the discovery of unknown countries. That is over, everything is discovered in the great world. We now discover the micro world. This is the adventure of our time."

To define always new goals is not easy for a natural scientist of today, if he/she performs experiments. Modern experiments are often extremely expensive, and the enthusiasm of the funders is limited when repeatedly new directions are envisaged since that needs continuously new money. In our case money for cryostats, furnaces, ultrahigh vacuum- chambers, X-ray devices and above all for using the expensive European large-science facilities.

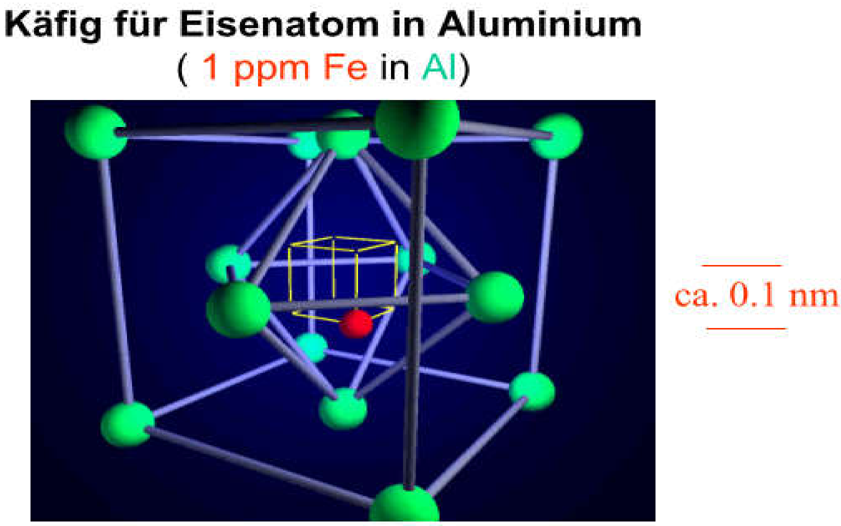
My thesis, tutored by Brigitte Weiß at the institute of Erich Schmid, Philosophical Faculty of the University of Vienna was on the change of the age-hardening of aluminium alloys under irradiation [1]. The result: age-hardening changed a lot, much more I could not tell.

I was lucky that I then got an offer by the distinguished professor Heinz Maier-Leibnitz whose disciple Rudolf Mößbauer had won the Nobel prize not too many years earlier, the first Nobel prize for a German physicist after the war. So I started 25 years old as assistant at the Physik-Department of the Technische Universität München in Garching. Was Maier-Leibnitz aware of how little I knew? Maybe he also searched for the adventure in the field of staff recruiting: new people may bring new ideas. Soon I was head of the low-temperature irradiation facility which Werner Schilling had constructed. At this world wide unique facility lattice defects in metals could be produced by high neutron bombardment and at liquid helium temperature (4 Kelvin). Their understanding was meant to enable further development of materials to be applied in the process of energy "production" by nuclear fission and nuclear fusion. I was actually too young for that task, coaching students who were older than me, and I had to learn intensively. The wonderful atmosphere in the group due – last not least – to Klaus Böning helped me overcome the initial difficulties and barriers. Soon both of us together directed the group and with our diploma and doctor students implied various methods for following the production and annihilation of defects in metals.

The Physik-Department in Garching appeared to me as the suitable place to set step on a bridge which fascinated me: to work in the field of Nuclear Solid State Physics. A risky bridge since the idea to **employ methods from nuclear physics to study solid state phenomena** required expertise in both fields. And I knew little about both of them, less than the specialists in either field at the Physik-Department who had received a long and deep training. But the chance to step on that bridge and open a new discipline appeared attractive to me: to proceed to **understand the dynamics of a single atom**. The start was a bit rough, the specialists had first to be convinced. To them exactly that appeared suspicious what fascinated me: the conjunction of solid state physics/materials science and nuclear physics.

With Wofgang Mansel I found a graduate student with high experimental skill – alone I would not have succeeded with the intricate experiments (nuclear reactor, very low temperatures for that time, first nuclear physics experiments on samples irradiated at 4 Kelvin and then transferred without warming to the lab).

And then the first successes with the discovery of the "interstitial cage" in aluminium by help of **Mössbauer spectroscopy** at $^{57}Co/^{57}Fe$ foreign atoms. This cage is formed quasi as a refugium by atoms which by irradiation had been knocked out of their regular sites. Since these atoms cluster together with impurity atoms they do not match into the well-ordered surrounding crystal lattice and stay in a continuous unrest. Already at very low temperatures they jump around in the cage but cannot leave it. Their freeing happens only at appreciably higher temperatures.



Iron atom (red) jumps in the interstitial cage (yellow) which is embedded in the lattice of aluminium atoms (green).

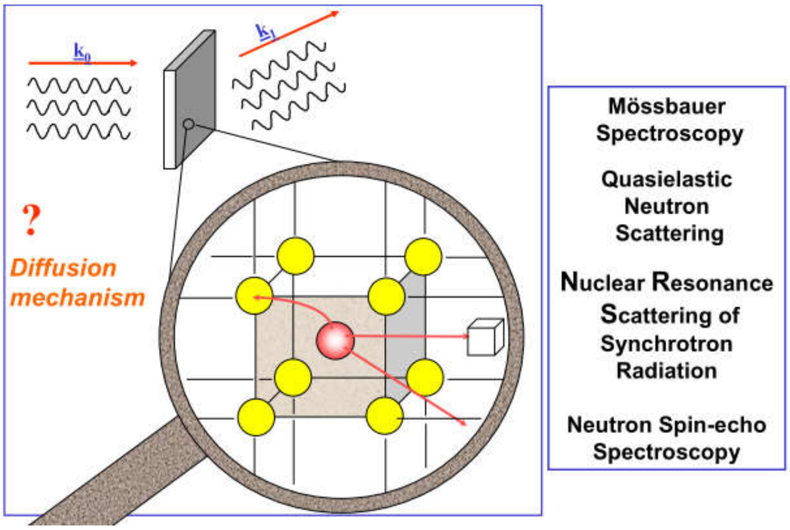
The results are described in [2], Peter Dederichs made the theory (baptizing somehow derisively the cage on my name), and Linus Pauling as a chemist honoured us by describing the cage in terms of the Pauling orbitals [3]. One may consider the dynamics in the cage as a **localized diffusion** of the interstitial atom. This was my entry into the field of what I like today to call "science of subnanomaterials" (following the buzzword "science of nanomaterials").

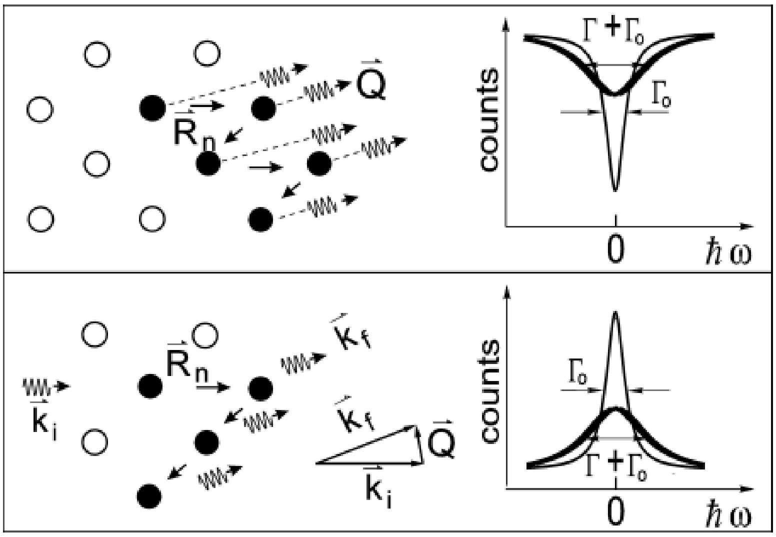
After my appointment to Freie Universität Berlin and Hahn-Meitner-Institut (HMI) I had to modify my field of research. An interesting diversion as should occur in a scientist's life about every seven years. Seven years it lasts according to my experience until a scientist succeeds in a new field. Then he/she can/should switch to a new one.

But in Berlin I had to overcome certain resistance in order to be permitted to use the heavy-ion accelerator VICKSI, a wonderful new device, for research outside nuclear physics. To "abuse the marvellous device as a hammer" was the reproach, not quite unjust and I should even now apologize for my penetrance. But my strategy was last not least a survival-strategy since my knowledge on pure nuclear physics was too marginal to keep up with the experienced nuclear physicists at the HMI. I had just succeeded to employ nuclear methods to materials science. Siegfried Klaumünzer, recruited to Berlin out of Bavaria and supported by our Chinese guest scientist Hou Minddong chose glassy material and discovered the surprising **growth of glasses under heavy-ion irradiation**, the Klaumünzer effect [4]. In later years of VICKSI (I was in Wien since years) irradiation developed to the working horse of the heavy-ion accelerator, not only for solid materials but even more for pioneering tumor therapy. That a man like me, lonely irritating fighter for "abusing VICKSI as a hammer" was back-recruited as head of the accelerator department demonstrated the liberal attitude in Berlin.

My graduate student Winfried Petry, who had followed me from Garching to Berlin, proposed not to cling to irradiation effects but rather to examine the dynamics of unirradiated solids. We decided to apply nuclear methods and aimed at demonstrating that we could illuminate the **atomistic details of diffusion jumps**, the "elementary jump", whereas the established radiotracer method could only provide indirect information on the single diffusion event.

We received some interesting results determining the elementary diffusion jump of iron atoms in aluminium and in copper [5]. We soon became attracted by another nuclear method, neutron scattering, and started studying diffusion with **quasielastic neutron scattering**.



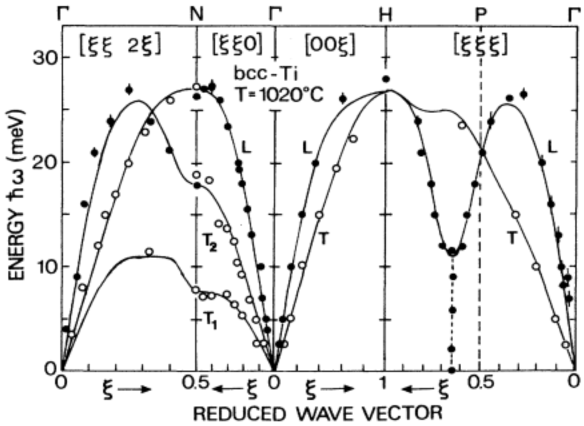


Comparison of Mössbauer spectroscopy (top) and quasielastic neutron scattering (bottom). These methods can determine frequency and displacement vector R_n of the elementary diffusion jump.
Diffusion leads to line broadening. For Mössbauer spectroscopy Q is the wave vector of the gamma radiation, for quasielastic neutron scattering Q is the scattering vector.

Soon we also started to study **phonons**, all that out of house at the Institute Laue-Langevin (ILL) in Grenoble. Our start was an adventure since we knew virtually nothing of the highly intricate devices for neutron spectroscopy. But today Winfried Petry is the scientific director of the Heinz Maier-Leibnitz neutron source at the Physik-Department in Garching and our first summer student Helmut Schober is the scientific director of the ILL.

After my appointment to Vienna I started to further widen my field of activity. My aim was in Vienna to introduce methods which on the one hand supplemented the existent spectrum of methods in my institute to **nanomaterials**, on the other hand would permit my co-workers to use the experience gained at home with X-ray scattering to do successful research at the European large-science instruments in particular the synchrotrons. Therefore my condition for accepting the appointment was the best available X-ray small angle scattering-device. We bought a high flux rotating X-ray tube and Peter Fratzl who joined us immediately after his graduation constructed the small angle scattering-device.

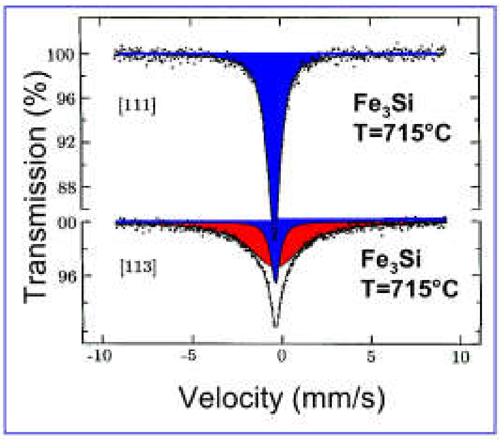
My own engagement was concentrated on "**subnano materials science**", for understanding the dynamics of single atoms in condensed matter, in particular the mechanisms of diffusion and vibrations. At the neutron source of the ILL Winfried Petry succeeded to explain the **connections of soft lattice modes and martensitic phase transitions** in the refractory metals zirconium, titanium and hafnium [6] and I extended these results to the explanation of fast diffusion in these metals [7].



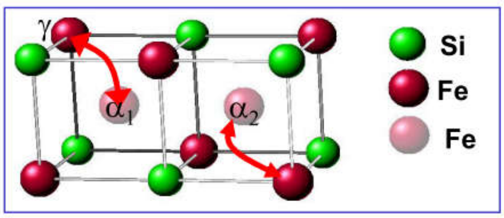
Dispersion relation for titanium at 1020°C. Evident are the soft vibration modes at 2/3 [111] which act as medium for fast diffusion and phase transitions.

Peter Fratzl and his diploma and graduate students by applying **X-ray small angle scattering** studied the nanostructure of the same class of solids [8]. Soon biomaterial research grew on that basis [9], a field that Fratzl now practises with extreme success in Potsdam, and meantimes in Vienna Herwig Peterlik exploits a new small angle scattering-device for the research on nanomaterials in collaboration with scientists from diverse fields of natural science.

Our interest then shifted to the scientifically attractive and technologically important class of **intermetallic compounds**. With our graduate student Oliver Randl I learned diagonalizing jump matrices and the determination of eigen values – I was slightly surprised to learn how much of mathematics even students of experimental physics meantimes had not only learned but also understood to handle. Here a particularly impressive result: the exceptionally fast jumps of iron atoms in Fe_3Si one of the generally diffusively "lethargic" because well-ordered intermetallic compounds [10].



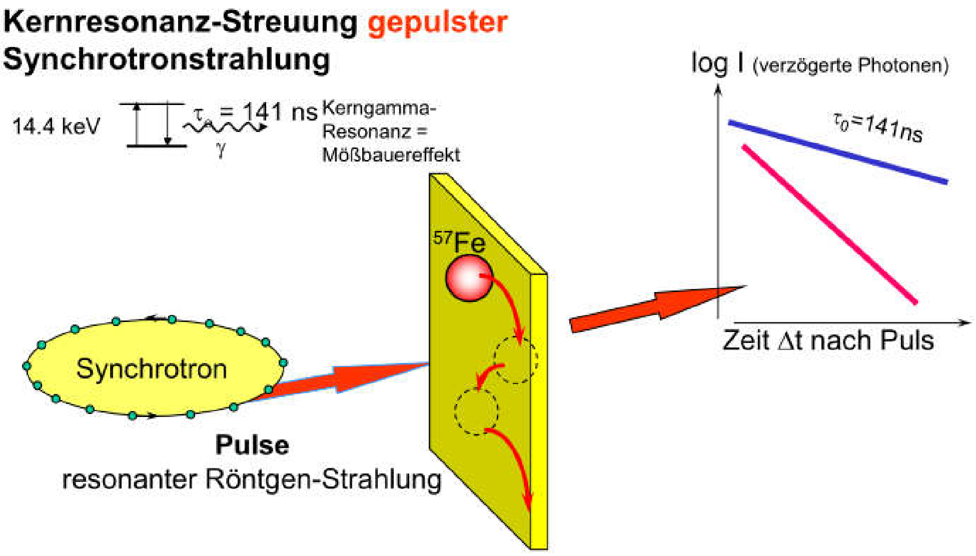
Mössbauer spectroscopy of fast diffusing iron atoms in an Fe_3Si single crystal. Note the extreme resonance line-broadening of the red line in [113] direction, whereas in [111] direction the line is narrow. From this asymmetry the details of the diffusion jump are derived.



The ordered intermetallic compound Fe_3Si has three iron sublattices and one silicon sublattice. The Mössbauer experiments prove that the iron atoms jump between the alpha sublattices and the gamma sublattice and that these jumps are much faster than the jumps of the silicon atoms.

Samuel Dennler and Jürgen Hafner have determined formation and migration enthalpies of defects in Fe_3Si by way of density functional calculations and convincingly explained the pronounced asymmetry in the jump behaviour of iron and silicon atoms [11].

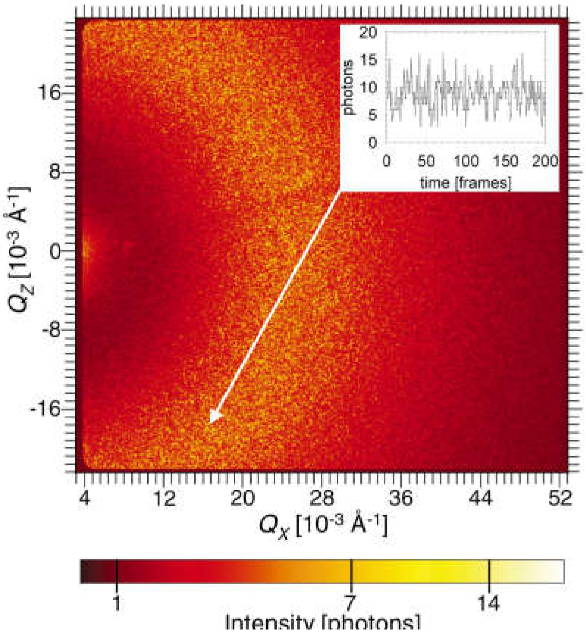
During one of my frequent scientific sabbaticals generously granted by my respective home universities, in the nineties I explored the prospects of the new synchrotron X-ray source ESRF in Grenoble (and the mountains of the Dauphinée, an attractive complement – or were the fascinating perspectives of the ESRF an attractive supplement of the mountain scene?). To apply **nuclear resonant scattering of synchrotron radiation**, i.e. the Mössbauer effect in time instead of energy domain, appeared as an intriguing chance to further study the diffusion in intermetallic compounds. Such experiments are only possible with an X-ray beam with high brilliance unavailable in the lab and only provided by a synchrotron. Here – differently from many of our experiments which had needed long series of preliminary studies - we succeeded immediately [12].



For the first time I left the dynamics metals and started studying the **dynamics of biological materials** [13]. Here again an initial hurdle had to be overcome as always when entering a new field – and more perfectly and above all more enduringly my young co-workers, in particular Martin Müller and Helga Lichtenegger, succeeded (they are now professors). With particular emphasis we investigated the dynamics of cellulose and of water in cellulose. Most surprisingly we found that liquid water in cellulose can be undercooled down to -75°C and then crystallizes in a new form of amorphous ice – alas we did not succeed to publish that result in a high status journal.

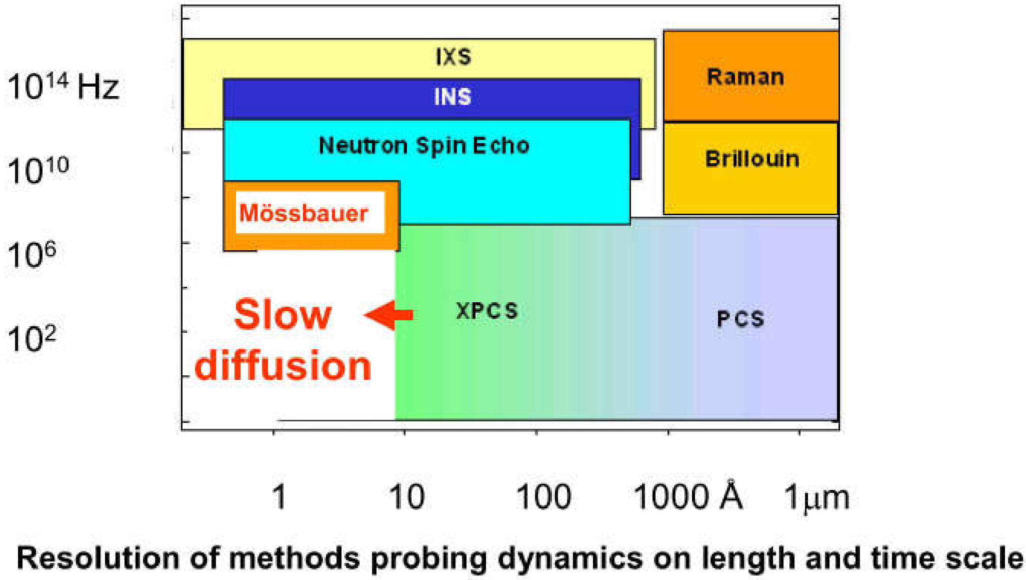
At that time I followed a new appointment to Berlin where I found the challenging task to head the newly formed department of structural research at the Hahn-Meitner-Institut. In this position only little time remained for my own research. I left Berlin and the biological materials after few years and returned to Vienna and Grenoble and to the physics of metallic materials. Now my ambition was to fathom the new perspectives offered by synchrotron radiation for understanding the dynamics. Until then our research on nuclear resonant scattering had just confirmed – though with a totally new approach, namely Mössbauer spectroscopy in time instead of energy – what we knew from earlier experiments with conventional Mössbauer spectroscopy and quasielastic neutron scattering about diffusion in intermetallic compounds. But the strong synchrotron beam with its high brilliance should enable us for the first time to illuminate the dynamics in thin layers and at surfaces. Thus we started studying surface diffusion [14] and surface phonons [15] applying synchrotron radiation in grazing incidence. Without the expertise of and the co-operation with the Cracow group of Jozef Korecki we would not have succeeded.

To me another appealing possibility for exploiting synchrotron radiation for dynamics studies appeared to be **X-ray photon correlation spectroscopy (XPCS)**, though a serious barrier to our particular scientific interests appeared to be the still weak scattering in the range of diffuse scattering where the atomistic dynamics shows up. We therefore started with investigations in the range of small angle scattering – familiar to us - in order to follow the dynamics of nanoparticles [16].



Small angle scattering at Al-6at.%Ag. The intensity of the speckles fluctuates in time (see inset) permitting to determine frequency and direction of diffusion.

Eventually we tried to extend X-ray photon correlation spectroscopy into atom dimensions. A new chance non-existent before : synchrotron radiation is partly coherent and becomes hundred percent coherent with the free electron X-ray lasers. Still from Berlin, together with Gerhard Grübel I had dared a prognosis: I had convinced that colleague experienced with XPCS that it should be possible by XPCS to follow the diffusion of single atoms [17].



Frequency and length scales which are covered by various dynamic methods. Note that with XPCS (red arrow) slow jumps (1 Hz) become accessible on the atomic scale (1 Angstrom).

I had not expected that already few years later Michael Leitner and Bogdan Sepiol would indeed succeed at the ESRF [18] – I had thought that the much more brilliant and completely coherent beam of a free electron X-ray laser would be necessary. Now the door is open to determine the atomistics of diffusion even at low temperatures and for virtually all elements.

Vibrations, jumps, dances

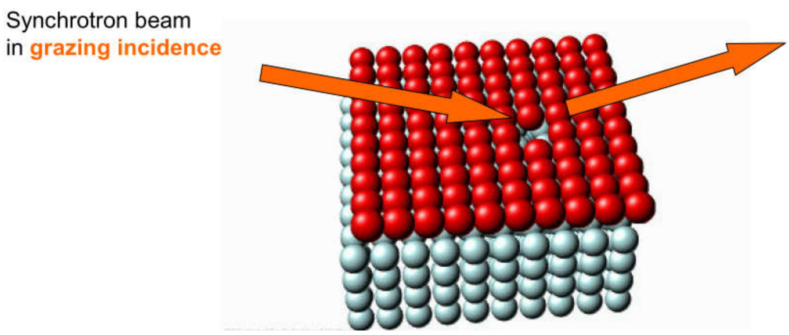
I think that we have introduced a couple of methods from nuclear, neutron and synchrotron physics into material science, in particular the exploration of solid state dynamics. By applying the methods to identical or similar metals and compounds we convinced ourselves that the results of the different methods are coherent and reliable.
For several metals and partly also for cellulose we determined the vibrations, the jumps of single atoms and the dances in a cage. We found the reasons for fast diffusion and for the tendency of some of these metals to undergo phase tranisitions.

Whether all that is important? Is it worth the money granted by the states where we did research together with scientists from these countries (Austria, Germany, France, Poland, China, India, USA etc.) in order to enable us to “gamble” with enthusiasm? I for myself am extremely grateful to the tax payer that he/she affords to support the culture of continuously **enlarging our horizon of knowledge** and that I was allowed to join the game. The game was not possible without hard work: experiments with many night shifts at the beam lines of the large international machines which are always booked out therefore have to be used without interruption during the beam time granted to the user. And travelling to the machines in Europe and USA in Grenoble, Paris, Berlin, Hamburg, Jülich, Argonne, Oak Ridge etc.

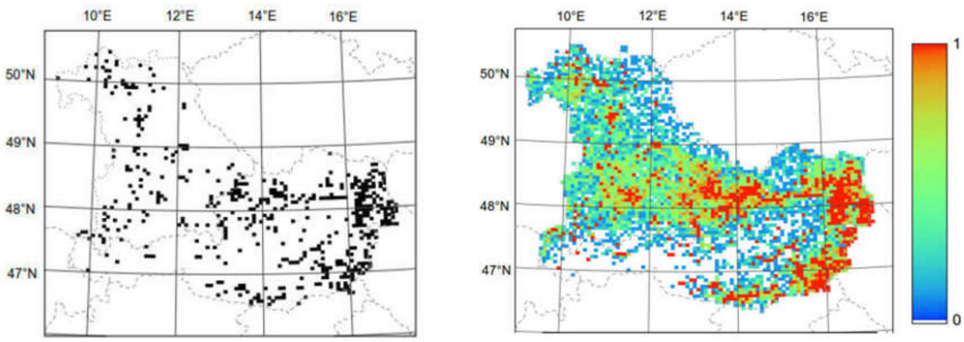
We have written no book on our subject “Vibrations, jumps, dances” and only short reviews in various collections – was it laziness or rather the concern to write one more of too many text books? Every seven years something new – can a scientific foot print remain? But science was and is still always inspiring sometimes often even exciting.

In the year of my retirement 2009 I was for the last time responsible for an experiment and its scientific evaluation in the field of sold state / materials science. That was surface diffusion investigated by grazing incidence of synchrotron radiation [14]. I regard that work as a pioneering study since we just had a short glance behind the veil. I hope that successors will come and harvest [19].

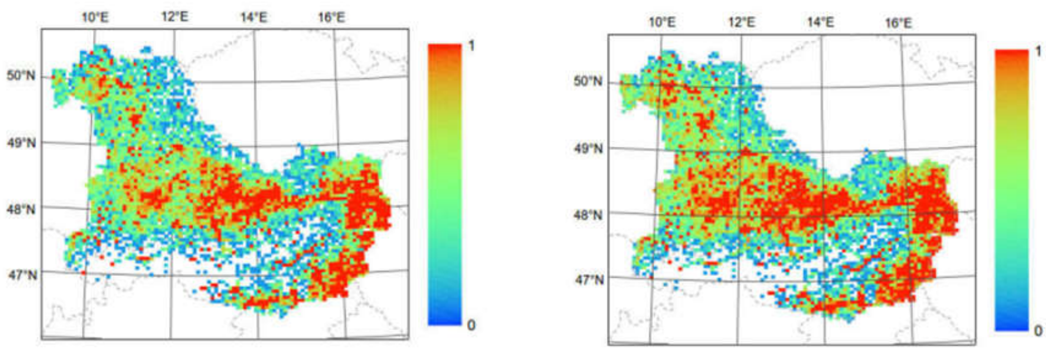
Diffusion of Fe in surface monolayer on W



Since a couple of years and intensified since 2009 I am involved in **interdisciplinary research**. I try to apply the ideas of diffusion based on methods from physics, i.e. the physical methodology and the mathematical models, to problems of spread/diffusion in ecology/biology, linguistics and possibly anthropology. In the field of ecology Lorenz Stadler launched a co-operation with the biologists/ecologists Franz Essl and Stefan Dullinger [20]. We simulated the **future spread of ragweed, introduced as a neophyte** from the USA, which triggers heavy allergies in a non-negligible section of our population. The study found some resonance and we hope that our suggestions how to mitigate further spread will be listened to and possibly even observed.

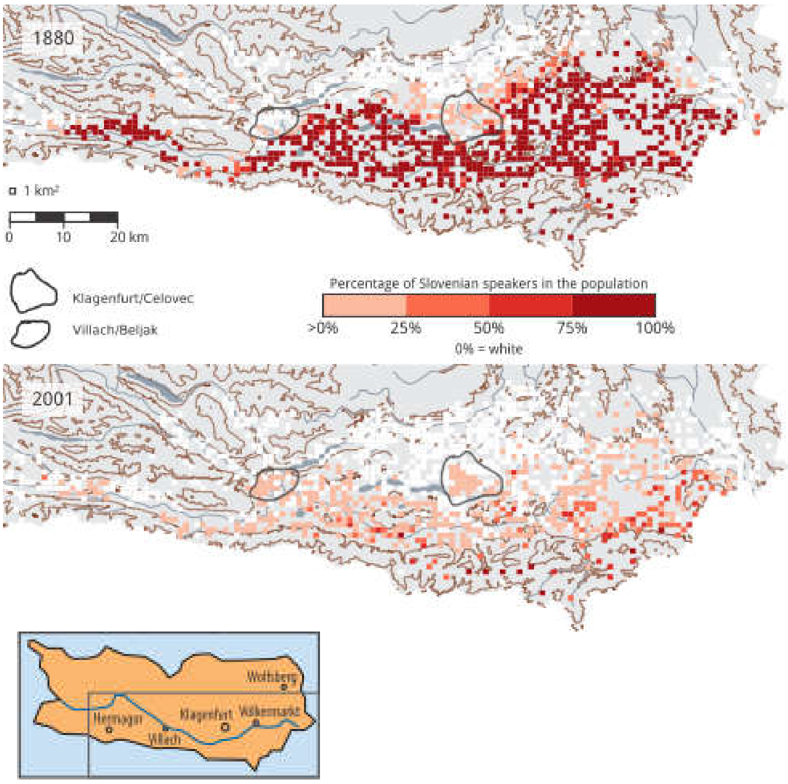


Left: Geographic cells infested by ragweed in Austria and Bavaria in 2005.
Right: Prognosis for 2050, probability indicated by the colour bars.
Size of geographical cells about 5x5km².

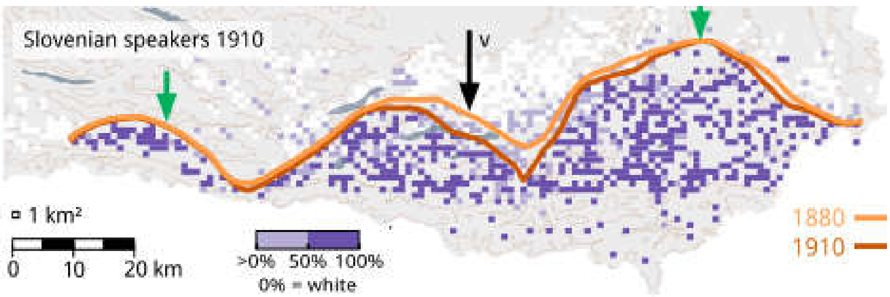


Same as right picture above, but now considering climate change as predicted by the IPCC in the limits of its range of variation between 0.025 °C/year (left) and 0.04 °C/year (right).

2015 a lady who had just gained her physics master, addressed me with the idea to apply our methods from diffusion to the **spread of languages**, in particular so-called **language shift**. I had always been fascinated by the distribution of languages and their development and since Katharina Prochazka explained to me that she had graduated in linguistics before studying physics I agreed to plunge into this new adventure. We decided to start exploring the power of our methods by investigating language shift in Central Europe making use of the extremely detailed census data of the former Austrian-Hungarian Empire and its successor states. We started with studying the development of the Slovenian language in Southern Carinthia. There Slovenian is retreating since the first censuses in 1880.

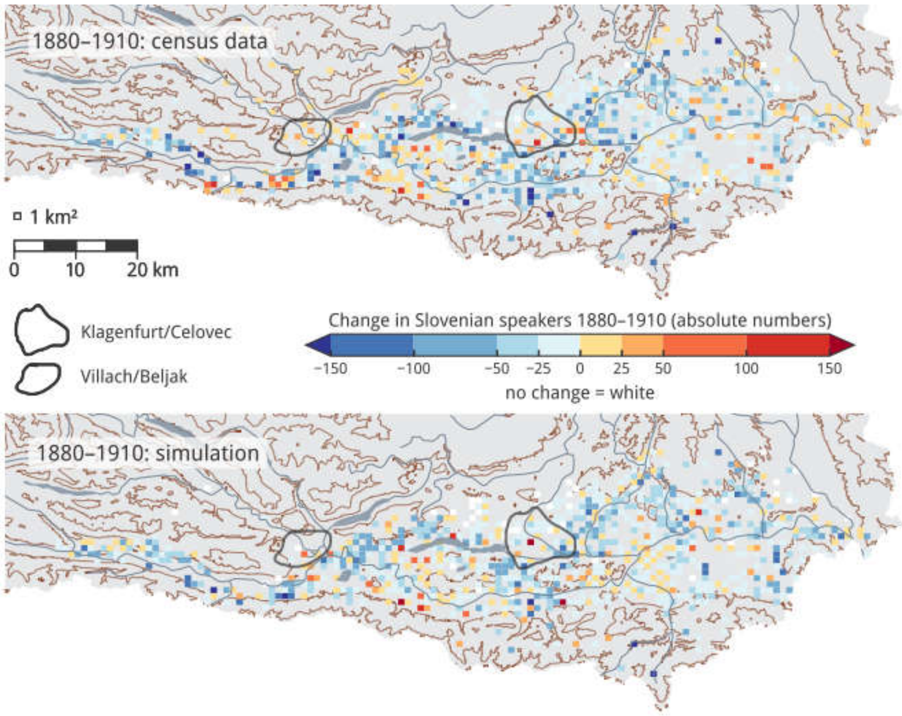


The larger maps of Southern Carinthia show the percentage of Slovenian speaking population according to the censuses in 1880 (top) and 2001 (bottom). Cell size is 1x1 km². It is evident that in 1880 Slovenian dominated in Southern Carinthia, whereas it has retreated to language islands in 2001. The smaller map shows Carinthia, the frame indicating the region of our investigations.



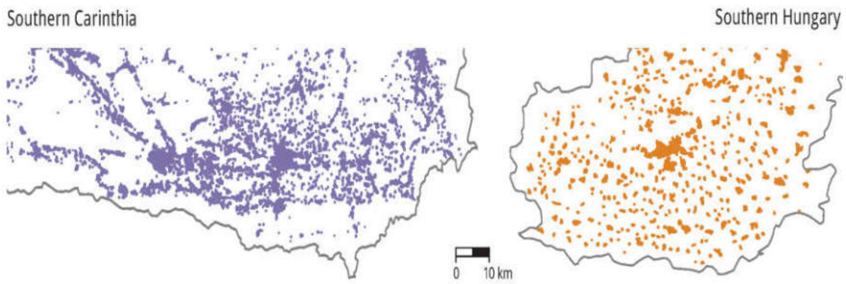
Slovenian language territory in Southern Carinthia in 1880 and 1910. Dark violet more than 50 percent Slovenian speakers, light violet less than 50 percent.
The language border moved slowly southward: hardly at the green arrows because there mountain ranges impeded language shift, more at the black arrow into rather flat and highly populated territory.

We were the first, so we believe, to make use of geographically and temporally highly resolved data. Our result is: at least in rural societies and in former time (no television etc.) - language shift occurs by contact with people from neighbouring settlements. In simulations based on this contact hypothesis we were able to show that the hypothesis can very well describe the real data (see following figures) and reference [21].



Decrease and increase of number of Slovenian speakers from 1880 till 1910. Top: census data, bottom: simulation.

We continued our language project by investigating the development of German in Southern Hungary. We found that in a region dominated by language islands (see following figure) language shift relies on a different mechanism. The study is still unpublished.



Settlement structures (without consideration of language)s in Southern Carinthia and Southern Hungary are very different.

Three booklets have arisen from my interdisciplinary interest in diffusion/spread [22]. They try to show bridges between the diffusion of atoms and the spread of living beings and possibly even ideas. I tried to convey a complex issue in a simplified way to the scientist and to the generally interested reader as well – maybe a problematic undertaking.

From a conference in the series **Diffusion Fundamentals** the book DIFFUSIVE SPREADING IN NATURE, TECHNOLOGY AND SOCIET [23] resulted which I edited together with three colleagues. Renounced scientists from diverse fields where spread and diffusion play a role have contributed. Particular credit has to be given to Jörg Kärger whose never-ending commitment enabled publication and wide reception in the relevant media of this first anthology in the field of interdisciplinary diffusion.

In my **lectures** I tried to interest the best students to join our group, as does every university teacher. Not few of my students and former co-workers are now university professors or in leading positions in economy. Of these people and their achievements I am more proud than on my own scientific harvest. Leonardo is cited saying: “Triste e quel discepolo qui non avanza il suo maestro.”

I am grateful to my wife that she has played the game or at least tolerated the vagrant life of a scientist husband. She even succeeded to take up her profession as teacher and psychologist as soon as our three daughters grew up.

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