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Report on the ESO Workshop

# KMOS@5: Star and Galaxy Formation in 3D — Challenges in KMOS 5th Year

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The *K*-band Multi-Object Spectrograph (KMOS) is one of the second-generation instruments at the VLT, and has been operating for five years. To celebrate this anniversary this workshop brought together astronomers to present scientific results from KMOS and complementary instruments. The topics ranged from star formation in the Galactic centre, to stellar populations in globular clusters, to galaxy formation and evolution at various redshifts, and feedback from active galactic nuclei (AGN). Another goal of the workshop was to assess the impact of KMOS on its core science goals and to develop new strategies and programmes, also in light of future integral field unit (IFU) instruments. About 60 researchers from the astronomical community and members of the Instrument Operations Team participated in the workshop and discussed the above topics; these discussions served to identify the highest priority improvements that could increase the scientific return of KMOS in the future.

## Motivations

Any advances in observational astronomy are ultimately based on the quality of observational data obtained with ever-improving, increasingly sophisticated, telescopes and instruments. KMOS enables deeper insights especially in areas related to galaxy formation and evolution, as well as a wider variety of scientific topics ranging from early stellar evolution to stellar populations and even including exoplanets.

Over the next few years, the community will have access to basic data on a large number of sources across a wide range of redshifts thanks to the upcoming or already available capabilities of survey instruments on powerful telescopes (for example, the Sloan Digital Sky Survey [SDSS], Wide Field infrared Camera for UKIRT [WFCAM], Visible and Infrared Survey Telescope for Astronomy [VISTA], VLT Survey Telescope [VST], High Acuity Wide field *K*-band Imager [HAWK-I], and Large Synoptic Survey Telescope [LSST]). The high-redshift samples will enable a new look at the early stages of the Universe when galaxies were young or still forming. Although the ensemble data already available — which have mostly been gathered by means of photometric techniques — are already providing valuable insights, a deeper understanding of the detailed physics underlying the formation and growth of galaxies requires more information about their individual properties. The coverage, in terms of star formation rates and redshifts, of the current KMOS Guaranteed Time Observation (GTO) surveys is shown in Figure 1. Such knowledge, in particular for high-redshift objects, was not sufficiently available so far. In particular, the one-dimensional spectra produced by classical spectroscopy are insufficient for a further investigation of the, often complex, galaxy morphologies and dynamics. Exactly the same limitation occurs in many other fields, for example, studies of metallicity gradients and dynamics in stellar clusters. This is indeed the framework within which KMOS is expected to play a fundamental role.

The KMOS@5 workshop aimed to bring together scientists working on all areas of star and galaxy formation and evolution using near-infrared IFU spectroscopy. The five-year milestone offered a perfect opportunity to assess the impact of KMOS on its core science cases. The workshop format allowed the exchange of strategies and ideas for analysis of the KMOS data, as well as fruitful discussion of future programmes. Finally, practical tutorials and demonstrations were offered and the users, together with the Instrument Operations Team (IOT), revised the priorities to improve and optimise the performance of KMOS over the next five years.

In the following sections we summarise some of the interesting talks and highlights from each session.

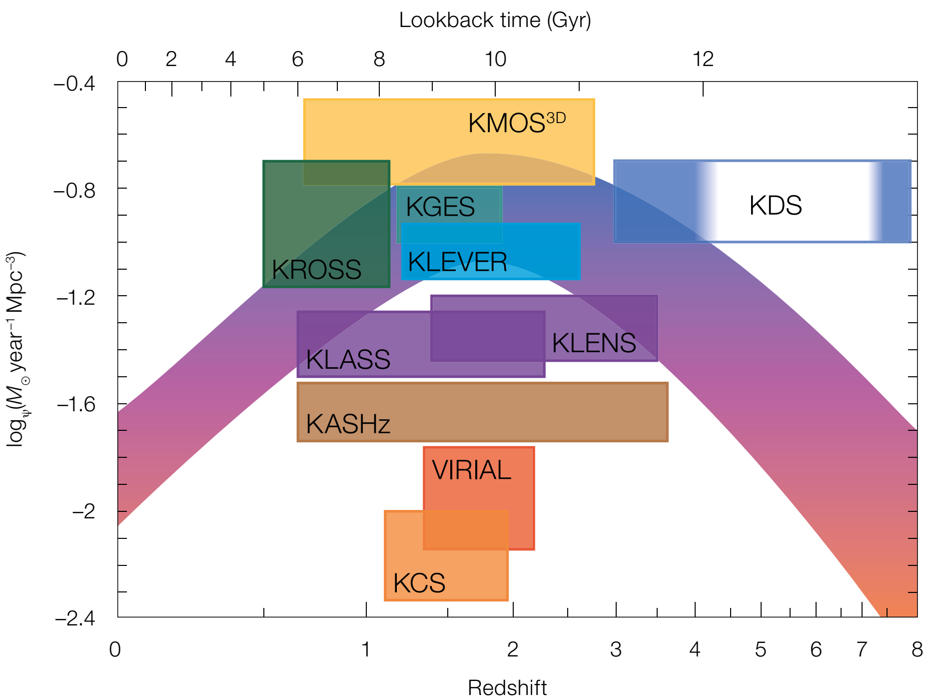


Figure 1. Cosmic star formation rate as a function of redshift and lookback time (plot from Natascha Förster-Shcreiber's talk; data from Madau & Dickinson, 2014).

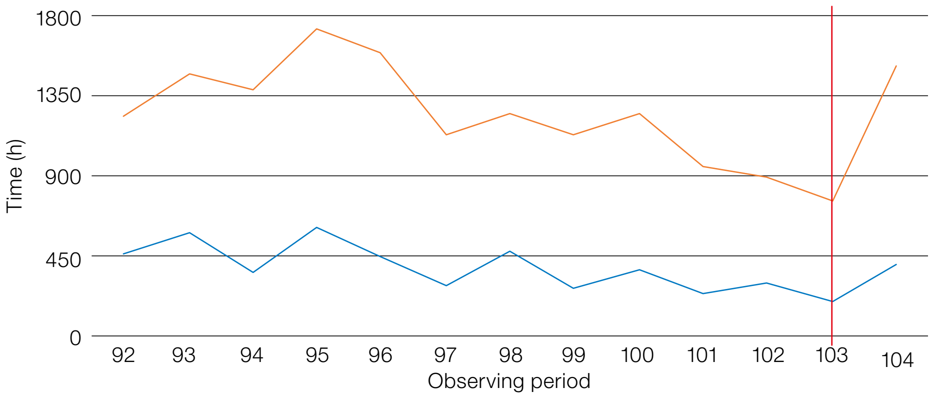


Figure 2. Requested and allocated time on KMOS. The vertical red line marks the small amount of time requested in Period 103, before the KMOS@5 workshop. The subsequent significant increase in Period 104 may be seen as the positive reaction of the community after the workshop.

## Workshop opening

The meeting began with a welcome talk by Bruno Leibundgut, who presented the rising publication statistics of KMOS, which are currently dominated by GTO data, a natural consequence of the recently expired GTO time. He also showed that the demand for KMOS as measured by proposal numbers and time requested is steadily decreasing, reaching a minimum of only ~ 750 hours in Period 103 (see Figure 2). Bruno warned the participants that under-requested instruments may not be supported by ESO and have an increased risk of being decommissioned. This had the effect of shaking up the participants, and the wakeup call animated all subsequent speakers, further motivating them to illustrate the importance of KMOS for their science. It also triggered lively discussion of the future of KMOS throughout the conference.

## Galactic and Local Volume science

The first scientific session concentrated on Galactic and Local Volume science with KMOS. It was convincingly shown that KMOS can be efficiently used to trace massive star formation and its feedback in both nearby star-forming galaxies as well as in the Galactic Centre and in star-forming regions of the Galactic disc.

Thanks to the multiplex capabilities of KMOS, as well as the mosaic mode with a monolithic IFU, it is possible to cover a large field of view (up to almost 1 square arcminute) and ~ 5 $pc^2$ of the Galactic centre have been observed. Anja Feldmeier-Krause discussed how young massive stars are centrally concentrated and that there exists a broad metallicity distribution of stars in the Nuclear Star Cluster (NSC) of the Milky Way based on ~ 700 KMOS spectra (Feldmeier-Krause et al., 2015, 2017). Anna McLeod also demonstrated that with the use of the mosaic mode of KMOS it is possible to examine the early stages of stellar feedback in star-forming molecular clouds within the Milky Way, which are only observable in the infrared because of extinction. In particular, it has become possible to trace the ionisation front and the molecular gas content at the same time. KMOS observations of massive star clusters reveal evidence for outflows and wind-blown bubbles in the environment of the clusters.

Francesco Ferraro described how the Multi-Instrument Kinematic Survey of Galactic globular clusters (MIKiS) allowed the determination of stellar kinematics across their full radial range. This survey was designed in synergy with the VLTI instruments, the Fibre Large Array Multi Element Spectrograph (FLAMES), KMOS, and the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI). Resolved kinematics of thousands of stars, combined with internal proper motions measured from Hubble Space Telescope (HST) campaigns (inner regions) and Gaia (outskirts), provide the first 3D kinematic maps of Galactic globular clusters. Surprisingly, they do not rotate as rigid bodies, but rather follow a Keplerian law with no significant evidence of intermediate mass black holes (see Ferraro et al., 2018; Lanzoni et al., 2018). The flexibility of KMOS allows studies of young massive star clusters in nearby galaxies, and Ben Davies showed how such clusters can be used as cosmic abundance probes to construct new mass-metallicity scaling relations based on red supergiants.

## Galaxy assembly, dynamics and evolution

Day 2 was dedicated to galaxy assembly, and galaxy dynamics and evolution. The results of the main KMOS GTO programmes were presented, with particular focus on KLEVER (talks by the Principal Investigator Michele Cirasuolo and Mirko Curti), KROSS and KGES (Mark Swinbank and Alfred Tiley talks), and KMOS$^{3D}$ the largest GTO programme (talks by the Principle Investigator Natascha M. Förster-Schreiber, Hannah Übler, Philipp Lang, David Wilman). Star formation rates, resolved kinematics and metallicities of more than 1000 star-forming galaxies at redshifts between 0.5 and 3 have been determined and have established the following:

i. Most galaxies (> 70%) are rotationally supported and the Hubble sequence emerged at around redshift $z$ ~ 1.5 (Stott et al., 2016, Swinbank et al., 2017).
ii. In terms of metallicity, non-axisymmetric patterns are revealed from resolved metallicity maps, while azimuthally-averaged metallicity gradients are flat. It is also possible to characterise outflow statistics; while the incidence of star-formation-driven outflows depends on star formation properties, the fraction of AGN-driven outflows depends on the stellar mass and its concentration (Förster-Schreiber et al., 2019; Harrison et al., 2016).

A controversial topic in this session was whether the outer discs of galaxies at redshift $z \sim 1$–2.5 have flat or falling rotation curves.

In his contribution, Philipp Lang discussed how a representative rotation curve for high redshift galaxies can be obtained with KMOS$^{3D}$; it is characterised by a significant decrease in velocity in the outer regions. Such a drop in rotation velocity can be explained by the dominance of baryons within the shallow inner dark matter potential. These results support the limited role of dark matter on disc scales (Lang et al., 2017; Übler et al., 2018). On the other hand, Alfred Tiley showed that stellar-scale rotation curves obtained from the KMOS Redshift One Spectroscopic Survey (KROSS) sample remain flat or continue to rise independently of redshift. This implies moderate to large dark matter fractions (≧ 66%) in star forming galaxies over the last 10 Gyr (Tiley et al., 2019).

On Day 3, the focus switched to lensed and very distant systems as well as AGN feedback and stellar kinematics. Results were presented from GTO surveys, such as KMOS$^{3D}$, the KMOS LENsing Survey (KLENS), and the KMOS Lens-Amplified Spectroscopic Survey (KLASS), related to the cosmic dawn. These surveys help in understanding the properties of distant systems. Charlotte Mason showed the first robust constraint on the intergalactic neutral hydrogen fraction at $z \sim 8$, inferred from deep spectroscopic limits on Ly$\alpha$ emission, and Marianne Girard discussed how the evolution of velocity dispersion depends on stellar mass.

AGN feedback and its effect on different stages of galaxy evolution were discussed during the afternoon, with results from the KMOS AGN Survey at High redshift (KASHz) and VIRIAL GTO programmes. Chris Harrison, Jan Scholz and Rebecca Davies argued that: (1) the most extreme gas kinematics are associated with AGN and outflows driven by low-power jets are important at low redshift; (2) there is no evidence of AGN-driven outflows quenching star formation in moderate luminosity AGN; and (3) the vast majority of the outflowing material does not have sufficient velocity to escape from the galaxy halos — rather it will be re-accreted, contributing to the build-up of stellar mass and angular momentum of the galaxies.

Trevor Mendel’s contribution dealt with the galaxy evolution mechanisms leading to massive and passive galaxies. He showed how they formed in a two-phase process: an early phase driven by rapid star formation on the main sequence, followed by the assembly of already existing stellar mass (Mendel et al., 2015). Also, such evolution can explain the typical decrease in dark matter fraction within the half-light radius.

The fourth and last workshop day was dedicated to the environment and late-stage evolution of galaxies. Alessandra Beifiori, Asmus Bohem and Sam Vaughan discussed KMOS Galaxy Cluster surveys like the KMOS Cluster Survey (KCS) and the KMOS Cluster Lensing And Supernova survey with Hubble (K-CLASH), showing that: (1) massive galaxies in big and old clusters are older than their analogues in the field; (2) gradual mass-growth mechanisms like minor mergers are favoured (Beifiori et al., 2017); (3) ram pressure stripping might compress gas in the inner discs, thus triggering star formation; and (4) non-circular motions are dominant in low-mass cluster members, thus indicating kinematic downsizing and/or interaction processes.

## KMOS current and future perspectives

In addition to the scientific sessions, discussions on the present and future status of KMOS were held. We asked the audience to complete a questionnaire, and the answers were used to drive further discussions. In Figure 3 the results of the online survey are reported. Concerning the needs of the community, it is clear that archival search and pipeline improvements are two key areas of interest:

i. Querying the archive for KMOS data is tricky because so far only the central

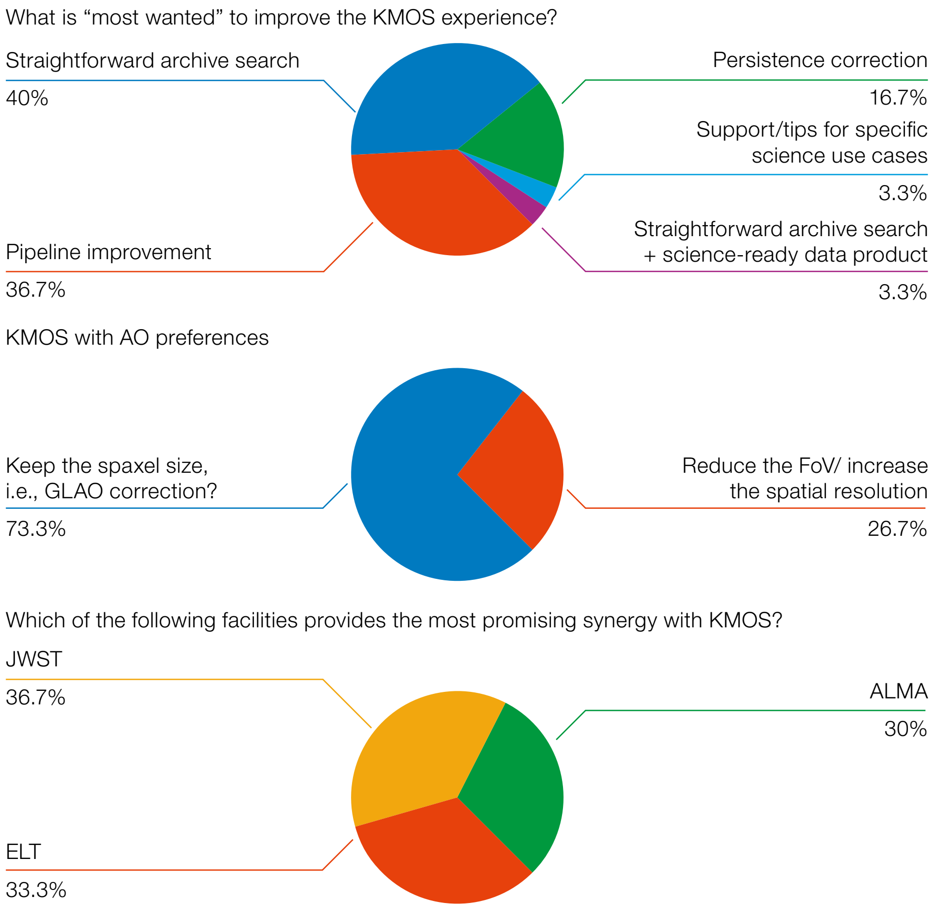


Figure 3. Online questionnaire about the most desired KMOS capabilities and synergies.

pointing coordinates of the KMOS field are searchable, rather than those of the individual targets. Such issues will be fixed shortly thanks to the new ESO Archive Science Portal and the data product release. ESO will indeed release reduced data cubes for single targets, which will be retrievable from the ESO Archive Science Portal[2].

ii. Pipeline capabilities should be improved. Since several recipes have been recently updated and released, the IOT asked the community to test the new releases and provide detailed feedback on specific tasks.

Moreover, the audience raised a concern regarding the ability of the Exposure Time Calculator (ETC) to provide the correct signal-to-noise ratio for the faintest objects. The ETC has been extensively tested on standard targets (such as stars and line-emitting regions, both Galactic and extragalactic) and it is able to provide a S/N fully consistent with the data. However, for those objects with a signal of the same order of magnitude as detector effects (i.e., variable bias, cross talk, remanence), the ETC underestimates the S/N by ~ 30% (Mason et al., 2019). The effect of imperfect sky subtraction cannot be simulated by simply scaling the S/N by a factor $\sqrt{2}$, and this, together with the above-mentioned factors, leads to the conclusion that the S/N for such extremely faint sources cannot be easily simulated within the ETC. Nonetheless, the IOT could provide the ETC with a fudge factor once the signal reaches a given threshold. A large amount of data (for example, from GTO and Large Programmes) is needed to determine this threshold, and the KMOS GTO teams together with PIs of Large Programmes are prepared to provide feedback to the IOT on this task.

We discussed possible upgrades of the instrument. The community was largely in favour of equipping KMOS with a Ground-Layer Adaptive Optics (GLAO) system to significantly improve the sensitivity, thanks to the AO correction, while still preserving the spatial sampling and hence the current field of view of each IFU. Another possibility considered (albeit not shown in Figure 3), is related to the deterioration of the arms — by far the most delicate optomechanical component in KMOS. In the unfortunate event that we run short on spares for the arms and are not able to build new ones, the solution could indeed be to reduce the number of arms, while increasing the field of view.

Regarding synergies between KMOS and other facilities, the community is divided on whether or not all of the major current and future facilities (for example, the Atacama Large Millimeter/submillimetre Array [ALMA], the Extremely Large Telescope [ELT], and the James Webb Space Telescope [JWST]) are considered crucial to fully exploiting the multiplex capabilities of infrared IFUs like KMOS. These themes also emerged during the sessions, for example, in the talks by Jan Scholz, Chian-Chou Chen, Michele Cirasuolo, Charlotte Mason and Dominika Wylezalek.

During a round table session the discussion turned to which approach would be more effective to increase demand for KMOS — whether it would be better to issue a call for Public Surveys[3] or for more Large Programmes. The community was in favour of the second option.

## Data reduction tutorial

In the afternoon of the last workshop day, about 25 participants attended practical tutorials with hands-on sessions dedicated to KMOS data reduction, followed by a final *Glühwein* and *Spekulatius* farewell reception. The aim of the tutorial was to introduce the instrument, the design of the data reduction pipeline and the data reduction cascade, and to present the KMOS ESOReflex (Freudling et al., 2013) workflow as data reduction tool[4, 5].

Special emphasis was given to the explanation of different data reduction strategies, including removal of telluric features and sky subtraction. Because KMOS data reduction can be complex, and the optimisation of the results can require different strategies and algorithms, members of the astronomical community have come up with their own solutions for specific datasets over the years, some of which were included in the KMOS pipeline and workflow.

Therefore, one aspect that was covered in the tutorial session was how to modify the KMOS workflow to include external Python scripts within the data reduction cascade.

## Main conclusions & ways forward

The workshop brought together the KMOS community to celebrate the fifth anniversary of the first second-generation VLT instrument. All GTO and Large programmes as well as some dedicated studies produced great scientific results, leading to a steadily rising publication and citation record.

The interaction between the community and the KMOS IOT has been fruitful and has led to the implementation of new strategies to broaden the number of users and plan the future of KMOS and its operations. Bruno Leibundgut's warning regarding a decline in the demand of KMOS had a very positive effect on the KMOS community. In Period 104, the requested KMOS time significantly increased, to a level comparable to the first time the instrument was offered (see Figure 3). This can be seen as a great success of the KMOS@5 workshop.

## Demographics

The Science Organising Committee sought fair representation from the KMOS science community in terms of gender, seniority and institutes. The committee invited 11 speakers to cover all scientific topics and major KMOS programmes, with a 6:5 ratio of male to female speakers and 5:6 ratio of senior (staff) to junior (postdoc level) speakers. The total number of participants was 60 (with a female fraction of 42%), which allowed a focused and interactive workshop with relaxed time constraints. We therefore had the luxury of accepting all requested talks (25) and posters (6), with the exception of three submissions that were out of the scope of the conference. The gender balance for different groups in the conference can be seen in Figure 4. The female representation was between 33% to 50% in all categories.

The level of participation from young researchers was very high, with the following breakdown according to seniority: ~ 33% students, ~ 35% postdoctoral researchers, and ~ 30% tenure-track or tenured faculty. In particular, the junior researchers were well-represented in the talks (see Figure 4). Given the nature of the KMOS science community, most of the attendees (excluding the LOC members) came from European institutes (~ 90%), and the rest (~ 8%) from the United States and Australia (~ 2%). The conference picture (Figure 5) shows the majority of the participants in front of the ESO headquarters.

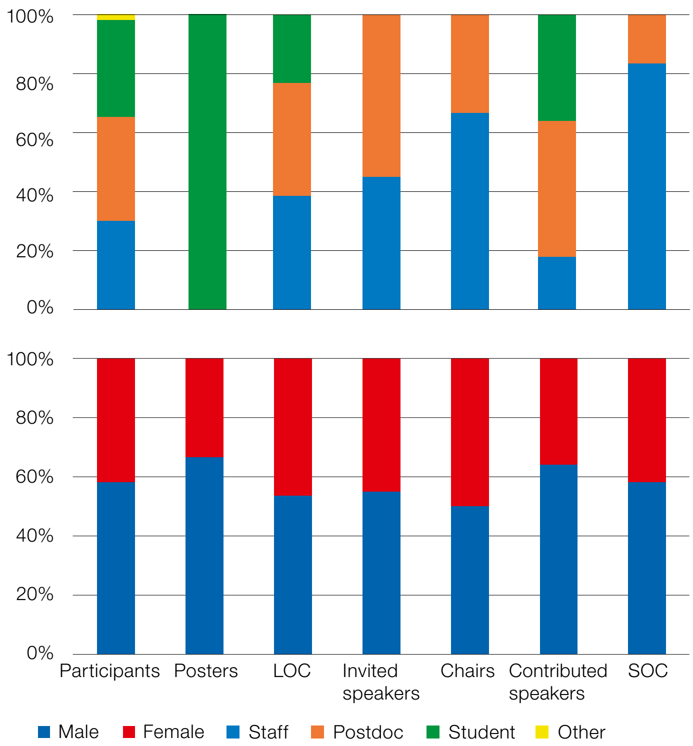


Figure 4. Gender balance and career stage statistics for the KMOS 2018 workshop.

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Tiley, A. et al. 2019, MNRAS, 485, 934

## Links

[1] Link to workshop programme and presentations: https://www.eso.org/sci/meetings/2018/KMOS2018/program.html
[2] The ESO Archive Science Portal: http://archive.eso.org/scienceportal/home
[3] ESO Public Survey Policies: https://www.eso.org/sci/observing/PublicSurveys/policies.html
[4] ESO Reflex: https://www.eso.org/sci/software/esoreflex/
[5] KMOS Tutorial Session at the workshop: https://www.eso.org/sci/meetings/2018/KMOS2018/tutorial.html

Figure 5. The KMOS@5 participants.

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