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CN2020B-20

Galactic panel
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faculty

A Clean Test of Gravity at Very Weak Accelerations

Abstract

We propose a long-term CNTAC program designed to provide the first unambiguous test for the behavior of gravity in the uncharted regime of accelerations that leads to the necessary adoption, under standard Lambda CDM cosmology, of large quantities of dark matter surrounding galaxies. This is the only available astronomical test today that is free from the ambiguities associated to the potential presence of any dark matter. Our gravity test will be achieved by measuring the 3D orbital velocities of the components of very wide binaries specifically chosen as having the highest quality astrometry delivered by the Gaia Data Release 2. Our program therefore consists of the measurement of the remaining velocity dimension, i.e., the radial velocities, of the components of the target binaries to precisions comparable to those of extrasolar planet studies. Only such measurements will allow us to control for the known systematics associated and provide a reliable result for the gravity test.

Observing Blocks

Instrument/Telescope	Req. time	Min. time	1^{st} Option	2^{nd} Option
FEROS/MPG 2.2-m	4 nights	3 nights	Any Any	Any Any

CoIs

Name	Institution	e-mail	Observer?
Victor Moraga	PUC	vmmoraga@uc.cl	True
Rafael Brahm	UAI	rbrahm@gmail.com	True
Andres Jordan	UAI	andres.jordan@uai.cl	False
Marcel Agueros	OnCL	marcel@astro.columbia.edu	False
Scott Tremaine	OnCL	tremaine@ias.edu	False
Jeff Andrews	OnCL	andrews@physics.uoc.gr	False
Simon White	OnCL	swhite@mpa-garching.mpg.de	False

Status of the project

- Past nights: 4
- Future nights: 12
- Long term: True
- Large program: False
- Thesis: False

List of Targets

ID	RA	DEC	Mag
Pair1A	14:16:47.58	-72:23:56.2	G=9.834166
Pair1B	14:18:17.87	-72:25:05	G=10.21355
Pair2A	04:02:10.02	-66:33:40.37	G=11.409089
Pair2B	04:02:25.32	-66:33:07.34	G=10.863148
Pair3A	04:33:11.83	-21:12:11.84	G=10.94978
Pair3B	04:33:16.15	-21:08:10	G=9.622008
Pair4A	05:08:16.22	-44:49:02.41	G=9.452269
Pair4B	05:09:39.80	-44:20:06.23	G=7.368841
Pair5A	17:40:44.38	-67:51:15.36	G=6.2019424
Pair5B	17:38:49.43	-67:49:14.68	G=9.965912
Pair6A	05:22:11.19	-03:27:45.69	G=11.080696
Pair6B	05:22:18.97	-03:23:06.9	G=11.112278
Pair7A	05:23:38.18	-55:35:26.39	G=9.052031
Pair7B	05:23:36.67	-55:33:48.44	G=10.377087
Pair8A	07:01:47.67	-87:20:31.69	G=9.341272
Pair8B	06:58:52.59	-87:18:17.73	G=8.480459
Pair9A	12:07:37.46	-42:24:52.03	G=10.631221
Pair9B	12:07:52.92	-42:20:19.91	G=8.862781
Pair10A	04:49:55.34	-22:14:31.19	G=11.023674
Pair10B	04:49:58.13	-22:14:49.79	G=9.442553
Pair11A	11:36:14.64	-44:14:06.45	G=11.321678
Pair11B	11:36:15.96	-44:08:03.78	G=10.942019

SCIENTIFIC AIM AND RATIONALE

Dark matter is one of the main ingredients of our current cosmology, ΛCDM, yet this is the case despite the increasingly worrisome fact that it continues to elude all efforts for its direct and indirect detection. All present-day evidence for its existence is of astronomical nature, and a large part of this evidence comes from the application of Newtonian dynamics (as a limit of General Relativity in the appropriate limit) to stars and gas in orbit at kpc distances from the centers of galaxies, where their rotation curves are observed to flatten. **However, it is often not realized, or largely overlooked, that applying Newtonian dynamics to this specific problem is, formally, an extrapolation of the theory**. This in the sense that, until today, there are no actual experiments, in the lab or even involving astronomical observations, in which Newtonian dynamics has been tested and validated for the regime of accelerations ($\sim 10^{-10}$ ms^{-2} and smaller) experienced by the stars and gas that act as test particles in the determination of the total mass of galaxies. There are also no precision tests of Newtonian dynamics on any scales larger than our planetary system (with possible exceptions being globular clusters, though in dynamical cluster models there are plenty of free parameters; and comets, where the consistency of models of the Oort cloud tests gravity up to a few tenths of a parsec). **This constitutes one of the main motivations behind the appearance of alternative theories of gravity, such as MOdified Newtonian Dynamics (MOND), and many others.**

Clearly, any practical ideas for clean, unambiguous experiments that can probe and constrain gravity at such weak levels of acceleration are of large importance today. **Note, therefore, that this is not a proposal for a program on alternative theories, but rather a proposal for a test of fundamental gravity in a regime where the standard theory has not been tested yet.** Our program is thus motivated by the fact that the orbital accelerations felt by the components of very wide binaries, with semimajor axes of a few thousand AUs and larger, fall within this special regime of gravity. **In addition, they do so without the ambiguities associated to the potential presence of any dark matter, thus offering us this important and rare opportunity.**

In principle, the test with wide binaries is straightforward. Newtonian gravity predicts that binaries with increasingly larger separations have decreasing orbital velocities (i.e., Keplerian dynamics), whereas modified gravity models predict a flattening of the orbital velocity at large separations. Although the orbital periods for these binaries are orders of magnitude longer than a human lifespan, in principle the orbital velocities of even these extremely long periods can be measured as the difference in the 3D spatial velocities of wide binary components. **However, not only these measurements probe the state-of-the-art in astronomical instrumentation, but the interpretation of the best data available are plagued by a series of systematic effects and biases.**

Because of their failure to account for these systematic effects (described below), most known attempts to perform this test using wide binaries have all concluded, wrongly, that these systems show clear departures from the expectations of Newtonian dynamics which would require us to abandon it in favor of MOND or similar alternatives (Hernández et al. 2012; Scarpa et al. 2017; Hernández et al. 2018). It is likely because of this failure that none of these works have been published in astronomy mainstream journals. The one exception is a very recent work by Pittordis & Sutherland (2019), where they conclude, rightly, that the present Gaia data are inconclusive for this test today. **In this proposal, we demonstrate that the test can be done correctly over a few years, accounting for all known systematic biases, using current state-of-the-art instrumentation available from the CNTAC, and propose a plan to carry it out from Chile.**

THIS PROPOSAL

We propose a program aimed to provide the first, unambiguous test for the behavior of

gravity in the regime of accelerations relevant for the problem of dark matter in galaxies. For this, we have selected the best available sample of very wide binaries, which today is allowed by the exquisite astrometry in the initial two data releases of the Gaia mission, TGAS and Gaia DR2.

For the test to provide reliable conclusions, **the demand in velocity precision** is set by the vertical distance between the blue and red regions in Figure 1, which show the theoretical expectations for the orbital velocities of wide binaries under Newtonian and MOND dynamics (simple MOND, with no external field effect), respectively. For a 1 $M_\odot$ binary, this difference in expected relative orbital velocity between the Newtonian model and the MOND model, for a binary separation of 0.1 pc, or 2×10^4 AU, is $\sim 50 - 200\,\mathrm{m\,s^{-1}}$, depending on eccentricity.

For precise constraints on gravity in the weak regime, thus, and even in the idealized case of perfect measurements, one should be concerned about any astrophysical effects that may alter the observed velocity difference between the two components of a wide binary to levels comparable to a few tens of $\mathrm{m\,s^{-1}}$. Thus, clearly, **the correct implementation of this test needs to worry first and foremost for the possibility of unseen companions to the components of the binaries used for the test**, as a close-in giant planet or a wide enough substellar companion would be enough to inflate the relative velocity among components, making it appear inconsistent with Newtonian expectations. **In this way, the potential presence of hierarchical triples in the sample, or massive planets hosted by the stars, is by far the most important systematic affecting the gravity test.**

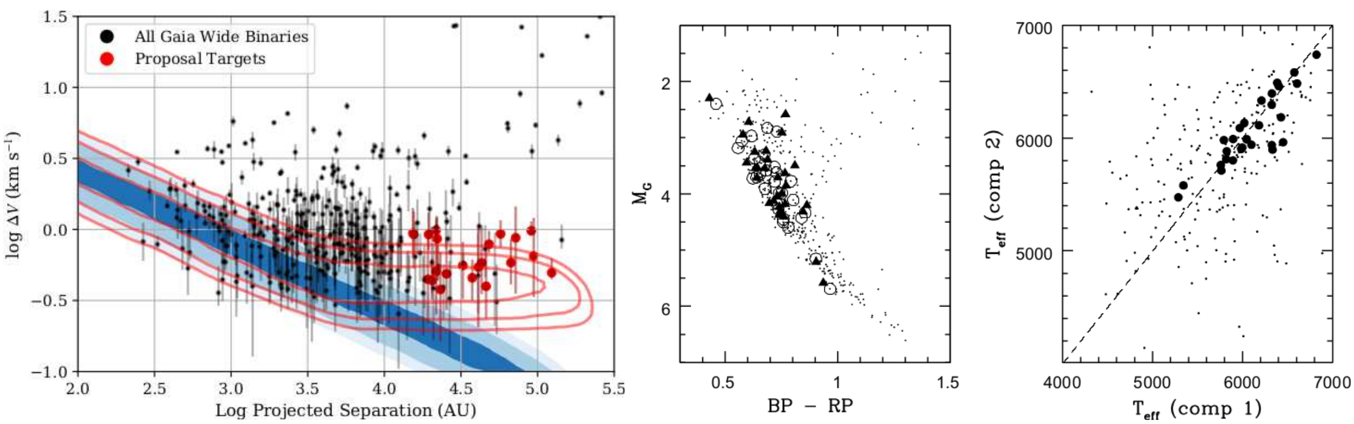


FIGURE 1: LEFT panel: 3D orbital velocities of the components of wide binaries from the TGAS-based catalog of Andrews, Chanamé, & Agüeros (2017), updated with Gaia DR2 astrometry and RVs, as a function of the projected separation on the sky. Blue regions indicate the expectations from Newtonian gravity, and red contours indicate those expected under MOND gravity with no external field effect. The red points with error bars indicate the 21 wide binaries (42 stars) selected as targets for this program, being the pairs with the best astrometry, and with projected separations larger than 10,000 AU, thus covering the region where differences between gravity models are largest. **MIDDLE panel**: Color-magnitude diagram of the Gaia wide binaries with the best astrometry, showing the locations of the components of pairs (open circles and triangles) with similar luminosities and colors. **RIGHT panel**: The luminosity-color selection criteria described just before produces a sample of targets (filled circles) with analog components, as shown by the correspondence between their estimated temperatures. This helps minimize systematic effects due to stellar structure.

The main task of our program, therefore, is to survey the components of the best wide binaries delivered by Gaia for the presence of close-in companions such as planets, brown dwarfs or low-mass stars. By cleaning the sample from the presence of these companions, the proposed observations will produce a set of wide binaries with isolated components having the most precise determinations of their 3D relative (i.e., orbital) velocities possible with present-day instrumentation, which is exactly what's needed to achieve a reliable test of gravity.

Other sources of systematic biases for the test include: (a) unrecognized pairs belonging to moving groups and stellar streams, as well as recently ionized former binaries, and (b) stellar structure effects. The first ones constitute the contamination that affects any wide binary catalog, and are easily dealt with by restricting to pairs not wider than ~ 1 pc, as shown in our series of papers based on Gaia data itself (Andrews, Chanamé & Agüeros 2017; 2018a; 2018b). Stellar structure effects include the small but finite gravitational redshifts of any stars (of the order of 600 $\mathrm{m\,s^{-1}}$ in the case of the Sun), and the convective blueshifts typical of stars with outer convective envelopes (which can be the size of a couple hundred $\mathrm{m\,s^{-1}}$ for a solar type star). The latter effects are unavoidable, but can be minimized by focusing on the binaries with similar components. In addition, they can also be dealt with statistically by studying the behavior of relative velocities as a function of spectral type. Accounting for these effects, therefore, requires working with a large enough sample that allows statistical corrections.

METHODOLOGY AND SAMPLE SELECTION

Gaia's astrometry is the best available and is only going to improve with upcoming data releases. What's left in order to reliably perform the gravity test, **and therefore the immediate objective of this proposal**, is the measurement of the RVs of the components of the binaries to the level of precision discussed above. This is a higher demand in precision than that offered by Gaia's own RVs (with errors $\sim 1 - 2$ $\mathrm{km\,s^{-1}}$ at the magnitudes of our targets). **Therefore, this requirement can only be delivered from the ground using instrumentation specifically designed for extrasolar planet studies.**

Our target selection is illustrated in Figure 1 and its caption. We extract our sample from the TGAS wide binary catalog of Andrews, Chanamé & Agüeros (2017), updated with Gaia DR2 astrometry. The full sample with the best astrometry is shown in the $\Delta V - \log s$ space that is the main diagnostic for the gravity test. This catalog is large and varied, with less than 5% contamination from random alignments. For the gravity test, however, the ideal targets are those with the best possible astrometry and RVs from Gaia DR2 (Fig. 1, left), and with projected separations larger than s $\sim 10^4$ AU, where the model predictions start to diverge from each other.

We selected the highest-quality binaries, pairs whose components have parallax errors < 0.05 mas, proper-motion errors < 0.05 mas/yr, and projected separations $s > 10^4$ AU, where the gravity theories start to diverge. Among those observable from La Silla during 2020-B, we further selected the pairs with the most similar luminosities and colors ($\Delta \mathrm{M_G} < 0.3$ mag and $\Delta(\mathrm{BP} - \mathrm{RP}) < 0.1$ mag, respectively), thus favoring binaries with components of similar spectral types, as demonstrated by the resulting approximate correspondence between their effective temperatures (Fig.1, right panel). Finally, we also dropped from our list any binary showing a Gaia DR2 source within 10 arcsec of any of its components.

Note that some targets in our list may appear not reachable during months of the 2020-B semester, but will be reached as this is a Long Term Program that, moreover, benefits from our agreement with MPIA astronomers (next sections) to combine each team's time allocations in order to maximize the baseline of observations for both programs.

REFERENCES: Andrews, J., Chanamé, J., Agüeros, M., 2017, MNRAS, 472, 675 • Andrews, J., Chanamé, J., Agüeros, M., 2018a, MNRAS, 473, 5393 • Andrews, J., Chanamé, J., Agüeros, M., 2018b, RNAAS, 2, 29 • Gaia Data Release 2, Brown, A., et al., 2018, A&A, 616, 1 • Hernández, X., Jiménez, M., Allen, C., 2012, The European Physical Journal C, 72, 1884 • Hernández, X., Cortés, R., Allen, C., Scarpa, R., 2018, International Journal of Modern Physics D, arXiv:1810.08696 • Pittordis, C., Sutherland, W., 2019, MNRAS, 488, 4740 • Scarpa, R., Ottolina, R., Falomo, R., Treves, A., 2017, International Journal of Modern Physics D., 26, 1750067.

JUSTIFICATION FOR LONG-TERM STATUS

The principal technical goal of the project is to determine the systemic radial velocity (RV) of each of the components of the wide binaries with a precision of the order of few tens of $\mathrm{m\,s^{-1}}$. Therefore, in general terms, as discussed in the previous section, the methodology required to achieve these measurements is essentially the same as that used in the detection of extrasolar planets with the RV method. Our co-Is Rafael Brahm and Andrés Jordán, who designed the Technical Justification of this program, are well known leaders on this field, with a long record of published discoveries of extrasolar planets and their characterization. What is required for our program to be completed, therefore, is to monitor each star for a long time span (years) in order to fully characterize the RV variation of the target stars. We will need to detect and model periodic and semi-periodic variations produced by planets, close binaries, and/or stellar activity, in order to estimate and subtract them, and therefore obtain the true systemic velocity of the star.

A monitoring time of two years is the minimum period for performing the proposed analysis. Fifteen (15) RVs per semester is a typical number of observations if compared to successful exoplanet discovery surveys (e.g., Hébrard et al. 2016, AA, 588, 145). In the proposed two years of observations we will characterize the presence of companions to each of the components of the wide binaries up to a distance of ≈ 2 AU, which corresponds to the distance at which the occurrence rate of exoplanets peaks (Winn & Fabrycky 2015, ARAA, 53, 409). The search for companions at even larger separations will be performed with high resolution imaging (please see Current Status) and future GAIA astrometry.

RESPONSE TO 2019-B AND 2020-A TAC COMMENTS

We consider important to address the few concerns expressed by the CNTAC referees on our 2019-B and 2020-B proposals. Please see also page of Current Status.

- *the team should also consider projection effects, which are suggested to cause the observed deviation (El-Badry 2019) at larger separations*: all our measurements of ΔV already include the effect of projection of the tangential and radial velocities at different positions on the sky, and this effect is also accounted for in the left panel of Figure 1. As can be seen, projection effects can be important at large separations, but they are not the responsible ones for the apparent discrepancy between the data and Newtonian predictions at the largest of separations.

- *restricting the sample to separations smaller than 0.2 pc makes the window to differentiate the models become too small*: this was due to an unfortunate choice of words in the 2019-B proposal, and we are not restricting our sample to that separation, but rather selecting only binaries with projected separations from 10,000 AU up to just short of a parsec (red circles in Fig.1). Therefore, we are indeed probing the regime of separations where the models are the most discrepant.

- *the test needs to worry about chance alignments*: indeed, but our sample has already been vetted against obvious chance alignments via the Gaia DR2 RVs, and the remaining probability of random alignments is small and well understood (see Andrews, Chanamé, & Agüeros 2017,2018a,2018b).

- *A significant recent publication, Clarke, C.J. (2019), discusses the effect in detail ... This work should have been referenced.*: indeed, the Clarke paper (2020, MNRAS, 491, L72) is relevant and makes the exact same case we make in our proposal. But, unfortunately, there is no way we could have referenced it in our 2019-B proposal as it only appeared in the arXiv on October 22nd, 2019, while our proposal was submitted a week earlier, by the deadline on October 15th.

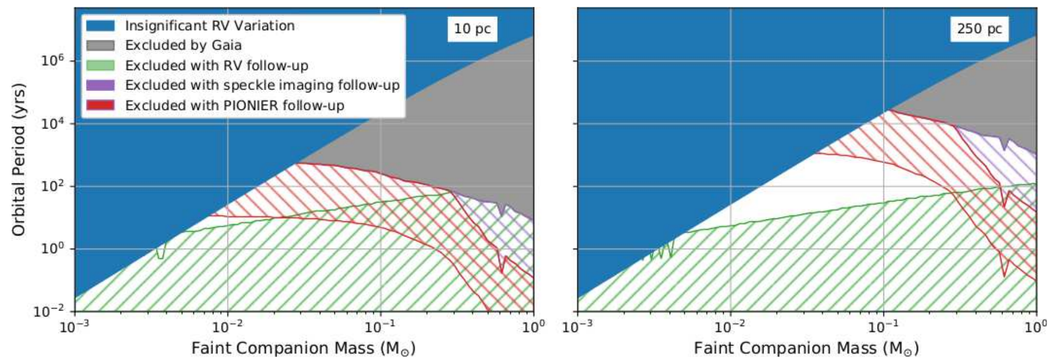
CURRENT STATUS OF THE PROJECT

This is a completely new project. We started with our first proposal on 2019-B, which was not accepted. In the previous section we provided answers to the points in the referee report from 2019-B. Our proposal was resubmitted in semester 2020-A, and the CNTAC awarded 4 nights with FEROS, though the request for Long Term Program was rejected. The 4 nights allocated for semester 2020-B are scheduled for the month of July 2020. However, due to the present world pandemic, La Silla is closed for operations and this program will most likely lose that observing run.

We also deem important to address here the comments raised by the TAC on our 2020-A proposal for a Long Term Program, as the most important of them actually prompted us to design a separate observing proposal that will be submitted to ESO next semester:

- *For the next semester, we expect a proposal for long-term status to include (i) sufficient results from the time awarded to demonstrate the expected single-epoch accuracy for the sample of stars observed*: please note that our co-Is RB and AJ have demonstrated this over many papers already.

- *For the next semester, we expect a proposal for long-term status to include: (iii) if it is decided not to do pre-speckle imaging of the sample prior to the spectroscopy then there must be a clear justification for this decision*: we explored this suggestion by the TAC very seriously, and concluded that, actually, speckle imaging does not help our goals by much, that the requested RV monitoring is indeed the best way to achieve our ultimate goal, and, moreover, that much better than speckle is the option of interferometry. The figure below illustrates this conclusion vividly.



We show different techniques for identifying faint companions to wide binary components. All constraints are for a putative close binary with a 1 M$_\odot$ primary at a distance of 10 pc (left) and 250 pc (right) from the Sun. For sufficiently small masses and large orbital periods, companions produce RV signatures too small for us to worry. In these cases (blue region), such systems can be ignored. At the same time, for sufficiently large orbital separations, Gaia would have identified any putative companion as a separately detected star. This regime (grey) can also be ruled out. Speckle imaging can directly detect companions at separations as small as tens of mas, provided the magnitude differece is not too great. Following the survey described in Tokovinin et al. (2019), we translate those joint constraints on magnitude and angular separation into observability limits in mass and orbital period (purple, hatched region). While speckle imaging can provide useful limits on the presence of a companion, the regime where it is sensitive is only a small sliver of parameter space. If instead of speckle we consider infrared interferometry as delivered by PIONIER at the VLT, companions at separations as small as 5 mas are detectable (red, hatched region). Alternatively, the RV follow-up described in this proposal eliminates a large swath of parameter space (green, hatched region). For this we have assumed an RV precision of 20 m/s, four epochs separated by 6 months (a simplification meant for an approximate estimation), and that we can remove systems with variations that differ by 3 sigma. Based on these results, we decided that we will work on a PIONIER/VLT proposal to be submitted for ESO Period 107 and that will include all our gravity targets bright enough for the instrument.

TECHNICAL DESCRIPTION

Co-Is Rafael Brahm and Andrés Jordán of this proposal have extensive experience in the use of precision radial velocities to detect extrasolar planets, and we will use their tools and knowledge to determine the true systemic radial velocities of the components of the wide binaries in our sample.

Our final sample consists of 21 wide binaries and hence 42 stars. Figure 1 shows the sample in various planes. We propose to use the FEROS spectrograph to monitor these 42 stars in a time span of 2 years, taking approximately 15 RV measurements per star per semester. We plan to obtain a precision of 20 m s^{-1} or better in each RV measurement, which translates in 300s exposures for a V=12 mag star (faintest magnitude of our sample), and we will set our minimum exposure time to 120s. By considering the particular magnitudes of each star and by assuming a pointing overhead of 180s per observation, we estimate that our project will require 16h (science observations) + 20h (pointing overheads) = 36h per semester. **Thus we are asking for 4 FEROS nights for each semester.** The code that we used to filter our catalog through Gaia and to compute the required amount of time has been made public[1]

The observations will be performed in the simultaneous wavelength calibration mode, where the secondary fibre is illuminated with a ThAr Lamp in order to trace the instrumental velocity drift during the observations. The data will be processed with the CERES pipeline (Brahm et al. 2017, PASP, 129, 4002) which has been extensively used for discovering exoplantes with FEROS and has recently proven its ability to reach the 3 m s^{-1} precision for bright stars (Espinoza, Brahm et al. 2020, MNRAS, 491, 2982). The data will be processed as soon as the spectra is obtained and we will be able to perform a spectral classification. Just after the first spectrum per star we will be able to identify if the target is effectively suitable for performing the long term study that we propose. For example we will reject targets showing significant rotational velocities ($>$ 20 km s^{-1}). As the RV measurements per star begin to accumulate, we will proceed to model these time series using the recently developed Juliet code (Espinoza, Kossakowski, & Brahm, 2020, MNRAS, 490, 2262) which will allow us to fit Keplerin signals and Guassian Processes if we identify a signal produced by close orbital companions (planets, brown dwarfs and stars) and/or stellar activity.

One important detail is that in order to have an optimal modeling of the RV signals of our stars, the observations should be performed as homogeneously spread over the semester as possible. **For this reason, if the 4n that we request through CNTAC are awarded, we have already established an agreement with researchers from the MPIA where our observing time will be combined with them in order to have a much homogeneous monitoring of our stars and theirs. Please see the attached letter of agreement. We stress that these other MPIA projects are completely unrelated to the scientific goals of our gravity test project, and that we have no means of obtaining MPIA time either.** This possibility of spreading our observations through the semester is not possible with other similar facilities offered by the CNTAC (e.g., CORALIE), and while in principle we could do it with the queue observing mode of CHIRON, the reduced size of the telescope would produce the necessity of a significant number of extra nights to fulfill our goals. These reasons make FEROS the optimal instrument to perform our program.

In a time span of 2 years of observations we will be able to derive the systemic RVs of the components of our wide binaries with a precision of 20 m s^{-1} or better. After these 2 years those stars that present linear or quadratic trends in their RVs won't be used for the final analysis, because these stars will require an even longer monitoring to derive their systemic velocities due to the presence of "long" period companions. On the other hand, those stars that don't present RV trends may be subject of high resolution imaging observations in order to further confirm the absence of "long" period orbital companions that could be accelerating the target star in a longer timescale.

[1]https://github.com/rabrahm/cntac-wbs

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Dear members of the CNTAC,

I am the Principal Investigator of the program “RV confirmation of TESS warm giant candidates” being executed with the FEROS spectrograph on the MPIA 2.2m telescope at La Silla Observatory. The present letter is to certify that I have an agreement with Prof. Julio Chanamé to coordinate the scheduling of FEROS observations for our two programs. In case his Long Term Program "A Clean Test of Gravity at Very Weak Accelerations" is approved, we will keep this agreement for the two years of duration of said program. This will benefit us both by giving us extended flexibility to design the best cadences possible for our two programs.

Thanks for your attention, and best regards,
Paula Sarkis (sarkis@mpia.de)