ERC Consolidator Grant 2015
Research proposal [Part B2]

Part B2: *The scientific proposal* (max. 15 pages)

Section a. State-of-the-art and objectives

Is there any universal slope of the substellar mass function? How do metallicity and age affect photospheres and colours? How do ultra-wide low-mass binaries form? Do the least massive stars have habitable exoplanets? These major questions in low-mass star and brown dwarf Astrophysics have been tried to be answered repeatedly in the last 20 years, but no uncontrovertible or precise responses to them exist to date. For answering them correctly, we need the accurate input of the European Space Agency's space mission *Gaia* and the most comprehensive, homogeneous, mistake- and bias-free sample of cool and ultra-cool dwarfs ever assembled. In spite of the recognised necessity of such a catalogue or meta-archive, as stated by several contributors of both sides of the Atlantic during the GREAT-ESF workshop on *"Gaia and the Unseen. The brown dwarf question"*[1], it does not exist yet. There are already some cool dwarf catalogue initiatives, but the provided data are limited by the dedication of the archive curators or by the restrictions imposed by the funding bodies.

The main objective of MAIA[2] is to help answering the major questions above on cool and ultra-cool dwarfs through the design, construction and maintenance of the 'M-, L-, and T-dwarf Archive of Interest for Astrophysics'. The MAIA meta-archive will be the first catalogue that will provide, in a friendly way and to all astronomers worldwide, a large compilation of data on late-type dwarfs, including *Gaia*'s astrometric data, high- and low-resolution spectra and homogeneously derived parameters.

At the beginning of this section, I have identified four representative major, state-of-the-art queries in low-mass star and brown dwarf science as illustrative examples of what the MAIA 'M-, L-, and T-dwarf Archive of Interest for Astrophysics' can provide to the field. Maybe not by chance I have contributed or am contributing significantly to try to solve the four questions:

1. *Is there any universal slope of the substellar mass function?* The substellar mass function has been investigated in the field (Reid et al. 1999; Gizis et al. 2000; Cruz et al. 2007) and in a number of star-forming regions, young associations and open clusters (e.g., Bouvier et al. 1998 and Bihain et al. 2006 in the Pleiades; Béjar et al. 2001 and **Caballero** et al. 2007 in σ Orionis; Muench et al. 2002 in the Trapezium; Briceño et al. 2002 in Taurus; Luhman et al. 2003 in IC 348). Some reviews on low-mass stellar and substellar mass functions have hundreds or even thousands of citations, but there is no agreement yet on the numeric value of the slope of the

[1] http://gaiabds.oato.inaf.it/
[2] **http://exoterrae.eu/maia/**

mass function below the hydrogen burning mass limit in the Salpeter's power law scheme, or even if the mass function is better described by a log-normal curve instead (Luhman et al. 2000; Kroupa 2002; Bate et al. 2003; Chabrier 2003). **Caballero** (2009) proposed that the Salpeter's slope of the power law at $\alpha=+2.35$ is valid in the σ Orionis cluster from 18 to 1 M_{sol}, approximately, but that below one solar mass there is a shoulder down to 0.4 M_{sol}, approximately, below which the slope is constant at $\alpha=+0.4\pm0.1$ down to below the deuterium burning mass limit at 0.013 M_{sol}. However, there is not an agreement yet on the location of that shoulder, the slope in the low-mass stellar and substellar domain in σ Orionis, other open clusters or the field (it has been reported to vary in different regions from $\alpha=-0.2$ to +1.0). MAIA will allow astronomers to determine the most accurate field mass function, to derive the best luminosity-mass relations, and to measure the most accurate distances to open clusters, from which astronomers will be able to determine the most accurate cluster mass functions. Once for all, mass functions in the field and in a number of clusters will be computed in a homogeneous way and, eventually, a direct comparison will be possible. It is expected that such a work will attract numerous citations.

2. *How do metallicity and age affect photospheres and colours?* As for high-mass and Sun-like stars, photometric colours of low-mass stars and brown dwarfs depend mainly on effective temperature, which rules the formation and destruction of atomic lines and molecular bands in photospheres. Basically, M dwarf spectra are dominated by deep absorption bands of metallic oxides, especially of TiO and, at the latest types, VO, and neutral metallic lines, especially of alkali atoms (Kirkpatrick et al. 1991; Alonso-Floriano et al. 2015 and references therein). The output flux in the blue optical is very low, with the peak of emission at the boundary between the red optical and the near infrared. L dwarfs are even redder in both the optical and infrared, and their spectra are characterised by the gradual condensation and desappearance of TiO and VO, which form dust grains, the appearance of hydrides and the broadening of alkali lines. Collisions of neutral and ionised H atoms also play a key rôle in the total photosphere opacity (Kirkpatrick et al. 1999; Martín et al. 1999). Colours of T dwarfs become redder and redder in the optical, but there is a reversion of colours in the near-infrared, produced by the appearance of methane absorption bands, which get stronger toward the latest T dwarfs (Burgasser et al. 2006). In the photospheres of Y dwarfs, with the latest spectral type defined to date, methane bands are replaced by ammonia and, in the coolest cases, water bands. Their effective temperatures are so cool that the peak of emission is shifted to the mid-infrared, and optical observations become unfeasible with current telescopes. On top of this complexity, there are second order variations of the spectra and, thus, colours of late-type dwarfs because of variations in their surface gravity and metallicity. Gravity is strongly related to age, epecially to young ages in cool and ultra-cool dwarfs (which have not had enough time since the formation of the Universe to quit the Main Sequence – or even some of them [brown dwarfs] never were in the Main Sequenc). Young and very-young stars and brown dwarfs have larger radii and, consequently, lower surface gravities than field dwarfs of the same spectral type and Sun-like age, because they are still in the contracting phase. It seems that these low-gravity features are still detectable in the

spectra of Pleiades brown dwarfs, of about 120 Myr (triangular profile in the *H* band, lesser absorption in the near-infrared; Bihain et al. 2010). The relative low number of investigated young brown dwarfs, especially in young moving groups, and heterogeneity in the data analysis, have prevented to draw a definitive, quantitative conclusion on how age (gravity) affects their photospheres. Something very similar happens to the presence of metals in those photospheres: the higher the metallicity, the redder the objects, and vice versa. While low-metallicity (purple) brown dwarfs do exist (Burgasser et al. 2003), there are not enough works yet on the comparative study of L dwarfs in wide multiple systems with F, G and K primaries, to which detailed metallicity analyses can be applied. Such comparative studies with M dwarfs in wide multiple systems with earlier primaries are becoming more and more common (Rojas-Ayala et al. 2012; Montes et al. 2013; Mann et al. 2014). MAIA will tabulate all available parameters ($T_{\rm eff}$, colours, log*g*, [Fe/H]) for the largest sample of MLT(Y) dwarfs ever compiled.

3. *How do ultra-wide low-mass binaries form?* With a spectral type ≥M9 V, DENIS-P J0021.0–4244 was at the end of the previous millenium one of the coolest known isolated field dwarfs (Tinney 1998; Delfosse et al. 1999). At that time, only a few benchmark cooler objects had been identified as companions to more massive bodies (Becklin & Zuckerman 1988; Nakajima et al. 1995; Rebolo et al. 1998) or free floating ones (Ruiz et al. 1997; Kirkpatrick et al. 1999). Since then, hundreds of stars and brown dwarfs with very late M, L, T and Y spectral types have been discovered in the field in direct imaging. By early 2007, many of them were faint companions to stars at separations of between 15 and ~3600 au (with mass ratios $q \equiv M_2/M_1 < 0.5$; Kirpatrick 2005; Burgasser et al. 2005, and references therein) or formed tight binary systems with separations smaller than ~20 au (with mass ratios $q > 0.5$; Burgasser et al. 2006). There were only three known relatively wide ultracool binary systems in the field with separations of the order of 30–40 au and total masses below ~0.2 $M_{\rm sol}$ (Harrington et al. 1974; Phan-Bao et al. 2005; Burgasser & McElwain 2006) and one truly very wide low-mass binary, with a physical separation significatively larger than the rest, discovered by Billères et al. (2005; ~220 au, $M_1 \approx 0.090\ M_{\rm sol}$, $M_2 \approx 0.075\ M_{\rm sol}$). As a result, there was a major surprise when **Caballero** (2007a) first and, next, Artigau et al. (2007) and Radigan et al. (2009) discovered ultra-fragile binary systems of the same total mass as the Billères et al.'s one, but with amazing projected physical separations greater than 1000 au. Such ultra-wide low-mass binaries, which were considered for a cover page in Astronomy & Astrophysics in the case of the Caballero's discovery, have not been matched yet. There are wider systems containing ultra-cool dwarfs, but have greater total masses (e.g., the widest system containing an L dwarf was also identified and confirmed for the first time by **Caballero** 2007b). This rare example of ultra-wide low-mass binaries represent a challenge for star-forming scenarios. It is thought that the two components were ejected simultaneously and with the same direction and velocity from the parental molecular cloud, and that later became gravitationally bound, but it may also happen that they were less separated originally and that the Galactic perturbation is slowly disrupting the system. MAIA will contribute with the provision of a precise statistics of the number of wide and

ultra-wide low-mass binaries and their separation as a function of total mass. Such statistics must be the input for new hydrodynamics simulations of fragmentation of molecular clouds and subsequent star and sub-stellar formation.

4. *Do the least massive stars have habitable exoplanets?* For M-dwarf stars, some radial-velocity studies have already been carried out and yielded results similar to Sun-like stars, but still with poor statistical significance (ESO CES, UVES and HARPS by Zechmeister et al. 2009, 2013; CRIRES by Bean et al. 2010a; HARPS by Bonfils et al. 2013). In particular, the abundance of planets as a function of mass and orbital distance to their M-dwarf hosts is very loosely constrained, and the much-sought value of $\eta_{\oplus}$, i.e., the relative abundance of Earth-type planets in the habitable zone, from HARPS data still has a one-σ interval of 0.28 to 0.95 (Bonfils et al. 2013). On the other hand, from *Kepler* data, Swift et al. (2013) calculated an occurrence rate of 1.0±0.1 planets per M dwarf, regardless of the planet mass. Afterwards, Dressing & Charbonneau (2013) and Kopparapu (2013) investigated the occurrence rate of planets with masses in the 0.5–1.4 and 1.4–4 $M_{\oplus}$ intervals around cool stars ($T_{\rm eff}$ < 4000 K in their sample). With the new conservative habitable zone estimations from Kopparapu et al. (2013), the terrestrial planet frequency around M dwarfs gets $\eta_{\oplus} = 0.48\pm0.12$, in agreement with the HARPS radial-velocity estimate at $\eta_{\oplus} = 0.41\pm0.54$. These values are certainly favourable for the detection of Earth-like planets around M-dwarf stars. Indeed, according to Dressing & Charbonneau (2013) and with 95 % confidence, the nearest non-transiting (transiting) Earth-size planet in the habitable zone of a cool star is just within 5 pc (21 pc).
The next exoplanet-devoted observatories in space, which are planned to be launched between 2017 and 2024, will use again the transit method: *TESS*, *CHEOPS*, and *PLATO*. Other space missions, such as *Gaia* and *James Webb*, which have a wider astrophysical interest, will also play a key rôle in the discovery and characterisation of exoplanets. On the ground, astronomers pin their hopes for updating current high-resolution optical spectrographs with laser combs or building new ones with a better thermo-mechanical stability and/or at larger telescopes (ESPRESSO/VLT; iLocater/LBT; G-CLEF/GMT - see Table 1 in Crossfield 2014). However, by the middle of 2015, many astronomers have now turned their eyes to M dwarfs and high-resolution spectrographs in the near-infrared. Dwarf stars of M spectral type have effective temperatures between the coolest K dwarfs and the warmest L dwarfs ($T_{\rm eff} \approx$ 3900–2300 K – Kirkpatrick et al. 2005; Rajpurohit et al. 2013). For ages older than that of the Hyades (considered to be among the oldest juvenile clusters for which members are spectroscopically indistinguishable from M dwarfs in the field), of about $\tau \sim 0.6$ Gyr, those effective temperatures translate in the main sequence into a mass interval from 0.55 to 0.09 $M_{\odot}$, approximately (Baraffe et al. 1998; Chabrier et al. 2000; Allard et al. 2011). In principle, the lower the mass of a host star, the higher the radial-velocity amplitude that an exoplanet of fixed mass induced on its star ($K_{\rm star} \sim M_{\rm planet}\, a^{-1/2}\, (M_{\rm star} + M_{\rm planet})^{-1/2} \approx (a\, M_{\rm star})^{-1/2}$ when $M_{\rm star} \gg M_{\rm planet}$). Besides, the lower luminosity of an M dwarf with respect to a star of earlier spectral type makes its habitable zone, the region around it within which a planet can support liquid water, to be located very close to the host star (not

counting tidal locking, coronal mass ejection activity, basic planet atmosphere parameters –albedo, surface pressure, heat transfer between illuminated and dark hemispheres–, or on-going tectonic activity and carbon cycle, among other issues). This closeness makes habitable planets around M dwarfs (at ~0.1 au) to be easier to detect than around solar-like stars (at ~1 au). All in all, one of the the suggestions in the 2010 report on Europe's 2–4 m optical/infrared telescopes over the next decade, prepared by the ASTRONET-OPTICON European Telescopes Strategic Review Committee (ETSRC), was the development of *"highly- stable, high-resolution spectrographs in the near-infrared, capable of delivering [radial-velocity] with precision better than 1 m* s^{-1} *[to] conduct [radial-velocity] surveys of M dwarfs to find Earth-size planets in the habitable zone"*.

As outlined in detail by Reiners et al. (2010), the most basic idea behind using near-infrared spectrographs instead of optical ones for intensive radial-velocity monitoring of M dwarfs is their faintness bluewards of 1 μm. While the spectral energy distributions of M dwarfs approximately peak at 1.0–1.2 μm, HARPS and its copy at the 3.6 m Telescopio Nazionale Galileo, HARPS-N, cover only the wavelength interval from 0.38 to 0.69 μm. That faintness is illustrated quantitatively with the tabulated *V* magnitudes of the brightest M dwarfs in the northern hemisphere (HD 79210, HD 79211, and HD 95735) at 7.5–7.7 mag, far from the limit of the naked human eye. Before the ETSRC report, the 21st century's first decade saw the birth and development of some projects aimed at the construction of high-resolution near-infrared spectrographs, which had varying degrees of success (Giano/TNG; IR ET/ARC 3.5 m; NAHUAL/GTC; PRVS/Gemini; UPF/UKIRT). Currently, the upcoming "battle horses" with secured funding and that have passed design reviews are SPIRou (Artigau et al. 2014, France-Canada), IRD (Kotani et al. 2014, Japan), HPF (Mahadevan et al. 2014, US), and CARMENES (Quirrenbach et al. 2014, Germany-Spain), of which **Caballero**, the MAIA PI, is the co-project manager. It is expected that all of these high-resolution near-infrared spectrographs will have their first light between 2015 and 2017, and that will be demanded at short term not only for radial-velocity surveys of M dwarfs with exoearths, but also at mid and long term for the spectroscopic follow-up and confirmation of exoplanet candidates of all masses discovered by *Gaia*, *TESS*, and *PLATO*. By the end of the next decade, we may also have HIRES+METIS at the 39 m E-ELT, NIRES- B+R at the 30 m TMT, and GMTNIRS at the 25 m GMT, which would fill the gap noticed by the ETSRC and many other astronomers worldwide and, perhaps, open the window to the spectroscopic characterisation of exoearths around cool dwarfs.

MAIA will provide astronomers with a comprehensive list of the brightest single M dwarfs with accurate astrophysical parameters. Some of these parameters will be activity indicators, rotational activity or photometric periods, from where one can select the targets with the narrowest lines (ideal for radial-velocity searches), the greatest photometric stability (and, thus, absence of cool spots) and, very interestingly, inclination angles if both *P* and *v*sin*i* are known (ideal for transiting searches when M dwarfs have high inclination angles – i. e., almost edge-on). Furthermore, **Caballero** & Rebolo (2002) proposed for the first time the search of habitable planes around early L dwarfs, which have very long main-sequence lifes.

Section b. Methodology

MAIA follows a strict project management structure in engineering, by which all activities are assigned to a series of specific work packages (WPs). The core of MAIA is the 'M-, L- and T-dwarf Archive of Interest for Astrophysics', the meta-archive itself. As seen in the "MAIA mind map" in Fig. 1 of document B1, all MAIA work packages radiate to and from the meta-archive:

- **WP1: Input**. This work package splits in turn into three complementary sub-work packages: WP1.1 on Catalogues, WP1.2 on Observations and WP1.3 on Data mining. They head for Archive.
- **WP2: Meta-archive**. The boundary between sub-work packages becomes blurrier, but the activities to be done are clear: implementation and maintenance of the data server and of a friendly graphical user interface, and massive data compilation. It heads for Output.
- **WP3: Output**. This is where the biggest novelty of MAIA lies with respect to previous catalogues. Together with all raw data, users will be able to download M-, L-, and T- dwarf basic astrophysical parameters determined by our team in the most accurate and homogeneous (or consistent) way. It heads for Science exploitation.
- **WP4**: **Science exploitation**. An archive that is not exploited scienfically is a waste of time and resources. The MAIA research team, alone and in collaboration with worldwide experts, will try to answer or revisit the major pending questions in low-mass Astrophysics. The main research lines are: Multiplicity, Luminosity/mass function, Young stars and brown dwarfs, Fundamental parameters, Benchmark objects, Peculiar objects, and Targets for exoplanet searches.

The MAIA research team will be composed of six people: **three postdocs, one computer engineer, one PhD student** and **the PI**. The main tasks of the computer engineer lie only within WP2, especially related to the data server and GUI. The PhD student will be in charge of the data ingestion into the archive and support of WP1 tasks (this approach has been sucessfully applied to Carmencita, the "CARMENES input catalogue"). The three postdocs will be responsible of the remaining work packages: the first one of WP1, including observations, data mining and catalogues; the second one of WP3, on parameter determination; the third one of WP4 and of helping the PI in coordinating all science exploitation efforts. The PI will participate in all WPs.

Although the three postdocs will have each their own responsibility, it is expected that they will collaborate in more than one WP, e.g., by attending to observations that are not carried out in service mode, helping other postdoc(s) or the PhD student with the target selection of numerous input catalogues and public archives, or taking the leadership of some science exploitation areas in which he/she is an expert. All postdocs and PhD students will collaborate in the science exploitation (WP4).

Apart from the reserch team, there is a large number of **external collaborators**, inside and outside the PI's host institution, in Spain and abroad, that have expressed their interest in participating in particular tasks of MAIA, especially related to their own areas of interest and expertise. All external collaborators will participate, again, in the science exploitation, which will benefit the useability and dissemination of MAIA. Besides, as described below, some external collaborators will also participate in work packages WP1 (input) and WP3 (output).

A detailed description of the **specific tasks** within each work package goes here (see again the illustrative "MAIA mind map" in Fig. 1 of document B1):

- **WP1.1. Catalogues**. The main input to MAIA targets are previous catalogues and meta-archives. Currently, the best examples of such meta-archives are DwarfArchives.org (of most L and T dwarfs and subdwarfs published to date with no selection criteria, and many bright M dwarfs) and RECONS (of nearby stars and brown dwarfs of all spectral types, including M, L, T and Y, with parallactic distance). A StarArchive.org of stars and brown dwarfs later than M6 V and closer than 25 pc is also under construction. Carmencita, which is not public yet, is the "CARMENES input catalogue" (**Caballero** et al. 2013; Alonso-Floriano et al. 2015) and contains all M dwarfs observable from the northern hemisphere that satisfy a certain spectral type-*J* magnitude selection criterion. MAIA would be fed by these meta-archives and by all known public catalogues and works on cool and ultracool dwarfs in the solar neighbourhood. Works from which MAIA will also benefit are the classic ones by Wolf, Ross, Luyten and Giclas, and the most recent ones by Henry, Reid, Cruz, Gizis, Lépine, Gaidos, etc. for M dwarfs, and by Delfosse, Kirkpatrick, Martín, Burgasser, etc. for L and T dwarfs. Besides, there exist preliminary conversations with Hartmut Jahreiss (ARI/ZAH Heidelberg), who is working on a new version of the famous Gliese-Jahreiss catalogue. Sabine Reffert (LSW/ZAH Heidelberg) will contribute to some tasks within WP1.1.
- **WP1.2. Observations**. Although most MAIA potential targets have been already subject of low-resolution spectroscopic studies, data are not in general accesible to the public or are not useable for a homogeneous parameter determination. To fill these gaps, a team including the PI and key external collaborators in Italy and Uinted Kingdom are working already on it. Main co-investigators of the telescope time proposals that fill those gaps are Richard J. Smart (INAF/OATo), Hugh R. A. Jones, Federico Marocco, David J. Pinfield (University of Hertfordshire), and the MAIA PI. He is the principal investigator of an on-going, 20-h awarded, filler programme of low-resolution spectroscopy of bright L dwarfs with Osiris at the 10.4 m Gran Telescopio Canarias (GTC). GTC science staff members Antonio Cabrera-Lavers and David García-Álvarez contribute to the data taking and reduction. A complementary proposal, but for bright L dwarfs in the southern hemisphere to be observed with X-Shooter at the VLT with higher resolution, is led by Smart, while another large proposal, led by Marocco and with the support of PhD student Neil Cook (University of Hertfordshire), has been submitted for international time of the Canarian telescopes (GTC, Isaac Newton Telescope, Mercator). In particular for this proposal, we ask for time to investigate astrometrically and spectroscopically new late-type companion candidates and their primaries. These observations will be complemented with previous and new ones. Among the previous observations, Adam J. Burgasser (UC San Diego) and Jacqueline K. Faherty (Carnegie DTM, Washington DC) will kindly provide us their numerous infrared spectra of late M, L and T dwarfs obtained with SpeX at the

IRTF. Another large assemble of optical spectra of identical targets collected in various telescopes may also be provided by J. Davy Kirkpatrick (IPAC Caltech). This provision of spectra is remarkable, because US funding bodies forbid using their resources to make them public, but allow that a third entity (EU funded, in this case) makes them available to all astronomers worldwide. Besides, we will include in our database all available data from other public archives, such as those from GTC, CARMENES, the European Southern Observatory and LAMOST. Preferent access to new LAMOST spectra of cool dwarfs might be feasible through ZhaoXiang Qi (SHAO Shanghai) and JianRong Shi (BAO Beijing). New observations will focus on building a homogenous sample of cool and ultracool dwarfs investigated with the same near-infrared and optical instrumentation suites, especially for high-resolution spectroscopy of late M and early L dwarfs (e.g., CARMENES in open time), mid- and low-resolution multi-band spectroscopy of late L dwarfs and early T dwarfs (X-Shooter in the south, Osiris in the north), and high-resolution imaging with adaptive optics or lucky imaging at all spectral types. Amelia Bayo (Universidad de Valparíso), Karla Peña-Ramírez and Juan Carlos Beamín (Pontificia Universidad Católica) will facilitate the access to some astronomical instruments in Chile. Alternative new observations may be carried out at sub-millimetre wavelengths with ALMA, but in this case the research team should look for new external collaborators.

- **WP1.3. Data mining**. The main target data source will be *Gaia*. The ESA's astrometry space mission will provide, in consecutive data releases during the execution of the MAIA project, accurate coordinates, proper motions, parallactic distances and optical photometry in at least *BP* and *RP* broad bands. For the brightest M dwarfs in the MAIA sample, *Gaia* will also provide radial velocities, although these measurements may be superseded quickly by RAVE, LAMOST and dedicated observations with long-slit or single-fibre-fed spectrographs at ground telescopes (e.g., ESO-*Gaia*). The *Gaia* parallactic distances and proper motions will be a turning point in the quality of measurements of cool and ultracool dwarfs (either bright single or faint companions to bright primaries). Carme Jordi (Universidad de Barcelona), Johannes Sahlmann (ESA) and Alessandro Sozzetti (INAF/OATo) will share their expertise on *Gaia* data analysis with our research team. Comparable accuracies in the remaining parameters are needed to derive the most precise astrophysical parameters for the MAIA targets. Current public catalogues that will be able to complement *Gaia* data are mostly photometric: *WISE* and *Akari* in the mid-infrared, DENIS, 2MASS, UKIDSS and VISTA in the near-infrared, the latest data releases of SDSS, UCAC and CMC in the optical, *GALEX* in the ultraviolet, and *ROSAT*, *XMM-Newton*, *Chandra* and eROSITA onboard *Spectrum-RG* in X-rays. Besides that, we will do data mining on *Gaia* data to look for unnoticed cool and ultracool dwarfs. Currently, Enrique Solano, Francisco Jiménez-Esteban (CAB) and the MAIA PI are carrying out pilot programmes of virtual observatory searches of bright late M dwarfs that had escaped previous proper-motion surveys (e.g., Jiménez-Esteban et al. 2012; Aberasturi et al. 2014).
- **WP2. Archive**. The "façade" of MAIA will be a friendly, minimal, web-based search tool that will allow all astronomers worldwide to download an enormous amount of data on individual low-mass stars and brown dwarfs. The search tool will

be developed under MySQL and be visualised with all common web browsers. The data server software will follow all Virtual Observatory standards and the hardware will allow a big data download flow. Mauro López del Fresno (CAB), a computer engineer of the Spanish Virtual Observatory who has developed several astronomical databases, including the CARMENES Guranteed Time Observations archive, will be helpful in the development of the data server. The archive will likely be split into three sub-archives:

- *The bright MLT dwarf catalogue*. The goal is to inclue all *Gaia* T and late L dwarfs, most early L dwarfs and the brightest late M dwarfs in the whole sky. It will be a compendium of a few thousand cool and ultracool dwarfs (Haywood & Jordi 2002; Smart et al. 2008, 2015; Sarro et al. 2013, 2015; **Caballero** 2015). Initially, before the *Gaia* parallax release, the sub-archive will contain a few hundred targets, including all *Gaia* T dwarfs, most late L dwarfs, the brightest early L dwarfs and a few selected late M dwarfs, and it will increase smoothly in size with periodic additions and upgrades. Volume-limited samples free of the Malmquist's binary bias will be able to be defined afterwards, with larger and larger distance limits for each periodic addition. The sub-archive will be contiunuosly updated until the end of the ERC funding, on time to prepare a low-mass target input catalogue for the forthcoming ESA's exoplanet mission *PLATO*.
- *Faint LTY dwarf companion catalogue*. Same as the bright MLT dwarf catalogue, but with approximately one thousand L, T and Y dwarfs undetected with *Gaia* that are common proper-motion companions to relatively bright primaries.
- *Brown dwarf cluster member catalogue*. Same as the bright MLT dwarf catalogue, but with all substellar objects in young open clusters (and open associations?) imaged by *Gaia*. As foreseen by **Caballero** (2015), most of these brown dwarfs, in amounts of several dozens only, will be found in the Pleaiades, Upper Scorpius and σ/λ Orionis. These clusters and star-forming regions display the right age, low extinction and background, and relative closeness combination for *Gaia*.

For each individual MLT(Y) dwarf, MAIA will tabulate the following data, which will be a available in a number of VizieR-compatible formats (ascii, html/php, xml):

- Identifier and discovery name,
- *Gaia* coordinates, proper motions and parallactic distances,
- radial velocities (from high-resolution spectroscopy with ground telescopes),
- Galactocentric spatial velocities (and potential membership in kinematic group),
- magnitudes in as much photometric systems as possible (in general from *GALEX FUV* and *NUV*, SDSS *ugriz*, through *Gaia BP* and *RP* and 2MASS *JHKs*, to *WISE W1–4*),
- wide and close multiplicity data (roughly one out of five field brown dwarfs is a close binary),
- activity indicators (pseudo-equivalent widths of Hα and calcium triplet emission, X-rays),

- rotational velocity,
- photometric period,
- hyperlinks to public low- and high-resolution spectroscopic data,
- if possible, hyperlinks to public high-resolution imaging data,
- all homogeneously derived astrophysical parameters (T_{eff}, *R, L, M*, some reliable metallicity proxy, age, etc. – see below),
- references for each item,
- and any remark relevant for the reader.

- **WP3. Output (parameter determination)**. As mentioned above, current meta-archives of cool and ultracool dwarfs only list "input" parameters, but no astrophysical parameters. MAIA will be the first (and perhaps only, for a few years) meta-archive that lists basic homogeneously derived parameters: effective temperatures, radii, luminosities, masses, ages, metallicities and rotational periods. In case that total homogenity cannot be reached, which will likely be the case given the large dynamical range of investigated magnitudes and the large amount of targets to be followed-up, MAIA will list *the most consistently derived astrophysical parameters*. As an example, T_{eff}, *R* and *Z* can be obtained from fitting real intermediate- and high-resolution spectra to synthetic spectra of different T_{eff}, log*g* and [Fe/H], but it can be accomplished only for a few hundred targets with current available facilities. Effective temperature, radius and metallicity for the remaining fainter objects should be determined from spectral type, colours and, if they accompany brighter F-, G- and K-type stars, from synthetic analysis of high-resolution spectra of their primaries. There is a number of external collaborators who will participate in the parameter determination: Céline Réylé, Arvind S. Rajpurohit (Observatoire de Besançon), Eduardo L. Martín, María Rosa Zapatero Osorio (CAB), David Montes, Hugo Tabernero Guzmán (UCM Madrid) and José Gregorio Fernández Trincado (Université de Franche-Comté).
- **WP4. Science exploitation**. While the MAIA archive is a tool, the science exploitation is the goal of this ERC project. I have made seven blocks of science topics that cover the four major questions enumerated at the beginning of this document and virtually all low-mass stellar and substellar keywords: solar neighbourhood, cluster and associaions, activity, radial-velocity, transiting and astrometric exoplanets, etc. (see "MAIA mind map" in Fig. 1 of document B1). The research team, excluding the computer engineer, will be able to cover efficiently only four or five blocks. Depending of the expertise of the best postdoc candidates, such blocks will likely be Fundamental parameters and Benchmark objects (led by the WP3 postdoc for Parameter determination), Multiplicity (led by another postdoc), Young stars and brown dwarfs, Luminosity/mass function and Targets for exoplanet searches (led by the MAIA PI). The science exploitation inside the seven blocks will benefit from the expertise of the external collaborators that have showed their interest in participating in MAIA. Some of them were listed above as contributors to work packages WP1 and WP3 (e.g., Multiplicity and Benchmark objects: Cook, Marocco, Solano; Young stars and brown dwarfs: Montes; Fundamental parameters: Martín, Pinfield, Qi, Rajpurohit, Shi, Zapatero Osorio; Targets for exoplanet targets: Reffert, Sozzetti). Other external collaborators study

areas of interest that overlap with MAIA and wish to join forces with our research team (Young stars and brown dwarfs: Javier López-Santiago at UCM Madrid, Thomas Henning at MPIA; Luminosity/Mass function: Phil Lucas at University of Hertfordshire; Targets for exoplanet targets: Andreas Quirrenbach at LSW/ZAH Heidelberg, Ansgar Reiners at IAG Göttingen).

The apparent long list of external collaborators does not imply that MAIA is a network, but that the project gets richer with their collaboration. In other words, MAIA could be done only with the research team of six people (3 postdocs, 1 engineer, 1 student, 1 PI), but the results would not benefit from the expertise of *current* external collaborators. If not for these collaborations, the research team that has built the MAIA archive would not benefit fully from it, either.

The research team at CAB will be managed by the PI at the host institution in a standard mode, with weekly meetings among the six members and continuous interaction under the same roof. The CAB site at ESAC offers all the facilities to postdocs, computer engineers and students (except for laptops): double-person office, desktop computer, office supplies and wide bandwith ethernet connection in a natural environment. Periodically, external collaborators will visit CAB (and participate in the weekely meetings) and MAIA postdocs and students will visit other institutions or go observing.

Section c. Resources (including project costs)

- The resources table in page 12 has been prepared using a comprehensive template provided by the host institution (CSIC). Therefore, it should not contain flaws or errors. The project cost estimation is as accurate as possible.
- The requested contribution is in proportion to the actual needs to fulfil the objectives of the project. The baseline of the proposal resources is: 60 man-month (MaMo) for the PI; 162 MaMo for three postdocs; 60 MaMo for one computer engineer; 48 MaMo for a PhD student; equipment: a data server, six laptops (one for each team member) and two high-capacity external hard discs; 10 kEUR/year for trips of the team members, plus 1.5 kEUR/year for supporting trips of external collaborators; fees for international conferences and open-access publications. There is no senior staff in the team.
- PI: according to CSIC rules, dedication of ERC StG and CoG PIs who are not CSIC senior staff must be 100% mandatorily, and with the maximum salary allowed by ERC. If a permanent CSIC position were obtained during the execution of the project (fairly probable, since I have a tenure-track contract), dedication of PI would be decreased to a realistic value in the interval between 60 and 70%, depending on the project phase. The corresponding significant amount of money would be dedicated instead to other resources needs (especially trips of research team members).
- After the PI's, the most critical contract is perhaps that of the computer engineer, who will design, build and maintain the archive. The engineer should have a moderate astrophysics background (e.g., astronomy or space databases). A few individuals with this profile have been already identified at the European Space Astronomy Centre (the PI's working site).

COST CATEGORY			TOTAL [EUR]
DIRECT COSTS	Personnel	PI	**427500**
		Senior staff	**0**
		Postdocs	**699607**
		Students	**141260**
		Other	**231436**
	i. Total direct costs for personnel [EUR]		**1499803**
	Travel		**50000**
	Equipment		**18627**
	Other goods and services	Consumables	**4000**
		Publications (including open access fees)	**20000**
		Others (please specify)	**7500**
	ii. Total other direct costs [EUR]		**99767**
A. Total direct costs (i+ii) [EUR]			**1599570**
B. Indirect costs (overheads) 25% of direct costs [EUR]			**399892**
C1. Subcontractting costs (no overheads) [EUR]			**0**
C2. Other direct costs with no overheads (A+B+C) [EUR]			
Total estimated elegible costs (A+B+C) [EUR]			**1999462**
Total requested EU contribution [EUR]			**1999462**

For the above cost table, please indicate the duration of the project in months:	**60**
For the above cost table, please indicate the % of working time the PI dedicates to the project over the period of the grant:	**100%**

- The three postdocs will have contracts with a length of 4.5 years. Temporal order of contracting follows the work packages: first WP1 (MAIA input), next WP3 (MAIA output), last WP4 (science exploitation). According to my experience as a PI of a national project at CSIC (funded with over 265 kEUR), contracting of the best candidate that fits the requirements takes a few months per individual, which partly explains the 4.5 yr contract duration. The "Postdoc Three" on WP4 science exploitation may start at Year=1, instead of at Year=0.5 (4.0 yr contract duration), which would save another amount of money from personnel that could be devoted to other resources needs, if needed. The three postdocs will have the same salary, at the CSIC internal level FC2.
- The PhD student would focus on WP2 (data compilation) and one or two topics of science exploitation, very likely "Targets for exoplanet searches" and "Fundamental parameters". My two current PhD students will defend their theses in mid 2015 and

early 2016. The two of them are working on these topics, but specifically on a sample of bright northern M dwarfs. There may be an overlapping of a few months between the MAIA PhD student and my "younger" current PhD student, which would be beneficial for the knowledge transmission. PhD theses in Spain are officially four years (48 months) in length.

- Most of the funding invested in equipment goes to one laptop for each team member (2000 EUR each – the PI's one is five years old, and with no plan to be renewed; it may happen the same to the other five members) and a data server for the archive. This data server is a generic RAID server with at least 8 TB of internal capacity and redundancy; a cheaper option, already implemented for the current CARMENES data server, is a powerful PC tower with inexpensive, removable, high-capacity hard discs. However, this is not the optimal solution, as the reliability of the descoped data server would depend on the frequency of the safety copies in external devices by CAB personnel instead of on a RAID system. The remaining two external hard discs are necessary for copying raw data obtained in telescopes.
- Consumables include conference fees and, in very specific cases, issues that cannot be covered in other way (e.g., http://maia.eu/ internet domain renting, coffee breaks of MAIA meetings).
- 'Others' refer to financial support to external collaborators for visits or stays in Madrid. As a member of the ESAC Faculty, I can ask for a certain amount of money that could cover completely or partly such visits of external collaborators. The ERC funding would supplement funding when the external collaborator's internal project or the ESAC Faculty cannot cover completely the expenses of a trip.
- Budget devoted to publications increases yearly from 2 to 6 kEUR (i.e., I expect that there will be more and more papers during the execution of the project). Saving is foreseen if papers are published in European Astrophysics journals (e.g., Astronomy & Astrophysics, Monthly Notices of the Royal Astronomical Society), where authors can publish with no charge. MNRAS and some sections of A&A (e.g., Letters, Catalogues and data) are available freely to the public. In any case, all publications will be deposited in the astro-ph repository, which makes open-access journals rather unnecessary.
- The amount of money devoted to trips is a minimum value. The goal is that PI and postdocs have 7000 EUR per full-time-equivalent and per year for travels. This amount will allow yearly a one-week trip to America (e.g., US, Canadá, Chile; ~3000 EUR), two trips to Europe (e.g., France, Germany, Italy, United Kingdom; ~2 × 1000 EUR) and four trips within Spain (e.g., Barcelona, Granada/Almería, Tenerife; ~4 × 500 EUR). The travel needs of the PhD student and computer engineer will be lower. This goal can be easily achived if the PI dedication gets lower (and gets a permanent position). Probable data server saving, delays of contract starts and use of ESAC Faculty funding for supporting external collaborators trips to Madrid, without any other cut, will lead to an amount close to 6000 EUR per full-time-equivalent and per year for travels of PI and post-doc. Besides, the German Alexander von Humboldt Foundation can cover lodging and per diem of the PI for most of his trips to Germany (related to MAIA).

References.

Aberasturi, M.; **Caballero, J. A.;** Montesinos, B et al. 2014, AJ, 148, 36
Allard, F.; Homeier, D.; Freytag, B. 2011, ASPC, 448, 91
Alonso-Floriano, F. J.; Morales, J. C.; **Caballero, J. A.** et al. 2015, A&A, in press
Artigau, Étienne; Lafrenière, David; Doyon, René et al. 2007, ApJ, 659, L49
Artigau, Étienne; Kouach, Driss; Donati, Jean-François et al. 2014, SPIE, 9147, E15
Baraffe, I.; Chabrier, G.; Allard, F.; Hauschildt, P. H. 1998, A&A, 337, 403
Bate, Matthew R.; Bonnell, Ian A.; Bromm, Volker 2003, MNRAS, 339, 577
Bean, Jacob L.; Seifahrt, Andreas; Hartman, Henrik et al. 2010, ApJ, 713, 410
Becklin, E. E.; Zuckerman, B. 1988, Nature, 336, 656
Béjar, V. J. S.; Martín, E. L.; Zapatero Osorio, M. R. et al. 2001, ApJ, 556, 830
Bihain, G.; Rebolo, R.; Béjar, V. J. S.; **Caballero, J. A.** et al. 2006, A&A, 458, 805
Bihain, G.; Rebolo, R.; Zapatero Osorio, M. R.; Béjar, V. J. S.; **Caballero, J. A.** 2010, A&A, 519, A93
Billères, M.; Delfosse, X.; Beuzit, J.-L. et al. 2005, A&A, 440, L55
Bonfils, X.; Delfosse, X.; Udry, S. et al. 2013, A&A, 549, A109
Bouvier, J.; Stauffer, J. R.; Martin, E. L. et al. 1998, A&A, 336, 490
Briceño, César; Luhman, K. L.; Hartmann, Lee et al. 2002, ApJ, 580, 317
Burgasser, Adam J.; McElwain, Michael W. 2006, AJ, 131, 1007
Burgasser, Adam J.; Kirkpatrick, J. Davy; Burrows, Adam et al. 2003, ApJ, 592, 1186
Burgasser, Adam J.; Kirkpatrick, J. Davy; Lowrance, Patrick J. 2005, AJ, 129, 2849
Burgasser, Adam J.; Geballe, T. R.; Leggett, S. K. et al. 2006a, ApJ, 637, 1067
Burgasser, Adam J.; Kirkpatrick, J. Davy; Cruz, Kelle L. et al. 2006b, ApJS, 166, 585
Caballero, J. A. 2007a, A&A, 462, L61
Caballero, J. A. 2007b, ApJ, 667, 520
Caballero, J. A. 2009, AIPC, 1094, 912
Caballero, J. A. 2015, MmSAI, 85, 757
Caballero, J. A., Rebolo, R. 2002, ESASP, 485, 261
Caballero, J. A.; Cortés-Contreras, M.; Alonso-Floriano, F. J. et al. 2013, prpl.conf, 2K020
Chabrier, Gilles 2003, PASP, 115, 763
Chabrier, G.; Baraffe, I.; Allard, F.; Hauschildt, P. 2000, ApJ, 542, 464
Crossfield, Ian J. M. 2014, A&A, 566, A130
Cruz, Kelle L.; Reid, I. Neill; Kirkpatrick, J. Davy et al. 2007, AJ, 133, 439
Delfosse, X.; Tinney, C. G.; Forveille, T. et al. 1999, A&AS, 135, 41
Dressing, Courtney D.; Charbonneau, David 2013, ApJ, 767, 95
Gizis, John E.; Monet, David G.; Reid, I. Neill et al. 2000, AJ, 120, 1085
Harrington, R. S.; Dahn, C. C.; Guetter, H. H 1974, ApJ, 194, L87
Haywood, M.; Jordi, C. 2002, EAS Publications Series, 2, 199
Jiménez-Esteban, F. M.; **Caballero, J. A.**; Dorda, R. et al. 2012, A&A, 539, A86
Kirkpatrick, J. D.; Henry, Todd J.; McCarthy, Donald W., Jr. 1991, ApJS, 77, 417
Kirkpatrick, J. Davy; Reid, I. Neill; Liebert, James et al. 1999, ApJ, 519, 802
Kirkpatrick, J. Davy 2005, ARA&A, 43, 195
Kopparapu, Ravi Kumar; Ramirez, Ramses; Kasting, James F. et al. 2013, ApJ, 765, 131
Kopparapu, Ravi Kumar 2013, ApJ, 767, L8
Kotani, Takayuki; Tamura, Motohide; Suto, Hiroshi et al. 2014, SPIE, 9147, E14
Kroupa, Pavel 2002, Science, 295, 82

Luhman, K. L.; Rieke, G. H.; Young, Erick T. et al. 2000, ApJ, 540, 1016
Luhman, K. L.; Stauffer, John R.; Muench, A. A. et al. 2003, ApJ, 593, 1093
Mahadevan, Suvrath; Ramsey, Lawrence W.; Terrien, Ryan et al. 2014, SPIE, 9147, E1G
Mann, Andrew W.; Deacon, Niall R.; Gaidos, Eric et al. 2014, AJ, 147, 160
Martín, Eduardo L.; Delfosse, Xavier; Basri, Gibor et al. 1999, AJ, 118, 2466
Montes, D.; Alonso-Floriano, F. J.; Tabernero, H. M.; **Caballero, J. A.** et al. 2013, prpl.conf, 2K022
Muench, August A.; Lada, Elizabeth A.; Lada, Charles J.; Alves, João 2002, ApJ, 573, 366
Phan-Bao, Ngoc; Forveille, Thierry; Martín, Eduardo L.; Delfosse, Xavier 2006, ApJ, 645, L153
Quirrenbach, A.; Amado, P. J.; **Caballero, J. A.** et al. 2014, SPIE, 9147, E1F
Radigan, Jacqueline; Lafrenière, David; Jayawardhana, Ray; Doyon, René 2009, ApJ, 698, 405
Rajpurohit, A. S.; Reylé, C.; Allard, F. et al. 2013, A&A, 556, A15
Rebolo, R.; Zapatero Osorio, M. R.; Madruga, S. et al. 1998, Science, 282, 1309
Reid I. Neill; Kirkpatrick, J. Davy; Liebert, J. et al. 1999, ApJ, 521, 613
Rojas-Ayala, B.; Covey, K. R.; Muirhead, P. S.; Lloyd, J. P. 2012, ApJ, 748, 93
Ruiz, Maria Teresa; Leggett, S. K.; Allard, France 1997, ApJ, 491, L107
Sarro, L. M.; Berihuete, A.; Carrión, C. et al. 2013, A&A, 550, A44
Sarro, L. M., et al. 2014, MmSAI, 85, 637
Smart, R. L., et al. 2008, IAU Symposium, 248, 429
Smart, R. L. 2014, MmSAI, 85, 649
Swift, Jonathan J.; Johnson, John Asher; Morton, Timothy D. et al. 2013, ApJ, 764, 105
Tinney, C. G. 1998, MNRAS, 296, L42
Zechmeister, M.; Kürster, M.; Endl, M. 2009, A&A, 505, 859
Zechmeister, M.; Kürster, M.; Endl, M. et al. 2013, A&A, 552, A78