The Mid-IR ELT Imager and Spectrograph (METIS) and its Science Goals in the Context of *AKARI*

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ABSTRACT

The Mid-infrared ELT Imager and Spectrograph (METIS) is one the first three scientific instruments on ESO's Extremely Large Telescope (ELT). At the time of anticipated first light in 2025, METIS will provide diffraction limited imaging, coronagraphy and medium resolution slit spectroscopy in the 3–19 μm range, as well as high resolution ($R \approx 100,000$) integral field spectroscopy from 2.9–5.3 μm. The unique combination of these observing capabilities with an angular resolution of 0$''$.020, and the sensitivity provided by a 40 m aperture, make METIS a very powerful tool to study the infrared sky – from objects in our Solar system, the Galactic center, brown dwarfs, evolved stars, and massive stellar clusters to active galactic nuclei (AGN), local starbursts, transient events, and luminous infrared galaxies at intermediate redshifts. Its main scientific focus, however, will be on the study of proto-planetary disks and exoplanets.

In this paper, we describe the instrument concept and performance. We discuss the scientific performance of METIS with respect to *AKARI*, and elaborate on the relevance of the *AKARI* archive with respect to the METIS observing program.

Keywords: extremely large telescopes, ELT, mid-infrared, METIS, proto-planetary disks, exoplanets, *AKARI*

1. INTRODUCTION: ESO'S EXTREMELY LARGE TELESCOPE (ELT)

One of the highest priorities over the next decades in ground-based astronomy are Extremely Large Telescopes. Currently, there are three projects under development: ESO's Extremely Large Telescope (ELT) with an aperture diameter of 39.3 meters, and the two US-led projects, the Thirty Meter Telescope (TMT) [30 m] and the Giant Magellan Telescope (GMT) [24.5 m]. All three of them target fundamental issues in astronomy, from the search for habitable planets to the study of the first galaxies in the Universe, and all three projects anticipate "first light" around the mid 2020ies.

The largest of the three telescopes, the ELT, is under construction by the European Southern Observatory (ESO) on Cerro Armazones in the Atacama Desert of northern Chile. It has a novel 5-mirror optical design, which includes a built-in adaptive optics system (mirrors M4 and M5) to compensate the atmospheric turbulence. An overview of the optical design is shown in Figure 1. The ELT will be equipped with three scientific "first light" instruments:

- HARMONI, the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph.
- MICADO, the near-infrared Multi-AO Imaging Camera for Deep Observations. To reach its nominal performance, MICADO is assisted by MAORY, the Multi-conjugate Adaptive Optics RelaY for the ELT.
- METIS, the Mid-infrared ELT Imager and Spectrograph, which is the focus of this paper.

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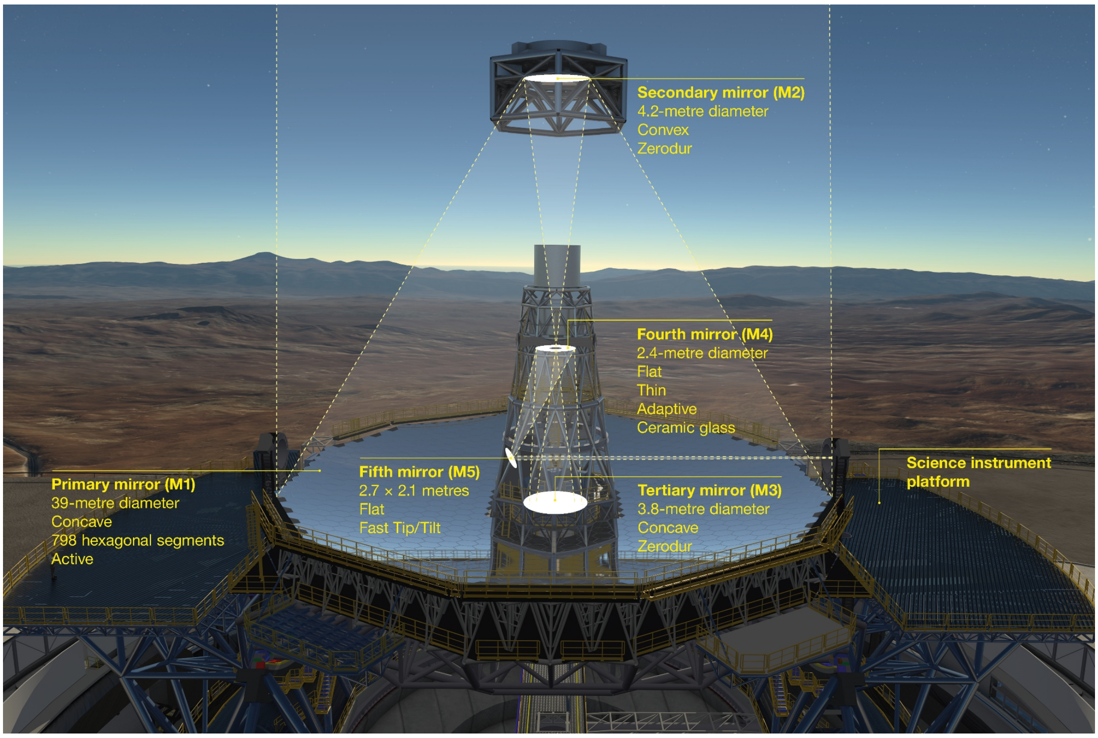


Figure 1. The 5-mirror optical system of ESO's ELT. The light is first reflected from the segmented 39-meter primary mirror (M1), and then bounces off the convex (M2) and the concave (M3) mirrors. The last two mirrors (M4 & M5) provide the adaptive wavefront correction. Credit: ESO (2017).

2. THE MID-INFRARED ELT IMAGER AND SPECTROGRAPH (METIS)

METIS will likely be the only "first light" instrument on any extremely large telescope to observe in the thermal/mid-infrared regime. In order to achieve the highest angular resolution and maximum sensitivity, METIS will observe at the diffraction-limit, given by the ELT's aperture size.

2.1. Instrument specifications

At the most basic level, METIS provides two fundamental functionalities: high contrast imaging and high-resolution integral field spectroscopy. Both modes are ideally complementing ALMA and *JWST*. The instrument sensitivity is shown in Figure 5. The main instrument specifications can be summarized as follows:

- Imaging at 3–13(19) μm. The imager with a field of view (FoV) of $\approx 12''$ includes:
  – Low/medium resolution slit spectroscopy,
  – Coronagraphy for high contrast imaging.
- High resolution ($R \approx 100,000$) IFU spectroscopy at 3–5 μm, over a FoV of less than $1''$, including a mode with extended instantaneous wavelength coverage ($\Delta\lambda \approx 300\,\mathrm{nm}$).

All observing modes work at the diffraction limit with a single conjugate adaptive optics (SCAO) system. To correct for the atmospheric turbulence, the wavefront information, gathered by the internal, near infrared wavefront sensor is used to control the surface shape of the ELT mirrors M4 and M5.

2.2. Project overview

METIS is a big project with an estimated total cost in the order of 50 million Euros. The major cost fraction is for labor. The design and construction of METIS follow the "ESO model", in which labor is provided by the consortium partners in exchange for GTO time on the ELT.

The METIS consortium consists of nine consortium partners:

- Netherlands Research School for Astronomy (NOVA; PI: B. Brandl)
- Max-Planck-Institute for Astronomy (Heidelberg, Germany)
- CEA DRF/IRFU (Saclay, France)
- Eidgenössische Technische Hochschule Zürich (Switzerland)
- Katholieke Universiteit Leuven (Belgium)
- STFC, ATC (Edinburgh, United Kingdom)

- A* consortium (Vienna, Linz, Innsbruck & Graz, Austria)
- University of Cologne (Germany)
- Centra (Lisbon & Porto, Portugal)

The formal phase-B kick-off of METIS was in September 2015, with “first light” anticipated in 2025.

3. THE SCIENCE CASE FOR METIS

The following section gives an overview of respresentative METIS science. Most of the discussion below has been adopted from Brandl et al. (2016).

3.1. Overview

Given its unique capabilities in terms of spatial and spectral resolution, the science case for METIS is broad and covers various science themes including the formation history of the solar system, massive stars and cluster formation, evolved stars and their circumstellar environment, the Galactic center, and also extragalactic science (e.g., starbursts in the local universe, luminous star-forming galaxies at high redshift and AGNs). Figure 2 illustrates the main science areas of METIS.

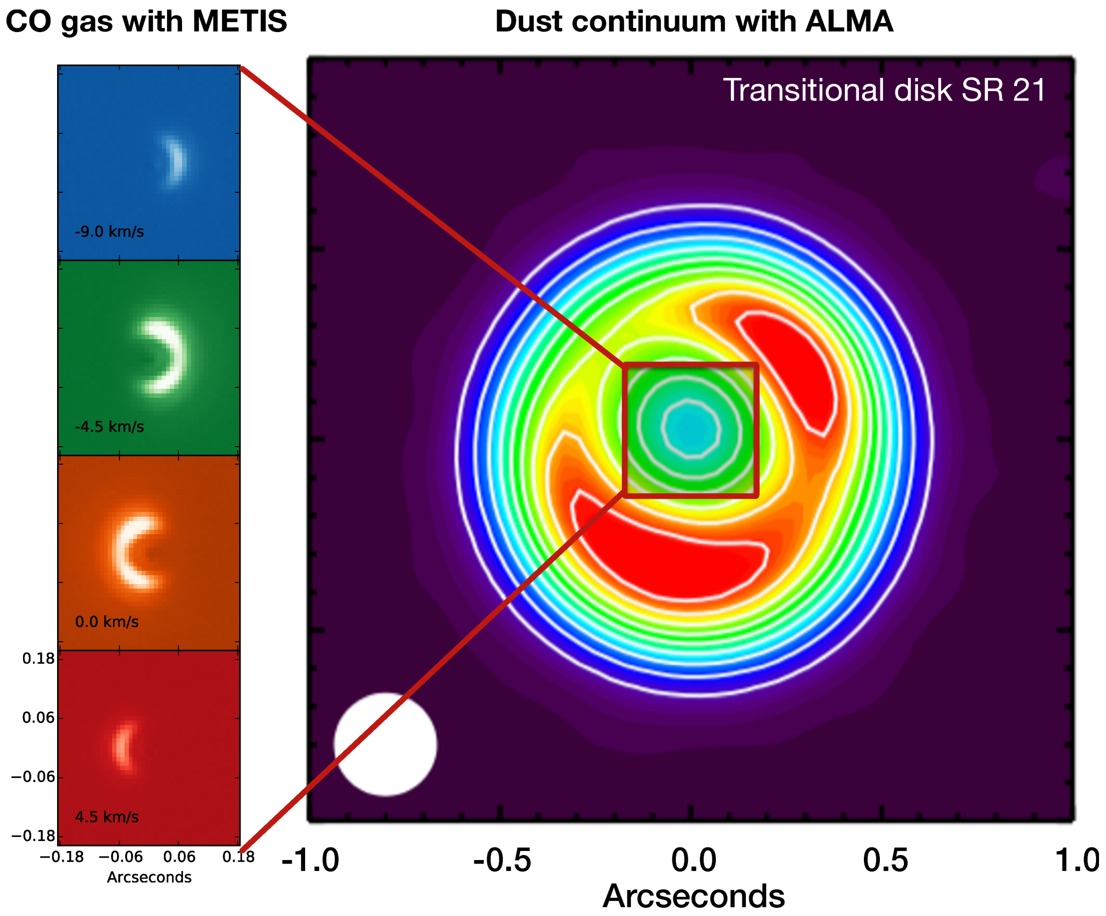
Figure 2. METIS focuses on the cool and dusty Universe. This figure gives an overview of the main science areas in which METIS is expected to make substantial contributions.

Two science themes are, however, driving the instrument requirements and these are (1) protoplanetary disks and the formation of planets, and (2) exoplanet detection and characterization. The following subsections give a brief summary of these two main science themes.

3.2. Protoplanetary disks and the formation of planets

Leveraging METIS’ high spatial resolution a key science objective is to observe, and image, the process of planet formation in the primary planet-forming regions from 1–10 au at all evolutionary stages from protoplanetary disks through debris disks. Specifically, METIS will have the potential to transform our understanding in five areas:

- Observe the physical evolution of planet-forming material. This includes imaging the distribution of small grains (a few microns) for direct comparison with large grains (millimetre to centimetre) observed by ALMA, measuring the gas kinematics and amount of warm molecular gas at 1 au scales in disks, and quantifying molecular disk winds that affect disk dissipation.
- Search for protoplanets embedded in gas-rich disks, either directly or through their kinematics reflecting dynamical interactions with gas and dust. This includes a search for molecular and atomic emission from circumplanetary disks around Jupiter-mass protoplanets. The physical properties of protoplanets can be directly compared to exoplanet demographics.


CO gas with METIS

Dust continuum with ALMA

Figure 3. Model of a METIS observation of CO ro-vibrational emission at 4.7μm in the transitional disk around SR 21, a G3 star at a distance of $\approx$120 pc in the Ophiuchus star-forming region (left panels), compared to the ALMA dust continuum (0.87 mm) image (right panel; based on data presented in Pinilla et al. (2015). Note that it is already known from CRIRES spectroastrometry observations (Pontoppidan et al. 2008) that the CO gas traces an inner ring at $\approx$7 au (corresponding to orbital separations between Jupiter and Saturn in the Solar system), separate from the outer dust ring at $\approx$ 35 au as seen with ALMA. METIS can directly image this inner ring and provide further constraints on any embedded planets shepherding the rings. The CO images represent a two-dimensional non-LTE model with gas/dust thermal decoupling using the radiative transfer codes RADLite/RADMC.

- Measure the chemical composition of planet-forming gas and dust inside of 10 au. This includes measuring the composition and distribution of warm molecular gas and PAHs in the innermost disk, observations of ices in scattered light and absorption, and the crystallinity and composition of small dust grains on 1–10 au scales.
- Image warm dust dust belts in nearby debris disks to determine their properties and radial distribution. This may reveal ongoing terrestrial planet formation and constrain models of the Earth's origin.
- Search for and image exozodiacal systems around nearby main-sequence stars to determine their demographics in comparison to those of exoplanets.

In Figure 3 we show an example how METIS will be able to spatially resolve the kinematics of molecular gas in planet-forming regions around young, disk-bearing stars. While dust observations are critical for our understanding of planet formation, the gas component plays a comparable and complementary role and does not only drive dust dynamics, but also provides the necessary ingredient for giant planet formation. In comparison to ALMA, METIS will produce full-aperture images of warm molecular gas in protoplanetary disks at angular scales of $0\farcs05$, with high efficiency and sensitivity, allowing for direct imaging of large samples of disks. In particular the CO $v = 1$–0 ro-vibrational transitions at 4.7 μm are excellent tracers of the 1–10 au region in protoplanetary disks (Najita et al. 2003; Blake & Boogert 2004; Brittain et al. 2007; Brown et al. 2013) probing gas with temperatures of a few hundred Kelvin to about 1000 K.

3.3. **Exoplanet detection and characterization**

The study of extrasolar planets will be one of the prime science goals and METIS will have a ground-braking impact in both areas of detection and characterization of extrasolar planets. The exoplanet science case can be subdivided into the following three topics:

- Exoplanet demographics: This includes the detection of (gas giant) planets with an empirically determined mass, either from ongoing radial velocity campaigns or from ESA's GAIA mission, and also the determination of the occurrence rate of gas giant planets at large orbital separations (5–30 au). At this point in time, none of the directly imaged planets has an empirically determined mass and current exoplanet imaging surveys have not sufficient spatial resolution (and sensitivity) to probe a large number of stars for planets with masses and separations comparable to the gas and ice giants in our solar system.

- Climates and atmospheric characterization: This topic includes both the study and characterization of close-in transiting and non-transiting planets (Brogi et al. 2012; Birkby et al. 2013; Brogi et al. 2014) and also distant cool giant planets. By tracing thermal emission from exoplanets in the mid-infrared, opacities of absorbers (molecular bands, dust, clouds), vertical temperature profiles, and the chemical composition of exoplanet atmospheres can be constrained. Thanks to its long-slit spectroscopy and high-dispersion IFU mode METIS will not only be able to characterize the composition and key physical parameters of exoplanet atmospheres, but it will also be capable of tracing atmospheric dynamics and exoplanets rotation rates (Crossfield et al. 2014; Snellen et al. 2014)
- Towards other Earths: The *Kepler* mission revealed that small planets with radii $< 4\,R_{\mathrm{Earth}}$ are abundant (Borucki et al. 2011; Rowe et al. 2015) suggesting that small planets also orbit other stars in the immediate Solar neighborhood. Theoretically, small, warm planets around the nearest stars emit enough thermal radiation for METIS to detect them and given that at the moment no space-based missions to image Earth-like planets are on the roadmap of any space agency significant efforts are invested to enable this science case.

Figure 4 illustrates the last topic mentioned above and more details on exoplanet science with METIS are given in Quanz et al. (2015). In that context, METIS offers an additional interesting possibility: Time differential, high-dispersion spectroscopy has already shown to be able to separate out planet signals in the time and spectral domain at the 10^{-4} level. Furthermore, high-contrast direct imaging spatially separates planets at even more extreme contrast levels. Simulations show that the METIS integral field spectrograph can combine these techniques, e.g., in the wavelength range from 4.8–4.9 μm. This will allow us to detect and characterize planets simultaneously in the time, spectral and spatial domain — reaching contrast levels of $1 \cdot 10^{-9}$ or better — bringing even the characterization of rocky planets around nearby stars within reach (Snellen et al. 2015).

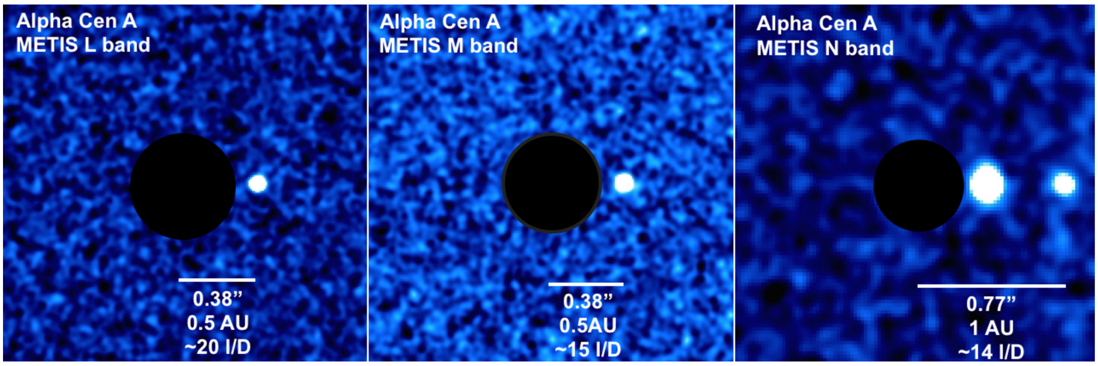


Figure 4. METIS simulations of small planets around Alpha Cen A. From left to right: 2 hour on-source integration in the L, M and N band filters, respectively. The central star has been masked out in all images. Each image contains two planets with a radius of 1 R_{Earth}, one planet located at 0.5 au the other one located at 1 au (the corresponding separation in λ/D is given in the different panels). Assuming a bond albedo of 0.3 for the planets and a luminosity of $L = 1.52\,L_{\mathrm{Sun}}$ for Alpha Cen A, the planets have equilibrium temperatures of ≈ 400 K and ≈ 280 K, respectively. While the inner planet is clearly detected in all filters, the planet at 1 au is only detected in the N band. All simulations assume that at the location of the planets METIS is background noise limited. The contrast ratios of the inner planet, relative to the central star, are approximately $3 \cdot 10^{-9}$, $2 \cdot 10^{-8}$, and $5 \cdot 10^{-7}$ in the L, M and N bands, respectively. The outer planet has a contrast of $1 \cdot 10^{-7}$ in the N band.

4. METIS IN THE CONTEXT OF *AKARI*

During its almost two year mission, *AKARI* (Murakami et al. 2007) with its 68.5 cm telescope has performed an all-sky survey until August 2008. Most relevent in the context of METIS are the data from the Infrared Camera (IRC; Onaka et al. (2007), which consists of three cameras covering 1.7–26 μm in 9 bands with fields of view of approximately $10' \times 10'$.

At the time of writing, the *AKARI*/IRC Point Source Catalogue contains 870,973 sources; observations in both S9W and L18W bands exist for 168,227 sources, and slitless spectroscopy is available for 625 objects, of which many have not yet been identified. The *AKARI* archive is therefore likely a fruitful source of potential targets for follow-up studies, either at much higher angular resolution, or with spectroscopy, or both.

Figure 5 shows a comparison between the point source sensitivities of several ground- and space-based infrared instruments – from the past, present, and future – including ELT/METIS and *AKARI*/IRC.

Sensitivity, angular resolution and sky coverage for both ELT/METIS and *AKARI*/IRC are also compared in Table 1. While, at first sight, the nominal sensitivity difference of two orders of magnitude may appear rather incompatible, one

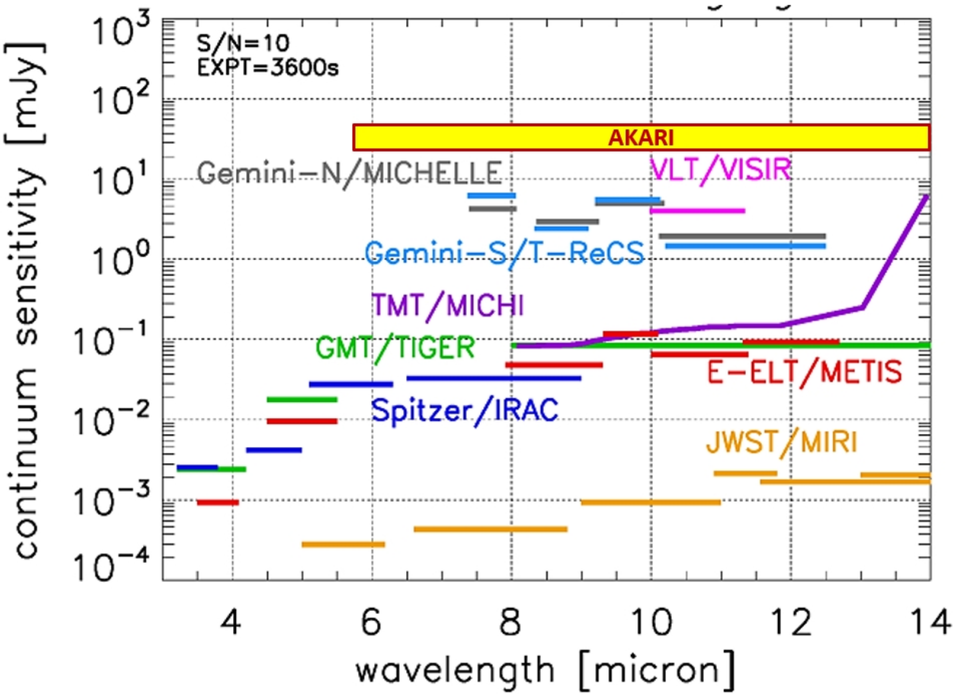


Figure 5. A comparison between the point source sensitivities of several ground- and space-based infrared instruments. The data have been taken from the literature and websites of the respective instruments, and recalculated for a signal-to-noise of $\sigma = 10$ for a one hour on-source integration time.

Table 1. The complementarity between *AKARI* and METIS

	AKARI/IRC	ELT/METIS
Sky coverage	all-sky	targeted observations
Point source sensitivity (1 hr, 10σ)	≈ 50 mJy	5 μJy
Angular resolution (at 3μm)	5″	0.″023

has to keep in mind that one *AKARI* infrared point source will – at the resolution of a 39 meter ELT – typically break up into numerous smaller – and thus weaker – components and, possibly, an extended, low surface brightness component. Sufficient sensitivity margin is thus required to ensure successful follow-up observations with ELT/METIS.

At the end, we would like to give one specific example for illustration. Aikawa et al. (2012) observed ice absorption bands towards edge-on young stellar objects. METIS, with its high resolution integral field spectrograph, will be able to spectrally image the disks in these objects, not only to detect CO absorption but also to trace their vertical gas/ice structure. Similarly, METIS spectroscopy will reveal the location and kinematics of the CO gas within highly extincted background stars with deep ice absorption, which have recently been discovered with *AKARI* (Noble et al. 2017). All of these studies will provide detailed constraints on the ice/gas interactions in proto-planetary disks.

ACKNOWLEDGMENTS

We would like to thank the Scientific Organizing Committee for the kind invitation to this interesting meeting, and the Local Organizing Committee for the flawless organization and the generous financial support.

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