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# NaCo — The Story of a Lifetime

Linda Schmidtobreick[1]
Nancy Ageorges[2]
Paola Amico[1]
Wolfgang Brandner[3]
Suzana Cerda[1]
Claudia Cid[1]
Laird Close[4]
Eduardo Garces[1]
Gordon Gillet[5]
Julien H. Girard[6]
Patricia Guajardo[1]
George Hau[7]
Wolfgang Hummel[1]
Yves Jung[1]
Markus Kasper[1]
Christopher Lidman[8]
Lars Kristian Lundin[1]
Pedro Mardones[9]
Dimitri Mawet[10]
Jared O'Neal[11]
Emanuela Pompei[1]
Ricardo Schmutzer[1]
Karleyne Silva[12]
Jonathan Smoker[1]
Christian Soenke[1]
Lowell E. Tacconi-Garman[1]
Elena Valenti[1]
Javier Valenzuela[1]
Jose Velasquez[1]
Gerard Zins[1]

[1] ESO
[2] KT Optics GmbH, Germany
[3] MPIA, Heidelberg, Germany
[4] University of Arizona, Tucson, USA
[5] Independent engineer, Antofagasta, Chile
[6] STScI, Baltimore, USA
[7] University of Bath, UK
[8] Australian National University, Canberra, Australia
[9] Universidad de Valparaiso, Chile
[10] Caltech/JPL, Pasadena, USA
[11] Argonne National Laboratory, Lemont, USA
[12] Gemini Observatory, La Serena, Chile

NaCo was switched off on 2 October 2019, almost 18 years after its first light. The last exposure was of the standard star HD590 as part of the close-out calibrations. To date, 699 papers have been published using NaCo data, including observations of the Galactic centre, direct images of exoplanets orbiting their stars, young stellar objects, brown dwarfs, massive stars, stellar clusters, Solar System objects, SN 1987A and several extragalactic sources. We present a short history of the life and achievements of NaCo from the viewpoint of the Instrument Operation Team, Instrument Scientists, and Instrument Engineers.

## Introduction

The Nasmyth Adaptive Optics System (NAOS) was developed by a French consortium[a] in collaboration with ESO, and the COudé Near-Infrared CAmera (CONICA) was built by a German consortium[b] in collaboration with ESO. Together they form NAOS-CONICA (NaCo) which was the first instrument with an adaptive optics (AO) system on the Very Large Telescope (VLT). It was first installed at the Nasmyth B focus of UT4 (Yepun), where it stayed from 2001 through 2013. In 2014 it was reinstalled on UT1 (Antu) at the Nasmyth A. Early tests and results from commissioning runs showed that, by compensating for a large fraction of the atmospheric turbulence, it could obtain spatial resolutions close to the 8-metre telescope's diffraction limit. The AO system was equipped with both visible and infrared, Shack–Hartmann type, wavefront sensors; the latter enabled observations inside regions that are highly obscured by interstellar dust and therefore unobservable in visible light. For almost 18 years, NaCo provided multimode, AO-corrected observations in the 1–5 µm range.

## The odyssey begins

Numerous boxes containing the many parts of NAOS and CONICA arrived at ESO's Paranal Observatory on 24 October 2001. Astronomers and engineers from ESO and the participating institutes and organisations[a, b] began the painstaking task of assembly on the Nasmyth B platform of UT4 (see Figure 1). After days of technical tests and adjustments, working around the clock, the team finally declared the instrument fit to attempt its first-light observation.

The UT4 dome was opened at sunset on 25 November 2001 and a small, rather apprehensive, group gathered in the VLT Control Room, peering intensively at the computer screens over the shoulders of their colleagues the telescope and instrument operators. As the basic calibrations required at this early stage were successfully completed, the suspense rose, as did expectations as the special moment approached when finally the telescope operator pushed the button that sent the telescope towards the first test object, an otherwise undistinguished star in our Milky Way.

The uncorrected image was recorded by the near-infrared imager and spectrograph CONICA and it soon appeared on

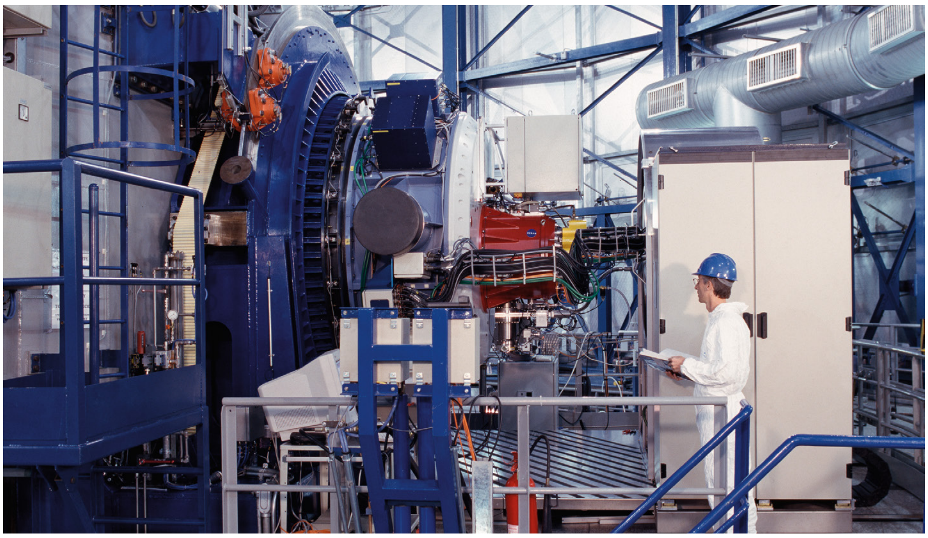

Figure 1. NAOS (light blue) and CONICA (red) are attached to the Nasmyth B adapter of UT4 (Yepun). The control electronics are housed in the white cabinets.

the computer screen. With a full width half maximum (FWHM) diameter of only 0.50 arcseconds, it already showed good image quality, thanks to the atmospheric conditions on that night. Then the NAOS adaptive optics system was switched on, thereby "closing the loop" for the first time on a celestial object. As the deformable mirror in NAOS began to follow the "orders" that were being issued 400 times a second by its control computer, the stellar image on the computer screen seemed to pull itself together. What seconds before had been a jumping, blurry patch of light suddenly became a rock-steady, razor-sharp and brilliant spot. The entire room burst into applause with happy faces and smiles all round. Nowadays, we are used to getting these sharp and steady images whenever the loop of an adaptive optics system closes. But at the time of NaCo's first light, this must have been a truly magical moment. The diameter of this first image was measured as 0.068 arcseconds (see Figure 2).

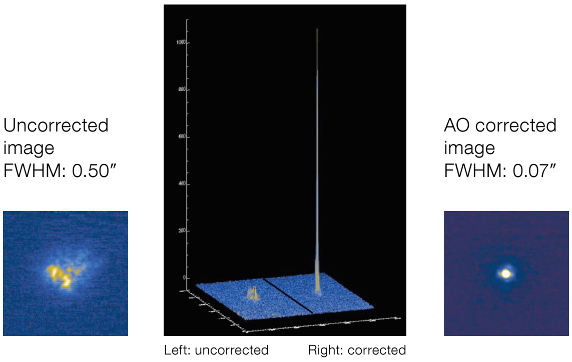


Figure 2 (left). The first image with NAOS-CONICA of a star (*V* magnitude of 8) obtained before (left) and after (right) the adaptive optics was switched on.

Figure 3 (below). The giant planet Saturn as observed with the VLT NAOS-CONICA Adaptive Optics instrument on 8 December 2001.

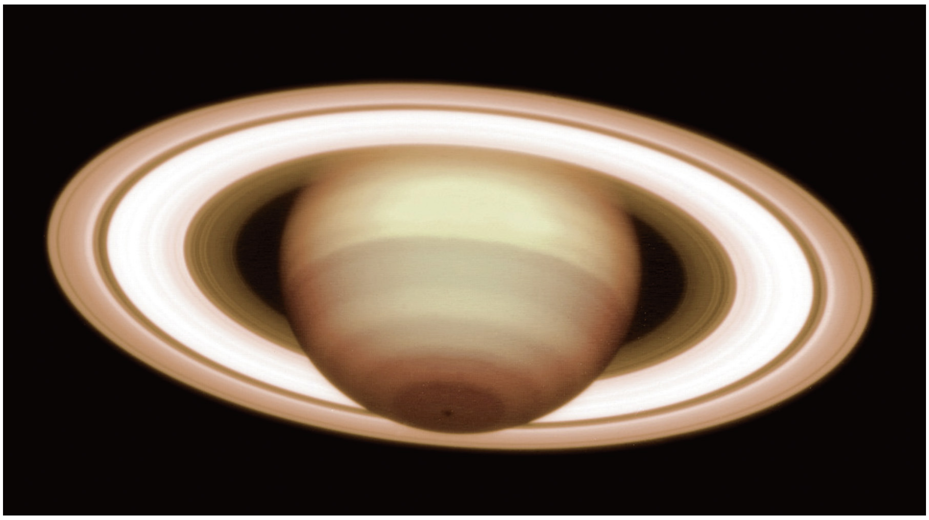


Figure 4. The central parts of our galaxy as observed in the near-infrared with NaCo. By following the motions of the most central stars over more than 16 years, astronomers were able to determine the mass of the supermassive black hole in the centre.

Even during those early tests and commissioning nights, NaCo delivered impressive astronomical results. Among the first images to be obtained was one of the stellar cluster NGC 3603, a high mass star-forming region. Only with the new, high-resolution *K*-band images was it possible to finally study the elusive class of brown dwarfs in such a starburst environment. Another early highlight was the observation of Io, the innermost of the four Galilean moons of Jupiter and the most volcanically active place in the Solar System (see press release eso0204[1] for details). And then of course, there was the "Lord of the Rings", Saturn itself, in all its beauty. These observations were very challenging. CONICA's field of view had to be steadied on Saturn, NAOS had to track the small moon Tethys, the reference source for the adaptive optics, and UT4 was tracking a star used for determining active optics corrections and autoguiding. As Figure 3 shows, it worked.

However, the commissioning itself was also under a lot of pressure. Firstly, there was strong competition for precious console places because the fibre positioner for FLAMES was being commissioned at the same time. Secondly, the centre of our Galaxy becomes observable in April and NaCo was supposed to start monitoring this region. There was a big rush to get NaCo operational in time for an early epoch observation. In fact, NaCo turned out to perform excellently (see Figure 4) and it became a key instrument for monitoring the motions of the stars close to the Galactic centre for many years. By measuring these stellar orbits with such amazing precision, it was possible to conclude that the central invisible object is very likely to be a supermassive black hole (Gillessen et al., 2009).

## The early years

Not everything worked immediately though and that's why NaCo is also a story of encounters and friendships between astronomers, amazing engineers and dedicated telescope operators. From the beginning, the instrument appeared to have its own moods and people had to comply with these to successfully operate NaCo and keep it observing through the night. Sometimes it just didn't work, often it required enormous effort and collaboration between various departments to get it up and running. Only with time and improved monitoring were these moods attributed — at least to a large degree — to specific atmospheric behaviour. In this way, NaCo also taught us the importance of monitoring and recording ambient physical properties as well as instrumental performance, now regular practice with all instruments.

Then there have been all the unforeseen circumstances: when the only NaCo-trained night astronomer fell sick just before the first visiting observer run, and a colleague had to take over at the last minute; when, in the aftermath of NASA's Deep Impact mission[2], NaCo broke down just before the time-critical observations, was urgently fixed and was still cooling down at the most crucial moment; and when the NAOS field selector broke, requiring two intensive weeks on the mountain to repair it. The Instrument Scientist at the time also vividly remembers the time when UT4 was observing with the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) under wonderful conditions and they needed to check some NAOS connection. They opened one of the cabinets and caused a complete shutdown of the telescope — and a shock for everyone involved.

On the other hand, there have been numerous special moments, like the Pluto occultation, when astronomers, operators, engineers and everyone else were all waiting enthusiastically for the event, but also very nervously as it was not clear whether Paranal was in the right viewing zone. When the event did happen, the tension broke and the visiting astronomer started applauding and kissed his wife. Afterwards everyone involved celebrated with excellent French cheese the smell of which lingered until the next day.

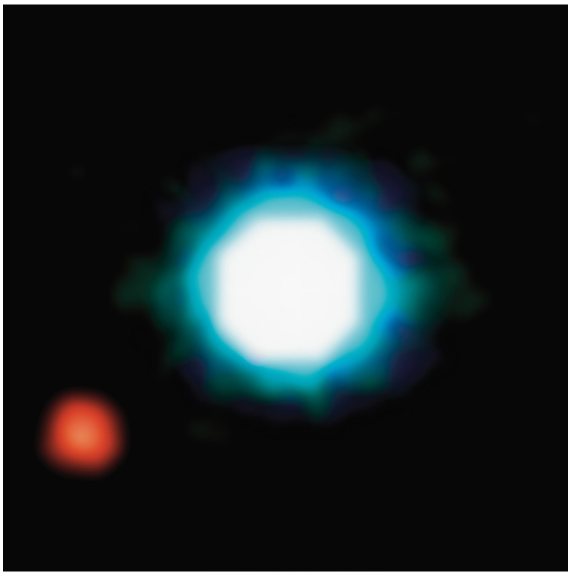

Figure 5. This composite image shows an exoplanet (the red spot on the lower left), orbiting the brown dwarf 2M1207 (centre). 2M1207b is the first exoplanet directly imaged and the first discovered orbiting a brown dwarf. It was imaged for the first time with NaCo on UT4 in 2004.

Another of these special moments was the observation of 2M1207, a brown dwarf in the young TW Hya association. In a series of NaCo exposures, a tiny red speck of light was discovered only 0.8 arcseconds away from 2M1207 (see Figure 5). The thrill of seeing this faint source of light in real-time on the instrument display is indescribable. Was this actually a planet orbiting the brown dwarf? A spectrum taken with NaCo shows the signatures of water molecules and confirms that the object must be comparatively small, cold and of about five Jupiter masses. However, to prove that it is a planet orbiting the brown dwarf, more images over a longer time interval had to be obtained. Only a year later, it was confirmed that indeed NaCo had taken the first image of a planet outside our Solar System (Chauvin et al., 2005).

## New observing modes

After several years of operation, a number of previously planned upgrades to NaCo were carried out (Kasper et al., 2005). These included the low-resolution prism which allowed simultaneous spectroscopy from *J*- to *M*-band, the installation of order-sorting filters that allowed *L*-band and *H*+*K*-band spectroscopy at various spectral resolutions, and the Fabry-Perot interferometer to take narrow-band observations tunable between 2 and 2.5 μm. Also the detector was upgraded, the new Aladdin III detector having better cosmetics, linear range and readout noise.

However, the NaCo instrument concept was always considered a flexible one, and this triggered new ideas about how to extend and optimise the capabilities of NaCo, especially for certain astronomical applications. For example, exoplanets, where for any kind of direct imaging the main problem is the high contrast between the light of the host star and the light of the planet. Of course, larger planets are easier to observe, as are planets around faint stars. It is no surprise that the first imaged planet was a giant, Jupiter-like planet around a brown dwarf. To decrease the contrast between star and planet, new modes were invented, such as simultaneous differential imaging (Lenzen et al., 2004), the four-quadrant phase mask together with a Lyot-Stop coronograph (Boccaletti et al., 2004), a pupil stabilised mode for Angular Differential Imaging (Kasper et al., 2009), the Apodising-Phase-Plate coronograph (Kenworthy et al., 2010), and the Annular-Groove-Phase-Mask (AGPM) coronograph (Mawet et al., 2013). NaCo served as a testbed to implement and evaluate all of them.

Other attempts were made to increase the spatial resolution and get down to the diffraction limit with a well calibrated point spread function. The interferometric mode using Sparse Aperture Masking (SAM; Lacour et al., 2011) as well as speckle holography (Schödel & Girard, 2012) and speckle imaging without AO (Rengaswamy et al., 2014) served in this respect and broadened the possibilities for NaCo science cases.

One of the major changes on Paranal in general but especially for NaCo and SINFONI was the installation of the first Laser Guide Star (LGS) facility, a collaboration between ESO and MPE. NaCo had to be upgraded for the extended spot of the LGS. A System for Tip-tilt Removal with Avalanche Photodiodes (STRAP) was installed, along with a new laser dichroic and a new wavefront sensor lenslet array with a larger field of view. The NaCo upgrade for LGSF was a collaboration between the Institut de Planétologie et d'Astrophysique de Grenoble (IPAG) and ESO, led by Gerard Zins who was at IPAG at that time (Kasper et al., 2010). Again, the collaboration made all the difference and much fun was had working with the Garching AO group installing the laser. Even the non-AO astronomers vividly remember being involved in the first nights of laser observations. Because the automated plane detection software had not yet been approved for safety, everybody was helping out with plane spotting, standing outside with a radio on the telescope platform, watching the sky, and sending the stop-propagation order if a plane was getting too close.

Dear outstanding professionals,

two nights ago our NACO had the last whisper on sky after observing a bright star.

It's been more than 20 years of amazing science and unique achievements!!

Together we've seen things you people wouldn't believe.
Engineers fighting their way through dichroics and wave front sensor. Astronomers worshipping a closed loop with seeing 2.0″ and coherence time 0.5 ms.
We watched violent storms on Jupiter's pole, planets orbiting desolate stars, Galactic Center glittering in the dark.
All those moments will be lost in time, like tears in rain.
Time to die.

Your sincerely,
Antu on behalf of NACO

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Estimados colegas,

dos noches atras NACO dio su ultima mirada al cielo.

Fueron mas de 20 años de maravillosa ciencia y resultados unicos!!

Juntos vimos cosas que ustedes no se pueden ni imaginar.
Ingenieros enfrentandose con dicroicos y sensores de frente de onda.
Astronomos cerrando el loop en condiciones proibitivas.
Hemos visto tempestas al polo norte de Jupiter, planetas orbitando estrellas desoladas, el Centro Galactico parpadeando en la oscuridad.
Todos estos momentos se perderan en el tiempo, como lagrimas en la lluvia.
Es tiempo de morir.

Cariños,
Antu por NACO

Figure 6. This email was sent by the support astronomers after NaCo's last night of operation. It shows what NaCo means for most of us: lots of emotions, lots of memories, and wonderful people working together.

## The final years

In 2013, NaCo was supposed to be decommissioned. However, an important astronomical event was on the horizon — the close encounter of the star S2 with the black hole in the centre of our Galaxy. As mentioned above, since the beginning of its operation NaCo played a key role in monitoring the motions of stars close to our Galactic centre. Now in 2018, one of these stars, S2, which has a highly elliptical orbit, was supposed to get so close to the black hole that the extreme gravity would make the effects of general relativity detectable. For this event, new instruments like GRAVITY were created, but an instrument was needed to actually follow the star and determine the precise orbit before and after the encounter. So, in 2014 NaCo was brought back to life, this time installed on the Nasmyth A focus of UT1. Consternation arose when it became clear that the CONICA detector couldn't be brought back to life. Luckily, ISAAC had been decommissioned a few years before and had also been equipped with an Aladdin detector. So the old ISAAC detector was refurbished and put into NaCo. Some long and frustrating re-commissioning runs were needed to get everything up and running. NaCo's facilities were drastically reduced — no more spectroscopy and everything had to be done in service mode, since Paranal did not have sufficient engineering resources to keep all the modes up and running.

Apart from the regular Galactic centre observations, another main science driver was the imaging of planets with the new AGPM mask, and the reduced NaCo was of course also offered in open time to the community. In 2018, after a major problem with the detector controler, the visible wavefront sensor had to be decommissioned. At that time, NaCo required several hours attention to be operational at night and may have become the most cursed instrument on Paranal but, when working, it delivered spectacular images; the monitoring and astrometry of the Galactic centre was a great success
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(GRAVITY Collaboration et al., 2018) and even in its old age NaCo was still contributing to exciting science results. At the moment of writing, 699 papers have been published using NaCo data[3].

NaCo's last night of operation, 1 October 2019, was cloudy, so a planned last-light image of Io could not be taken. Last light was instead recorded from the standard star HD590 at 04:22:50 UT on 30 September 2019. After that last night of operation, a very emotional email was sent by the night crew to all colleagues in Paranal (see Figure 6), expressing the emotions that we all felt when NaCo was finally switched off.

## Beyond NaCo

NaCo leaves a legacy of amazing data that are available in the archive. The pipeline will be kept alive and updated with system changes in order to ensure the ongoing use of these data. A history of NaCo, in particular a list of events that might influence which calibrations to take for which epoch of observations is available on NaCo's webpage[4].

Of course, NaCo is not the end by any means. AO continues to evolve, new generations of AO instruments like the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE), the Multi Unit Spectroscopic Explorer (MUSE) and the Enhanced Resolution Imager and Spectrograph (ERIS) are being operated at Paranal or will be coming soon. AO techniques will be key for any instrument on the ELT in future. All of these operational modes were originally tested on NaCo. We are continuously improving these techniques but, to quote a former Instrument Scientist, "NaCo was instrumental in making adaptive optics mainstream".

### Acknowledgements

We acknowledge the extensive use of ESO press releases, ESO newsletters and ESO images. Many people have contributed to making NaCo observations possible. We would like to thank the engineers and scientists who built the instrument, and those who developed and installed new modes at later stages, the various commissioning teams, the hardware and software engineers who kept this delicate instrument in good shape, the colleagues in Garching working on instrumental upgrades, pipeline development, quality control and user support, all the members of the Instrument Operation Team over the time, and all the support astronomers and telescope operators using NaCo at UT1 or UT4. Last but not least, we would like to thank the astronomical community for their interest and for using NaCo to advance their fascinating science cases.

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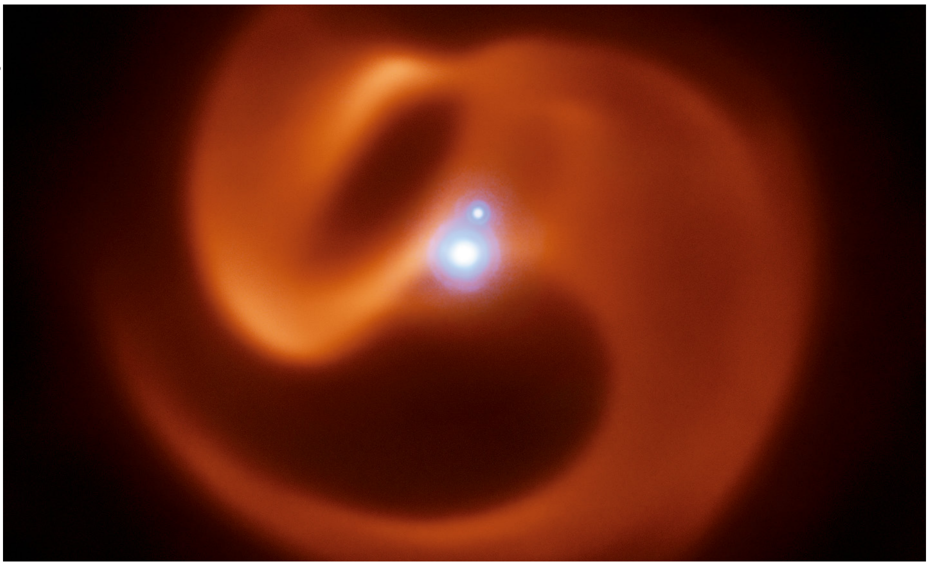
### Links

[1] ESO Press Release 0204 showing NaCo image of Saturn's rings: http://www.eso.org/public/news/eso0204
[2] NASA Deep Impact mission: https://www.jpl.nasa.gov/missions/deep-impact/
[3] Publications with NaCo: http://telbib.eso.org/?boolany=or&boolaut=or&boolti=or&year-to=2020&instrument%5B%5D=naco&boolins=or&booltel=or&search=Search
[4] NaCo's history: www.eso.org/sci/facilities/paranal/decommissioned/naco/History.html

### Notes

[a] The French consortium consisted of Office National d'Etudes et de Recherches Aérospatiales (ONERA), Laboratoire d'Astrophysique de Grenoble (LAOG) and Observatoire de Paris (DESPA and DASGAL). The Project Manager was Gérard Rousset (ONERA), the Instrument Responsible was François Lacombe (Observatoire de Paris) and the Project Scientist was Anne-Marie Lagrange (Laboratoire d'Astrophysique de Grenoble). It was supported by the Institut National des Sciences de l'Univers (INSU) of the Centre National de la Recherche Scientifique (CNRS).
[b] The German Consortium included the Max-Planck-Institut für Astronomie (MPIA) (Heidelberg) and the Max-Planck-Institut für Extraterrestrische Physik (MPE) (Garching). The Principal Investigator (PI) was Rainer Lenzen (MPIA), with Reiner Hofmann (MPE) as Co-Investigator.





The VISIR instrument on ESO's VLT captured this stunning image of a newly-discovered massive binary star system. Nicknamed Apep after an ancient Egyptian deity, it could be the first gamma-ray burst progenitor to be found in our galaxy. The triple star system was captured by the NACOadaptive optics instrument on the VLT.