MASSIF

MAssive Stars Study in InterFerometry

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April 26, 2021

Abstract: Being affected throughout their lifetime by a strong mass-loss due to radiative winds, fast rotation, and a high binarity rate, massive stars pose several challenges to the understanding of their observational properties and evolution. The aim of our project is to improve our knowledge of these objects by coupling state-of-the-art two-dimensional simulations of stellar interiors including rotation, pulsations, and mass-loss, with radiative transfer models of their atmospheres and environment, in order to compare the resultant predictions with observations at the highest spectral and angular resolutions. This unique combination of fundamental modelling, radiative transfer, and confrontation with observations will enable us to improve the models of massive stars, as well as our understanding of the underlying physics. Finally, we will deliver to the community, improved grids of models of typical massive stellar interiors, atmospheres, and extended environments, as well as constraints on the stellar and circumstellar parameters of the closest O, B, and A stars. Our project relies on the unique expertise in the development and exploitation of spectro-interferometric instruments in Nice, in particular MATISSE, the new mid-infrared instrument of the Very Large Telescope Interferometer (VLTI) array at ESO-Paranal, and SPICA, the upcoming visible beam-combiner for the Center for High Angular Resolution Astronomy (CHARA) array at Mount Wilson Observatory, as well as the successes of the ESTER code, developed in Toulouse, which models rapidly rotating early-type stars in 2D, and the TOP pulsation code, developed in Paris-Meudon, for carrying out seismic inferences.

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1 General description of the project

1.1 Context

Massive stars are key components of the Universe and understanding these extreme objects is crucial for all astronomical domains, including stellar physics, galactic evolution, and the early Universe which they re-ionised. Through strong winds and supernovae, they inject kinetic and radiative energy, dust, and metals in the interstellar medium. Their collapse is at the origin of neutron stars and, most probably, of black holes such as those observed with the gravitational wave detectors LIGO and VIRGO.

Massive stars are therefore fascinating objects, which call for a clear understanding of their birth, evolution, and death. But such an understanding requires a good description of their interior, their observable atmosphere and their often-complex environment. Hence, they have been the target of many observational programmes like the VLT-FLAMES spectroscopic Tarantula Massive Binary Monitoring (Almeida et al. 2017). Nevertheless, among all available observing techniques, interferometry is the only one providing the milli-arcsecond (mas) angular resolution needed to resolve stellar surfaces and close-by environments, allowing us for instance to directly probe departure from spherical symmetry induced by fast-rotation (Meilland et al. 2007, 2012 , Domiciano de Souza et al. 2007, Millour et al. 2011, Stee et al. 2013, Mourard et al. 2015, Dalla Vedova et al. 2017) or binarity (Millour et al. 2009, Meilland et al. 2011, Chesneau et al. 2014, Lamberts et al. 2017, Soulain et al. 2018). A comprehensive review on interferometry of massive stars is given in Meilland & Stee (2015).

Many problems have arisen while trying to understand massive stars. For instance, classical Be stars, i.e., main-sequence B-type stars with emission lines produced in a circumstellar disk, are the fastest-rotating group of non-degenerate stars. However, even if their quasi-critical rotation is known to be a key in the formation of their decretion disks, their true angular velocity is still highly debated (e.g. Townsend et al. 2004). Indeed, the centrifugal flattening and gravity darkening due to fast rotation and the presence of the circumstellar disk make it difficult to derive accurate v sin(i) values without a thorough modelling of these stars and their disks.

For more luminous stars, fast rotation breaks the symmetry of the radiative wind, and depending on the luminosity, metallicity, and rotation rate, can favour the formation of bi-polar outflows or bi-stable winds, i.e. a fast and diluted polar wind and a slower and denser region at the equator. Such a scenario, originally proposed by Lamers & Pauldrach (1991) to explain the B[e] phenomenon of some supergiant B stars, was confirmed using interferometry (e.g. Millour et al. 2011; Domiciano de Souza et al. 2007). The detailed roles of rotation and binarity in the formation of these extreme circumstellar environments (CSE) are not well-known, yet, in addition to fast rotation, binarity seems to be ubiquitous in massive star systems (Sana et al. 2012). Even when dealing with “regular” blue supergiant stars such as Rigel and Deneb, the mass-loss rate is still poorly constrained, and spectro-interferometric measurements have shown departure from spherical symmetry that can bias its determination (Chesneau et al. 2010).

Besides all these issues found in the present populations of massive stars, some theoretical issues related to the early Universe also raise exciting questions. Indeed, the properties of the first stars are fascinating: the population III stars are supposed to harbour extremely massive stars up to $1000\ \mathrm{M}_\odot$ where pair instability supernovae (PISN) or hypernovae could be quite common. Recent detections of supernovae in the remote young Universe (Cooke et al. 2012) show that we are progressively heading to a direct observation of the first stars, especially in the forthcoming E-ELT and JWST era. For these stars, and not just for the most massive ones, rotation is a key parameter. As the lack of metals reduces the gas’s opacity and diminishes mass and angular momentum losses, this leads to a high probability of fast rotation among the first stars. Moreover, low metallicity environments seem to be the prime location to form binary black hole progenitors, again as mass loss is more limited. However, mass loss in such environments is poorly constrained, partly due to the difficulty to observe such systems in the nearby universe. State-of-the-art models of rotating massive stars are therefore crucial to infer the properties of these objects.

1.2 Objectives

A complete modelling of massive stars is a formidable project which would take much more than four years... but, fortunately there are some key questions on which we may progress regarding the data accumulated until now, those that may be collected in a near future, and the theoretical tools that are now available. These questions may be summarised by two words: **mass-loss** and **rotation**. These two physical processes that occur simultaneously in most of the massive stars make their multi-dimensional modelling unavoidable. The difficulty of modelling is increased by the rise of large-scale flows inside the star, namely differential rotation and meridional circulation, driven by these two phenomena. To be complete, massive stars are often part of multiple systems, which may make the situation even more complex, by either tidal, wind or irradiation interactions.

As far as this project is concerned, we will attempt to characterise and decipher the main effects of rotation and mass-loss on the characteristics of massive stars, and conversely propose new ways to measure the fundamental parameters of these stars, including rotation and mass-loss themselves.

To make progress, we choose to be guided by multi-technique data since in multi-dimensional problems the number of parameters grows very quickly with the details to be reproduced. In this very problem, turbulent transport is the main source of uncertainty as so nicely illustrated by Meynet et al. (2013) on the evolutionary path of a massive 15 solar mass ($\mathrm{M}_\odot$) model.

In view of the complexity of the problem, we shall refrain from being exhaustive, and propose to concentrate on stars with masses in between ~ 4 and $\sim 20\ \mathrm{M}_\odot$, namely the low-mass end of massive stars. Stars are usually considered as massive above 7 $\mathrm{M}_\odot$, thus we include in our study the high-mass end of intermediate-mass stars so as to have stars with high rotation rates, strong luminosities but still weak winds, for reference. In such a way, we leave aside monstrous stars, for which we feel that our tools are not adapted yet, and the data too scarce to be efficient guides.

In the targeted mass range, data are relatively abundant, and our models sufficiently reliable. On the main sequence, these stars are typically late O-stars and B-stars. They include the classical Be stars, other fast rotators, pulsators like β Cephei stars, and quieter B stars. We also include in our study more evolved objects, such as hot supergiant and B[e] stars, as the models we are developing could help constrain their mass-loss and the effects of rotation on it.

2 Project organisation

The MASSIF ANR project is dedicated to the study of massive stars using synergies between experts in the fields of numerical simulations of stellar interiors, asteroseismology, high-angular resolution observations and data analysis.

This multi-technique approach and the collaboration between our groups in Nice, Toulouse and Paris began five years ago with the ESRR ANR project (2016-2020). Using our expertise in our respective fields of research, we demonstrated the power of combining state-of-the-art interferometric observations with asteroseismology and 2D stellar interior modelling in our work on the intermediate-mass star Altair published in Bouchaud et al. (2020).

Building on this success, we now propose to apply the same methodology on a large sample of more massive stars. To reach this goal, we need to improve our modelling of stellar interiors including rotation, pulsations and the launching of a radiative wind. These tasks will be performed in the first two work-packages of this ANR project (WP1 & WP2). The third work-package (WP3) deals with modelling large amounts of interferometric data, with a focus on improving grids of radiative transfer models of CSE of massive star disks and winds, and on polychromatic model-fitting and image reconstruction techniques. The last work-package (WP4) focuses on surveys of massive stars observed at the highest possible resolution, which includes data already acquired from the first generation of instruments at the VLTI and CHARA and new visible and infrared observations of 200 stars. Fig 1 summarises the organisation of our ANR MASSIF and the WPs are detailed in the following sections.

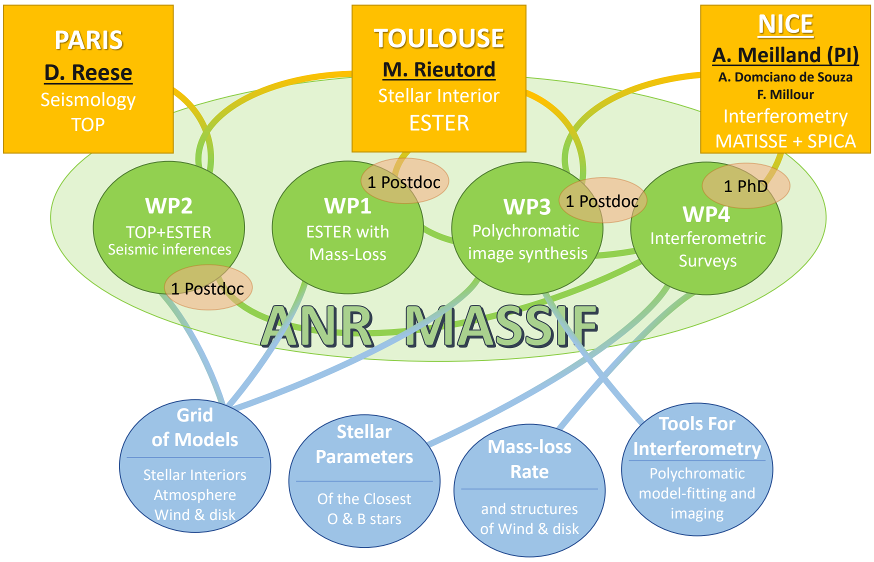

Figure 1: Organisational diagram of the MASSIF project. In yellow the institutes involved and their expertise, in green the work-packages described in this document, and in blue the deliverable.

2.1 Our team

The team is led by A. Meilland, a renowned specialist of long-baseline interferometry and modelling of the environments of massive stars. After initial studies in astrophysics at the Nice University, he passed his PhD on radiative transfer and spectro-interferometric analysis of classical Be star decretion disks in 2007. A. Meilland is one of the main contributors to the long list of publications made with the first-generation instrument AMBER, especially on massive stars (including Be stars, supergiant B[e] stars, blue supergiants, and yellow hypergiants) and he also contributed significantly to other scientific breakthroughs in the fields of young stellar objects, active galactic nuclei, and novae. With this impressive luggage, A. Meilland made a major contribution to the 2$^{\mathrm{nd}}$ generation instrumental developments at CHARA and VLTI. He contributed to the development and test of CHARA/FRIEND (Martinod et al. 2018), a prototype to test new technologies (detector, spatial filtering) now being implemented in CHARA/SPICA. He was the main developers of MATISSE Near-Real-Time software, and worked for ESO during the MATISSE commissioning to implement observing procedures. A. Meilland supervised, with A. Domiciano de Souza, the PhD thesis of E. Saldanha (defended in 2020) on the multi-band multi-technique modelling of disks and winds around massive stars. He coordinates teaching efforts at the JMMC, the French centre for infrared and optical interferometry, and he is organising the 10th VLTI school this year, aimed at teaching interferometry to PhD students and postdocs from all over the world.

M. Rieutord is the creator of the 2D ESTER code (Rieutord et al. 2016), with a large experience in fluid mechanics and the physics of stellar interiors and photospheres of rotating stars. He was the PI of the ANR project ESRR (2016-2020), where ESTER has been further developed, and used to interpret interferometric observations of Altair (Bouchaud et al. 2020, see Fig. 2). The code can now compute self-consistently the structure and the large-scale flows of early-type stars at any rotation rate below critical. The results of Gagnier et al. (2019a,b) on rapidly rotating massive stars have shown the major influence of mass-loss on the rotational evolution of these stars. Gagnier & Rieutord (2020a) have further shown the impact of the spin-down due to mass loss on the internal large-scale flows of massive stars. The subject is now ripe for a coupling between angular momentum extraction by a radiative wind and internal spin-down flows that may trigger, if a threshold is crossed, a chemically homogeneous evolution.

D. Reese is very experienced in asteroseismology and numerical simulations, for instance by developing the AIMS code for carrying out seismic inferences in a grid of stellar models, and InversionKit an interactive Java code for seismically probing 1D stellar profiles and determining global stellar properties via inverse techniques. He is the creator of the 2D TOP code (Reese et al.

2021) which computes the eigenmodes of rapidly rotating 2D-ESTER models. He has developed both an adiabatic and non-adiabatic version of TOP, and extended mode visibility calculations to rapidly rotating stars (Reese et al. 2013) for the purposes of mode identification (Zwintz et al. 2019; Bouchaud et al. 2020). Such a 2D-code is needed to study the pulsations of massive stars, as rotation cannot be ignored, many of them being fast rotators. For instance, as shown by Burssens et al. (2020), the TESS mission has caught several massive stars in its photometric data (e.g. Balona & Ozuyar 2020, Pedersen et al. 2019) but the modelling of their pulsations has been left aside since 1D models cannot cope with their rotation rate. D. Reese and A. Domiciano de Souza supervised the PhD thesis of K. Bouchaud (defended in 2020).

A. Meilland, A. Domiciano de Souza, and F. Millour are experts in modelling massive stars using spectro-interferometric observations. In the last fifteen years they participated in the development and scientific exploitation of the first generation of instruments at the VLTI and CHARA arrays, focusing on the fields of stellar surfaces of rapidly rotating stars and CSE of massive hot stars. They have been PI of many observing programs in these fields, and possess a wealth of interferometric data from a decade of successful observations of astrophysical objects including, for instance, 48 classical Be stars, 15 B[e] stars, and 5 blue supergiants. Some of these data have already been published, allowing us to put strong constraints on the surface and environment of many massive stars but sometimes showing the limits of the current generation of radiative transfer models or the lack of accurate stellar parameters.

A good example is their last work on classical Be stars, the modelling of o Aqr (de Almeida et al. 2020). Their study showed how spectro-interferometric measurements can help constrain some stellar parameters (diameter and inclination angle) and circumstellar properties (disk mass, and density structure and dynamics) when analysed with state-of-art interferometric-modelling tools and radiative transfer codes. But it also evidenced some of the limits of the current generation of models which use over-simplistic disk density and temperature laws. Finally, it showed the need of more accurate v sin(i) to better constrain stellar and disk rotation and determine a Be star's true rotation rate. To solve these issues a better model of the underlying star is needed.

The team in Nice is also involved in the development of the new generation of interferometric instruments. In the framework of MATISSE's design (Lopez et al. 2018), the new mid-infrared and latest VLTI instrument designed and built in Nice, A. Meilland led the development of the real-time coherencing software while F. Millour coordinated the work on the data reduction software. They both participated in MATISSE's commissioning and, with A. Domiciano de Souza, they all are involved in the scientific exploitation of the instrument either through Guaranteed Time Observation (GTO) or open time proposals. Fifteen nights of data on massive stars have already been collected since its first light in 2018. Note that F. Millour coordinates the GTO programmes of the MATISSE consortium concerning stellar physics.

The group in Nice is also involved in the development and in the science group of SPICA, the CHARA high-accuracy visible spectro-interferometer expected to be operational by 2022 (Mourard et al. 2018). A. Domiciano de Souza is coordinating the programmes concerning stellar rotation, which include the study of its effects on the stellar surface (flattening and gravity darkening) and on the CSE (decretion disk of classical Be stars and loss of symmetry in the radiative winds of massive stars). SPICA will observe for the first time more than 100 hot, massive stars at a sub-mas resolution as part of its all-sky survey, allowing us to probe their photosphere and CSE.

Partner	Last name	First name	Current position	Role & responsibilities	Involvement (pers.month)
Université Côte d'Azur	Meilland	Anthony	CRCN	PI & WP4 Coordinator WP3, WP4	40 p.m
Université Côte d'Azur	Domiciano de Souza	Armando	AAHC	WP3 Coordinator WP1, WP3, WP4	30 p.m
Université Côte d'Azur	Millour	Florentin	AA	WP3 & WP4	16 p.m
Université de Toulouse	Rieutord	Michel	PR	WP1 Coordinator WP1, WP2, WP3, WP4	40 p.m
Observatoire de Paris	Reese	Daniel	AA	WP2 Coordinator WP1, WP2, WP4	30 p.m

2.2 WP1: Modelling the star

WP leader: M. Rieutord, participants: A. Domiciano de Souza, D. Reese + 1 postdoc

This WP deals with the modelling of rapidly rotating massive stars. By rapidly rotating we mean stars whose centrifugal distortion exceeds 5% or, equivalently, whose equatorial velocity is larger than 30% of the Keplerian angular velocity. For these stars two-dimensional (2D) models are required. Such models can be computed by the ESTER code developed in the Toulouse group. This code is presently dedicated to early-type stars and its latest success was on the design of the most complete model of Altair (Bouchaud et al. 2020), which is the closest fast rotating star to Earth at 5.13 pc (but see summary in Fig. 2). This code has also been used in the works of Gagnier et al. (2019a,b) to investigate the rotational evolution of massive stars. Hence, the present WP builds on these latter results in order to strengthen the links with observational data, especially spectro-interferometric data, which can constrain 2D-models on the shape of the stars and their surface brightness distribution.

To follow up the work of Gagnier et al. (2019a,b), where local mass-loss was derived from the 1D-models of Vink et al. (2001), we shall first devise a simple kinematic model of mass loss that gives the outflow and density distribution of a radiative wind that meets the photospheric conditions of a massive star ESTER 2D-model. This star+wind model can then be used as an input to radiative transfer codes of extended CSE like HDUST (described in WP3) to predict spectro-interferometric observables at various wavelengths and give a first interpretation of interferometric data. The way interferometric data are inverted is presented below in WP3.

In parallel to this first simplified modelling, we propose to improve ESTER models so that they can predict the wind launch of a rotating star, namely the part of the photosphere where the out-flowing gas reaches the sound speed. This is the second goal of this WP. The way to reach this goal is to modify the boundary conditions of ESTER models. Presently, these boundary conditions impose a vanishing normal velocity at the stellar surface. We shall relax this restriction by extending the stellar models to the sonic point where matter reaches the sound speed and flows further out as a supersonic wind. For that purpose, we shall use a simple modelling of the radiative acceleration thus carrying on the work of Gagnier et al. (2019a). The result of this work will be 2D models of massive stars which consistently include mass and angular momentum losses at a given time together with the internal large-scale flows.

The large-scale internal flows (differential rotation and meridional circulation) triggered by both the mass-loss and the baroclinic torque will therefore be simultaneously taken into account and provide the basis for determining internal mixing in massive stars. In other words, such models will combine the previous work of Gagnier et al. (2019a) and Gagnier & Rieutord (2020b).

The foregoing work will deliver self-consistent models but with simplified physics as far as radiative acceleration is concerned. But this is in preparation for the last (ultimate?) step where radiative acceleration is computed from an atmosphere model. This line of work is presently undertaken in the Toulouse group where Axel Lazzarotto (a PhD student), Alain Hui Bon Hoa (an associate professor) and Michel Rieutord are coupling the ESTER code with the PHOENIX code of Peter Hauschildt (Hamburg Observatory, but see e.g. Jack et al. 2009). This new tool will therefore deliver beginning of 2022 the first synthetic spectra of 2D ESTER models for fast rotating early-type stars. With these two codes coupled, we can work out stellar models with $\mathrm{T_{eff}}$ up to 25000 K, and thus cover stars up to 10 $\mathrm{M_\odot}$ or typically up to spectral type B1. However, we plan to go higher in mass (about 20 $\mathrm{M_\odot}$), and thus in $\mathrm{T_{eff}}$ (up to 35000 K). For this we shall couple the ESTER code with the TLUSTY/SYNSPEC codes, which are designed for B-type and O-type stars (e.g. Hubeny et al. 2021) and which include the wind models. PHOENIX, used in Toulouse, and TLUSTY, used in Nice, have a common range of effective temperatures, namely 15000-25000 K, where they can be compared with each other.

With these tools, we will be able to invert the spectro-interferometric data of stellar photospheres, and derive the fundamental parameters of the observed stars when the wind is not too dense. The use of these ESTER-PHOENIX or ESTER-TLUSTY models on actual data is detailed in WP4. Finally, we plan to deliver in this WP a grid of models that spans the mass range from 4 to 20 solar masses at different stages of evolution along the main sequence.

Deliverables: An improved version of the ESTER code including the latest updates on mass and angular momentum losses (`http://ester-project.github.io/ester/`), and grids of ESTER interiors models, and of ESTER-PHOENIX & ESTER-TLUSTY atmosphere models computed for typical main sequence O&B stars.

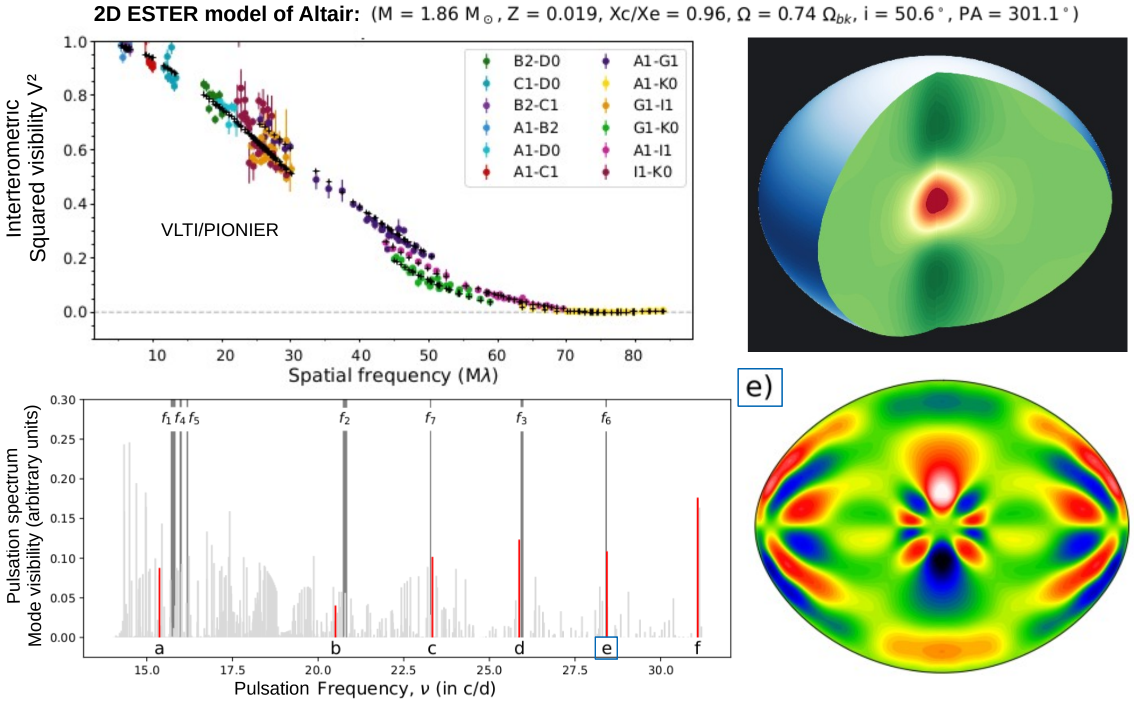

Figure 2: Synthetic view of our work on Altair, resulting in the first complete interior and photosphere model of a star other than the Sun, based on interferometric, spectroscopic, and asteroseismic observations (Bouchaud et al. 2020). *Top left:* Squared visibilities from VLTI/PIONIER observations and the best-fit 2D ESTER model (in black). *Top right:* Composite image of the photosphere and the internal angular rotation rate. *Bottom left:* Theoretical pulsation spectrum of Altair computed with the ESTER+TOP model (grey lines with thickness proportional to the pulsation amplitude). By matching these theoretical models (red lines labelled a to f, corresponding to island or mixed gravito-island modes) with the pulsation frequencies observed with the WIRE satellite (f_1 to f_7) we determined the remaining parameters of our 2D model: mass M, metallicity Z, and hydrogen mass fraction in the core X_c. *Bottom right:* Example of a meridional cross-section of an island mode (e) matching the observed pulsation frequency f_6; the colours correspond to Lagrangian pressure perturbations. The age of Altair was also revised thanks to our estimate of X_c and stellar evolution models: we found that Altair is much younger ($\simeq$ 100 Myr) than previously believed (1 Gyr), which is more compatible with its high rotation rate.

2.3 WP2: Asteroseismology of Massive stars

WP leader: D. Reese, participants: M. Rieutord + 1 postdoc

The goal of this WP is to seismically constrain massive rotating stars. Indeed, stellar pulsations is currently the only way we have to probe stellar interiors, and as such complements the constraints obtained through interferometry and spectroscopy. This then provides stringent constraints on the stellar interior models obtained with the ESTER code, and in particular on differential rotation and more generally on transport processes. A second goal is to enrich the grid of rotating stellar models with seismic observables, namely pulsation frequencies, and surface quantities from which to calculate multicolour photometric mode visibilities as well as line profile variations.

Currently, the TOP pulsation code is able to calculate both adiabatic and non-adiabatic pulsations in rapidly rotating ESTER models. Nonetheless, various improvements need to be carried out. Indeed, the non-adiabatic implementation remains somewhat preliminary and needs to be thoroughly tested. Furthermore, it was recently noticed that in some cases, it is necessary to improve the eigenmode solutions through iterative refinement (see, e.g., Reese et al. 2021). Further improvements also include taking into account the structure of an atmosphere in the non-adiabatic computations following the approach described in Dupret et al. (2003). This will be particularly important for calculating accurate photometric and spectroscopic signatures of pulsations modes as described below. The coupling of ESTER models and PHOENIX/TLUSTY stellar atmosphere models is therefore particularly welcome and timely.

We propose to update the TOP code so that the entire pulsation spectra and labelling of the most visible modes are automatically calculated, using for instance the approach described in Mirouh et al. (2019). This improvement will allow us to generate a large number of oscillation spectra spanning a large set of parameters in the targeted range of mass. Hence, we will produce large sets of asteroseismic synthetic observables. The sets of pulsation frequencies and modes will go along with the grid of massive rotating stellar models to be calculated in WP 1. Such frequency spectra can then be used as an input to the *Asteroseismic Inference on a Massive Scale* (AIMS) code, which constrains stellar parameters by fitting seismic and classic constraints thanks to an Markov Chain Monte Carlo (MCMC) search while interpolating in a grid of stellar models (see Rendle et al. 2019). In particular, it will be necessary to adapt the AIMS code so as to handle spectra of rotating stars by introducing the azimuthal order as a supplementary quantum number.

Furthermore, surface quantities, namely the Lagrangian displacement, as well as temperature and gravity fluctuations induced by the pulsation modes, will be included in the outputs. Such surface quantities then allow us to calculate multi-colour mode visibilities integrated over the stellar surface like in Reese et al. (2013, 2017b), as well as line profile variations (e.g. Townsend 1997; Reese et al. 2017a). Confronting these theoretical mode signatures with photometric and spectroscopic observations are particularly important for placing constraints on the underlying mode geometry and hence identifying the observed pulsations, i.e. finding the theoretical modes that match the observations. Identifying individual modes is then one of the key steps to carrying out detailed asteroseismology since it allows us to know what regions of the star are probed by the pulsation modes. It is precisely the lack of a clear mode identification that has, up to now, prevented detailed asteroseismology in rapid rotators (e.g. Goupil et al. 2005). The results on Altair by Bouchaud et al. (2020, see also Fig. 2) show that we are now close to solving this issue.

The foregoing improvements of existing tools can be realised rather quickly. The tools are then to be applied to a set of massive stars, chosen in relation with other WP to be the most promising targets as far as observational constraints are concerned. We already have identified targets like ζ Oph (star in the cover image) for which seismic, spectroscopic data exist, and which are a high priority of the SPICA interferometer programme (cf. WP4). A list of such stars, including ζ Oph, and their contribution to modelling constraints is given in Table 1. As was demonstrated in the case of Altair, seismic interpretations of rapidly rotating stars go hand-in-hand with characterising the stars via interferometry and spectroscopy. Indeed, it is not straightforward to interpret the pulsation spectra of such stars, thus making the constraints from these other techniques particularly crucial for reducing the parameter space. In addition, we will make use of multi-colour photometric observations and line profile variations to identify the observed pulsation modes, thus opening the way to detailed seismic investigations. Conversely, asteroseismology can remove degeneracies by bringing in orthogonal constraints and providing information on the internal structure such as the core helium abundance, and thus the age of the star. Furthermore, if a sufficient number of non-axisymmetric modes are identified, it may be possible to probe the internal rotation profile of these stars using inverse techniques (e.g. Reese et al. 2021). Figure 2, based on Bouchaud et al. (2020), illustrates this multi-technique process quite nicely. Our goal is then to generalise this to other landmark stars, namely those in Table 1, which include massive stars from different types in terms of mass, type of environment, mass loss, and pulsations.

A class of particularly important targets for seismic investigation are Be stars. As mentioned earlier, these stars are close to break-up and have a decretion disk that is periodically fed through stellar outbursts. Various mechanisms, including pulsation modes and waves, have been proposed to explain the mass ejection and disk formation. For instance, Neiner et al. (2020) recently proposed stochastically driven g-modes as a means of transporting angular momentum to the surface thereby spinning it up to the critical rotation rate, thus destabilising it and leading to an outburst. In order to test this scenario as well as other similar scenarios, we plan to construct 2D models with self-consistent rotation profiles using the ESTER code, and calculate pulsation modes using the non-adiabatic version of TOP. This will allow us to calculate more accurately the geometry of the pulsation modes, the amount of angular moment they transport, and their growth rates, thereby enabling us to provide better estimates of the expected times between successive outbursts and of the amount of matter fed to the disk. We also plan to carry out a detailed seismic investigation of one or two carefully chosen targets including spectroscopic time series, using the above mode identification techniques. If the number of identified modes is sufficient, this will allow us to probe their internal rotation profile thus providing constraints on angular momentum transport.

Deliverables: seismic observables (frequencies, surface quantities from which to calculate mode visibilities and line profile variations) for the grid of rotating stellar models, public release of the TOP code, seismic interpretation of landmark stars.

2.4 WP3: Polychromatic image synthesis

Circumstellar radiative transfer and tools for interferometry

WP leader: A. Domiciano de Souza, participants: F. Millour, A. Meilland, M. Rieutord + 1 postdoc

This WP aims at creating and using polychromatic model images of massive stars (central star and environment) and developing the corresponding analysis tools to interpret spectro-interferometric observations. The images will be obtained by combining the central 2D stellar models (developed in WP 1 and 2) with 3D radiative transfer in the CSE (winds and disks). With this state-of-the-art model we will:

1. compute grids of polychromatic intensity maps (images) for different types of massive stars (in particular those to be studied in WP4).
2. develop tools for multi-band analysis (image reconstruction and model fitting) dedicated to our spectro-interferometric study of massive stars.

2.4.1 Radiative transfer models of winds and disks

Once the central star model is defined (results from WP 1 and 2), the final polychromatic images including the CSE (winds and disks) will be computed using the radiative transfer code HDUST (e.g. Carciofi & Bjorkman 2008). HDUST is our primary choice because (a) it is optimised to model CSE of massive stars in 3D, and (b) our team from Nice has a long-lasting, fruitful collaboration with A.C. Carciofi (Brazil), the creator of HDUST, together with J. Bjorkman (USA).

Given a physical description of a star (which can be rotating, i.e., non-spherical) and its CSE (density and velocity distributions), HDUST uses a Monte Carlo approach to solve the transfer of polarised radiation in the non-local thermodynamic equilibrium regime (NLTE). The environment can be composed of many components (winds, disks, inhomogeneities) and can be composed of gas and dust. As output, the code provides polychromatic synthetic images and the associated spectral quantities (SED, line profiles, etc.). Examples of HDUST outputs from some of our previous works using this code are shown in Fig. 3.

For some years now, a new version of HDUST, called HDUST3, has been developed and is expected to be operational first half of 2022. This new version will allow us to make an enormous leap forward, as it solves a long standing issue with HDUST. Indeed, the current version only includes hydrogen in the chemical composition of the gas. With HDUST3, other chemical species such as He, C, and N will also be available in full 3D and NLTE, allowing us to tackle problems that have never been properly addressed before. In particular, this code will be a fantastic tool to study inhomogeneous winds around massive stars (e.g. 2D winds from rotating stars and also 3D structures for winds with clumps for example). HDUST already incorporates a central, rotating (non-spherical) star including gravity darkening and rotational flattening. In WP3 we, together with the postdoc based in Nice, will combine our multiple expertise in order to obtain a full (star+environment) NLTE modelling tool for massive stars:

- The central rotating star model will be based on the outputs of the 2D ESTER code (plus stellar atmosphere models) up to the sonic point, which will also provide latitudinal dependent mass-loss rates (see description of WP1).
- Starting from this central star model, the CSE will be computed with HDUST3. For example, the circumstellar disks will be described using the viscous decretion disk (VDD) model in Keplerian rotation (Lee et al. 1991), which is well adapted for several massive stars (e.g. Meilland et al. 2007; Carciofi 2011). To model the wind of massive stars, a first approach is to adopt the classical models from the theory of radiation-driven winds, or CAK-like models (cf. Castor et al. 1975; Puls et al. 1996, and references therein). From the ESTER mass-loss rates and the CAK theory (including the associated force multiplier parameters), we can determine the velocity and density structure of the wind, which can be adapted to the 2D case of rotating stars (e.g. Maeder 1999; Gagnier et al. 2019a).

This WP will thus provide the needed tool to interpret massive star observations, from the interior through the photosphere, and up to the circumstellar wind and/or disk. Spectro-interferometric studies (e.g. from MATISSE, SPICA, and GRAVITY observations) of massive stars will largely benefit from such state-of-the-art models. In particular, such modelling will be crucial to the physical analysis of the landmark stars to be studied in WP4 (see Table 1).

We will also create grids of models (e.g. polychromatic images, spectra, SED) that will be delivered to the astronomical community (via the aforementioned web service AMHRA). These grids will be made compatible with the Virtual Observatory standard and will constitute an invaluable catalogue of models to be used for the preparation, analysis, and physical interpretation of spectro-interferometric observations. An example of a previous grid of HDUST model images for B[e] supergiants (Domiciano de Souza & Carciofi 2012), already provided to the community in AMHRA[1], can be found at `https://amhra.oca.eu/AMHRA/sgbe-hdust/input.htm`.

This published grid is only a first version, and the new grids to be created in this ANR prject will be based on more physically consistent models and will cover a much larger range of parameters. The computation of the model grids will be mostly performed in high performance computing centres available to our team: Mésocentre SIGAMM (Nice), CALMIP (Toulouse), Tycho or MesoPSL (Paris/Meudon).

Deliverable: a full polychromatic 3D radiative transfer model of the circumstellar environment (winds and disks), with the central part based on the 2D ESTER model. Grids of models (images and spectra) for different types of massive stars (e.g. classical Be, B[e] supergiants) to be made available to the astronomical community via the web service AMHRA/MOIO/JMMC[1].

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[1] The AMHRA service (resp. A.Domiciano de Souza) is developed at OCA and it is part of the French Center for Infrared and Optical Interferometry JMMC. It is dedicated to the use of astrophysical models to optimise the scientific exploitation of interferometric instruments. AMHRA's web site: `https://amhra.oca.eu/AMHRA/index.htm`

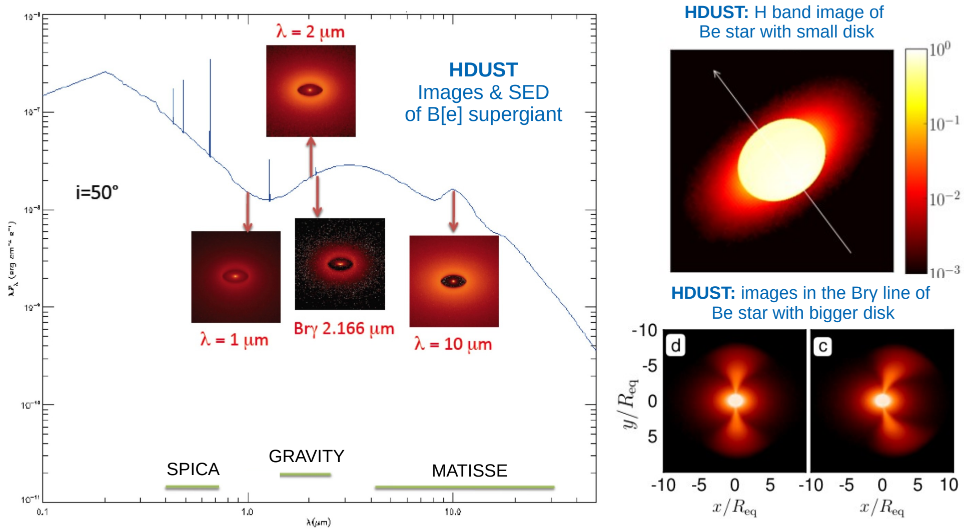


Figure 3: Examples of HDUST outputs computed for some of our previous published works. These models were obtained with the first version of HDUST, which included only hydrogen in the gas composition. *Left*: SED for a typical HDUST B[e] supergiant star model with a CSE composed of gas and dust (based on the bi-stable wind model described in the text). The four images are HDUST intensity maps corresponding to selected wavelengths of these SED, showing the relative contribution of gas and dust from the near-IR to the mid-IR (Domiciano de Souza & Carciofi 2012). The main interferometric instruments to be used in this ANR project are also indicated. *Top right*: HDUST model (H-band continuum) of a Be star, constrained by interferometric data (VLTI/PIONIER), showing a flattened star with gravity darkening surrounded by a small disk (Dalla Vedova et al. 2017). *Bottom right*: HDUST model showing intensity maps (Faes et al. 2013) at two selected wavelengths inside the Brγ emission-line for a Be star with an extended rotating disk (*d*: line centre; *c*: red part of the line). Spectro-interferometric observables (e.g. differential phase, visibilities, and spectra) can be computed from these type of images, for example to physically interpret the current and future data, which will be used extensively in this ANR project (cf. WP4). In this ANR project, we will make an important leap forward concerning the models of massive stars by combining ESTER models (WP1 & WP2) with the new version of HDUST, which includes several other chemical elements in addition to hydrogen (see WP3).

2.4.2 Tools for multi-bands spectro-interferometric analysis

It has now been almost 20 years since the VLTI first started producing spectro-interferometric data (also called ”polychromatic” data), and yet the number of general user tools able to handle this type of data properly is limited. Our team has contributed significantly to this field, be it for polychromatic toy models (Meilland et al. 2012), polychromatic model-fitting (Millour et al. 2009; Lamberts et al. 2017), or polychromatic image reconstruction (Millour et al. 2011; Mourard et al. 2015). Some of these tools have been distributed (self-cal, fitomatic), and some of the models we have developed have been incorporated into dedicated web services (AMHRA), but none of them have been extensively used in surveys, the time needed to implement them and use them being significant.

With the advent of MATISSE and GRAVITY on the VLTI, and soon SPICA on CHARA (all described in WP4), which is specifically designed for surveys, we already face today a “tsunami” of multi-band, polychromatic data (also known as “panchromatic” data), dedicated to batch characterisation of massive stars and image reconstruction of their environments. The very interesting aspect of the current period is that we have access today to a wide wavelength coverage (available bands: V, H, K, L, M, N), including spectroscopic (spectral resolution) and imaging capabilities. This was only partially achieved when the 1st generation instruments were in operation (AMBER, MIDI, VEGA).

The main advantage of using multi-band and spectroscopic information at the same time is to strongly constrain the different components of the objects: the star is mainly seen in the visible and absorption lines, hot gas contributes to the near infrared, the mid-infrared and the emission lines, and warm dust contributes in the near and mid-infrared. However, these three sources also contribute in the other bands, thus biasing the results if one uses models that are too simple (star+dust, omitting the gas, as shown in Meilland et al. 2010, see also Fig. 3). Therefore one needs an integrated model able to cope with panchromatic data, which is not yet done in a self-consistent way and with the more up-to-date models of massive stars.

The same problem arises with image reconstruction: “grey” image reconstruction has made advances in the last few years (IRBIS, OImaging), but there is still clearly room for progress and discoveries, with e.g. recent work done on artificial intelligence (Claes et al. 2020). On the other hand, in polychromatic imaging, self-cal is still the mainstream algorithm (Millour et al. 2011; Mourard et al. 2015), and while there have been developments for other polychromatic image reconstruction algorithms (PAINTER, Schutz et al. 2014), they still have not found their user base yet, being notoriously difficult to tune to achieve a good result.

Our approach is therefore twofold: (a) contributing to provide simplified ”brick” models that can be assembled for interpretation of panchromatic data, and (b) explore new paths for image reconstruction to retrieve physical information from panchromatic datasets.This work package will be backed up by a solid set of real data coming from WP4 with MATISSE and SPICA data (we are part of the respective consortia), as well as data from other instruments (GRAVITY, PIONIER).

(a) Putting together chromatic models As explained earlier, we have at our disposal a series of ”bricks” of very heterogeneous origins, and one of the goals of this task is to assemble them into an homogeneous, user friendly tool that will be used to interpret the data from the surveys, both at first order, and then more in depth, once our grids of physical models have been created. These models are threefold: simple geometric models with spectra (e.g. used in Millour et al. 2009; Lamberts et al. 2017), line-modelling ”toy” models (e.g. Millour et al. 2011; Meilland et al. 2012; Chesneau et al. 2014, and those in AMHRA), and finally, grids of pre-computed physical models (for which we will use an approach similar to the one used in Bouchaud et al. 2020, see also Fig. 2), in particular the one described in Sect. 2.4.1.

However, not all of these models have an easy-to-use unifying framework that enables us to combine multiple models together (for example, geometrical models with a blackbody spectrum are only available in LitPro, while toy models for lines are only available in IDL or fitomatic), even though there were attempts to do so in the past (a few examples: simtoi, fitomatic, LitPro). Therefore, the work in this WP is to build an integrated framework able to combine many spectral models together, in order to provide a toolbox similar to, but more complete than fitomatic, that was used at the 2016 Beauty contest to retrieve chromatic images using a hybrid approach (participation 2 of F. Millour in Sanchez-Bermudez et al. 2016).

Our proposal is to build this framework with the now well-established and widely used python software environment, that now offers a series of powerful toolboxes for inverse problems and model fitting. This framework will also include optimal χ^2 descent algorithms now available in python, such as simulated annealing (already part of fitomatic), or MCMC methods. We have shown that these MCMC descent algorithms are well-adapted to fit panchromatic models (e.g. Bouchaud et al. 2020; de Almeida et al. 2020). Our team has experience with python, as some of us wrote the MATISSE data reduction tools and some toy models in AMHRA in this language. The following steps will be used to carry out this work:

- Set the framework in python in a similar way to fitomatic (i.e. a modular scheme with wavelength and time as inputs, in addition to u, v-plane coverage, and a choice of descent algorithms),
- Build a chromatic simple geometrical models library (uniform disks, point sources, Gaussian disks) to get the same capabilities as fitomatic,
- Add toy models such as a rotating/expanding disk, or a rotating star,
- Write a normalised interface (API) to external models, especially the grids of models contained in the AMHRA web service, and the one developed in Sect. 2.4.1,

- Write additional interfaces with specific model grids (TLUSTY, PHOENIX, ATLAS-Kurucz, HDUST, ...).

This python framework will be extremely useful for interpreting the data from the interferometric surveys described in Sect. 2.5, and will be developed throughout the duration of the ANR project. The result will be an integrated, chromatic model-fitting tool, that we will distribute freely to anyone interested through the collaborative coding platform GitHub or an equivalent one.

(b) Progressing on panchromatic image reconstruction Image reconstruction in optical interferometry has its roots in radio-interferometry aperture synthesis. Indeed, image reconstruction really took off with the introduction of the twin hybrid mapping/self-calibration techniques (Cornwell & Wilkinson 1981; Pearson & Readhead 1984), which built upon the following initial ideas: ”sparse” or ”greedy” algorithms (Högbom 1974), Maximum Entropy (MEM, Wernecke 1977), as well as Bayesian approaches (see e.g. a complete description in Wiaux et al. 2009).

In the optical domain, the same approaches (sparse, MEM and Bayesian) have also been used thanks to theoretical developments in the 2000s. However, they lack most of the chromatic information contained in the interferometric data. Chromatic reconstructed images rely on splicing the image reconstruction process in independent slices. Since aperture synthesis with optical interferometers will still need to rely on a low number of apertures for a long time, the need for improved reconstruction algorithms is still alive today.

New approaches have been invented, that attempt to group wavelengths by inputting a model in the reconstruction process (SPARCO: Kluska et al. 2014), use intrinsically wavelength-linked observable like differential phase (self-cal: Millour et al. 2011), or try to link the wavelength domain using regularisation (PAINTER: Schutz et al. 2014). However, these techniques are still only applicable to a limited set of cases. In this ANR project, we thus propose to further develop these approaches as well as new ideas that would solve many of the caveats of today’s chromatic image reconstruction algorithms. These ideas aim at producing a ”pan chromatic” image reconstruction algorithm, usable for mapping the massive stars studied in the MASSIF ANR project: using physical maps based on our models on the one hand, and injecting Artificial Intelligence (AI) into the image reconstruction process on the other hand (Fig. 4).

To reconstruct physical maps, we wish to focus on the following: instead of attempting to reconstruct the intensity per image pixel, each pixel may have a flux and other physical quantities as free parameters. These physical quantities can be, for example, a black-body temperature (an idea also proposed in Soulez et al. 2016, but not really used in practice), a velocity field, a composition fraction of chemical elements/molecules, among others (Fig. 4). The wavelength-wise image cube pixels will then have a spectrum constructed on the basis of these physical-

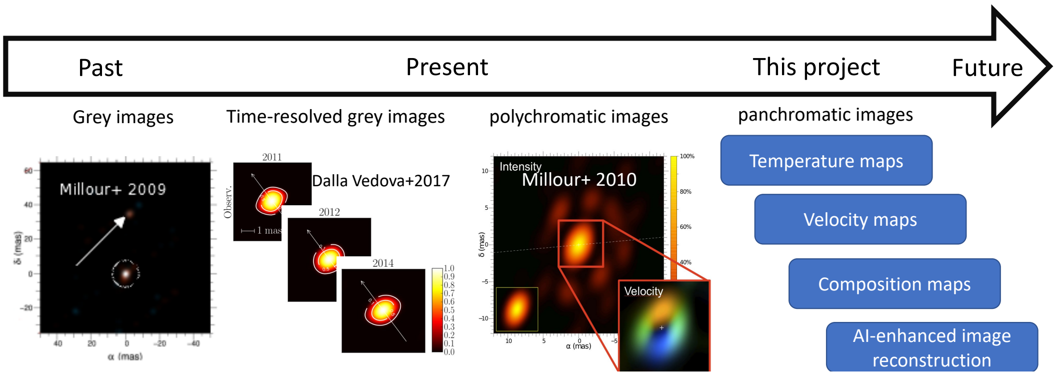


Figure 4: How image reconstruction has evolved until now, illustrated with works published by our team, and what we wish to add to the image reconstruction algorithms during this ANR project. *Left:* the situation at the first VLTI image (grey image reconstructions). *Middle:* the demonstration that time-resolved imaging can be done using the VLTI, then polychromatic imaging using self-calibration. *Right:* The proposed steps we wish to develop in the course of this ANR project.

quantity maps. This image cube can then be adjusted to the interferometric data (visibilities, closure phases) the usual way (with Fourier Transforms, regularisation and descent algorithms). Once adjusted to the data, these maps can then be compared with the physical-quantity maps computed with our physical models.

All the other aspects of the image reconstruction process (interfacing with oifits files, minimisation routines, regularisations) will be the same as in already well-established image reconstruction software. That means that such an approach could be implemented with little effort as a plugin into an existing image reconstruction software such as MIRA. The goal here is therefore to focus on one image reconstruction software, MIRA, starting with the implementation of simple temperature map. This will be done in Nice with the help of the postdoc or with the PhD student.

In a second phase, we want to investigate the use of AI in image reconstruction. To build on this approach, that was initially proposed by J. Kluska, we need to have a database of images for the objects of interest. The grid of CSE models built in Sect. 2.4.1 as well as ESTER-TLUSTY and ESTER-PHOENIX stellar atmospheres from WP1 are exactly the type of database needed. We aim at building neuronal networks and using these models to train them. Two approaches can then be adopted: (1) the same as in Claes et al. (2020), i.e. try to construct a prior with the neural network, which is fed into standard image reconstruction software (e.g. MIRA), and (2) another approach that tries to construct directly the visibilities and closure phases. Once trained, the network will be applied both to new simulations and real data, in order to benchmark its performances. As soon as the neural network is trained and validated on synthetic datasets, it should be ready to be used on real datasets to reconstruct images of massive stars and their environment, in particular our targets listed in WP4.

Deliverables: improved kinematics model, panchromatic model-fitting tool, panchromatic image reconstruction software, temperature mapping from multi-band images.

2.5 WP4: Interferometric surveys

Resolving the photospheres, and close-by winds and disks of massive stars

WP leader: A. Meilland, participants: all MASSIF team + 1 PhD student

The goal of this WP is to derive accurate stellar parameters (mass, $\mathrm{T_{eff}}$, radius, rotational velocity, gravity darkening, etc.) and constrain the structure of the CSE (mass-loss rate, density and temperature laws) of a variety of close massive stars using visible-to-mid-infrared spectro-interferometric measurements and the models developed in the previous WP.

We restrict the scope of our study to 4 to 20 $\mathrm{M_\odot}$ stars close to the main-sequence, with an effective temperature above 8000K. We also include a few more evolved objects, i.e. hot supergiants and B[e] stars in the same mass and temperature range, since the modelling of these objects will strongly benefit from the development of the models and tools described in the three previous work packages.

As far as main sequence O & B stars are concerned, including fast-rotators and β-Cephei type pulsators, we shall use the improved ESTER interior models (WP1) and asteroseismic constraints from TESS observations modelled with the TOP code (WP2) to derive more accurate stellar parameters, as was done for the lower mass star Altair by Bouchaud et al. (2020, cf. Fig. 2). The stars above 20000 K will also strongly benefit from the addition of the radiative-wind launch zone in the ESTER models (WP1) as well as the computation of new 3D radiative transfer models of anisotropic wind with HDUST (WP3).

We will also use these combined ESTER+HDUST models to probe winds of more evolved objects such as hot supergiant stars. In the case of B[e] stars we will be able to test the hypothesis of bi-stable wind models, and compare the results with models with decretion disks also computed in WP3. In the case of the classical Be stars, we will be able to model the fast-rotating star, in the same way as for other fast-rotators using the tools developed in WP1 & WP2, and their decretion disks (WP3). Finally, panchromatic analysis and image reconstruction tools as described in WP3 will also greatly help in constraining the physical properties of all these stars and their CSE for instance, by allowing us to detect departures in geometry and kinematics from the images produced from radiative transfer codes.

In Nice we have a privileged access to the two major optical/IR interferometric facilities in the world: VLTI (Southern hemisphere) and CHARA (Northern hemisphere). For almost two decades, we have been developing instruments for these facilities starting with AMBER (Petrov et al. 2007), the now decommissioned but still most prolific interferometric instrument ever built (22% of all refereed publications on optical interferometry by 2021) and VEGA (Mourard et al. 2009) a visible beam combiner of CHARA. Nice is now the PI institute of MATISSE (Lopez et al. 2018), the new mid-infrared VLTI instrument and SPICA (Mourard et al. 2018), the upcoming next generation visible instrument at CHARA, the two key instruments of our survey.

Thanks to these instrumental developments and the expertise in analysing interferometric observations, especially of massive stars and their CSE, the team in Nice has been PI of many observing programs and now owns a wealth of interferometric data on more than 60 massive stars. Our sample is still growing as MATISSE is now producing a large amount of data on massive stars, and SPICA will observe more than one hundred of them during its three-year all-sky survey starting next year.

2.5.1 MATISSE: dust and gas around massive stars

MATISSE is the new four-telescope mid-infrared combiner at VLTI. It was designed and built by a consortium of institutes led by the Observatoire de la Côte d'Azur (OCA, Nice) and is available for the scientific community since April 2019. It was developed as a successor to the N-band instrument MIDI, but unlike its predecessor, MATISSE offers for the first time in the mid-infrared, real imaging capabilities as demonstrated by its test imaging programme on the disk of the B[e] star FS CMa (see Fig. 5).

In addition to the N band, MATISSE opens two new spectral windows at the VLTI, the L and M bands, filling the gap between the K and N bands of the VLTI first generation instruments and allowing us to probe more efficiently the star's surroundings. With its very extended spectral domain, i.e. from 2.8 to 13μm, it is sensitive to dust with temperatures ranging from the sublimation limit (~ 1500 K) down to ~ 200 K. Moreover, thanks to its higher spectral resolution modes, dust and molecular bands as well as atomic lines can be spectrally resolved, allowing us to disentangle gas and dust emission, probe dust mineralogy, and constrain gas dynamics.

Such a combination of spatial and spectral resolutions in a large near-to-mid infrared spectral domain offers us a unique opportunity to constrain the physical properties of the CSE (i.e., density, temperature, chemistry, and dynamic laws). In the case of hot massive stars, it will provide strong constraints on the parameters defining these physical properties, since they are the input quantities of models of radiative winds and decretion disks. Moreover, interpreting these multiband observations with physical models will help to significantly improve our understanding of the mechanisms responsible for the mass-ejection, and subsequent CSE formation and dissipation, and finally to characterise the effects of mass-loss on stellar evolution and on the chemical and energetic enrichment of the interstellar medium.

As the PI institute of the MATISSE consortium, OCA has a privileged access to the instrument, mainly through the Guaranteed Time Observations (GTO). An important part of this time is being used to observe various types of massive stars. In the scope of this project, we focus on three classes of massive stars: the classical Be stars and their gaseous disk, the complex CSE of B[e] stars, and the radiative wind of hot supergiant stars.

Nine classical Be stars have already been observed and 12 others will be observed during the time of this ANR project through GTO time. One of our aims is to study the size variation of disk emission through the L, M and N bands. As explained in Meilland et al. (2009) the wavelength dependence of the emission in the mid-infrared is linked to the temperature and density distribution in the disk, which can be constrained via physical models.

The second goal is to constrain the disk geometry and kinematics in the L-band emission lines, mainly Brα and some Pfund and Humphreys lines, and compare them with measurements obtained in Brγ (AMBER) and Hα (VEGA). As demonstrated in our last paper on classical Be

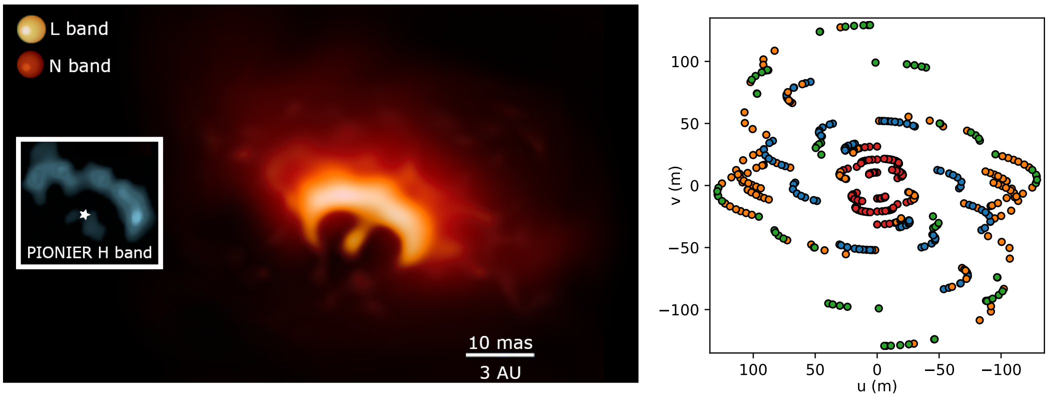


Figure 5: *Left*: FS CMa circumstellar disk image reconstructed from VLTI/MATISSE L and N band observations. The H-band VLTI/PIONIER image from Kluska et al. (2020) is overplotted at the same scale for comparison. *Right*: corresponding uv-plane coverage.

stars (de Almeida et al. 2020), multi-line spectro-interferometry is a powerful tool to remove degeneracies on model parameters and can help constrain the fine structures of disks, such as its vertical stratification or the putative variation of the rotational law between the stellar surface and the outer edge of the disk, thus providing new insights on the disk formation and its influence on mass-loss and stellar evolution.

MATISSE is also very well suited to study B[e] stars, i.e., hot stars showing an important infrared-excess due to hot circumstellar dust, as well as hydrogen and forbidden lines in emission. Their environment is likely to be highly anisotropic as dust requires regions of high density and low enough temperature to form whereas forbidden lines are usually associated with highly diluted and extremely illuminated environment. The mechanisms causing the large mass-loss and the formation of such complex CSE are still not clear, and several models have been proposed, which include fast rotation, a bi-stability mechanism, a magneto-rotational instability mechanism, non-radial pulsations, and/or binarity or even binary mergers (Maravelias et al. 2018, and references therein). Constraining the circumstellar geometry in the mid-infrared is one of the most efficient ways to test these models as they imply different density distributions (Meilland 2017).

The Nice team started a MATISSE GTO survey of the brightest B[e] stars last year, and 16 objects have already been observed in low spectral resolution before the VLTI lockdown in April 2020. Complementary observations will be carried out on 4 additional targets this year. This represents the largest sample of B[e] stars observed at high spatial resolution, and more than half of the objects had not been observed with the first generation of VLTI instruments.

2.5.2 SPICA: Surface mapping and hot gas around massive stars

SPICA (Mourard et al. 2018) is the new visible beam-combiner developed in Nice that will be installed on the CHARA array in 2022. Unlike its predecessor VEGA (Mourard et al. 2009), it will simultaneously combine the beams of up to six telescopes and will offer real imaging capabilities with a resolution down to 0.5 mas. Using a state-of-art photon-counting detector, spatial filtering with optical fibers, a dedicated fringe-tracker in the near-infrared, and the newly installed adaptive optics of the CHARA telescopes, observations with SPICA will be faster and more accurate than the previous generation of visible instruments and will offer a better sensitivity limit.

SPICA will be a unique instrument to resolve the photospheres of stars, with a capability to measure accurate stellar diameters down to 0.2 mas and to image stellar surfaces down to 0.8 mas. One of the main challenges of the instrument is to measure a sample of 1000 stars (800 diameters + 200 images) in a three year period between 2022 and 2024.

Moreover, thanks to its high spectral spectral modes it will also allow us to resolve atomic lines and perform spectro-interferometric analysis and imaging of stellar surfaces (in photospheric lines) and CSE (in emission lines), putting additional strong constraints on the physical (dynamical in particular) properties of stars and their environments compared with broad band studies. For instance, Domiciano de Souza et al. (2004) and Delaa et al. (2013) showed how spectro-imaging could constrain differential rotation on the surface of fast-rotating stars.

In the context of this project, SPICA should be able to partly or fully resolve the surfaces of more than a hundred main-sequence O & B stars during its three years survey, including 34 fast-rotators, 20 β-Cephei type pulsating stars and 53 normal B stars.

SPICA will also observe about 60 classical Be stars in medium spectral resolution (R$\sim$3000) allowing us to simultaneously resolve the stellar surface and the circumstellar disk in the Hα emission line, which will then allow us to clarify the connection between disks and processes involved in mass ejection. One challenge is to derive a consistent model of these stars and their environment using ESTER models for fast-rotating stars (WP1), including asteroseismic constraints (WP2), and a full modelling of the CSE with HDUST models and the polychromatic tools described in WP3. For hotter Be stars, we will also be able to investigate the strength of putative polar (Kervella & Domiciano de Souza 2006) and disk winds similar to those detected in young stellar objects (Weigelt et al. 2011).

Finally, SPICA will allow us to probe the winds of 37 hot supergiant stars and the hot gaseous emissions of at least 8 B[e] stars in Hα thus enabling us to simultaneously probe their photoshere and CSE.

2.5.3 Our sample of massive stars at high angular resolution

Our sample of high-angular resolution observations of massive stars is built using the MATISSE classical Be and B[e] star surveys, stars from the SPICA all-sky survey with a mass between 4 and 20 $\mathrm{M}_{\odot}$, and data from the previous generations of interferometric instruments: mainly VLTI/AMBER (K-band), and CHARA/VEGA (R-band). For some objects, we also have access to data from VLTI/PIONIER (H-band), VLTI/MIDI (N-band), and CHARA/MIRC (H-band). We note that we will also perform complementary observations with VLTI/GRAVITY (K-band) as well as the VLT imager SPHERE. This sample contains more than 200 objects for which we have, or we will obtain, interferometric data before the end of this ANR project. We have divided it into six classes of objects that will allow us to study different aspects related to massive stars and their environments: fast-rotators, β Cephei type pulsating stars, slowly rotating B stars, classical Be stars, B[e] stars and hot supergiants stars.

As interferometry is a time consuming technique, and image reconstruction requires many observations, i.e. up to several nights, we have separated our sample into two categories. 25 primary targets have been selected among the brightest and biggest (in angular size) stars of our sample, also taking into account the existence of previous interferometric observations at various wavelengths. They were chosen to cover all six classes of objects described above and the largest possible parameter space in term of stellar mass and effective temperature.

Dedicated imaging programmes will be performed with MATISSE and/or SPICA on these primary targets whereas the rest will be observed in a survey mode (only a few measurements per target). Primary and survey targets are complementary in our study: the data from the primary targets will allow us to put more constraints on the models and to determine the fine structure of the stellar surface or CSE, whereas survey targets will offer a better statistical view of massive stars, allowing us to study rotation, pulsations, mass-loss and mass-ejection processes as a function of the effective temperature, spectral type or luminosity.

A summary of our selected targets is presented in Table 1. It shows the 25 primary targets and the number of survey targets per class of objects, and for each the data already available as well as future MATISSE, SPICA, and complementary observations. For each target, we also show the availability of TESS photometric time-series.

Deliverables: Stellar parameters (mass, $\mathrm{T}_{\mathrm{eff}}$, age, rotation rate...), mass-loss, wind & disk structures (density and temperature law, chemistry, dynamics) on the 200 stars of the survey, statistical analysis of the dataset (dependence of the studied phenomena on stellar parameters), detailed view on the 25 primary targets including models and reconstructed images. All the reduced interferometric data will be available on the JMMC OiDB database.

	Estimated Params				Available Interferometric Data				New Observations			TESS
	Name	spClass	Teff (K)	M (Mo)	VEGA	AMBER	MATISSE	other	MATISSE	SPICA	Other	Time series length (d)
Fast Rotators	ζ Oph	O9.2IVn	32000	20	-	Survey	-	PIONIER	-	Imaging	GRAVITY/SPHERE	-
	η Uma	B3V	19000	8	-	-	-	-	-	Imaging		25
	δ Per	B5III	15000	7	-	-	-	-	-	Imaging		24
	α Leo	B8IVn	11500	4.5	-	-	-	MIRC	-	Imaging		-
	α Peg	B9III	10500	4	-	-	-	-	-	Imaging		-
	+ Surveys				-	-	-	-	-	34		-
β-Cephei pulsating stars	β Cep	B0.5III	27000	18	-	-	-	-	-	Imaging		5x25
	ε Per	B1.5III	23000	16	-	-	-	-	-	Imaging		25
	α Vir	B1V	25000	14	-	-	-	-	-	Imaging		-
	γ Peg	B2IV	21000	13	-	-	-	-	-	Imaging		-
	d Per	B4III	17000	10	-	-	-	-	-	Imaging		25
	+ Survey				-	-	-	-		20		-
Normal B stars	β Tau	B7III	13000	6	-	-	-	-	-	Imaging		-
	α And	B8IV	11500	4.5	-	-	-	-	-	Imaging		25
	+ Survey				-	-	-	-	-	53		-
Classical Be Stars	γ Cas	B0.5IVpe	26500	15	Imaging	-	-	-	-	Imaging		50
	ϕ Per	B1.5Ve	23000	12	Imaging	-	-	-	-	Imaging		24
	α Ara	B3Ve	18000	8	-	Survey	Survey	MIDI	Survey	-		25
	κ Dra	B6IIIe	14000	5	Imaging	-	-	-	-	Imaging		214
	O Aqr	B7IVe	13000	4.5	Imaging	Survey	-	-	Survey	Imaging		-
	β CMi	B8Ve	11500	4	Survey	Survey	Survey	MIDI	Survey	Imaging		24
	+ Surveys				29	26	7	PIONIER	12	60		+29 stars with data
B[e] stars	FS CMa	B2V[e]	19000	5	-	Survey	Imaging	PIONIER/MIDI	-	Imaging	SPHERE	22+26
	HD 50138	B9V[e]	11000	4	-	Survey	Imaging	PIONIER/MIDI	Imaging	Imaging	GRAVITY	22+26
	l Pup	A4Iab[e]	8500	15	Survey	Imaging	Imaging	MIDI	-	Survey	GRAVITY	2x25
	MWC 300	B1Ia+[e]	19000	20	-	Survey	Survey	MIDI	Imaging	-	SPHERE	-
	+ Surveys				3	6	12	MIDI/PIONIER	4	5	GRAVITY/SPHERE	+1 star with data
Hot Supergiants stars	Rigel	B8Ia	12000	18	Survey	Survey	Survey	GRAVITY	-	Imaging	SPHERE	Raw data
	η Leo	A0Ib	9600	10	-	-	-	-	Survey	Imaging	SPHERE	-
	Deneb	A2a	8700	20	Survey	-	-	-	-	Imaging	-	Raw data
	+ Surveys				2	-	-	-		34	-	-

Table 1: List of the primary targets of the ANR project, detailing the available data and future observations, and including the number of secondary (survey) targets for each class of objects.

2.6 Distribution of the work and scheduling

The organisation of the project is straightforward: each node is responsible for one of the theoretical work packages: Toulouse for stellar interiors (WP1), Paris for asteroseismology (WP2), and Nice for polychromatic image synthesis (WP3). Each of these work-packages can be started independently with the presently available tools.

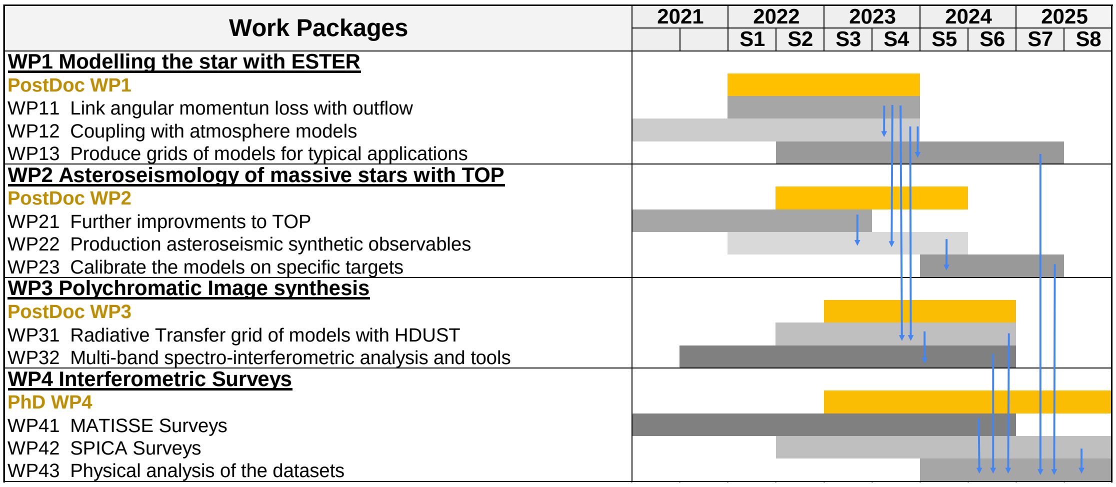
M. Rieutord will focus on the development of the ESTER code, and a postdoctoral fellow will work on the inclusion of angular momentum loss and outflow (Task WP11) supervised by M. Rieutord who will continue working on the coupling of the code with atmosphere models (WP12) and the production of a grid of interior and photosphere models (WP13) that will be publicly distributed and used in other work packages of the project (WP3 & WP4).

D. Reese will continue to develop the TOP code in order to finalise the non-adiabatic version and use updated versions of ESTER models after the inclusion of mass and angular-momentum loss (Task WP11) and atmosphere models (Task WP12). Under his supervision, a postdoctoral fellow will work on setting up realistic line profile variations and supplementing the grid of models with seismic observables (WP22). He/she will also participate in the seismic interpretation of landmark stars using these seismic observables (W23).

The interactions between WP1 & WP3 will focus on updating the HDUST radiative transfer tool (task WP31) using outputs from ESTER (from tasks WP11 for the CSE and WP12 for the central star). This will be the main task of the postdoctoral fellow under the supervision of A. Meilland and A. Domiciano de Souza. He/she will also interact with F. Millour on aspects of multi-band spectro-interferometric analysis (WP32).

The interferometric survey on 200 stars (WP4) will centre on the interactions between the groups. Observations with MATISSE & SPICA will be performed by people from Nice, including the PhD student who will focus on SPICA observation data analysis and image reconstruction under the supervision of A. Domiciano de Souza and F. Millour. Nevertheless, the physical analysis of the data will depend on the results of all WPs, and involve the entire ANR team.

MATISSE observations (WP41) have already started and will continue until 2025. SPICA will



Work Packages	2021		2022		2023		2024		2025	
			S1	S2	S3	S4	S5	S6	S7	S8
WP1 Modelling the star with ESTER										
PostDoc WP1			■	■	■	■				
WP11 Link angular momentun loss with outflow			■	■	■	■				
WP12 Coupling with atmosphere models	■	■	■	■	■	■				
WP13 Produce grids of models for typical applications				■	■	■	■	■	■	
WP2 Asteroseismology of massive stars with TOP										
PostDoc WP2				■	■	■	■			
WP21 Further improvments to TOP	■	■	■	■	■					
WP22 Production asteroseismic synthetic observables			■	■	■	■	■			
WP23 Calibrate the models on specific targets							■	■	■	
WP3 Polychromatic Image synthesis										
PostDoc WP3					■	■	■	■		
WP31 Radiative Transfer grid of models with HDUST				■	■	■	■	■		
WP32 Multi-band spectro-interferometric analysis and tools		■	■	■	■	■	■	■		
WP4 Interferometric Surveys										
PhD WP4					■	■	■	■	■	■
WP41 MATISSE Surveys	■	■	■	■	■	■	■	■		
WP42 SPICA Surveys				■	■	■	■	■	■	■
WP43 Physical analysis of the datasets							■	■	■	■

Table 2: Gantt diagram of the MASSIF Project. Blue arrows represent interactions between tasks.

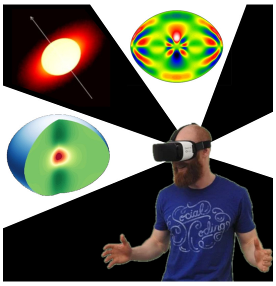
be installed in CHARA next year, and observations should start in late 2022 or early 2023 (task WP42). Its three-year survey will last until the end of the ANR project. The collected data will be reduced, analysed with simple models and published continuously (4 or 5 publications). The physical analysis (WP43) will be performed on each type of objects as soon as the modelling tools from the other packages will be available. Statistical results will be published at the end of the surveys.

The scheduling of the project, planned over 4 years, is sketched out in a Gantt diagram presented in Table 2.

2.7 Timeliness of the project

In the context of the recent developments of astrophysics, this project is timely and relevant for many reasons. First, as mentioned above, recent observations are yielding a wealth of data about massive stars that are only very partly understood. All these data come from costly investments, either space missions (e.g. KEPLER, TESS, CHEOPS) or VLT(I) instruments (e.g. SPHERE, GRAVITY, MATISSE). Moreover, during the foreseen run of the project (2021-2025) GAIA will release its third catalogue with increased accuracy in the distances (interesting for massive stars, which are all quite distant from Earth), not to forget SPICA (PI D. Mourard), which will be on the sky in 2022 at the CHARA array (Mount Wilson). We note that the SPICA all-sky survey will be funded by the newly awarded ERC ISSP just obtained by D. Mourard. In the longer term this project also prepares for future observations with the E-ELT (coronographic observations of massive stars), and with GRAVITY+, a combiner increasing the sensitivity by 5 magnitudes in 2024 that could observe massive stars in the LMC & SMC. The new HDUST version under development will allow a more realistic description of the CSE. The project is also timely as the ESTER project, supported by ANR in 2009-13, is now showing its true potential. It delivered the first reliable and self-consistent 2D models of early-type stars (differential rotation and meridional circulation are not ad hoc). The code is available at `http://ester-project.github.io/ester/`. The proponents are now at the cutting edge of multi-dimensional modelling of stellar evolution with fast rotation. The application of ESTER to massive stars will naturally follow the PhD work of D. Gagnier, who made the first steps into their complicated rotational evolution, and will take advantage of the new spectral synthesis of fast rotating stars which is presently under design.

2.8 Dissemination and outreach activities



Besides the classical dissemination of our results such as publications in international academic journals like A&A, their presentation in international conferences, as well as outreach activities like press releases, articles in popular science journals (e.g. *l'Astronomie* n^{o}141), outreach videos, and public conferences, that we already do on a regular basis, we foresee developing a Virtual Reality (VR) environment able to display our 3D models "as if" we were flying into the environment of massive stars. Such an environment will be developed using Unity (a free 3D game development system), a gaming PC and a VR headset.

2.9 Financial side

The foreseen financial support requested by this project amounts to 515.6k€ (including the 12% environmental costs). The main part of the requested funding will be used to finance non-permanent researchers (rounded values):

- 104k€: for the 2 years of salary for the postdoctoral fellow working in Toulouse on WP1.
- 115k€: for the 2 years of salary for the postdoctoral fellow working in Paris on WP2.
- 97k€: for the 2 years of salary for the postdoctoral fellow working in Nice on WP3.
- 105k€: for the 3 years of fellowship for the PhD student working in Nice on WP4.

The remaining funds will be used as follows (rounded values):

- 13k€: to buy computers and other equipment, for permanent and non-permanent researchers.
- 19k€: for missions between our institutes and conferences.
- 10k€: for internships of master students.

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