Wave-front sensors for adaptive Optics on extremely Large telescope using Fourier filtering [WOLF]

!Make each photon count!

Development, test and on-sky implementation of innovative wave-front sensors for the forefront astronomical instrumentation on ground-based telescopes

Evolution(s) éventuelle(s) de la proposition détaillée par rapport à la pré-proposition

The total cost of the project has slightly changed between the pre- and the final proposal. The increase (within the 15% allocated margin) is essentially due the inclusion of a specific funding for the telescope nights at WHT and a precise computation of PhD and post doc costs by the ANR partners.

Summary table of persons involved in the project:

Partner	Name	First name	Current position	Role & responsibilities in the project (4 lines max)	Involvement (person.month) throughout the project's total duration
ONERA	Fusco	Thierry	MR2[1]	ANR Coordinator WP1 and 2 Coordinator	20p.month
ONERA	Sauvage	Jean-Francois	IR	WP2, WP3, WP4	12p.month
ONERA	Petit	Cyril	IR	WP2, WP4	6p.month
ONERA	Mugnier	Laurent	MR2	WP2	5p.month
ONERA	Conan	Jean-Marc	MR1	WP4	5p.month
ONERA	Janin-Potiron	Pierre	Post doc	WP3	12p.month
ONERA	ONERA PhD	To be hired	PhD	WP2 and WP3	36p.month
ONERA	ANR PhD	To be hired	PhD	WP3 and WP4	36p.month
LAM	Neichel	Benoit	CR	Local coordinator WP3 manager	20p.month
LAM	El-Hadi	Kacem	IR	WP3	10p.month
LAM	Ferrari	Marc	Astronome	WP1	4p.month
LAM	Ballard	Philippe	IE	WP3	4p.month
LAM	Caillat	Amandine	IE	WP3	4p.month
LAM	Gach	Jean-Luc	IR	WP2, WP3	5 p.month
LAM	Le Mignant	David	IR	WP3	5p.month
LAM	Beuzit	Jean-Luc	DR	WP2,WP4	4p.month
LAM	Correia	Carlos	Chair d'excellence	WP2,WP3	10p.month
LAM	Brulé	Yoann	Post doc	WP2 (LGS activities)	12p.month
LAM	ANR Post doc	To be hired	PhD	WP3 and WP4	18p.month
LESIA	Rousset	Gérard	Professeur	Local coordinator WP4 manager	10 p.month
LESIA	Gendron	Eric	Astronome Adjoint	WP2 & 4	14 p.month
LESIA	Vidal	Fabrice	IR	WP4	6 p.month
LESIA	Lapeyrère	Vincent	IR	WP4	6 p.month
LESIA	Sevin	Arnaud	IE	WP4	4 p.month
LESIA	Dembet	Roderick	IE	WP4	4 p.month
LESIA	Buey	Tristan	IR	WP4	8 p.month
LESIA	Perret	Denis	IE	WP4	6 p.month
LESIA	Chapron	Frédéric	IR	WP4	4 p.month
LESIA	LESIA PhD	To be hired	PhD	WP4	10 p.month
LESIA	ANR post doc	To be hired	Post doc	WP3 and 4	18 p.month
Durham Univ.[2]	Morris	Tim	Professor	WP4	5p.month
Durham Univ.	Basden	Alistair	IR	WP4	5p.month
INAF-Arcetri	Esposito	Simone	Professor	All WP (XAO activities)	4p.month
INAF-Arcetri	Pina	Enrico	researcher	WP3	4p.month
INAF-Arcetri	Busoni	Lorenzo	IR	WP3	4p.month
INAF-Padova	Ragazzoni	Roberto	Professor	All WP (LGS activities)	5p.month
INAF-Padova	Viotto	Valentina	IR	All WP (LGS activities)	4P.month

[1] IR, MR1 and 2 at ONERA are equivalent to IR1, CR1 and DR2 for the CNRS classification
[2] Durham Univ and INAF are associated partners. They do not directly receive funds from the ANR

I. Proposal's context, positioning and objective(s)

a. Objectives and scientific hypotheses

Adaptive Optics: a new standard for ground-based astronomical observations

Astronomy is a science where the observations of extremely distant objects are the single source of information. Therefore, over the last hundred years , the size of ground based telescopes has steadily increased to reach diameters of the order of ten meters. This important growth has two main goals, to increase the total flux collected, thus reducing the photon noise that represents the fundamental limit of any observation, and to improve the angular resolution on the observed object.

If the first objective is reached - the number of photons collected increases with the square of the telescope diameter - it is unfortunately not the same for the angular resolution. Indeed, the presence of the Earth's atmosphere significantly limits this resolution. The latter never exceeds the theoretical resolution of a telescope of a few tens of centimetres at optical wavelengths, regardless of the telescope diameter considered. In 1953, Babcock[1] proposed a technique called Adaptive Optics [AO] to compensate for this effect. To that end, AO technology is based on a deformable mirror which corrects the incoming wave front in real time by using information coming from a Wave Front Sensor [WFS] which measures the turbulent phase . Figure 1 illustrates the principle of AO, in a configuration where the deformable mirror is integrated inside the telescope itself.

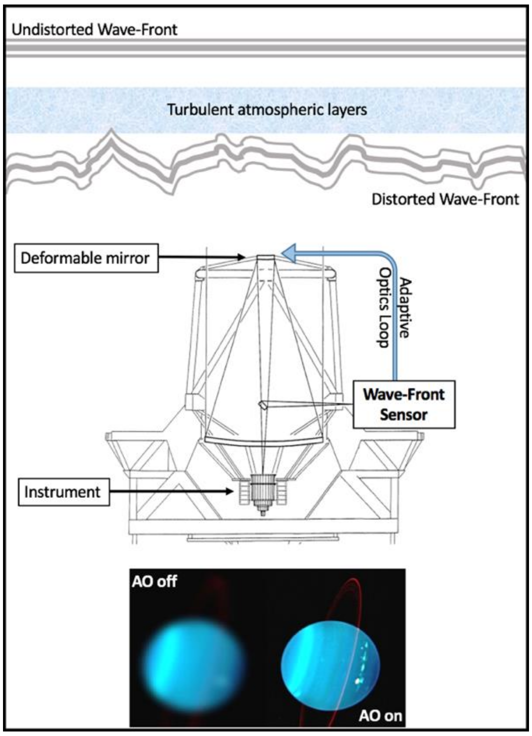

Figure 1. Schematic representation of an AO system integrated in a ground-based telescope. In that example, the deformable mirror is the telescope secondary mirror.

Over the last twenty years, AO has gone from being a demonstration stage to a technique that is both proven and operational (from TRL 4 to TRL 9), and almost all large telescopes are equipped with AO. AO observations have brought some of the major discoveries in astronomy with, among others, detailed study of the massive black hole at the center of our Galaxy[2,3], detailed images of the surface of solar systems planets[4,5], precise morphology and dynamics of very distant galaxies[6,7,8], and the first direct detections of exoplanets[9,10]. AO has revolutionized the ground-based telescope by providing the highest achievable image quality so far[11].

The next step forward will come from the so-called Extremely Large Telescope (39 m diameter European ELT [E-ELT][12], 30 m north American TMT[13], 24 m American and Australian GMT[14]) that should have their first light as soon as 2024. These giants are all relying on AO systems, starting operations from day one. The colossal size of these telescopes and the complexity of the scientific instruments compel us to a complete rethinking not only to improve the overall system performance, but more specifically the sensitivity and the robustness of the AO systems, thus maximizing the astrophysical returns of AO assisted instruments. So far, the science impact of AO has benefitted greatly from case studies of relatively few intensively studied objects. In the future, the use of AO on large and diverse samples will become increasingly important. **In the next decade, Adaptive Optics will become a new standard for ground based astronomical observations.**

One of the most exciting promises of this new generation is probably the detection of exoplanets. Figure 2 shows a recently discovered exoplanet - HIP 65426b – as seen by the SPHERE instrument installed on the Very Large Telescope (VLT) in Chile. This exoplanet is between 6 and 12 times the mass of Jupiter and orbits a young and surprisingly fast rotating star[9]. This planet may have been formed together with the star, as a binary system, or alternatively, in a disc of gas and dust that would have rapidly dissipated in the early stages of this system. Discovering new planetary systems is then crucial to understand the distribution of planets around stars of various types, to study the range of their physical and orbital characteristics, and to estimate their number in the Galaxy. Determining those statistics for a wide range of planet mass, orbit radius, system age and star mass is key to understand the planet formation process and how planetary systems are evolving.

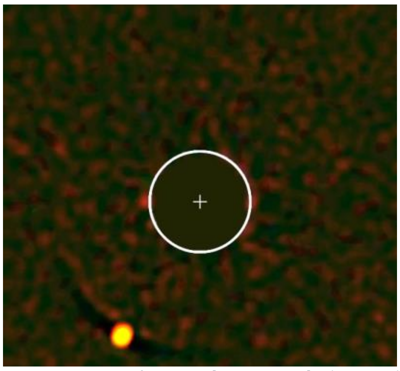

Figure 2 Image of an exoplanet recenttly discovered by the SPHERE instrument on the VLT

The angular separation of planet and star revealed by AO permits direct photometric and ultimately spectroscopic studies and characterization of these objects atmosphere/photosphere. The ELT generation equipped with AO will allow for the discovery of planets down to Earth-like masses, direct imaging of larger planets and even the characterization of their atmospheres. Detecting presence of water, or even complex molecules in an exoplanet would revolutionize our view of the Universe and offer strong evidence for life on other planets. Imaging exoplanets with an ELT is however extremely challenging, and technological breakthroughs are still required. Stars are typically billions of times brighter than the exoplanet we are trying to image and any uncorrected starlight completely swamps the signal coming from the planet. One of the key milestone toward imaging exoplanets is to dramatically improve the AO performance. For exoplanet imaging it translates to "extreme" adaptive optics (ExAO) for extreme wavefront control, combining high actuator count deformable mirrors, fast real-time control algorithms, and **the use of highly sensitive and highly accurate (nanometric precision) Wave-Front Sensors.**

On the other hand of astronomical scales, trying to understand galaxy formation and evolution has become one of the most active fields of astrophysics over the last few decades. When and how does the Hubble sequence build up? Does merging play a major role, as expected from hierarchical ΛCDM scenario? Are elliptical galaxies assembled mainly via mergers or are there other ways to build such galaxies? Is cold gas accretion along cosmic filaments an efficient process to form bulges in spirals? Are these different mechanisms dominant at different cosmic times?

To understand the physical processes taking place in galaxy formation and evolution and to differentiate between intrinsic and environmental effects, the ability to obtain resolved spectroscopy and images across the objects is a must. Distant galaxies are marginally resolved in seeing-limited conditions and AO is required. Over the past years, AO has been determinant to spatially resolve the internal structure and kinematics of star forming galaxies at z ~ 1.5 - 3, the peak epoch of mass assembly[6,7]. In particular, these studies revealed a population of large disks, rapidly forming stars in giant star-forming complexes or clumps, probably triggered by high gas accretion rates through cold flows. These observations, although still relatively few, have already led to fundamental developments in our understanding of galaxy evolution.

Most of the current extra-galactic AO studies are however constrained by the number of targets available to AO correction (the so-called sky coverage), and the need for statistics that requires observing many objects across the largest possible field. Those constraints called for the development of a new generation of AO, called Wide Field AO [WFAO]. By using multiple Laser Guide Stars [LGS] (see Figure 3), WFAO significantly increases the field of the AO corrected images, and the fraction of the sky that can benefit from such correction. Therefore, where the ExAO systems are well suited for observations of exoplanets, the new

Figure 3 The 4 Laser of the Adaptive Optics Facility [AOF].This AO system feeds the MUSE instrument on the VLT

generation of WFAO is opening the path for extragalactic observations.
Very recently, such capability has been brought to its apogee by coupling the ESO-operated Adaptive-Optics Facility (AOF) with the cutting-edge instrumentation of the MUSE integral-field (3D) spectrograph. Similar instrumental capabilities on the ELTs (e.g. HARMONI, MOSAIC) will revolutionize the extra-galactic field, as we will be able to reproduce the observation of the galaxy structure and kinematics out to distances of tens of millions of light-years. This will certainly modify our understanding of the galaxy mass assembly mechanisms and the Hubble sequence build-up. The use of multi-LGS in astronomy is however a young technology, and the extrapolation of the technique to the ELTs sizes leads to **technological barriers regarding Wave-Front Sensing and associated detectors.**

Wave-Front Sensing: toward a new paradigm

The Wave-Front Sensing device is the heart of every AO system. Its goal is to measure incoming phase perturbations and send this information to the deformable mirror that will correct for it. **Ultimately the Wave-Front Sensor performance drives the final performance of the AO correction and thus the associated astrophysical instrumentation.**

What is a Wave-Front Sensor?

A Wave-Front Sensor transforms the light information - the photons - into a phase information - the optical path difference.

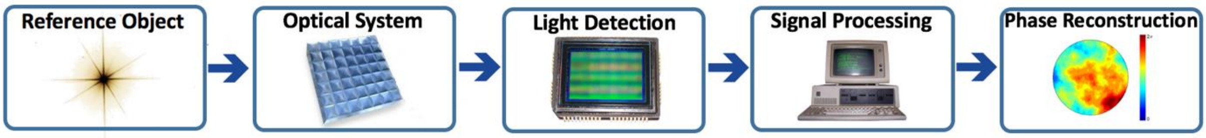

Figure 4Generic description of any wave front sensor

In this generic scheme, the reference source may be point-like - e.g. a star hosting an exoplanet - or extended and structured as for a Laser Guide Star. The role of the optical system is then to code the phase information into intensity variations. This is the keystone of the WFS concept and where most of the innovation can be developed. Once encoded, the photons are detected and the resulting signal is inverted to reconstruct the phase information. Because the atmospheric turbulence has a very fast temporal evolution, a WFS has to perform measurement every millisecond or so, leading to strong constraints in terms of light detection and signal processing. For this latter, linear approaches will be promoted in order to reduce the real time computing burden.

Until very recently, the vast majority of AO systems had used the Shack-Hartmann[15] WFS [SHWFS]. In this WFS, the optical system is a lenslet array located in a pupil plane, spatially sampling the wave-front. Each lenslet (also called subaperture) is forming an image of the source on the detector. Displacements of image centroids are proportional to the local wave-front gradient, which provides a linear transformation with respect to the incoming phase. Increasing the number of measurement points across the wave-front (i.e. increasing the number of subapertures) allows the measurement of higher spatial frequencies and proportionally reduces the wave-front estimation error. However, more subapertures means dividing the flux into more pieces and consequently the need for brighter reference stars and also more detector pixels. This impossible trade-off already illustrates the intrinsic limitations of a SHWFS.

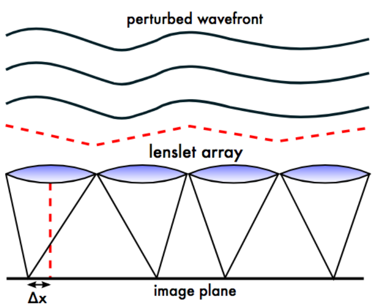

Figure 5: The Shack-Hartman WFS principle

Why is it limiting the detectability of exoplanets?

For exoplanet applications, the state of the art AO instruments – SPHERE @ ESO and GPI @ GEMINI – are both using SHWFS. Those instruments have been designed for an extreme Wave-Front control, hence a high subaperture density. They typically provide 40x40 phase measurement points across the 8meter telescope pupil, and can work with stars as faint as V < 11 mag.

It has been shown that one of the main performance limitation of these instruments comes from the fast atmospheric residuals, not properly compensated by the AO correction[16,17]. Figure 6 illustrates this case: when the atmospheric conditions are evolving faster than the AO correction rate, significantresiduals from uncorrected star light pollute the images in the region where exoplanets could be discovered. The exoplanet detectability (or contrast) is reduced by factors 2 to 10.

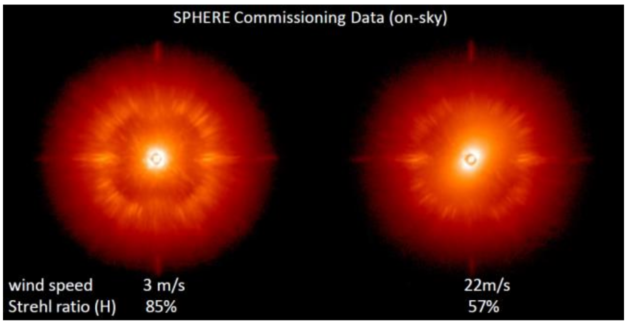

Figure 6. Impact of wind speed on SPHERE data. Temporal error is the main limitation for the system. Faster and more sensitive WFS are required to improve the performance

To tackle this issue, the AO corrections must be applied at a faster rate, typically 2 to 3 times faster than the 1 kHz which is the current standard for both SPHERE and GPI. Using the same SHWFS, this would mean reducing the limiting magnitude, and hence the number of suitable targets by at least 1 magnitude. This also means having access to a noiseless detector running at > 3kHz, which may be at the limit of what current technologies can do, but out of the scope of future ELT requirements. Indeed, scaling a SPHERE-like instrument for the ELT would require 200x200 phase measurement points across the pupil, and the need for noiseless, large format (1 million pixels) detectors.
If this error term can be eliminated (such as when observations are luckily acquired during collaborative atmospheric conditions), the resulting images are limited by the aliasing and the photon noise propagated by the WFS into the AO loop: SHWFS are known to be suboptimal regarding those errors. Here also, detectability gains on the order of 2 to 10 may be achieved with optimized WFS.

Exoplanet detectability will be improved (x10) with faster (x2-3), more sensitive (1-2mag) and specifically optimized (against noise x2 and aliasing x2) Wave-Front Sensors.

Why is it limiting the observability of distant galaxies?
To achieve significant sky-coverage, extragalactic observations assisted by AO require the use of LGS. The artificial reference source is created by shining a laser from the telescope (as shown in figure 3). Light from the beam is absorbed and reemitted by atoms in the upper atmosphere (a Sodium layer in the mesosphere) back into the WFS. However, due to the vertical extension of the Sodium layer (typically 20km), the AO guide star is now an extended object, with a complex shape, and temporally evolving with Sodium layer dynamical variations. When considering SHWFS – which is the baseline of all current LGS-based AO systems - this Sodium layer extension creates elongated spot in each sub-aperture which can be as large as 20 arcsec for an ELT.
This is illustrated by Figure 6, which shows a sample of LGS elongated spots acquired with the CANARY experiment (see Section II.b.2.b, page 17).

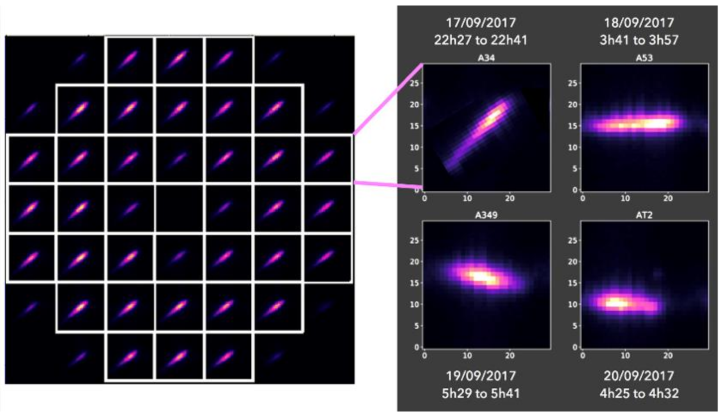

Figure 7. Example of Laser Guide Star WFS. On-sky data obtained with the CANARY experiment (see section II.b.2.b, page 17). The spot elongation (due to the sodium layer thickness) and its temporal evolution (due to the evolution of sodium density) is highlighted

Dealing with such a spot elongation using a classical SHWFS requires a tremendously large number of pixels. It calls for very sensitive (almost photon noise limited), very fast (larger than 500 Hz, most likely 1kHz) and extremely large (typically 5 million pixels) detectors. Such kind of devices are far beyond existing and first generation of WFAO systems on the ELT (currently in their preliminary design phase) which have to consider lower performance detectors (smaller, slower and noisier). The consequence is a reduced wave front sensing performance, creation of spurious effects and biases (so-called “truncations effects”) and a limited performance of the full AO system[18]. For spectroscopic studies of distant galaxies, reduced AO performance translates in sensitivity loss, or equivalently, it limits the observation of the faintest and more distant objects[19].

The sensitivity of extragalactic observations will be improved (x2-3) with dedicated WFS concepts optimized to deal with complex, extended and evolving reference soures while reducing the number of pixels required.

b. Originality of the project

Optimizing a wavefront sensor means maximizing the Signal to Noise Ratio of each phase measurements. Following the scheme presented in Figure 4, that is nothing but:

1. Finding the most efficient transformation procedure of phase into photons
2. Minimizing the number of useful pixels on which the signal is coded.
3. Developing new signal processing approaches to deal with the various noises inherent to photon detection: photons, detector read-out, background.

The first step toward these ambitious goals is to leave behind the historical SHWFS (quite limited in terms of ultimate performance and by far too demanding in terms of detector size), and explore alternative optical systems. In this direction, the most impressive example is certainly the introduction of the so-called Pyramid[20] WFS, which provided AO-corrected images with an astonishing quality at the Large Binocular[21], Subaru[22] and Magellan[23] Telescopes. From a conceptual point of view, the Pyramid WFS can be seen as a generalization of the original Foucault's knife test, replacing now the knife by a filtering mask. In terms of performance, the Pyramid WFS demonstrated gains in terms of sensitivity (1 to 2 magnitudes), aliasing and noise propagation (x2). It therefore appeared as the natural WFS for the first light instruments of the ELTs (HARMONI, MICADO, MAORY, METIS for the ELT, NFIRAOS for the TMT, GCLIF for the GMT). But the pyramid WFS is not the end of the story. It suffers from linearity and robustness issues and the original concept can be modified and optimized depending on the considered application. In particular, it can actually be seen as a particular case of a more general class of WFS: The Fourier Filtering WFS [FFWFS].

Fourier Filtering WFS [FFWFS]

Very recently, LAM and ONERA proposed a unified and rigorous analytical description[24] of this new particular class of WFS. In this general formalism, the WFS is divided in three stages, gathering: (i) the beam shaping (for instance the modulation for the Pyramid), (ii) the spatial Fourier filtering (for instance the pyramid object) and (iii) the detection, including detector and signal processing. Depending on the application, we can literally derive the analytical equations of those three stages and define an ideal WFS. This way, we could think on using pyramids with 3, 5 or N faces, cones, and combine that with arbitrary modulation and an optimized detection stage[25].

In particular, we have proposed a "flattened pyramid", where the signal processing stage is performed optically, with a coherent superposition of the pupil images[26]. This is illustrated by Figure 8: the four pupils formed by the classical pyramid (left) are drawn up until a quasi-total superposition is reached. We have shown that such a device would actually improve the sensitivity and the linearity of the performance with respect to the (already so-called) classical Pyramid. And more importantly, this device allows to condensate the information in almost 4 times less pixels than the classical pyramid, opening the path to ELT-scale applications!

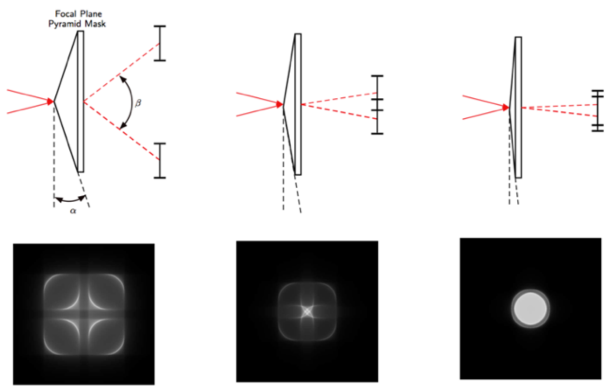

Figure 8. Principle of the classical Pyramid WFS (left) and the flatten Pyramid proposed by our group (right)

Based on our general mathematical formalism, it is now possible to better understand the existing WFS. But, above all, this new and unified approach opens the possibility of proposing new WFS and to develop them with respect to specific applications. This is precisely the main goal of the WOLF project: **propose disruptive WFS concepts, specifically optimized toward the ultimate detection limit for exoplanets, and "flexible" (or "adaptive") WFS able to deal with complex, extended and dynamic reference source structures, to boost the sensitivity of extragalactic observations.**

c. Methodology and risk management

Methodology

The end goal of the WOLF project is to deliver a set of innovative WFS, fully tested, validated, and ready to be implemented on future VLT and ELT AO instruments. To reach this ambitious goal, the work plan has been divided around three steps of growing complexity - each one representing a key milestone.

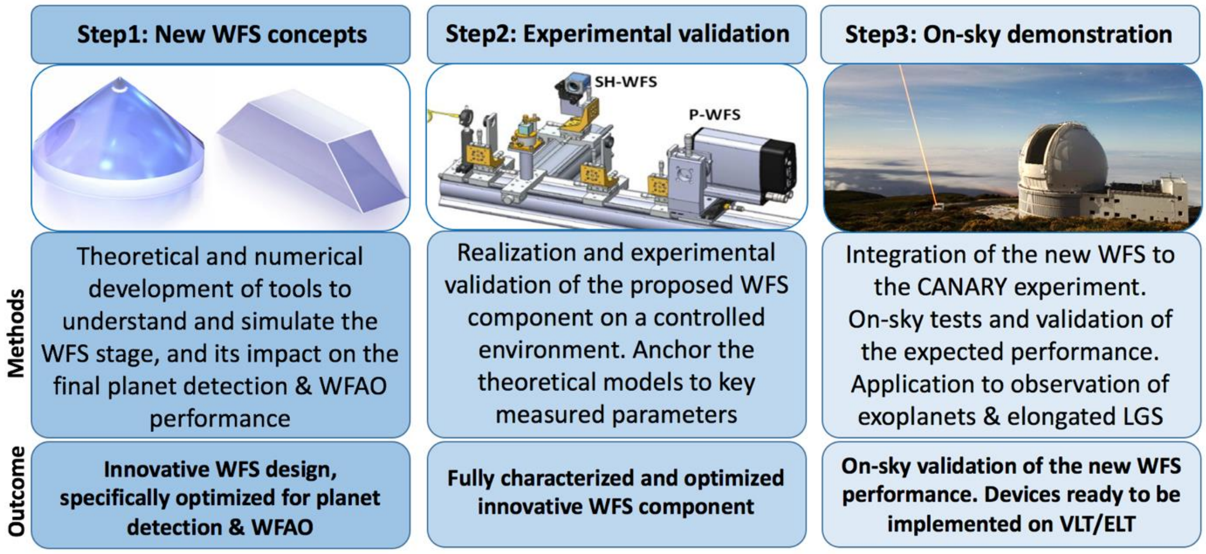

Figure9: WOLF Development plan

Step1 – New Wave-Front Sensor Concepts.
The top-level specifications are clear: improve the exoplanet detectability by a factor of 10 and boost the extragalactic sensitivity by at least a factor of 2. These specifications translate into AO performance and WFS optimization objectives and define the starting point and the main motivation of our work.

The foundation of this step is the recent mathematical formalism developed by our group. Using this powerful analytical scheme, it now becomes possible to play with the main characteristics of the WFS (opto-mechanical features and signal processing) and directly see the impact on the AO performance. It is now a matter of using this formalism to optimize the WFSs both in terms of ultimate performance (sensitivity) and robustness (linearity and dynamics). **Using rigorous inverse problem approaches, we will be able to parameterize the main characteristics of the Fourier WFS to ensure the best possible sensing performance** (from the AO point of view) considering the many technical constraints. Beyond these performance indicators, we are also aiming at accounting for the operational and observational constraints of the AO correcting loop, with issues related to real-time calculation, calibration to environmental specificities and structures within the observed object.
As a starting point, we will benefit from on-going theoretical developments already in progress within the WOLF ANR partners namely (i) The "flattened Pyramid[26]" for the ExAO applications and (ii) the "Ingot WFS[27]" proposed by R. Ragazzoni for LGS applications. These starting points are fundamental to give a coherent framework and put boundaries on the developments proposed in the ANR. Thereby,

it will be possible to reduce the timescale of the theoretical developments and ensure that a conceptual phase will last less than 2 years.

The outcome of the research to be conducted in this first step will be the design and manufacturing of (at least) two new wave front sensor concepts, specifically optimized toward exoplanet imaging and WFAO observations of distant galaxies.

Step2 – Experimental validation and demonstration of the new WFS performance
(See the description of the LAM testbed (LOOPS) in Section II.b.2.a, page 16)
The objective of this step is to provide an experimental validation of the numerical models and the devices developed during Step1. This is achieved in a controlled laboratory test, taking advantage of the WFS testbed at Laboratoire d'Astrophysique de Marseille. This bench is uniquely suited for that: it features a turbulence simulator, deformable mirror for correction, and reference WFS (Shack Hartmann and Pyramid Sensor) in order to perform comprehensive comparisons with existing well-understood devices.
The new sensors developed in Step1 will be integrated with two state-of-the-art OCAM² camera that will be provided by LAM and First Light Imaging (SME). The two sensors will be entirely developed at LAM with well-defined interfaces provided by LESIA and Durham to ensure a further on-sky implementation in CANARY is possible (see next point). This will require some modifications and adaptations of the existing bench at LAM. These modifications will be performed thanks to a combination of in-kind contributions of the WOLF partners and ANR support.
During the laboratory experiments, special attention will be given to calibration and optimization procedures related to each concept. More specifically, we will test: (i) the dynamic sensitivity for each spatial frequency, (ii) the linearity of the WFS, and the ability to "bootstrap" an Adaptive Optics loop, (iii) the data-processing of the WFS pixels, and the best calibration strategies.

The primary goal of Step2 is to **quantitatively demonstrate the superior performance of our new WFSs**. As a top-level goal, we would like to anchor our theoretical models to measurements of key parameters. **Once validated and calibrated, the theoretical framework will be used to derive the behavior of any Fourier WFS**, or in other words, we will be able to optimize the design of any Fourier-based WFS to the precise astronomical application. This will represent a major milestone in the WOLF project.

Step3 - On-sky validations on the CANARY bench at the William Herschel Telescope (WHT).
(see the description of the CANARY AO system on section II.b.2.b, page 17).
The goal of this third step is simple: to implement the prototypes designed in step1, and tested in step2 into a real AO system, and perform an on-sky validation of their performance. This on-sky demonstration benefits from the world-wide unique features of the CANARY system:

a. Sodium Laser Guide star that mimics the same spot elongation than the one of a 40m telescope
b. High density deformable mirror (60x60 actuators) provided by LESIA (as an in-kind contribution) providing access to an unprecedented level of correction (the density of actuators will be 10 times the one of SPHERE!).

The on-sky demonstration on CANARY will represent a unique and invaluable step, allowing us to demonstrate, under realistic conditions, the superior performance of the new concepts proposed.
The on-sky demonstration requires a set of hardware/software developments and investments. Modifications and adaptations of the CANARY bench will be performed thanks to a combination of in-kind contributions of the WOLF partners and the ANR support. *The inherent risks associated to such developments are high but the potential gains for the WOLF partners and more generally the whole community, are even higher.* The access to CANARY will allow us to test the WFS in the most realistic conditions possible today. We will be as close as possible to the real operation on a 40m telescope. *The lesson learnt with this experiment will be absolutely unique and priceless.*

Risk mitigation strategy

The major risks associated to the project is related to its experimental part and more specifically the on-sky validation aspects.

Several strategies have been considered to minimize these risks and allow sufficient confidence in our ability to achieve all the proposed tasks. Those are

1. **From the management point of view:** all the WOLF partners have successfully worked together in many instrumental and scientific project (FP5,6 and 7, H2020 from the European side, ESO projects for instrumental developments, previous ANRs on the French side).
2. **From the scientific point of view:** The WOLF program has been built on a team that led or participated to most of the European AO systems in the last 3 decades (from NACO to SPHERE on the VLT, AO systems on the LBT) and which is now deeply involved in the ELT instrumentation (lead of AO systems for HARMONI, MICADO, MOSAIC, MAORY). It therefore combines unique expertise in the field and benefits from operational feedback that will be key in the success of the project. WOLF is carried by renowned institutes, which have an impressive record of successful projects in the instrumentation domain.
3. **From the technical point of view:** WOLF also gathers a large team of Engineers that have participate to large astronomical project and more specifically that have built the LOOPS bench and the CANARY instrument. Their perfect knowledge of any detail of the two experimental platforms is a guarantee of success.
4. **From the telescope access point of view:** telescope access is THE major risk of the project (but also its greatest interest). Several actions have already started in order to guarantee a sufficient access to the WHT. There are listed hereafter:
   a. *Strong involvement of Durham and LESIA teams in the project*. Both institutes are the leaders of the CANARY developments for over10 years;
   b. *Access to WHT nights through the existing or future OPTICON H2020 project* (Durham, INAF, ONERA, LESIA and LAM are all partners of the program). Several potential schemes for telescope access are available including the OPTICON program (that has provided up to 30 nights of telescope time over the past 5 years). In addition to this, schemes such as the International Time Program (ITP) exist. CANARY has had several ITP awards for collaborative international work.
   c. *Specific ANR funding for 4 WHT nights* that is 28k€;
   d. *Additional night requests through the classical WHT proposals* led by Durham Univ.

   Finally if the WHT and/or the CANARY bench will not be available for WOLF activities, as risk mitigation strategy, our group also benefits from privileged access to the ONERA ODISSEE bench on the 1.5m telescope at Observatoire de la Cote d'Azur (OCA). The ODISSEE bench is operational on this telescope since 2014 and has been widely used for space imaging activities. The bench itself has been designed to include visitor WFS and to compare them with a fully characterized state-of-the-art Shack-Hartmann WFS.

As a conclusion, we can emphasize that the timing for initiating the WOLF project is ideal. It will run in parallel with the SPHERE upgrade project, the proposal of new AO-assisted instruments on the VLT (MAVIS) and the design of the most complex AO systems ever build on the ELT (MICADO and HARMONI AOs, MAORY MCAO and MOSAIC MOAO). It will naturally bring strong improvements in their design with obvious synergies and win-win interactions. It will enable the design and realization of brand-new AO-assisted instrument on 8- and 40-meter class telescopes and push the AO systems toward their ultimate frontier in terms of both performance and robustness. It will eventually serve at demonstrating that this type of gain allows to observe objects and phenomena inaccessible to date.

II. Project organisation and means implemented

a. Scientific coordinator and its consortium / its team

The project coordinator (WP1) and WP2 leader is Dr. Thierry Fusco (ONERA). He received his PhD degree (Partial correction and anisoplanatism in AO) in 2000 from Nice University and his HDR (Optique adaptative et traitement d'images pour l'astronomie) in 2008. T. Fusco is a Senior Researcher at ONERA since 2001 where he is the scientifically responsible for Adaptive Optics activities. For more than 15 years, he has successfully managed several research and industrial projects in defense, civilian and astronomical domains both in French or European contexts. From 2006 to 2015, he was the project manager of SAXO, the extreme AO system of SPHERE. He is now the AO scientist of HARMONI, the first light spectro-imager of the European ELT. He participates to several scientific committee (GIS-PHASE, Labex Focus) and SOC of international conference (SPIE, AO4ELT). He was feature editor of JOSAA (vol. 21) and Applied Optics (vol. 49) in 2010. In 2009, he won the “Fabry de Gramont” price (Optical Society of France). He is co-author of 159 articles in peer review journals (14 as first authors, 43 in the first 3 authors) and more the 349 articles in international conferences (42 as first authors and 6 as invited speakers) with a H-index of 47.

Since 2011, T. Fusco shares his time between ONERA (in charge of the AO for astronomy activities) and LAM (as invited researcher and now manager of the LAM AO activities). He is/was the supervisor of 16 phD thesis and 13 post-docs, some of them co-supervised with both B Neichel (ANR deputy coordinator and WP3 leader) and G. Rousset (WP4 leader). The very nature of his research and management activities is in perfect *ad equation* with the WOLF ANR and its scientific coordination.

The project deputy coordinator (WP1) and WP3 leader is Dr Benoit Neichel (LAM). He got his PhD in 2008, from the Paris VII University. During his PhD he worked at the Observatoire de Paris on Integral Field Spectroscopy observations of distant galaxies. In parallel, he worked at ONERA on Wide Field Adaptive Optics (WFAO) systems and derived the first application of this technique for extragalactic observations on Extremely Large Telescopes. After his PhD, he worked at the Gemini-South telescope for 4.5 years. He acted as Instrument Scientist for the GeMS instrument, which is the first WFAO system implemented on an 8m telescope and offered to the astronomical community. During that period, he managed a technical and scientific team of 10 FTE, and led 130 nights of telescope time. In 2013, he was granted a “retour post-doc” ANR program that he developed at LAM. He also took the responsibility of Co-I for HARMONI - the first light Integral Field Spectrograph for the European ELT. In 2016 he got a permanent scientist position at CNRS, and he is leading a young team of 3 PhD students, and 2 post-docs.

The WP4 leader is Dr Gérard Rousset (LESIA). He is “Professeur de Classe Exceptionnelle” at Paris Diderot University - Paris 7 (CNU Section 34). From 1985 to 2005, he was first research engineer and then research director at ONERA. He was in particular the person responsible for NAOS, the first AO system at the VLT. From 2005, he became a professor at the Paris Diderot University, at the Physics UFR and at the Denis Diderot Engineering School. He is also a researcher at LESIA (Laboratory of Space Studies and Instrumentation in Astrophysics, UMR8109, Paris Observatory). He is the coordinator of the scientific pole “High Angular Resolution in Astrophysics". He chaired the scientific council of GIS PHASE from 2006 to 2015, a research partnership between Paris Observatory, ONERA, LAM and IPAG. He is responsible of European Contracts (FP7 and H2020) for LESIA, co-PI of the multi-object AO demonstrator CANARY, and contributes to several phase A and B adaptive optics studies for the instrumentation of the Extremely Large Telescope of the European Southern Observatory (ESO), including the recent MICADO and MOSAIC instruments, as well as the production of SPHERE and GRAVITY instruments of ESO's Very Large Telescope (VLT) (2006-2015).

The WOLF consortium is composed of three main French institutes: ONERA (PI institute), LAM and LESIA. They gather most of adaptive optics experts in France and have a long history of common projects (both research and instrumental developments) and collaborations. ONERA and LESIA have been at the origin of the very first AO system for astronomy in 1989 (COME-ON project) and have strongly collaborate on NAOS (first AO system of the VLT in 2001). They have strongly collaborated for SPHERE (the first planet finder of the VLT installed in 2014) and in the preliminary design of ELT instruments (HARMONI, MICADO, MAORY, MOSAIC …). From a research point of view, ONERA and LESIA have created the GIS-PHASE (“Groupement d’Intérêt Scientifique pour la Haute resolution Angulaire Sol et Espace”) from 2006 to 2015. LAM has joined the GIS-PHASE in 2010.

The WOLF project will be jointly led by the ONERA and LAM R&D Group (GRD). Since 2011, ONERA and LAM have developed an integrated team around the problematic of AO developments in astronomy. The team's stated mission is to increase the maturity level of innovative technologies specifically in the areas of high resolution and high contrast imaging and to lead large AO projects for both VLT and ELT. Quoting the HCERES committee: "The strength of the GRD group is demonstrated by its strong presence and leadership at conferences (e.g. the SPIE large telescope conference and the AO4ELT conference), its ability to attract researches to the workshops it organizes and hosts, its ability to attract international researchers for extended stays and collaborations, and its ability to attract young researchers who contribute new research and go on to good positions elsewhere." The team has expanded dramatically over the past five years and now it gathers researchers, engineers and students (PhD and post docs) from the two institutes (roughly 15 to 20 people) and is coordinated by T Fusco for ONERA and B. Neichel for LAM.

In addition to its three main institutes, the WOLF ANR will benefit from a strong international collaboration support, especially including INAF and Durham University. In particular, we will take full advantage of the support provided by R. Ragazzoni (Pyramid Inventor and now leading the LGS WFS of MAORY), S. Esposito (who successfully implemented the first Pyramid WFS on a 8-m class telescope (LBT) and now Co-I of MAORY) and their team (E. Pinna, L. Busoni, V. Viotto), as well as T. Morris and A. Basden having unique knowledge of the CANARY experiment.

b. Means of achieving the objectives

1. Work Breakdown Structure and WP description

The goal of WOLF is to propose, test and quantify the performance of innovative WFS based on the Fourier Filtering. The project has three main development stages (as shown in Figure 9) and is structured in four (one management and 3 scientific) work-packages and associated tasks as shown in Figure 10. Their temporal evolution and their interactions and dependencies is shown in Figure 11.

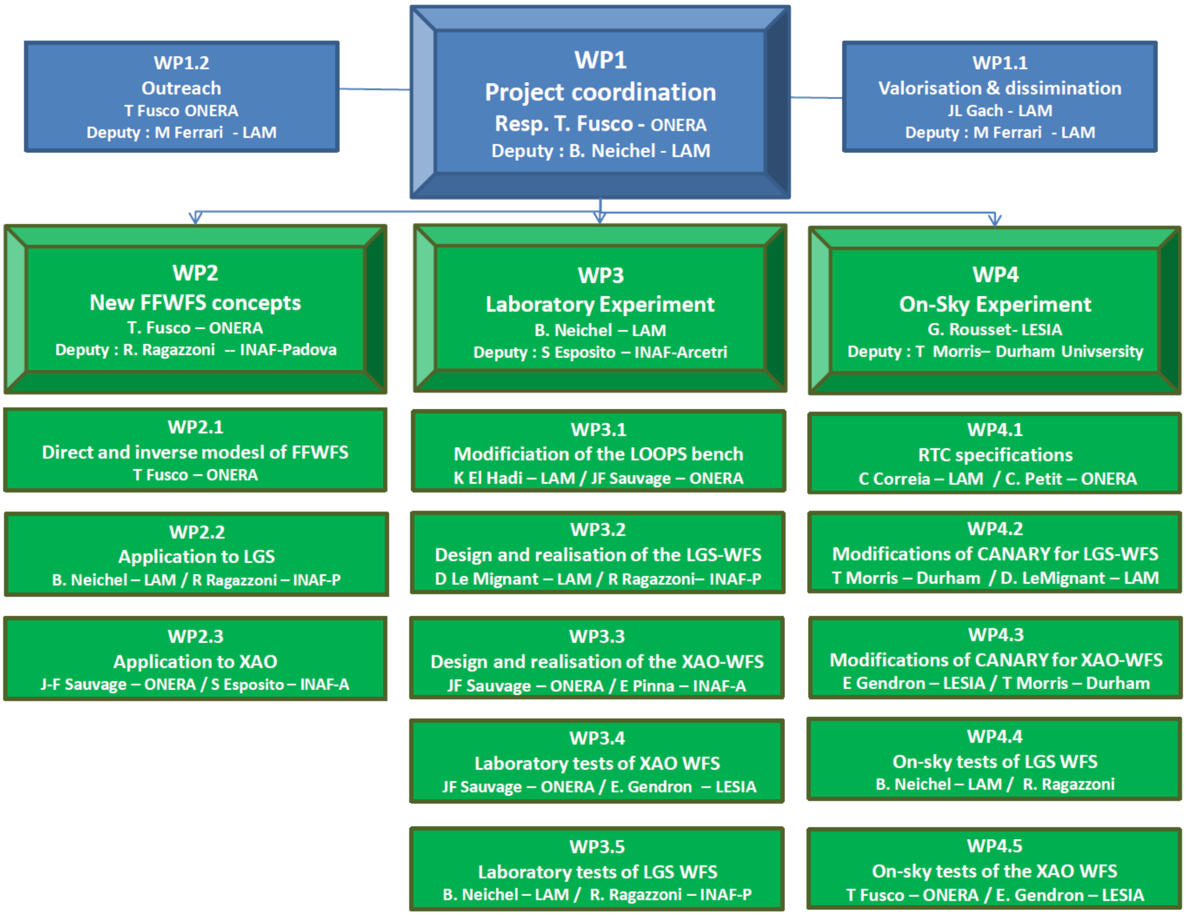

Figure 10: ANR Work Breakdown Structure

WP1: Project coordination
Management: T. Fusco (ONERA) and B. Neichel (LAM)

Description and associated tasks: WP1 will ensure the scientific and technical coherence of the project, both from an internal and external point of view. Particular attention will be paid to interactions with associated partners (INAF and Durham) and with ESO in order to ensure the relevance of WOLF developments and the instrumental needs of the European astronomical community. See Section III for an exhaustive description of the valorisation and dissemination processes.

Duration: 4 years (all project duration)

People involved: T Fusco, B Neichel, J-L Gach, M Ferrari, G Rousset, R Ragazzoni, S Esposito, T Morris. For a total of 36p.months

Outputs and deliverables: Organisation of kick-off and progress meetings, Minutes of meetings, Documentation for ANR, coordination of the WOLF scientific production, organisation of workshops, redaction of additional funding proposal (CSAA, ASHRA, Region …)

ANR Budget: 20k€ for travels (5k€ per year).

In-kind contributions: 25 k€ for workshops and outreach (ONERA, ASHRAA and CSAA funds)

WP2: Theoretical developments.
Management: T. Fusco (ONERA) and R. Ragazzoni (INAF-Padova)

Description and associated tasks: It will take advantage of the major breakthrough brought by our new analytical formalism in order to develop a WFS design-oriented tool applicable to any kind of FFWFS. The WP2 has three specific sub-tasks.

- WP2.1 is dedicated to the realization of the mathematical and numerical tool that will allow the sizing and the study of new wave-front sensors. It includes the development of adequate simulation tools to integrate the new sensors proposed in the ANR into a complete AO loop. It will be based on the OOMAO simulator that has already been extensively used at LAM for OA system studies including both VLT and ELT (note that this simulator was mainly developed by C. Correia at LAM). This tool is a reference in the AO community
- WP2.2 is dedicated to the design of an optimized WFS for the ExAO application. It will use the tools developed in the WP2.1 task to perform the study.
- WP2.3 is dedicated to the design of a optimized WFS for the Laser Guide Star application. It will use the tools developed in the WP2.1 task to perform the study

Duration: 2.5 years (from T0 to T0+2.5)

People involved: T Fusco, J-F Sauvage, JM Conan, L Mugnier, C Petit, B Neichel, C Correia, JL Beuzit, JL Gach, Y. Brulé, G Roussset, E. Gendron, ONERA PhD, R Ragazzoni, V. Viotto, S Esposito, L. Busoni, ANR PhD (2 year), for **a total of 85 p.months**

Outputs and deliverables: FFWFS concepts for each application (LGS and ExAO) – Modification of the OOMAO code – 2 papers in peer review journals and 2 international conferences – Patents may be considered (in link with WP1.1)

Risks / mitigations: issues in the problem inversion and development of the dimensioning tools / The project includes specialists in signal processing and data inversion (L Mugnier and JM Conan for instance) that will bring their expertise for the task.

ANR Budget: Travels (including conferences)= 15k€. 2 years of PhD = 75 k€ **- Total = 90k€**

In-kind contributions: 2 years PhD (from ONERA) = 75k€, 1 year post-doc (P Janin Potiron, from ONERA) = 62k€, 1 year post-doc (Y. Brulé from LAM) = 62k€ **- Total = 199k€**

WP3: experimental validation of the proposed FFWFS concepts.
Management: B. Neichel (LAM) and S. Esposito (INAF-Arcetri)

Description and associated task: A prototype of each FFWFS will be realized and tested on a dedicated experimental test bench. This bench, located in LAM premises, will be based on existing facilities (see Section II.b.2.a, page 16). It will be modified to accommodate all the specificities related to the FFWFS environment. The sensors will be tested sequentially on LOOPS in order to avoid conflict on the bench. LGS WFS will come first (at T0+1.5year) and then the ExAO (at T0+2.5year). WP3 has five specific sub-tasks.

- WP3.1 is dedicated to the LOOPS bench modification to be able to integrate and test the 2 WFS proposed in WP2. WP3.1 will use the interface document provided by WP4.1 and 4.2 to ensure that the WFS will be compatible with the on-sky experiment (CANARY)
- WP3.2 and WP3.3 are dedicated to the opto-mechanical design and the realization of the LGS and ExAO WFS. They will use as input the conceptual design provided by WP2.2 and WP2.3. They will also use the interface document produce in WP3.1 to ensure the design compliance with the various test benches (in labs and on-sky)
- WP3.4 and WP3.5 are dedicated to the implementation and tests of the WFS in the LAM Loops bench.

Duration: 2 years (from T0+1 to T0+3)

People involved: <u>B Neichel</u>, K El-Hadi, K Dohlen, P Ballard, A. Caillat, JL Gach, C Correia, J-F Sauvage, T. Fusco, ONERA PhD, <u>S Esposito</u>, E Pinna, L Busoni, V Viotto, R Ragazzoni, E Gendron, ANR PhD (1year), ANR post doc (1.5 year) for **a total of 127 p.months**

Outputs and deliverables: Interface document - modified LOOPS bench - two WFS prototypes themselves as well as their associated test reports - 2 papers in peer review journals and 2 international conferences proceedings describing the lab results. A first workshop will be organized at that point of the project.

Risks / mitigations: technical issues with the LOOPS bench (modification and implementation of the WFS prototype) / strong interactions are planed between WP2 and 3. Interface document will be issued as soon as possible (T0+1.5y) in order to ensure the compatibility (opto-mechanics, electronics, software) between the prototype and the bench**.**

ANR Budget: travels (including participation to conferences) = 15k€. Opto-mechanics (prototype development) = 30k€, subcontracting (electronic and software development for coupling with loop bench) = 20 k€, 1year of PhD = 37.5 k€, 1.5 year of post doc = 96 k€ **- Total = 198.5k€**

In-kind contributions: 230k€ for two OCAM² cameras (from LAM), 15 k€ for LCD (from LAM), 1 year of PhD (from ONERA) = 37.5k€ **- Total = 282.5k€**

WP4: experimental validation of the proposed FFWFS concepts.
Management: G. Rousset (LESIA) and T. Morris (Durham University)

Description and associated task: After having been successfully validated and tested in labs, the WFS prototypes will be implemented on the CANARY bench (see section 1.b, page 17). Two configurations will be tested: First the Laser guide star configuration, and 1 year later the ExAO sensor.

- WP4.1 is dedicated to the specification and implementation of the Canary Real Time Computer (RTC) in order to be able to deal with the real time signal coming from the two WFS prototype as well as dealing with all the AO loop calibration and optimisation procedures.
- WP4.2 and 4.3 are dedicated to CANARY opto-mechanical modifications in order to implement the WFS prototypes. These two tasks will be done in close relationships with WP3.2 and 3.3
- Finally, WP4.4 and 4.5 are dedicated to the on-sky tests of the two WFS prototypes.

Duration: 2.5 years (from T0+1.5 to T0+4)

People involved: G Rousset, E Gendron, F Vidal, V Lapeyrère, A Sevin, R Dembet, D Perret, F Chapron, T Morris, A Basden, R Ragazzoni, S Esposito, LESIA PhD (1 year), ANR post doc (1.5 year) for a **total of 100p.months**

Outputs and deliverables: the modified Canary bench - the on-sky test reports - 2 papers in peer review journals and 2 international conferences proceedings describing the lab results. A workshop will be organized at the end of the ANR in order to present the results and advertise them to the community.

Risks & mitigations: The on-sky validation represent the main risk of the project. Risks and their mitigations are described in Section 1.c (pages 9 and 10)

ANR Budget: Travels (including conference and observation runs) = 30k€. Subcontracting (Telescope night) = 28 k€, 1.5 year of post doc = 96 k€ - **Total = 154k€**

In-kind contributions: Modifications of the CANARY bench; High density Deformable mirror for ExAO tests : 500 k€ (provided by LESIA). This deformable mirror has been jointly funded by Région Ile de France and CNRS-INSU. This deformable mirror will be primarily used in the frame of the MICADO project. The WOLF schedule may have to be adjusted to ensure the system compatibility with CANARY – **Total = 500k€**

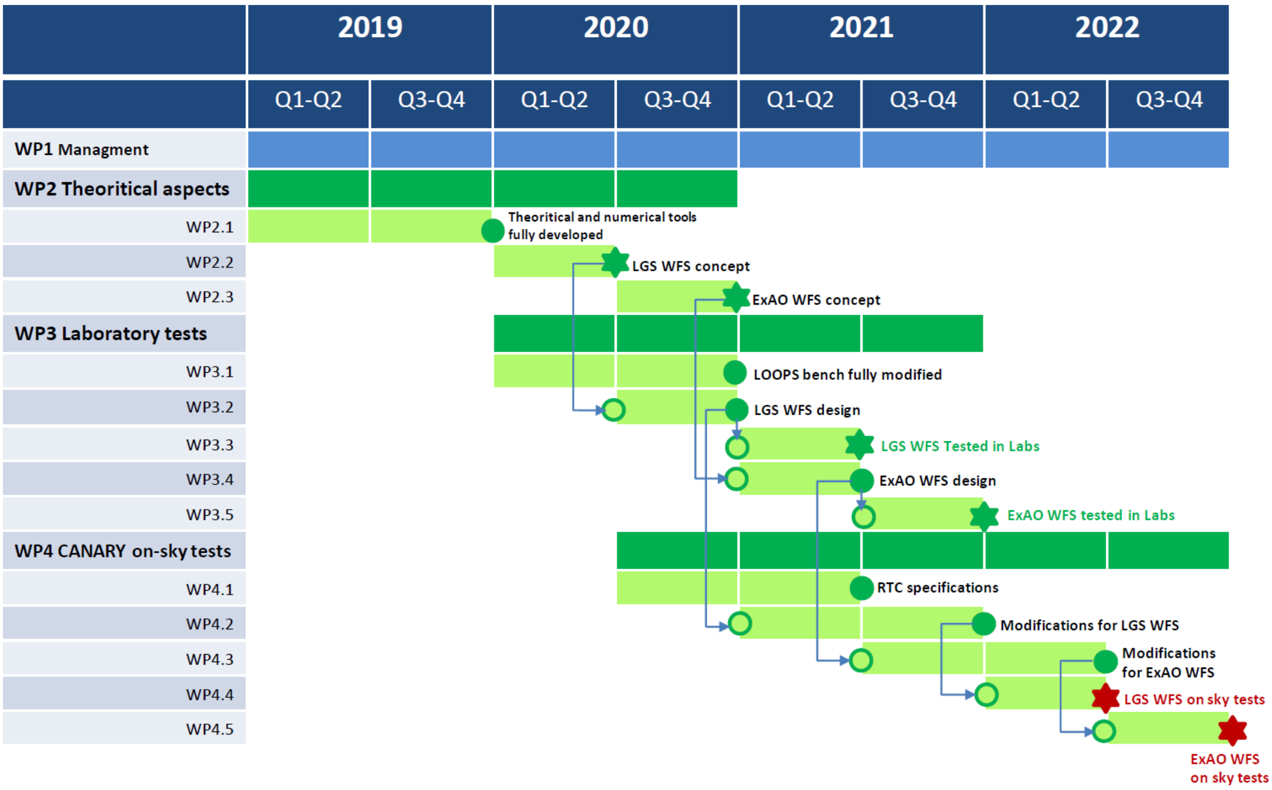

Figure 11 GAANT chart of the WOLF project. The green and red stars represent the final test reports and papers on the WFS prototypes after their tests in labs and on-sky.

The main deliverables of the projects are:
1. The dimensioning (theory, simulations) tools and the OOMAO development related to the new WFS
2. The LOOPS bench and CANARY modifications required to implement the WFS
3. The WFS prototype for LGS: concept, device, tests in labs and tests on sky
4. The WFS prototype for ExAO: concept, device, tests in labs and tests on sky
5. Papers, conferences, patents (if relevant) related to the project

2. The experimental resources

WOLF is by nature an experimental project. A large part of its plus-value will be related to the laboratory and on-sky tests of the proposed WFS concepts. Hence, WOLF strongly rely on the development and the availability of experimental resources:

- The LAM AO bench "LOOPS" that is dedicated to the lab tests of new WFS concepts in a complete and well-mastered AO environment.
- The CANARY on-sky experiment on the WHT. This unique on-sky facility gathers all the required features (LGS, high density DM) to test the WOLF WFS concepts in realistic operational conditions on large (4m) telescope at the state of the art from the AO point of view.

a. The LAM AO bench (LOOPS) – labs experiment

Since 2013, LAM Research and Development group (with the support of ONERA in the frame of the LAM-ONERA integrated team) has developed the experimental bench LOOPS for testing Adaptive Optics components, for validating concepts, and for demonstrating system performance based on Pyramid wave-front sensing. LOOPS is a complete AO bench in the visible (630nm) including a turbulence module, a 10x10 deformable mirror, pyramid WFS (including its modulator) based on a OCAM² Camera and an Open Source RTC based on the OOMAO code.

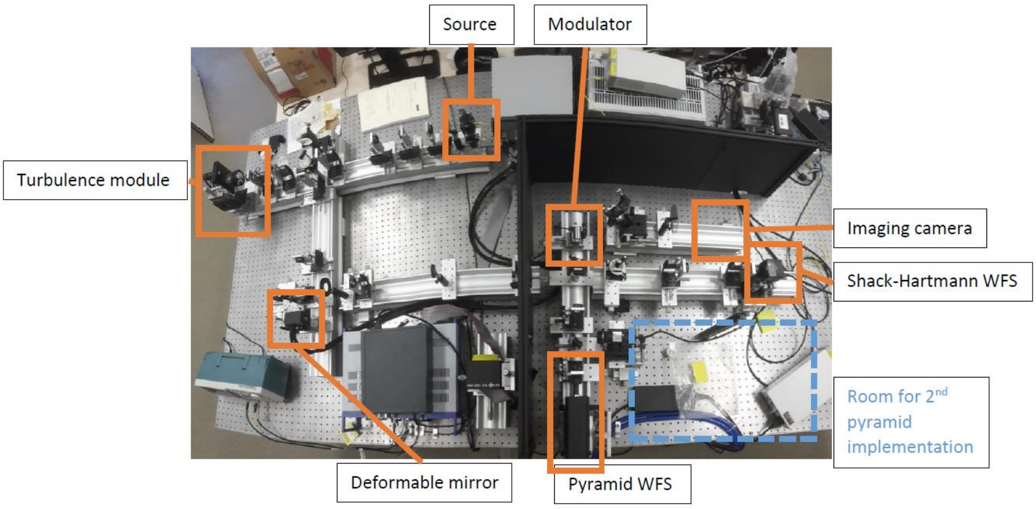

Figure 12 LOOPS bench picture. The AO system takes almost the totality of a 2m bench with Pyramid and Shack-Hartmann working in parallel with an imaging camera.

A high order liquid crystal mirror is also available at will for emulating high density deformable mirror or for creating any focal plane filtering feature. The bench includes an imaging arm with a visible camera and second WFS arm based on an industrial Shack-Hartmann is usable in parallel to the pyramid to measure the residual aberrations. This industrial Shack-Hartmann is also easily movable in different positions of the bench to monitor the aberrations before / after the turbulence module and before / after the deformable mirror. The bench is highly modular from the opto-mechanical point of view, with large space available for implementing new devices in parallel of the existing ones. Finally, it is important to mention that the control of the AO component (OCAM and DM) by an open-source matlab OOMAO code. This allows to easily test different control laws, strategies for pixel recombination and selection, and process the result.

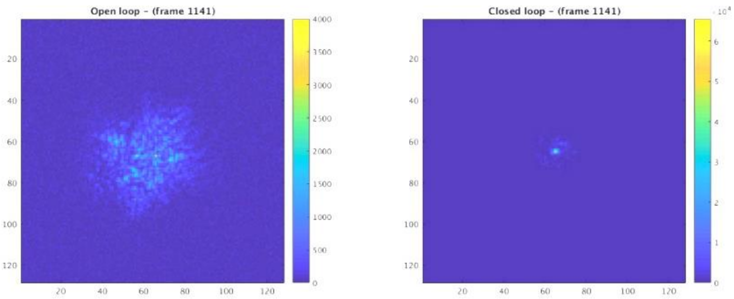

Figure 13 Example of LOOPS results – AO off and AO on

Recent results

After a period of bench development and first understanding of Pyramid behavior, the LOOPS bench is now fully mastered and optimized. Figure 13 shows a typical example of closed loop performance of the LOOPS bench[28].

The LOOPS bench is a perfect tool to implement and test new WFS concepts in the frame of the WOLF ANR. It has both the functionalities, the flexibility and the performance required for all the laboratory tests foreseen during the WOLF project.

b. The WHT AO bench (CANARY) – on-sky experiment

CANARY is an adaptive optics (AO) on-sky demonstrator, intended for developing and testing AO concepts for the future 39m European Extremely Large Telescope[29,30]. It is operated on a Nasmyth platform of the 4.2m William Herschel Telescope, one of the Isaac Newton Group of Telescopes (ING) of the Observatorio del Roque de los Muchachos (ORM), La Palma, Canary Islands, Spain.

CANARY is currently configured for the study of Tomographic AO using Natural Guide Stars (NGS). Single Conjugate AO (SCAO) and Ground Layer AO (GLAO) are also available. There are 3 off-axis NGS 7x7 SH WFS, 1 on-axis 7x7 or14x14 truth SH WFS, a closed-loop 52-actuator Deformable Mirror (DM), a closed loop Tip Tilt Mirror (TTM), an open loop 241-actuator DM, a near IR science camera, a flexible real-time computer, two DM figure sensors, calibrations systems, and a full suite of calibration, operation and analysis software. In 2010, CANARY provided the first on-sky demonstration of open-loop tomographic AO correction, demonstrating a key operating technology required for AO instrumentation planned for the ELT.

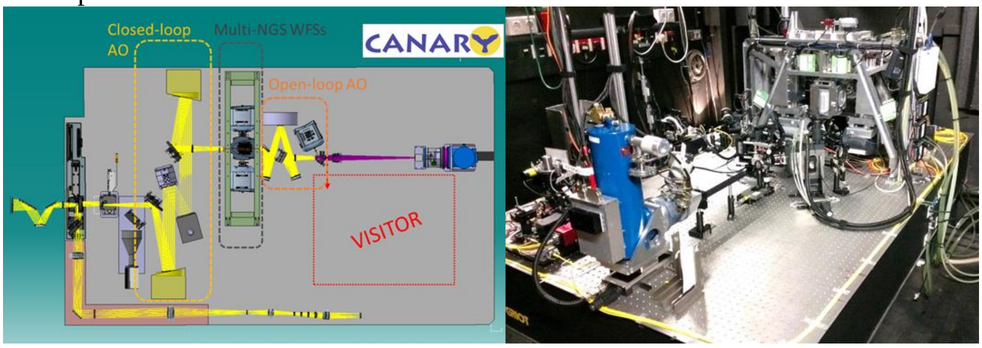

Figure 14 Left: CANARY schematic layout showing principal AO functional modules and visitor space envelope available for WOLF experiment. Right: CANARY installed in the Nasmyth platform of the WHT

ESO has installed the Wendelstein Laser Guide Star Unit (WLGSU) on site adding a 20W sodium-tuned laser (upgrading to pulsed operation in 2019) for LGS AO experiments with ELT scale spot elongation and investigations of other novel LGS AO configurations. This combination provides a unique facility for sodium LGS AO experiments for both present and future LGS AO R&D. Also installed are two LGS receiver telescopes used for LGS photometry and monitoring. The Canary LGS WFS is capable of imaging up to 20" elongated LGS spots from a 7x7 SH WFS, emulating the worst-case elongation expected at the ELT. A high-vertical resolution sodium profiler or turbulence profiling Stereo-SCIDAR can also be made available on the nearby 2.4m INT. Both the WLGSU and INT instruments can be operated independently of the CANARY system on the WHT.

Canary is both an open and high performance on-sky platform that combines state-of-the-art components in the field of AO. For several years, CANARY has been used to successfully validate innovative concepts in OA. CANARY can be used in a Laser guide star or natural star mode. ***It is the ideal platform to test, characterize and validate the WOLF WFS prototypes***

3. Requested means by item of expenditure and by partners

		Partner *ONERA*	Partner *LAM*	Partner *LESIA*
Staff expenses		112 500	95 580	95 580
Instruments and material costs (including the scientific consumables)			30 000	
Building and ground costs				
Outsourcing / subcontracting		28 000	20 000	
General and administrative costs & other operating expenses	Travel costs	30 000	25 000	25 000
	Administrative management & structure costs**	13 640	13 646.4	9 646.4
Sub-total		**184 140**	**184 226.4**	**130 226.4**
Requested		**498 592.8**		

4. Partner In-kind contributions

The three main partners and the three associated partners of the WOLF project will all bring significant in-kind contribution to the project. It will go from expertise and manpower for the associated partners to specific hardware for the main partners.

a. Permanent and non-permanent staff

- Permanent staff from the main partners***:*** ONERA, LAM and LESIA bring a total of **<u>175p.months for the whole project</u>** (combination of researchers and engineers).
- Expertise from associated partners (permanent staff): The University of Durham bring its unique knowledge and access to the CANARY experiment. The two INAF groups bring their invaluable expertise on the Pyramid WFS. It represents **<u>31p.months</u>** to the project
- Non-permanent staff from the main partners: ONERA and LESIA bring **<u>46p.months of PhD</u>** and ONERA and LAM bring **<u>24p.months of post doc</u>** to the project

⇨ **<u>Note that ANR non-permanent staff represents ONLY 20% of the whole WOLF staff</u>**

b. Hardware

- LAM ensures the access to the LOOPS bench
- For the WFS prototypes: LAM brings 2 state-of-the art OCAM² Camera estimated to 250k€, two LCD device (15 k€) and opto-mechanical material (10k€)
- LESIA develops the required modification on CANARY to implement the WFS prototypes. In particular, LESIA provides access to a high density deformable mirror for the ExAO tests on CANARY (the DM is estimated to 500k€).
- Durham develops the required modifications of the CANARY bench for the implementation of the LGS WFS prototype.

III. Impact and benefits of the project

Dissemination and valorization strategy

The WOLF project includes the formation of PhD students and collaboration with post-docs. These students will be at the center of a rich scientific context, at the interface between instrumentation and astronomical results, sharing work and results with an international team. We expect that these young researchers will be an excellent way to disseminate the results of their research in the international community and reinforce the collaboration between the institutions involved in this project. In addition, over the 4 years duration of the project, the coordinators and their team will organize dedicated workshops, which will be a perfect means to disseminate the project results. We have been leaders in organizing the "WFS workshops" in the past two years (see goo.gl/UBcmd9 and goo.gl/BdxEdK), and we will use this channel to advertise our work toward a targeted community. A specific budget, partially raised outside of this fund, will be allocated to the organization of these workshops. WP1 will also make sure that scientific publications are produced in the frame of the WOLF project. The research to be conducted under the WOLF project, in the domain of astronomy, optics and instrumentation, is of international importance and the publication of results in peer-reviewed journals and international conferences will be a priority. A particular effort will be devoted to support the PhD and post-doc in this task. As a goal, we are aiming at one journal publication per year for the post-docs, and 2 journal publications over the course of the PhD.

Scientific publications are not the only desirable way to disseminate results and special emphasis will be placed on sharing results with a wider audience. For this outreach aspect (WP1.2) we will rely on both academia and industry, through

- ONERA communication office and channels (ONERA newsletters, web site, podcasts …)
- CNRS or University communication offices (CNRS letters, Press releases, etc..)
- OPTITEC cluster task force (Newsletters, Special bulletins, Mass-Media, Special events for general audience, etc...).
- LAM and ONERA also rely on the OPTITEC network and its links with regional SMEs (FLI, Shaktiware, SILIOS, Winlight …) and large national groups (Thales, Cilas) to carry out this activity.

Scientific impact

The scientific impact of the WOLF project will first and foremost materialize in astronomy instrumentation projects for giant ground-based telescopes. In the case of existing 8-10m class telescopes, the potential applications of the ExAO prototype to the SPHERE instrument upgrade on the VLT and the new generation of high-contrast instrumentation on the LBT will be essential. Still on the VLT the arrival on 2025 horizon of 3rd generation instruments based on the concept of laser-assisted multiple-cone OA for imaging and spectroscopy in the visible (the MAVIS project) is a natural outlet for the LGS WFS prototype. In addition, the participation of some members of the WOLF project (notably T Fusco and S Esposito) to the various Keck upgrade projects but also the strong links with the 24m GMT and 30m telescope projects (TMT) could pave the way for potential North American instrumentation projects.

In the case of the ELT, feasibility studies and now design and construction phases of AO assisted instruments for first light have highlighted critical limitations especially concerning the Wave Front Sensors themselves. Although these limitations do not jeopardize the first light instrument concepts and realisation processes (due to their “moderate” requirements in terms of AO performance), they will certainly be a killer for 2nd generation of instruments that would aim to revolutionize astronomy at the horizon 2030-40. The WOLF project could be a cornerstone that will allow the ultimate performance of these instruments and open the ELT observations to **100% sky accessibility** at its finest resolution (smaller than 10 milli-arcsec) and **an ultimate contrast** toward a super-earth direct detection and characterization.

Finally, Astronomy has always been the frontrunner of AO development. As it has been seen in the past, we envision that some (not to say most) of the developments proposed by the WOLF project will be applied to other domains such as the free space optics telecommunications, space awareness (space debris observation and management) or biomedical imaging and laser surgery. A special effort to communicate our results toward these communities will also be engaged.

IV. References related to the project

[1] H.W. Babcock, « The Possibility of Compensating Astronomical Seeing », PASP, 1953, Vol. 65, 386,
[2] Ghez A. et al., « Measuring Distance and Properties of the Milky Way's Central Supermassive Black Hole with Stellar Orbits » 2008. ApJ, 689, 1044
[3] R. Genzel et al., « Near-infrared flares from accreting gas around the supermassive black hole at the Galactic Centre », Nature, 2003, Volume 425, Issue 6961, pp. 934-937
[4] N. Ligier et al., «VLT/SINFONI observations of Europa : New insights into the surface composition », AJ, 2016, 151, 163
[5] K. de Kleer et al., « Time variability of Io's volcanic activity from near-IR adaptive optics observations on 100 nights in 2013–2015 », Icarus, 2016, 280, 405-414
[6] N. Forster Schreiber et al., « The SINS/zC-SINF survey of z~2 galaxy kinematics: SINFONI adaptive optics-assisted data and kiloparsec-scale emission line properties », AJ Supplement Series, 2018
[7] R. Genzel et al., « From Rings to Bulges: Evidence for Rapid Secular Galaxy Evolution at z ~ 2 from Integral Field Spectroscopy in the SINS Survey », AJ, 2008, 687, 1
[8] S. Wright et al., «Dynamics of Galactic Disks and Mergers at z~1.6: Spatially Resolved Spectroscopy with Keck Laser Guide Star Adaptive Optics», AJ, 2009, 699, 1
[9] G. Chauvin et al., « Discovery of a warm, dusty giant planet around HIP 65426 », A&A, 2017, 605, L9 or see also https://www.eso.org/public/announcements/ann17041/
[10] B. Macintosh et al. « Discovery and spectroscopy of the young Jovian planet 51 Eri b with the Gemini Planet Imager », 2015, Science 350 (6256): 64-67
[11] « Ten Years of VLT Adaptive Optics » https://www.eso.org/public/announcements/ann11078/
[12] https://www.eso.org/sci/facilities/eelt/
[13] https://www.tmt.org/
[14] https://www.gmto.org/
[15] Shack, R. B. and Platt, B. C., « Production and use of a lenticular Hartmann Screen » JOSA, 1971, 61
[16] T. Fusco et al., "SAXO, the SPHERE extreme AO system: on-sky final performance and future improvements", SPIE, 2016, Volume 9909, id. 99090U
[17] V. Bailey et al., "Status and performance of the Gemini Planet Imager adaptive optics system", SPIE, 2016, volume 9909, id. 99090V
[18] B. Neichel et al., « The adaptive optics modes for HARMONI: from Classical to Laser Assisted Tomographic AO », SPIE, 2016, Volume 9909, id. 990909
[19] B. Neichel et al. "ELTs adaptive optics for multi-objects 3D spectroscopy: key parameters and design rules", SPIE, 2006, Volume 6272, id. 62721X
[20] R. Ragazzoni, "Pupil plane wavefront sensing with an oscillating prism", J. of Modern Optics, 1996, vol 43, issue 2
[21] Esposito et al., « Large Binocular Telescope Adaptive Optics System: new achievements and perspectives in adaptive optics», SPIE 8149, 2010, 814902
[22] Jovanovic, Guyon et al., « Development and recent results from the Subaru coronagraphic extreme adaptive optics system », SPIE 2014, 91471Q
[23] Males, J.R., et al. "Magellan Adaptive Optics First-light Observations of the Exoplanet β Pic b" ApJ, 786, 32M (2014).
[24] O. Fauvarque, B. Neichel, T. Fusco, J-F Sauvage « General formalism for Fourier-based wave front sensing", Optica, 2016, Vol 3., Issue 12, pp. 1440-1452
[25] O. Fauvarque, B. Neichel, T. Fusco, J-F Sauvage, O Girault "General formalism for Fourier-based wave front sensing: application to the pyramid wave front sensors", JATIS, 3(1), 2017
[26] O. Fauvarque, B. Neichel, T. Fusco, J-F Sauvage, "Variation around a pyramid theme: optical recombination and optimal use of photons"; Opt. Let., 2015, vol. 40, Issue 15, pp. 3528-3531
[27] http://web.oapd.inaf.it/adoni/wfs2017/pdf_wfs2017/ragazzoni_wfs2017.pdf
[28] C Bond et al, "Experimental study of an optimised Pyramid wave-front sensor for Extremely Large Telescopes", Adaptive Optics Systems V, SPIE, 2016, Volume 9909
[29] E Gendron et al. "MOAO first on-sky demonstration with CANARY", A&A, vol 529, L2, 2011
[30] T Morris et al, "CANARY Phase B: the LGS upgrade to the CANARY tomographic MOAO pathfinder", AO4ELT2, Victoria, 2013