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KEOPS: Kiloparsec Explorer for Optical Planet Search, a direct-imaging Optical Array at Dome C of Antarctica

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ABSTRACT

Recent site seeing testing campaigns conducted by our team from University of Nice¹ show that Dome C represents the best site on Earth for astronomical high angular resolution (HAR) observations at optical and IR wavelengths. The dramatic gain over relevant HAR parameters r_0 , L_0 , θ_0 and τ_0 , added to very low temperatures during the polar winter nights (-70°C), the dry atmosphere and the possibility of continuous observations during several nights make Dome C the ideal site for deploying a kilometric optical interferometer before the 2015 horizon. Here we describe the concept of Kiloparsec Explorer for Optical Planet Search (KEOPS) that is studied by our group at LUAN. KEOPS is an interferometric array of 36 off-axis telescopes, each 1.5m in diameter. Its kilometric baselines open sub-mas snap-shot imaging possibilities to detect and characterize extra-solar planetary systems, especially exo-Earths out to 300 parsecs from the visible to the thermal IR. KEOPS can be considered as a DARWIN/TPF challenger but at a much lower cost.

Keywords: imaging interferometry, high angular resolution

1. INTRODUCTION

KEOPS is envisioned as a mission facility at Dome C. Its primary goal is to explore all G, K and M stars out to 1 kiloparsec following a solar-systems outside our solar-system observing strategy and point of view. The collecting area of 36 telescopes of 1.5m diameter makes KEOPS comparable to a 10m class telescope. Operated at Dome C, KEOPS attains however the sensitivity of a 20-30m ELT from today's ground sites. The primary goal of KEOPS is the direct detection and the spectral characterization of exoplanets (ExPNs), ultimately hunting exo-Earths in habitable zones. This is done following the nulling method called IRAN² (Fig. 1).

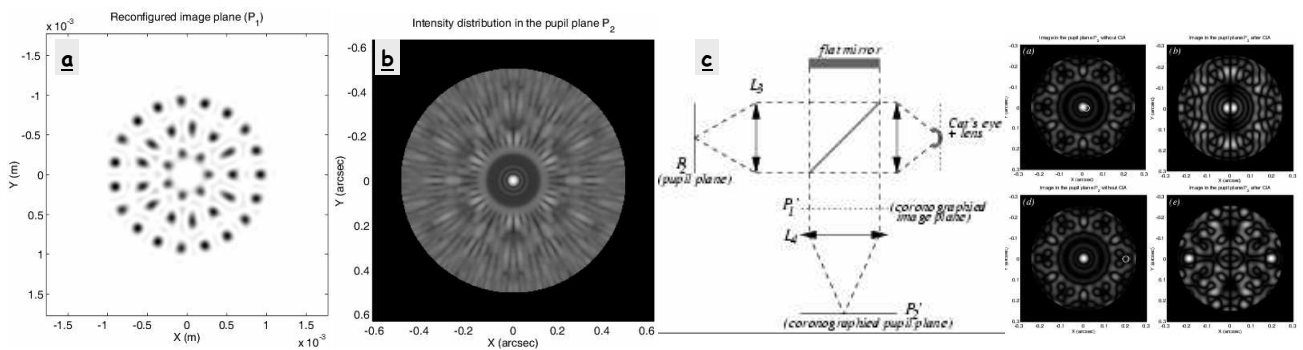


Fig. 2. IRAN concept: (a) image densification, (b) pupil plane interferometry, (c) AIC - (Achromatic Interfero-Coronagraph) to detect high contrast exoplanetary systems

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Other KEOPS targets are imagery of gravitational mirages from μ -lensing events by measuring the impact parameter and derive the lens mass distribution from the temporal follow-up interferometry of these events, spatial resolution of central regions of AGNs to measure their astrometric dance due to SNe explosions, direct asteroseismology of disc-resolved nearby stars by spatial tuning/filtering $2 < l$ & $m < 10$ pulsational modes, plus imagery of stellar magnetic topology, rotational flattening & differential rotation.

Measuring the angular diameters of RSG, post-AGB and winds of WR, LBV and early-type SG in Magellanic clouds (circumpolar) and kinematics of globular clusters from narrow angle differential astrometry can also be envisioned.

2. GENERAL FEATURES OF KEOPS

KEOPS is a deployable array of 6, 12 and 18 (final 36) 1.5m optical telescopes spread over 3 rings (Fig. 2). In its final version, the total collecting surface will be $\sim 60\text{m}^2$ (equivalent to a Keck), but because of reduced atmospheric emission in the IR, the array will be the equivalent of a 30m ELT: we show below that working in the mid- and thermal infrared at $2\text{-}10\mu\text{m}$ (K band), up to 3 mag gain over classical sites is achieved. The radial distances of 250m, 600m and 980m respectively from the central beam-collector-hub are calculated so as to optimize the array antenna beam to be a 1 mas at $10\mu\text{m}$ (1 AU at 1kpc) IRAN pseudo-Airy pattern across a FOV limited to $1''$. This means snap-cot direct imaging with coronagraphic capabilities of about 700^2 resels in the FOV.

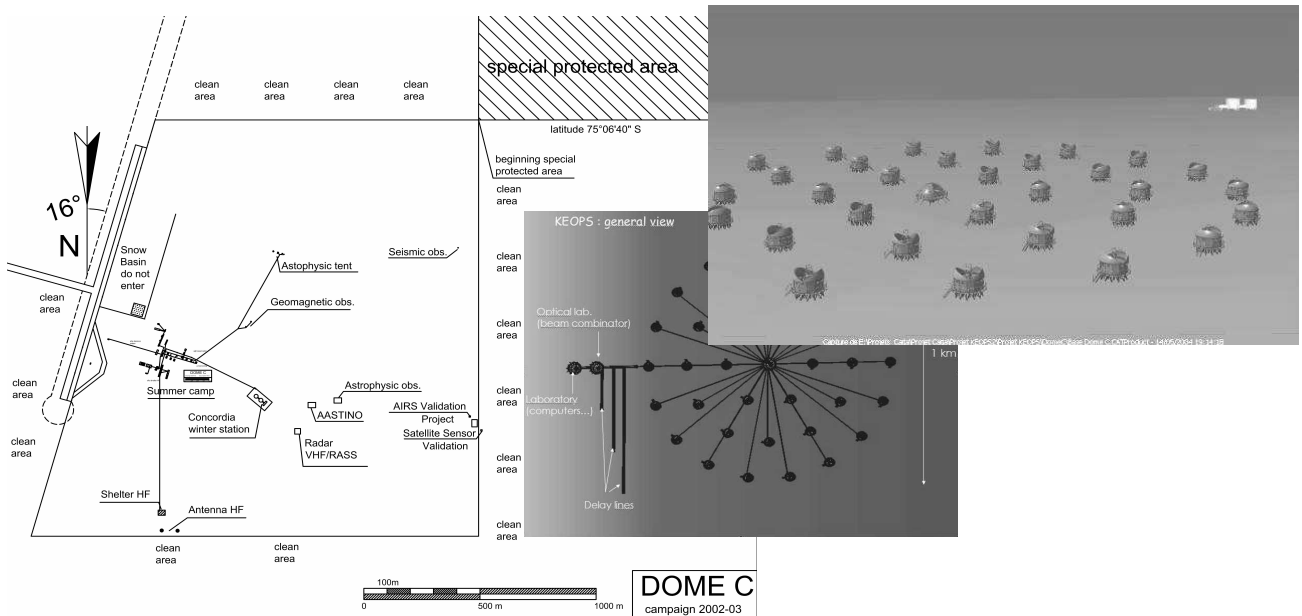


Fig. 2. Proposed layout at Dome C

The afocal beams from the Cassegrain-Coudé telescopes are sent through buried pipelines in a 10^{-2} vacuum minimizing horizontal propagation seeing and atmospheric dispersion effects for off-zenith sources. The 3 bundles of afocal beams from the 3 rings of telescopes are directed from the central hub towards a sideral Optical-Path-Equalizer (OPE) outside the array. The central hub, hosting the metrological laser, encloses field relay optics & tip-tilt correction that transmit the 36 beams towards the OPE. The delay lines are disposed circularly homothetical of KEOPS array and use switch-yards for minimum stroke. Secondary stage piezo delay-lines co-phase the 36 primary wavefronts.

3. INSTRUMENT ELEMENTS

1.1. Off-Axis Telescopes Optimized for IR Interferometry & Coronagraphy

KEOPS primary telescopes (Fig. 3) are 1.5m off-axis parabola (from master F/D=1 paraboloids) with 3 reflection Cassegrain-Coudé afocal optics and 60° zenithal distance pointing. Thus KEOPS can access all sources in a 120° cone from Dome C. The alt-alt mount is similar to the ESO-CAT at La Silla. It is transportable in a standard Antarctica container and can be assembled from 4 main parts: the mirror+mirror-cell, the light folding secondary+tertiary mechanics, the horse-shoe support, the horse-shoe mount itself. The optics can be passively cooled to -60°C during the winter night. The absence of central obstruction minimizes both the IR background and the diffraction noise for coronagraphy in the nulling mode of KEOPS (see below). The pointing primary FOV is 1', and 20" at the central hub. Field-rotation is corrected by a K-prism.

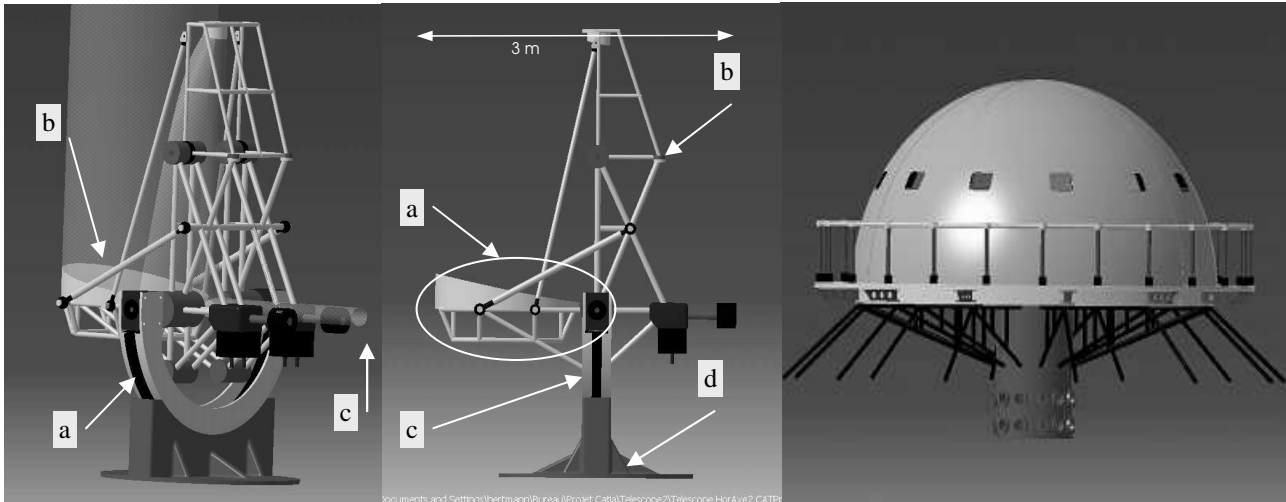


Fig. 3. **Left:** KEOPS telescopes Cassegrain-Coudé afocal optics: (a) Alt-alt mount similar to ESO CAT (La Silla), (b) Off axis parabola $d=1.5\text{m}$ $F=3\text{m}$ (from master $F/D=1$) (avoid central obstruction and IR emission), (c) afocal output beam. **Center:** Easily transportable in 4 parts in standard containers, assembled on site: (a) Part 1 : mirror+support, (b) Part 2: optical tube + secondary and tertiary mirrors, (c) Part 3: horse-shoe mount, (d) Part 4: horse-shoe support. **Right:** central beam collector (hub)

The Central beam collector (hub) collects the 36 afocal beams from the 3 rings of telescopes, that have traveled through 10^{-2} vacuum optical tunnels, in order to minimize horizontal propagation seeing and atmospheric dispersion effects for off-zenith sources. The problem of the deformation of the snow surface over hectometer scales could be overcome by external service tunnels of compacted snow, the by-product of the metrology becoming a gift for the glaciologists.

1.2. Optical study

P. Assus (OCA) has realized a ZEMACS study (Fig. 4) of the off-axis PSF of KEOPS individual telescopes (V band, $\lambda=550$ nm). The unaberrated field is approx. 2 arcmin, which is consistent with interferometry limitation where field is 1 arcsec.

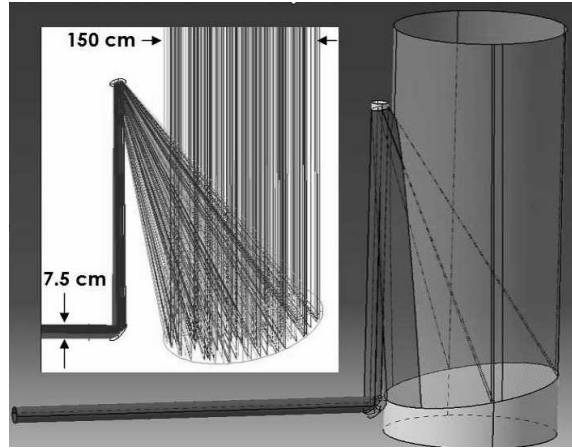
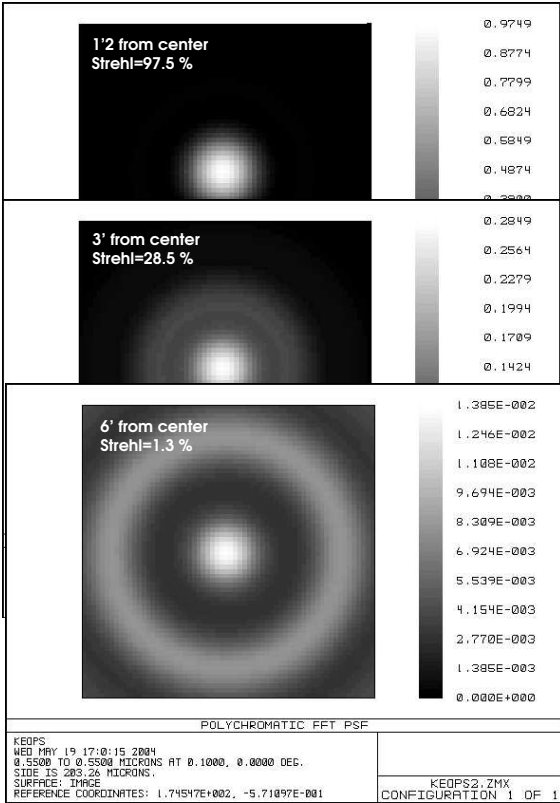


Fig. 4. Ray-tracing and the PSF for KEOPS telescopes at the level of the beam-collector central hub (V band, $\lambda=550$ nm). The unaberrated field is approx. 2 arcmin, which is consistent with interferometry limitation where field is 1 arcsec.

SCIENCE WITH KEOPS

Beichman proposed³ to associate the planet detection probability to a Poisson law with the parameter ηN (η being the mean number of planets around a star and N the number of observed stars). If the η parameter value is 0.1 (suggested by giant planets studies) observing 30 stars should be enough to get a probability of 95% to detect one planet, 175 observed stars to detect at least 10 planets with the same probability. If the sample contains about 400 stars, we notice (Fig. 5) that an η parameter of about 0.01 still allows the detection of at least one planet (with a probability of 95%). We conclude that observing about 500 stars will give a good probability (95%) to detect at least one planet if the η parameter is almost 0.01 and more than 10 planets if the η parameter is almost 0.1.

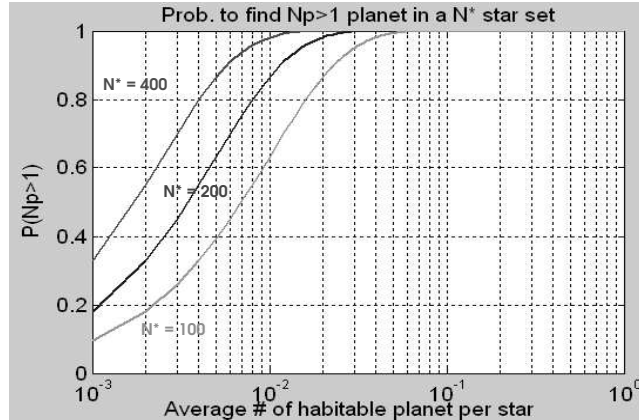


Fig. 5. Computed probability of finding at least 1 planet versus unknown average number of habitable planets per star. N is the total number of planets screened.

According to the CDS, there are about 300 G, 30 K and 30 M sub-giant, main-sequence and sub-dwarf stars in the Dome C sky (at less than 60° away from the south pole's zenith; 45° because of KEOPS possibilities of orientation + 15° because Dome C is 15° away from south pole). Those stars are up to 300pc (M), 60pc (G) and 20pc (K) away from the

Earth. If we assume the stars repartition constant up to 300pc away from the sun, we have densities of $5.63 \cdot 10^{-6}$, $1.01 \cdot 10^{-4}$ and $2.81 \cdot 10^{-3}$ for respectively G, K and M stars. KEOPS will be sized to get an observable sky including 500 stars in these conditions.

1.3. KEOPS observable sky

The KEOPS observable sky shape is obtained by considering a volume limited by a maximum zenith angle of 45° . KEOPS is an interferometer and its resolution allows it to see up to a distance decreasing with the zenith angle so that the volume is also limited by a depth d that decreases with the zenith distance ($d=d_0 \cos z$). We also have to take account of the Earth rotation that moves the described volume around the Earth's rotation axis

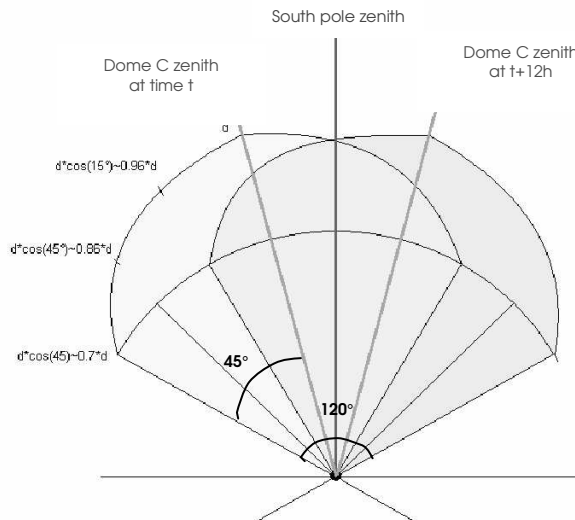


Fig. 6. KEOPS observable sky

So KEOPS can access a volume limited by a zenith angle of 60° from the South Pole. At a given time, this volume is not fully reachable but is entirely covered in 1 day (Earth rotation period, see Fig. 6). The volume includes a constant observable part limited by a zenith angle of 30° .

We calculated that to observe possible planets in the habitable zone of 500 stars KEOPS must be able to see G stars up to 254pc, K stars up to 161pc and M stars up to 70pc for the $10\mu\text{m}$ band. It must be able to observe G stars up to 160pc, K stars up to 128pc and M stars up to 76pc in the $2\mu\text{m}$ band. Those numbers are taking account of the habitable zone position that is function of the star's temperature and the contrast ratio that is function of the wavelength but also of the star temperature.

The coronagraph's extinction ratio should be about $3.7 \cdot 10^5$ in the $10\mu\text{m}$ band and $2 \cdot 10^7$ in the $2\mu\text{m}$ band.

1.4. Exposure time

At $10\mu\text{m}$, the exposure time is mainly increased by the atmosphere's background emission and the instrument thermal emission. Since we attempt to detect an Earth-like planet in the habitable zone, its emission spectrum is close to Earth's own atmosphere and the one of the instrument. A first way to reduce the integration time it is to go to Dome C (-70°C); there, the exposure time is more than 10 times shorter than in temperate sites (0°C). A second way to reduce the exposure time is to use the $2\mu\text{m}$ band (Fig. 7).

The exposure time needed to detect a planet located at 25pc, with a signal to noise ratio of 5 is 100 days in the $10\mu\text{m}$ band. It falls to less than 6 hours in the $2\mu\text{m}$ band for a planet hosted by a G star and less than 1 hour for a planet hosted by a M star (because of thermal background and lower instrument emission level).

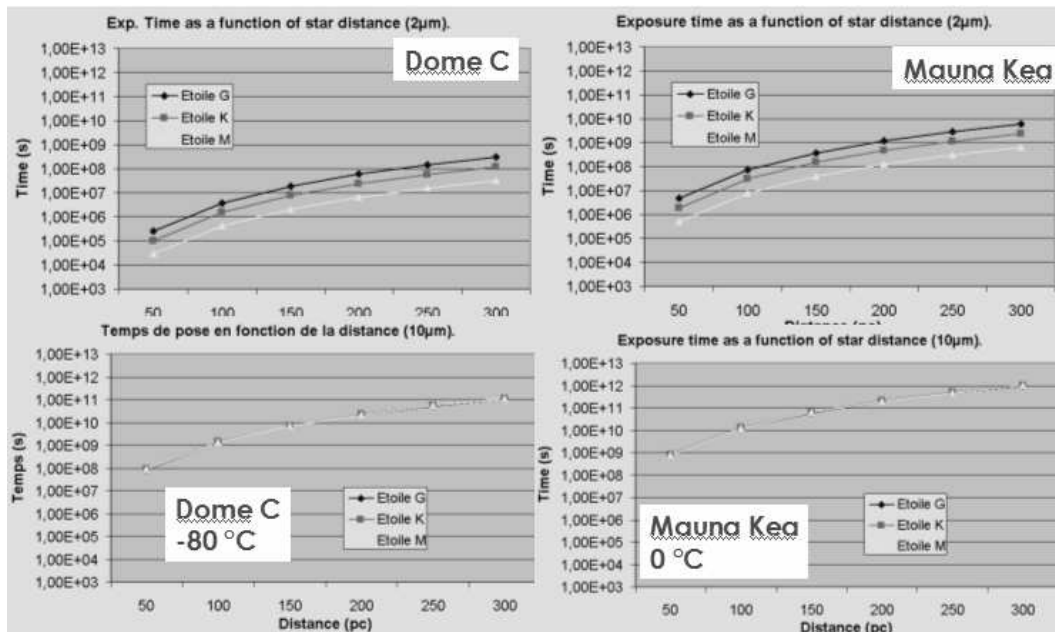


Fig. 7. Exposure time as a function of distance

For the very far planet observations, the exposure time rise 10^8s at 50pc and 10^{11}s at 300pc in the $10\mu\text{m}$ band. In the $2\mu\text{m}$ band, it is around 10^5s at 50pc and 10^8s at 300pc.

Overall, the 10 μ m band looks unusable for the observation of far, faint objects. KEOPS will therefore work in the 2 μ m band.

In a 6 hours exposure time, its sensibility allows KEOPS to observe far enough to access about 100 stars and to detect at least on planet with a 99.9% probability if $\eta=0.1$, and with a probability of 63% if $\eta=0.01$. In 12 hours, KEOPS scans 250 stars in its observation volume that will allow to ensure the detection of at least 1 planet with a 99.9% probability if $\eta=0.1$ and with a probability of 91.8% if $\eta=0.01$. In 1 day exposure time, KEOPS will extend its observation volume enough to include 350 stars and ensure the detection of at least 1 planet with a probability of 99.9% ($\eta=0.1$) or a probability of 97% ($\eta=0.01$).

1.5. Other science targets for KEOPS

Direct snap-shot imaging capabilities make KEOPS suitable for stellar surface imaging. At 2.2 μ m a 0.4 mas resolution would yield 25² resels on α Cen.

Another opportunity would be direct microlensing imaging, as proposed by Delplancke⁴.

4. DEVELOPEMENT TIME SCALE AND CONCLUSIONS

The KEOPS development can be split in 6 steps from 0 to 5. The 0 step (the current one) consists in R&D studies and is planned to last until 2006. Among the challenges: telescopes, beam stabilisation, cophasing, delay lines, recombiner, coronagraph, science. The step 1 will be the single telescope operations and will happen during 2007. This is a testbench and science operation phase, including planeto/asterosismology (Schmider JISCO/Mosser SIAMOIS) and μ lensing as proposed by Ragazzoni. Next, the step 2 will make two telescopes working in interferometer mode (2008-2009). This could be a result of a synergy with the APISD project⁵. The next step will deploy the first KEOPS ring composed of 6 telescopes, and here a connection with the API project can be envisioned⁶. Finally, the KEOPS project will be ready with its 36 telescopes around 2015.

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