Community paper „FIR/submm/mm Facilities“

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Executive summary

The (sub)mm/FIR wavelength range enables crucial observations to study the physical properties of astrophysical objects, ranging from star forming regions in our Galaxy, to the most distant galaxies in the Universe. Thanks to past investments, and training of the next generation of scientists, the current state of the field can be described as healthy,including a strong instrument development component, and the science output by German researchers has a large impact in the community worldwide. Of crucial importance for the general user base is to maintain continued access to ALMA through ESO, to NOEMA and the 30m facilities through IRAM. In this context, securing funds for the currently missing 2 antennas to complete NOEMA phase 2 is highly desirable. Unique access to the important FIR wavelengths range is provided by SOFIA. In the future, obtaining access and being involved in a large single-dish telescope with (sub)millimeter capabilities (preferably in the Southern Hemisphere, to complement ALMA) is a very desirable goal, and would naturally build on the ongoing legacy of the German-led APEX facility and strengths of the German instrumentation groups. In summary, there are outstanding opportunities for the growing FIR/(sub)mm community. It is imperative to ensure that we, as a community, capitalize on our past investments.

1. Introduction

The FIR/submm/mm wavelength range spans two orders of magnitude in wavelength, from about 50 µm to 7 mm. It contains a significant fraction of the radiation energy produced in the Universe. Most of this radiation is reprocessed starlight that is absorbed by dust, and re-emitted according to the temperature and dust grain distribution. The realization of this fact in the 1980s and 90s has revolutionized our understanding of the process of star formation and galaxy evolution through the cosmic ages. Whole populations of very massive galaxies in the early universe have been missed by the traditional optical studies, since they are enshrouded in dust and the starlight can only escape in the FIR/submm/mm range. Emission in this frequency range always has been and remains a critical tool for studies of star formation in the local universe (including our Galaxy), since stars form in dusty regions where temperatures are low enough that continuum radiation is emitted in the FIR/submm/mm range.

Moreover, the FIR/submm/mm range contains a large number of atomic and ionic fine structure lines (e.g., from CI, CII, OI, OIII, NII), which are excellent tracers (and agents) of cooling processes and stellar feedback, as well as molecular lines (e.g., from CO, HCN, etc., up to lines from very complex organic molecular species), see Fig. 1. These lines can serve as diagnostic tools to determine temperature, density and chemical composition (which often can be used as a proxy for evolutionary status), again because the excitation conditions of these tracers are well matched to the physical conditions in regions of galactic and extragalactic star formation, as well as to the conditions in planet-forming circumstellar disks. Resolving the lines spectroscopically allow one to study the velocity structure / turbulence of the regions under consideration and the dynamics of the gas, including dynamical masses of entire galaxies.

Thus, the grand theme of science in this frequency range is studying the origins of galaxy, star and planet formation. There are other exciting scientific areas which require studies in this wavelength regime, such as the Sunyaev-Zel'dovich effect in galaxy clusters, the cosmic microwave background, and the study of black hole event horizons, dust polarization and pulsar timing studies.

The considerable progress that was achieved by studying the FIR/submm wavelength range in the last decades was only possible because of technological advances in detector technology that opened up this range, and because observatories on high mountain sites, in airplanes or in space became available (emission in the submm/FIR range is partly blocked by the Earth's atmosphere, see Fig. 2).

2. Upcoming Facilities in the Coming Decade

Many of the facilities that will be the workhorses for studies in this wavelength regime have their origin already in the last decade(s), although many of them are only fully coming online now, or are undergoing major upgrades, with significant performance increases. Because of that, we discuss those cases on a par with new facilities. There are also plans for completely new facilities, but no firm commitments yet. We will discuss all the facilities that will play a major role in the next decade, if existing or planned, in the following. They are complementary in that they occupy different areas of the parameter space (Fig. 3).

ALMA

ALMA is an international mm/submm interferometer on the Chajnantor plateau, at an altitude of 5000 m, in Northern Chile (Fig. 4 left). The high site is superb for submm science in all bands below 1 THz, and the large collecting area (66 antennas in total, among them 54 with 12m diameter[1]) and corresponding high sensitivity and high spatial resolution (down to 0.01") constitutes a major breakthrough, since it is orders of magnitude more sensitive than earlier instruments, particularly at higher frequencies[2]. ALMA started early science operations in 2011, and is now approaching regular operation mode – not all observing modes have been commissioned yet, and as a consequence a significant fraction of the time is not available for science. German access is through ESO, which has a ~34% share (the other partners being North America, East Asia, and Chile as host country).

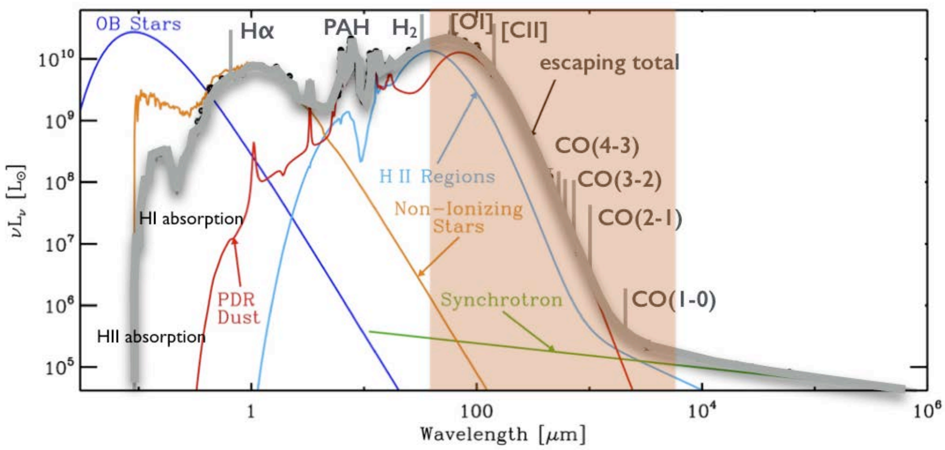

Figure 1: *Spectral energy distribution of the nearby galaxy M82, highlighting the (sub)mm—to—FIR range (in orange) that is discussed in this document.*

In the Cycles 0-4, the oversubscription rate of about 10:1 for EU proposals was the highest among all partners, with Germany taking a share that matches its contribution to ESO. This shows that there is a vibrant community, and ALMA has managed to interest scientists

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[1] Among these, 50 are in the interferometer, and 4 are single dish antennas to provide short spacing. Due to antenna movements, maintenance etc., the goal is to have 45 12-m antennas available for science operation at any given time.

[2] See discussion of NOEMA for relative performance at lower frequencies.

beyond the traditional core mm/submm community. As a consequence, it has been realized that many excellent proposals did not get time in the early ALMA years.

User support is provided primarily through the ARC (ALMA Regional Center) nodes, the German node in Bonn/Köln, and the IRAM node in Grenoble for Institutes of the Max-Planck society, in addition to core tasks provided by the central ESO ARC. In contrast to all other European ARC nodes, neither the German node (catering to the German University community) nor IRAM (catering to MPG) receive funding for user support, just for ALMA software development. The work load for user support of the ARC nodes is very high, and has further increased, since they have been asked to take over core tasks of the central node (in particular quality assurance). Some of them have accepted this for the sake of maximizing the ALMA throughput for their communities. It would be highly desirable if a funding scheme could be developed that finances the user support work, which is essential if ALMA is to remain an instrument accessible to all astronomers, not just the mm/submm interferometry experts.

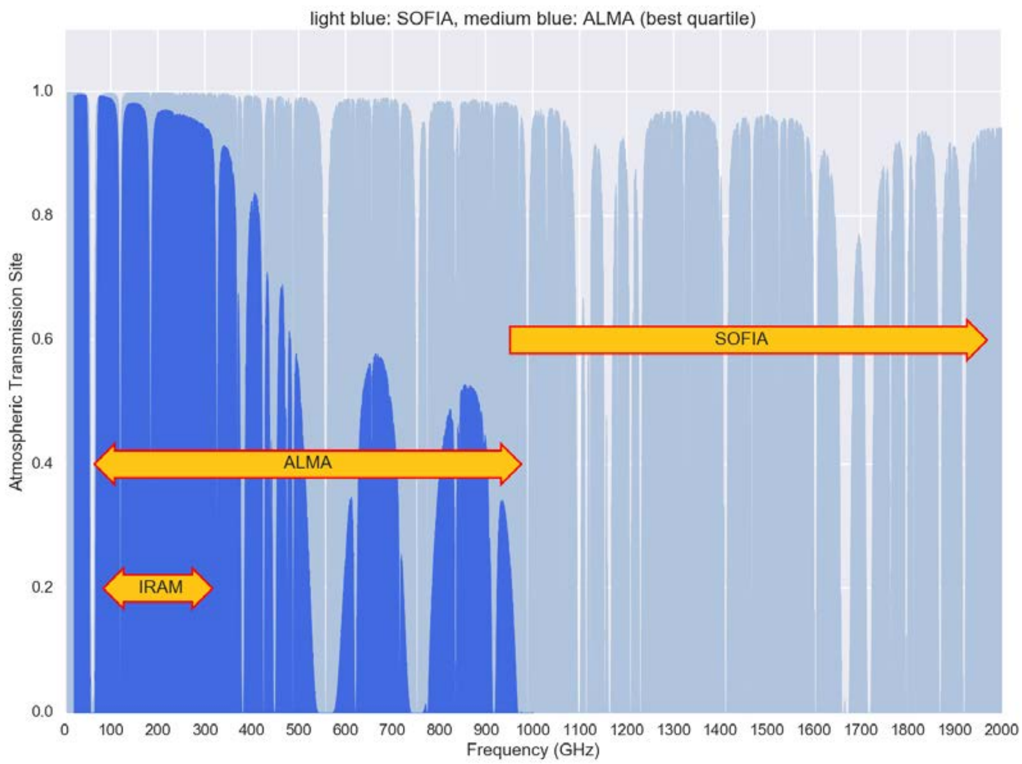

Figure 2: *Atmospheric transmission as a function of frequency, here shown for one of the best sites on the Earth (ALMA, medium blue), and the airborne observatory SOFIA (light blue).*

In the next years, the main task is to offer all currently envisioned observing modes to the community, which includes observations at high frequencies at very long baselines, full polarization, and VLBI observations. As this happens, more time for science operations will become available, further increasing the scientific output of ALMA. For the time beyond (ALMA 2030 roadmap) one can envision enhancements such as multi-beam receivers, larger receiver bandwidths, increased frequency coverage, a large single dish complement (see below) and more advanced data processing and analysis methods. The latter aspect is quite important, since for the high throughput of ALMA, the bottleneck from observation to publication for most projects is the data analysis part. As the archive is filling up, it is anticipated that archival research will play an increasingly important role in the future, and a support structure for that needs to be in place.

It can be expected that ALMA will remain the flagship instrument for the mm/submm science in the southern hemisphere for the next decades, and it is important to make sure that maintaining and improving this facility receives sufficient financial support.

NOEMA

The Northern Extended Millimeter Array(Fig. 4 right) is the successor to the Plateau de Bure interferometer, operated by IRAM, located in the French Alps. It will have, in Phase I (completed in 2018) 10 antennas with 15m diameter, 2 new generation Polyfix correlators, allowing for dual frequency observing and polarization experiments, and each frequency will allow for 16 GHz bandwidth per polarization, hence 2 times the ALMA bandwidth, with higher sensitivity relative to ALMA receivers due to newer technology, and will operate from 72 up to 345 GHz. The correlators also will have a higher sampling rate than the ALMA correlator, resulting in increased correlation efficiency. A baseline extension to 1.6 km allowing for higher spatial resolution was funded by an extra contribution from MPG, and will be available in 2018. Its host institution, IRAM, is funded by the German Max-Planck-Society, the French CNRS, and the Spanish IGN. Access to the German community is provided through the MPG participation, and is open also to non-MPG institutions, such as universities. NOEMA plays an important role, since it is the only remaining large mm interferometer in the northern hemisphere, after the demise of CARMA. It also gives the German community a scientific edge, due to its privileged access to the instrument – the oversubscription is significantly lower than for ALMA, and the German share is larger. Apart from being a powerful instrument in its own right, access to NOEMA also enables pilot studies that eventually would facilitate access to ALMA. There is the training aspect for interferometric observations as a technique, and the scientific aspect of trying out science projects that then develop into extremely competitive ALMA proposals.

With Phase II of NOEMA, which includes 2 additional antennas (not yet funded), the detection capability will get close to the ALMA capability at mm wavelengths. NOEMA is therefore a powerful and competitive facility that is well on its way. It is certainly of vital interest to the German community that this Phase II will be realized, and that there is continued access to this world-class facility. NOEMA will also serve as a technology platform where new technologies will be pioneered which later can be applied in ALMA.

IRAM 30m

The IRAM 30m telescope (Fig. 5 upper right) on Pico Veleta in Spain is also operated by IRAM, and the access is therefore provided through the same channels. It still is the largest fully operational millimeter telescope in the world, although in the next decade the 50m LMT in Mexico will probably get online, with currently unknown performance parameters, and no guaranteed access to German observers. The 30m telescope has given the mm science a huge boost, and continues to be a unique instrument. In its 30 years of operations, its instruments have undergone major upgrades, and its current equipment is state of the art. In particular the new, very sensitive heterodyne receivers, and the wide FFTS backends have to be named, which allowed for transformational science. In the near future, a large dual color continuum camera, and in the mid-term new heterodyne arrays are foreseen.

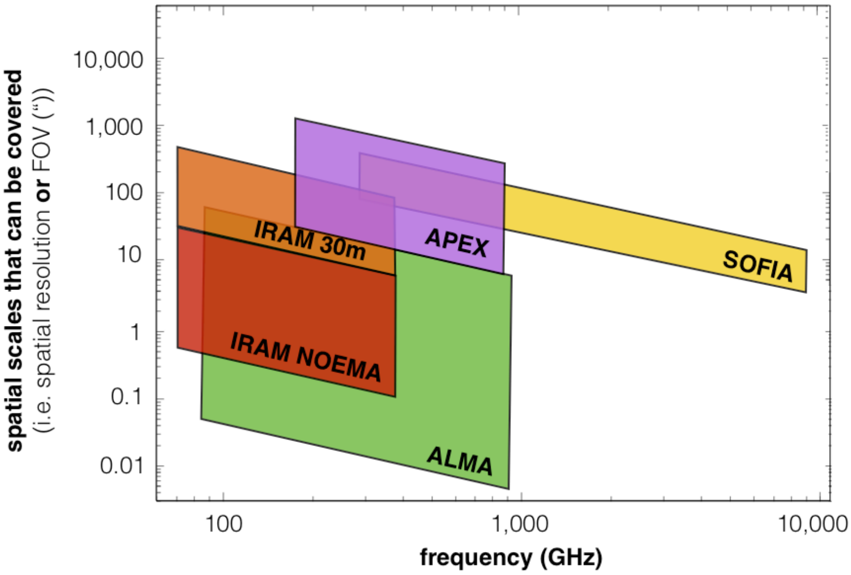

Figure 3: *Parameter space (spatial scales that can be covered as a function of frequency) for key (sub)mm facilities.*

Like NOEMA, the 30m can do outstanding and complementary science in its own right, particularly on large scales inaccessible, by nature, to interferometers, and using broad-band incoherent continuum instruments. It also facilitates access to other instruments, such as NOEMA or ALMA, through its capability to perform pilot studies with a lower access threshold, to demonstrate the need for higher resolution/sensitivity provided by interferometric follow-up. It also can serve as a technological test bed, since testing on a single dish instrument is easier than at an interferometer, where naturally multiple receivers have to be provided. Currently, a large dual color continuum camera is being commissioned.

The German community has benefited enormously from access to this instrument in the past, and present. It therefore remains a cornerstone of mm science in the next decade, and should be continuously upgraded to maintain its position on the forefront of technological development.

Figure 4: *The two (sub)millimeter interferometers that are extensively used by the German community (left: ALMA, right: IRAM NOEMA/PdBI)*

APEX

The APEX telescope (Fig. 5 upper left) is a modified copy of a 12 m ALMA prototype. It is operated by the MPIfR in Bonn, together with ESO and Onsala Space Observatory. It is located on the ALMA site, and therefore capable of submm operations. It is, apart from the Japanese 10m ASTE telescope, the only larger submm facility in the southern hemisphere.

Access for the German community is provided through MPIfR and ESO. Similar to the IRAM 30m, its strengths are large-area survey projects and, even more than the 30m, pathfinder science for ALMA. This is because it reaches up to the same frequencies as ALMA does and is on the same site, having access to the same sky. Because the German community has the additional access channel through the MPIfR time, access has been easier than for other European countries, which can just apply for time through ESO. Projects are being conducted with a quick turn-around so that APEX allows also for rapid ALMA follow-ups. As a consequence, APEX is a very valuable asset. It is also a superb testbed for technological development, such as submm array receivers, and an innovative continuum camera based on the MKID technology is currently under development. The current agreement expires in the end of 2017 and an extension of operation to the end of 2022 is currently being prepared among the partners.

SOFIA

After the Herschel satellite ceased its operations in 2013, SOFIA provides the only access to the FIR window for the coming decades and gives the German community (together with the US partners) a unique advantage. SOFIA is a refurbished Boeing 747SP (Fig. 5 bottom), which hosts a 2.5 m telescope. It is flown at altitudes up to 14 km, which is above most of the atmospheric water, the main agent of atmospheric absorption at FIR wavelengths. It is operated jointly by NASA (80%) and DLR (20%), which, within Europe, gives Germany privileged access to SOFIA. It has a range of instruments, but it excels at high-resolution spectroscopy, which is provided by the German upGREAT receiver and, at somewhat lower resolution, the FIFI-LS instrument, from Bonn/Cologne and Stuttgart, respectively. SOFIA enables the only access to the main cooling lines of the ISM, [CII], [OI] and [NII], in the Milky Way and nearby galaxies, and is therefore an important prerequisite for the interpretation of measurements of the same lines at high redshifts with ALMA. Another important role is a technology platform for receivers developed for the THz range. Although it has the disadvantage that there still is some atmosphere present (i.e. the transmission is not as good as in space), the advantage is that it is accessible, and can, in contrast to space missions, always fly up-to-date instruments

Figure 5: *Single element telescopes that are actively used by the German community: APEX, the IRAM 30m telescope, and the airborne SOFIA facility.*

An example is e.g. the recent transition from the single pixel GREAT receiver to the 2x7 pixel upGREAT array, which increases the mapping speed, also compared to Herschel, considerably.

Large Single Dish in Chile

A recent poll by ESO identified a large single dish in Chile as one of the highest priorities for the community in the 2020's. The rationale is that ALMA, while very good at high resolution mapping of small and moderately sized regions, lacks the capability to efficiently map large areas on the sky, which are important for studies of the high-redshift universe as well as for Milky Way and nearby galaxies science (in particular the Magellanic Clouds). These studies can then followed up by higher resolution observations of selected regions/targets by ALMA. The IRAM 30m (and also the LMT) do not have access to a large part of the ALMA sky, and are also limited to longer mm wavelengths. APEX does share the sky and the wavelength regime, but is smaller than desired, and its availability beyond 2022 is uncertain. Similar plans for a large single dish sub(mm) facilities have been voiced by the East Asian, particularly the Japanese, community.

There are several attempts to build such an instrument, or precursors thereof, e.g. the CCAT project. It aims at getting a telescope at 5600 m (600 m above the ALMA site), which would result in better accessibility of the 450 µm and 350 µm windows compared to the ALMA site, and some access to the 200 µm window, which is inaccessible to ALMA. None of these projects have managed to secure funding yet, and the timescale for possible large instruments built by ESO or the ALMA consortium is unclear. A strong push from the community is required to make this happen.

Such an instrument would build on the ongoing legacy of APEX, and to protect the scientific and technological expertise gained with APEX, it is of vital interest to the German community to support such a project. It should be noted that this is the only genuinely new project (all the others being upgrades, albeit upgrades that very significantly enhance current capabilities) opening new science areas, and providing an attractive telescope platform for instrument development. Since the path forward is not clear yet, one should allow for flexibility in funding schemes to be able to grasp opportunities to secure access. To maximize the impact and benefit for the community, such an instrument should be implemented between 2020 and 2030.

3. Main Achievements in the Past Decade

The past achievements have already been highlighted in the previous section, and for the sake of brevity not all information is repeated here. However from the discussion above it is clear that German researchers have played critical roles in the construction and operation of a large number of (sub)millimeter facilities and their state-of-the-art instrumentation. For the Herschel Space Observatory, German groups have led the construction of the PACS instrument and significantly contributed to HIFI. Involvement in various Herschel key projects, partly as guaranteed time through instrument development, have given a huge push to the German star and galaxy formation, protoplanetary and debris disk communities, that is now exploited and extended through use of other instruments such as SOFIA or ALMA. The APEX single dish telescope exists largely due to efforts by the German community (in particular the MPIfR), German participation within IRAM (PdBI, NOEMA, 30m) is very significant, at a 40% level. A number of different groups in Germany are part of the CCAT consortium. Regarding ALMA, German astronomers represent a major user base, with a number of successful proposals in ALMA early science. By construction, German participation in the SOFIA project is at the 20% level.

It should be stressed that these achievements build on a variety of aspects. E.g. ESO / ESA membership has been crucial, such were significant investments in IRAM, APEX, Herschel, and SOFIA, that resulted in privileged access to these facilities. Over the last decade, unique experience in receiver/detector/telescope building/operations has been built up in expertise centres. Lastly , the funding structures within Germany, e.g. through DFG (SFBs, ISM-SPP), MPG, VB, DLR, Leibnitz, Helmholtz, as well as junior groups (e.g., Emmy Noether, Max-Planck) are exemplary for the success of multi-branching funding structure in Germany.

As a consequence, Germany is now playing a worldwide leading role in the field, both scientifically & technologically. This is partly also a result of a significant increase of the community over the past decade (in particular regarding the infrastructural achievements: IRAM, SOFIA, APEX, Herschel, ALMA, NOEMA, SOFIA). German researchers are thus uniquely positioned to capitalize on potentially newly emerging facilities (e.g. a large single dish telescope, and potentially the 'next generation Very Large Array [ngVLA]'.

4. Particular Role/Strengths of Research Groups in Germany

There are a number of centres in Germany that focus on (sub)mm/FIR studies, and we here concentrate only on the largest centres. All researchers in Germany have access to IRAM, APEX, SOFIA and ALMA (through ESO). These observational centres are complemented by strong theoretical groups all over Germany that work on theories of star and galaxy formation. In the last decades these theories have evolved to the point of making strong and testable predictions. The strong ties that exist between these theory groups and observational groups and the resulting close interconnections and exchanges are one of the most valuable assets in the German astrophysical community, that need to be fostered even further in the next decade.

The Bonn/Köln groups have a very strong background in instrument development and telescope operations. They have been major players in the operation and construction of the APEX and NANTEN telescopes. Instruments were built for Herschel, SOFIA, APEX, NANTEN, and IRAM. These instruments have been a large part of the success of the facilities and ongoing as well as future instrument development is considerably expanding the scientific opportunities of the facilities for the next decade. In addition, the German ALMA regional centre (ARC) is located in Bonn/Köln. Numerous large observational programs are led by these groups, e.g. SZ science at the University of Bonn, the ATLASGAL and SEDIGISM surveys, and studies of galaxies in the high-redshift universe.

The MPIA in Heidelberg has established itself at the forefront of Galactic and Extragalactic studies worldwide, in many cases in collaborations with other institutes within Germany. A number of large IRAM programs have been led by MPIA staff, including the CORE, PAWS, EMPIRE and HERACLES surveys. The focus ranges from Galactic studies of high-mass star forming regions, over studies of the interstellar medium in nearby galaxies, to high-redshift studies, including the highest-redshift galaxies/quasars. The MPIA also provided significant contributions to Herschel PACS instrument.

The MPE in Garching has led the construction of the PACS camera and spectrometer on board the Herschel space telescope, and of the FIFI imaging spectrometer for SOFIA. The MPE group has also led major IRAM NOEMA/PdBI surveys (PHIBSS/PHIBSS2, SOLIS and COLD GASS I&II), using more than 2000 hours to characterize molecular gas in distant galaxies. The Herschel PEP and SHINING surveys had a major impact in resolving the cosmic infrared background and characterizing distant and local galaxy samples.

5. Dominant Science Cases

For brevity, we here only highlight a few recent high-impact results, based on large programs led by German researchers, that give a snapshot of current community interests and competence but that also position the community to tackle the next big questions on star formation through cosmic times:

- PHIBSS/PHIBSS2: first characterization of molecular gas in normal, main-sequence high-redshift galaxies.
- PEP: Galaxy evolution from unbiased far-infrared 'deep fields'.
- SHINING: ISM conditions and molecular outflows in nearby AGN and infrared galaxies
- PAWS: first GMC-resolution map of a nearby massive galaxy (M51)
- CORE: high-resolution imaging of a sample of high-mass star forming regions
- HERACLES: characterization of the molecular gas content in nearby galaxies
- LESS: LABOCA Extended Chandra Field South Survey
- ATLASGAL: Unbiased submillimeter dust continuum survey of the inner Galactic plane and its molecular line follow-up programs
- SEDIGISM: Large scale line map of the southern Galactic plane

Many results emerging from smaller, individual studies are too numerous to be listed here, but also resulted in groundbreaking research. The future success in these science areas will depend crucially on the access to facilities enabling a combination of large area survey capabilities, resolving power (spatial and spectral) and large range in accessible wavelengths.

6. Summary and Conclusion

The (sub)mm/FIR wavelength range enables crucial observations to study the physical properties of astrophysical objects, ranging from star forming regions in our Galaxy, to the most distant galaxies in the Universe. Thanks to past investments, and training of the next generation of scientists, the current state of the field can be described as healthy, and the science output by German researchers has a large impact in the community worldwide. Of crucial importance for the general user base is to maintain continued access to ALMA through ESO, to NOEMA and the 30m facilities through IRAM. In this context, securing funds for the currently missing 2 antennas to complete NOEMA phase 2 is highly desirable. The only access to the important FIR wavelengths range is provided by SOFIA. In the future, obtaining access and being involved in a large single-dish telescope with (sub)millimeter capabilities (preferably in the Southern Hemisphere, to complement ALMA) is a very desirable goal, and would naturally build on the legacy of the German-led APEX facility. In summary, there are outstanding opportunities for growing FIR/(sub)mm community. It is imperative that we ensure that we, as a community, capitalize on our past investments.