# 1. Introduction and scientific context

Understanding the physical processes that shaped galaxies in the Universe is a key goal for the astrophysics community. However, there is a fundamental problem between theory and observations in explaining the characteristics of massive galaxies. Theoretical models suggest that galaxies evolve though hierarchical mergers in a gradual assembly of galaxies. As gas-rich galaxies merge together such interaction naturally induces contemporary starburst activity from the interacting gas and dust, this is supported by observations of interacting galaxies in the local universe. This also agrees with the standard cosmological model, which predicts star formation should be happening on all scales over all epochs of the Universe. However, in stark contrast to this model, this scenario is simply not observed.

The prime example is giant elliptical galaxies, which are defined by their old stellar populations and deficiency in the large quantities of cool dust and gas needed for star formation. This constitutes one of the most outstanding problems in Astrophysics: **In the context of galaxy evolution through hierarchical mergers, what inhibits star formation and galaxy growth in massive, elliptical galaxies?** Powerful active galactic nuclei (AGN) – super-massive black holes in the nuclei of galaxies, which during brief, but vigorous activity periods emit copious amounts of energy in form of radiation and/or (radio) jets of relativistic elementary particles – are now considered the most likely culprits to inhibit star formation in galaxies from their early evolutionary stages until today, but a direct link between AGN activity and star formation is still missing. Is this scenario, often referred to as 'AGN feedback' correct? This is the main scientific question that inspired our Marie-Curie project: ***The hierarchy probe*****.**

In order to solve the hierarchy problem we need above all a reliable tracer of star formation. The infrared emission of warm and hot dust produced in star-forming regions, as sampled by the latest space observatories (Spitzer, Wise, Herschel), is arguably our best indicator of star formation across the Universe. Dust absorbs the radiation from hot young stars and re-emits it at infrared wavelengths, e.g. in local luminous infrared galaxies. However, for AGN host galaxies, the dust emitting the far-infrared emission can be heated by the AGN itself instead of star formation. Naturally, as AGN power increases, its contribution to the infrared emission also becomes more important. This is also important because the fraction of galaxies that contain powerful AGN increases significantly with redshift.

Unfortunately, separating the infrared emission due to star formation origin from that due to AGN is not easy. The primary reason why this seemingly simple task presents such a problem is that the vast majority of the thermal mid-to far-infrared emission from AGN comes from scales much smaller than the host galaxies (kpc scales); even our most advanced infrared satellites cannot spatially map and isolate the central powerful infrared emitting regions of an AGN. However, it is possible to overcome this difficulty by conducting multi-wavelength surveys of complete samples of AGN, correlating the properties of the objects across the electro-magnetic spectrum.

*The hierarchy probe* enables us for the first time to obtain direct constraints on the cold dust, the dominant dust component of these galaxies, and most direct, quantitative tracer of star formation observed at far-infrared wavelengths above ~100 μm. This wavelength range, robed by the Herschel observatory samples the emission from dust in a part of the electro-magnetic spectrum that is most efficiently heated by star formation. Therefore, Herschel data serves as a reliable *quantifier* of star formation in our objects. Herschel photometry also sample the total amount of dust from the cold ISM in these galaxies - the fuel of star formation- allowing us to quantify the star formation efficiency, the star formation rate per unit ISM. This is essential to quantify the impact of AGN in the host galaxies and a necessary ingredient of any study addressing what physical and astrophysical process may control star formation in the Universe.

As part of T*he Hierarchy Probe*, we obtained an exceptional allocation of 29 hrs of Herschel Director's Discretionary « Must Do » photometry at 100-500 μm to address the hierarchy problem with a radio-selected sample covering a large range of AGN and star formation properties. The observations carried out as a priority during the final months of the lifetime of the Herschel. This Marie-Curie fellowship allowed us to exploit this rich, unique and important data set to investigate the impact of the powerful radio-loud AGN on their host galaxies, while also opening up new scientific avenues for the fellow.

## 2. Work carried out during the project and results

The fellow has begun this project by utilising the expertise in Herschel data processing at IAS to analyse the new Herschel data and produce preliminary spectral energy distributions (SEDs) from the results. The last data were obtained in spring 2013, right before the end of the Herschel mission, about a year later than initially expected. As a first step, the fellow modelled the optical-to-infrared-to-radio spectral energy distribution with modified black-body curves, obtaining a range of dust temperatures and masses. The superb performance of the Herschel observatory gives it sensitivity over a wide range of infrared wavelengths (100 to 500 microns for our PACS and SPIRE observations). This range samples dust composed of many different types and temperatures.

We find that most of our galaxies contain a total of about $10^{5\text{-}8}$ $M_S$ of dust, which are relatively large amounts compared to similar sets of galaxies without radio-loud AGN, and that 15% have even higher dust masses, comparable to intensely star-forming galaxies. In these galaxies, likely triggered through a major merger, black hole and galaxy are growing rapidly. In the others, in spite of their higher dust and gas masses than in comparable galaxies, star formation is strongly suppressed. This is the first time we obtain quantitative results of the warm dust content in massive, radio-selected AGN host galaxies on a complete sample of galaxies, i.e., a sample that allows us to generalize to the overall population of galaxies.

In a second, still on-going step delayed by the unexpected late data taking, we are now fitting physical dust models to our spectra. IAS has some of the leading experts worldwide in the dust modelling of the ISM which the fellow is taking advantage of in this analysis to create a new and sophisticated dust model for powerful AGN. To our knowledge this is the first time that the detailed dust models, developed and validated through particularly rich observational data sets of the the interstellar medium in our own Milky Way, is being applied to study AGN host galaxies, e.g., to quantify the star formation and their cool ISM components. This also enables us, for the first time, to construct a purely empirical, robust, representative SED template for an AGN. Previous such templates bear the risk of being contaminated by dust emission from star formation. This will be important for a large number of studies of the co-evolution of AGN and galaxies across large redshift ranges. The fellow is now based at a neighbouring institute, and continues to collaborate closely and intensely with the colleagues he met at IAS during the fellowship. This work has already led to one publication, with two more pending. It has also justified additional observations with ground-based instruments, and given rise to subsequent observing requests at major telescopes, e.g., to study the gas content and link between star formation and ISM in parts of the sample in more detail.

## 3. Outlook

The fellowship has led to several accompanying papers on related science at IAS and other institutes worldwide (see list of publications), and allowed the fellow to extend his skills in several ways. This includes, e.g., the study of star formation and AGN activity of two powerful quasars in the distant universe with several millimeter interferometers, the eVLA in New Mexico and the SMA in Hawaii, which the fellow is leading, and important contributions to the analysis of high-redshift radio galaxies with the optical/NIR Very Large Telescope of ESO and the Australian Compact Telescope Array in the millimeter. This enabled the fellow to complement his broad expertise in multi-wavelength photometry through multi-wavelength observations with spectrographs, including interferometry, which is currently at the forefront of astrophysical research with the advent of ALMA.

The fellow had also already developed a deep interest in space-based instrumentation while working with the Spitzer IRS team at Cornell University during his first postdoc, and was able to extend this work by becoming the IAS representative in the European consortium for theMid-Infrared Instrument (MIRI) of the next great space observatory the James Webb Space Telescope (JWST). His contributions were essential to demonstrate that the instrument meets its delivery sensitivity requirements. While at IAS, this was only a minor part of his activities, but allowed him to foster a close collaboration with the neigbouring astrophysics branch of the Comissariat d'Energie Atomique in Saclay, established during the fellowship, which resulted in his current six-year postdoctoral position. which is foreseen to be turned into a full staff position at the end of the term.