Exoplanet Spectroscopy with ExoNINJA

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ABSTRACT

ExoNINJA will optically couple the output of SCExAO to the NINJA spectrograph, enabling high contrast NIR spectroscopy of exoplanets at R~4000 in the near-IR (0.9-2.5 um) (*El Morsy et al. 2024*). ExoNINJA will provide spectro-imaging capability, optimized for revealing the morphology of accreting protoplanets and the atmospheric composition of young exoplanets orbiting nearby stars. ExoNINJA's high-contrast imaging (HCI) is provided by the existing Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system; and its high-sensitivity near-IR spectroscopy is provided by the Near-INfrared and optical Joint spectrograph with Adaptive optics (NINJA). Light will be transported from SCExAO to NINJA by using an optical fiber bundle that preserves spatial information, allowing spectro-imaging of a small field of view centered on the (proto-)planet.

ExoNINJA is currently under development (funded by JSPS), and will be deployed in approximately 2 yr.

Why ExoNINJA? SCIENCE OBJECTIVES

Exoplanet spectroscopy at R~4000 with spatial resolution for atmosphere characterization.
Optimized for sensitivity and for access to small angular separation companions, probing the 1-10 AU orbital range where the dominant population of giant planets lies.

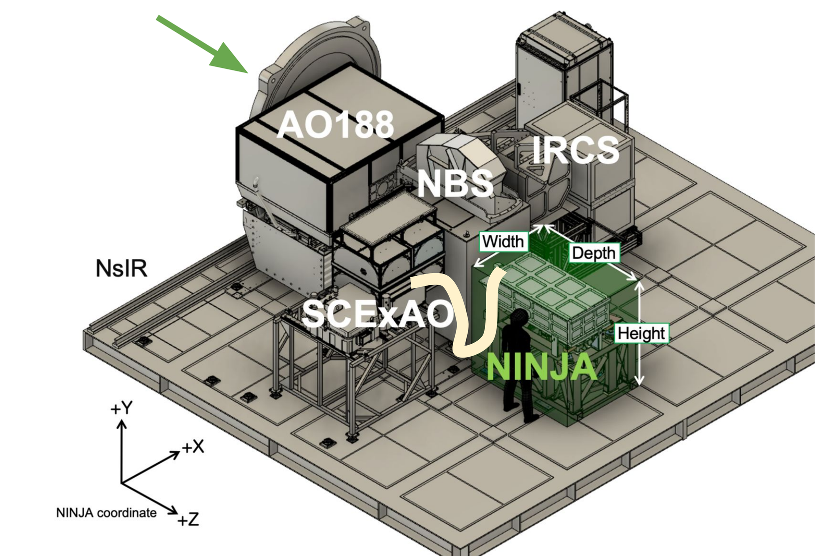
ExoNINJA's key Science Objectives

- **Mapping the accretion and early evolution of proto-planets**. ExoNINJA's spatial+spectral resolution will map protoplanet's dust (thermal emission + scattered starlight), exoplanet atmospheres (featuring molecular absorption) and gas accretion (1.28μm Paβ emission).
- **Measuring the early evolution of exoplanet atmospheres through cooling stages**. ExoNINJA's sensitivity will allow characterizing exoplanet atmospheres across a broad range of mass, age, and orbital distance.
- **Connecting the chemical composition of giant planets with formation processes**. By measuring atmospheric composition (eg. C/O ratio) and physical characteristics (temperature, surface gravity), ExoNINJA will probe exoplanet formation processes by constraining chemical enrichment processes (in-situ gravitational collapse, vs. core accretion, vs. enrichment from outer planetesimals/comets) and initial temperature.
- **Measuring the binarity of low-mass companions and exoplanets**. ExoNINJA's spectro-astrometry mode will for the first time probe high-contrast exoplanets and low-mass companions for multiplicity.

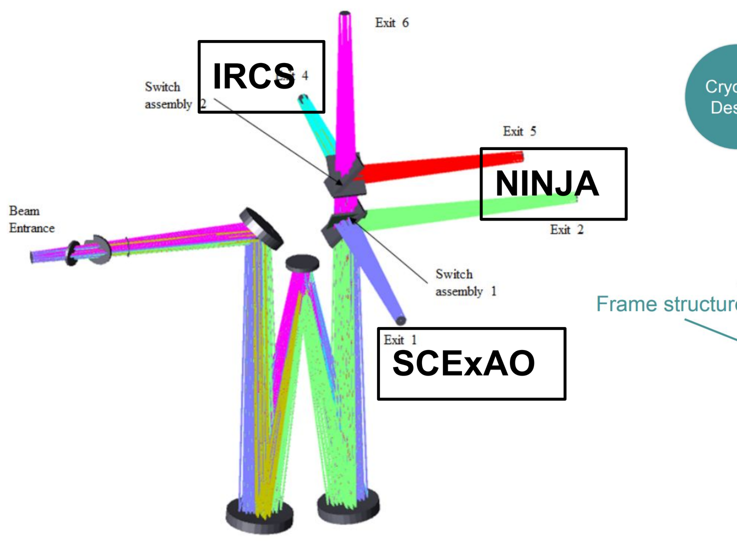
Higher spectral resolution (~200x) than CHARIS, higher sensitivity and spectral coverage than REACH. Combined spectral+spatial information enables spectro-astrometry.

DESIGN & IMPLEMENTATION

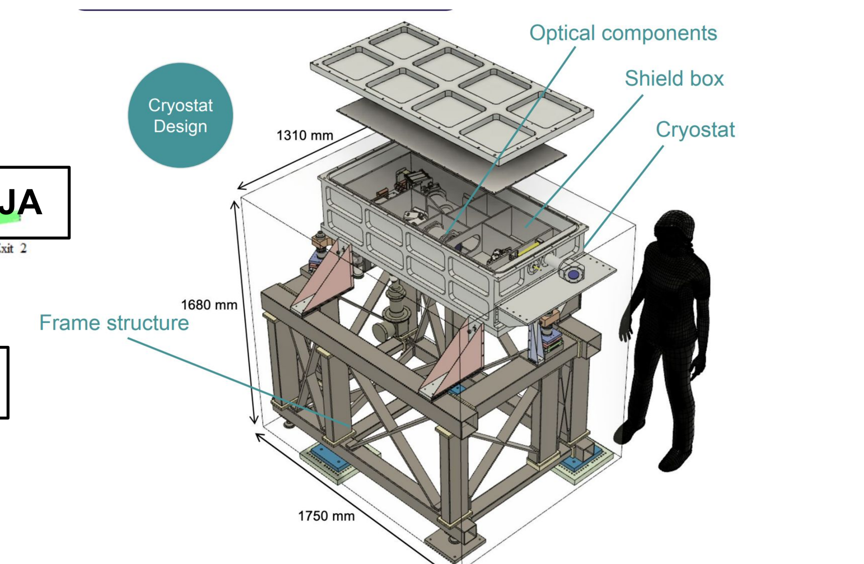
ExoNINJA will add an optical fiber coupling between the SCExAO high contrast instrument and the NINJA NIR spectrograph



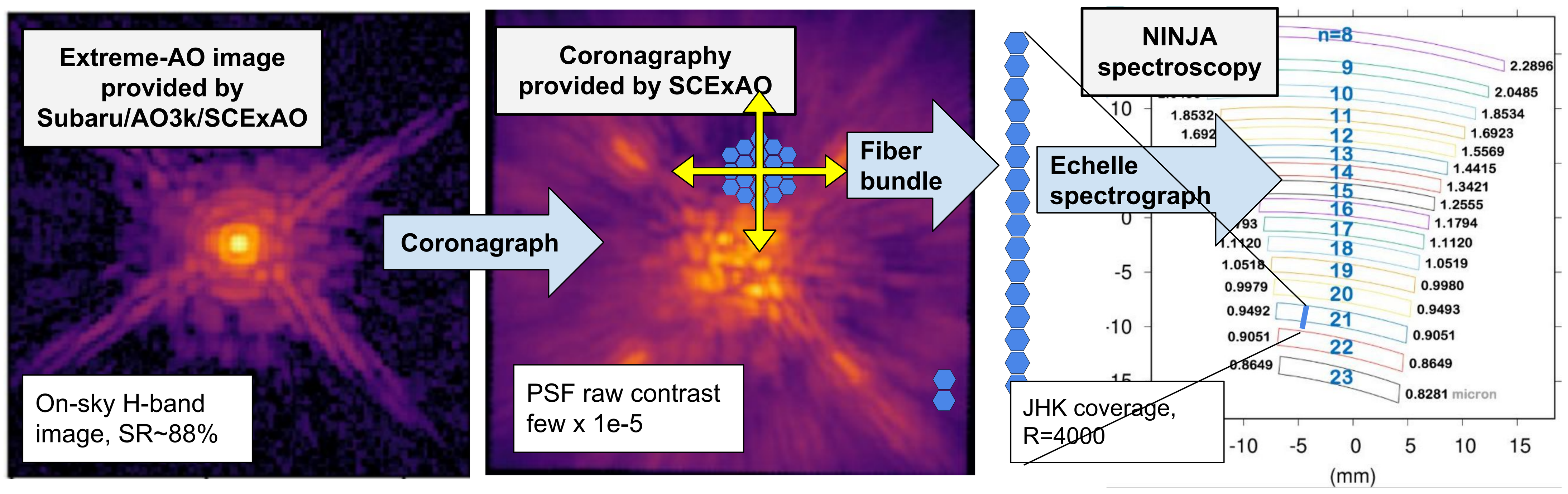
ExoNINJA optical configuration on Subaru Telescope's NasIR platform. Platform layout. Light enters from the telescope (green arrow) into the AO system (AO188/3k/LTAO), and then to the Nasmyth beam switcher (NBS). The 3 main science instruments are SCExAO, NINJA (green) and IRCS.



NBS beam paths. Light enters from AO188/3k/LTAO on the left, and is optically relayed to remotely actuated mirrors and beam splitters to be directed to either NINJA, SCExAO or IRCS. For ExoNINJA, light will be directed to SCExAO, and then fiber-fed (yellow line) from SCExAO to NINJA.



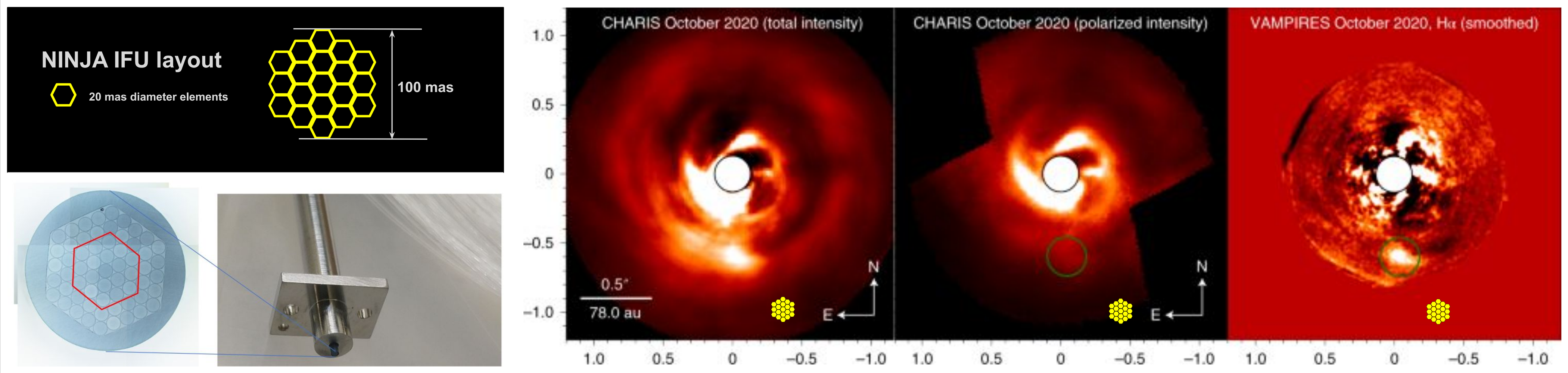
NINJA mechanical design. The platform on the entrance side (right side in the image) of the cryostat will host ExoNINJA's deployable pseudoslit injection unit.



ExoNINJA combines high contrast imaging with mid-R spatially resolved spectroscopy. Left: The existing extreme-AO system SCExAO on Subaru Telescope delivers high-quality images of bright (mH~<11, mR~<11) stars thanks to a 2-stage adaptive optics correction and VIS + IR wavefront sensing. Center: SCExAO features coronagraphic modes, where a set of optical masks removes most of the starlight. The residual starlight is at ~1e-5 contrast in the resulting image. A small steerable 2D field of diameter ~0.1" will be coupled in a bundle of 19 single mode optical fibers (SMFs) and re-arranged in a 1D pseudo-slit to be injected in the existing NINJA echelle spectrograph (right). The full system, named ExoNINJA, is a nearIR high contrast integral field unit (IfU) optimized for exoplanet characterization. Left and center are on-sky H-band SCExAO images. Right image is the designed spectra layout on the NINJA detector.

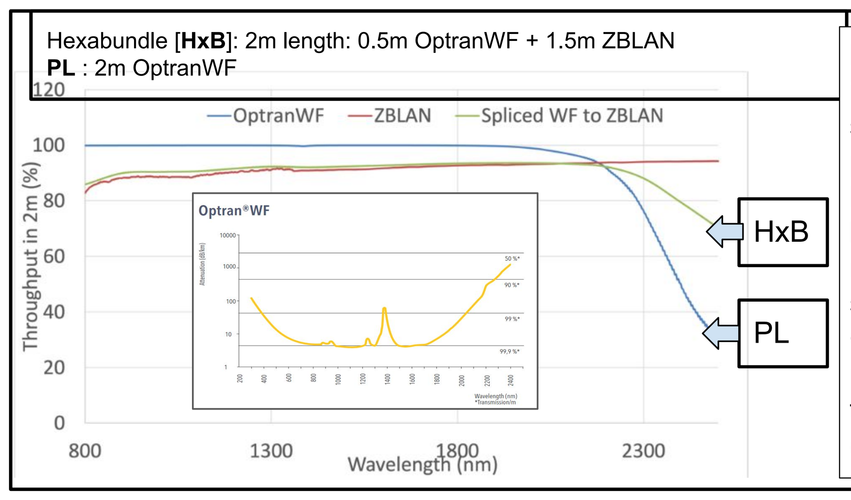
Mini-IFU mode with fiber hexabundle

Optimized for throughput and efficiency



ExoNINJA mini-IFU mode. Top left: Hexabundle lenslet geometry. Bottom left: ExoNINJA hexabundle prototype. Right: Object AB Aur b imaged in nearIR thermal emission (left), not detected in near-IR polarized light (center) and detected in visible H-alpha emission (right). Ref: Currie et al. Nature Astronomy 2022. The object is spatially extended by approximately 0.1" in both NearIR and visible. ExoNINJA's mini-IFU mode would disambiguate exoplanet from circumplanetary disk components.The ExoNINJA 19-element lenslet array is shown to scale (yellow) on the 3 images.

	NINJA	ExoNINJA	
		IfU	PL
Teles. M1+IRM2+IRM3	0.87		
AO188/3k	0.82		
NBS	0.93		
LTAO	0.91	-	
NINJA (opt+spec+det)	0.26		
SCExAO relay optics	-	0.85	
SCExAO coronagraph	-	0.8	
FIM + Fiber bundle	-	0.90	0.80
Pseusoslit injection	-	0.85	0.85
TOTAL	15.7%	9.7%	8.0%



ExoNINJA H-band throughput. The NINJA part is shown in yellow, averaging ~15% for single-shot 0.8-2.5μm spectroscopy. Right: To preserve high K-band throughput, the ExoNINJA mini-IfU hexabundle will use 0.5m length Optran WF material + 1.5m ZBLAN material. The ExoNINJA photonic spectrograph (photonic lantern) will use OptranWF only, prioritizing shorter wavelength performance. The overall ExoNINJA throughput will be 9.7% (IfU mode) and 8.0% (photonic spectrograph mode).

Spectro-astrometry mode with Photonic Lantern

Modal Decomposition of light with a Photonic Lantern (PL)

In a PL, light transitions adiabatically (no loss) from the MMF input to multiple SMF outputs. **The PL performs a modal decomposition of the input electric field** over a small FOV.

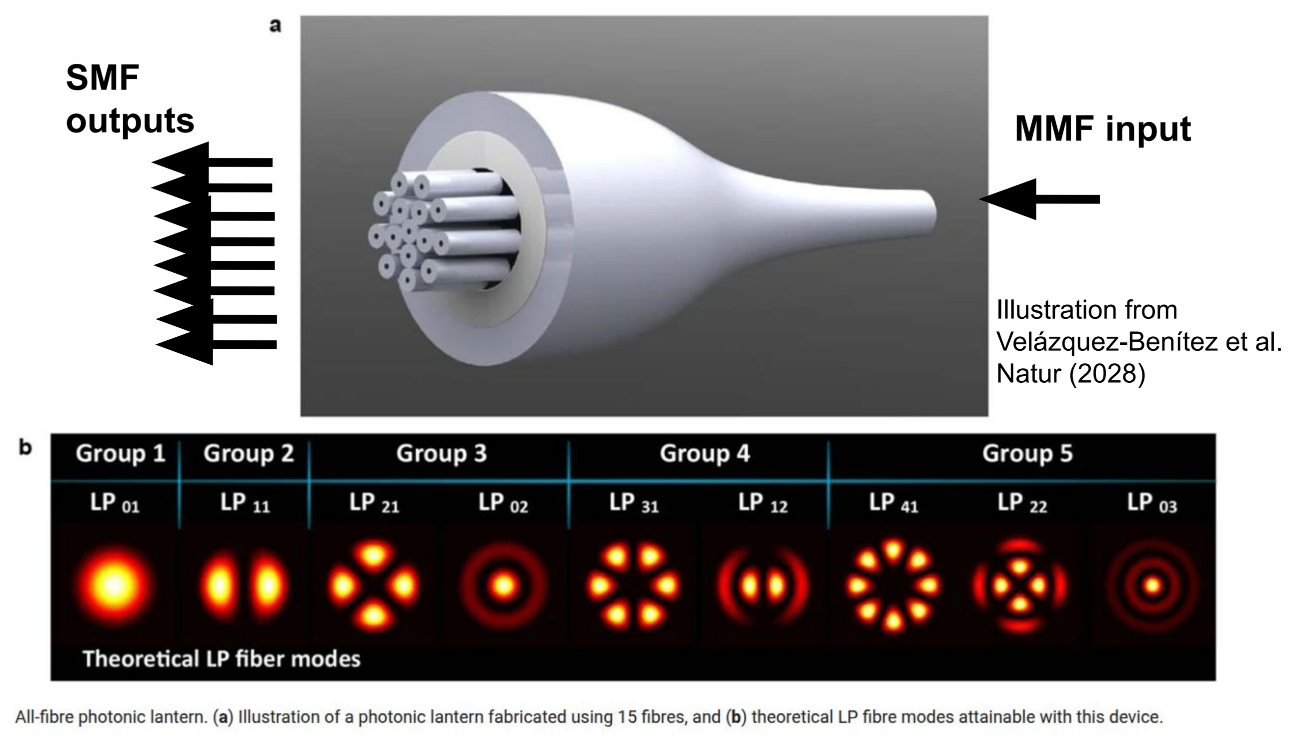


Illustration from Velázquez-Benítez et al. Natur (2028)

All-fibre photonic lantern. (a) Illustration of a photonic lantern fabricated using 15 fibres, and (b) theoretical LP fibre modes attainable with this device.

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