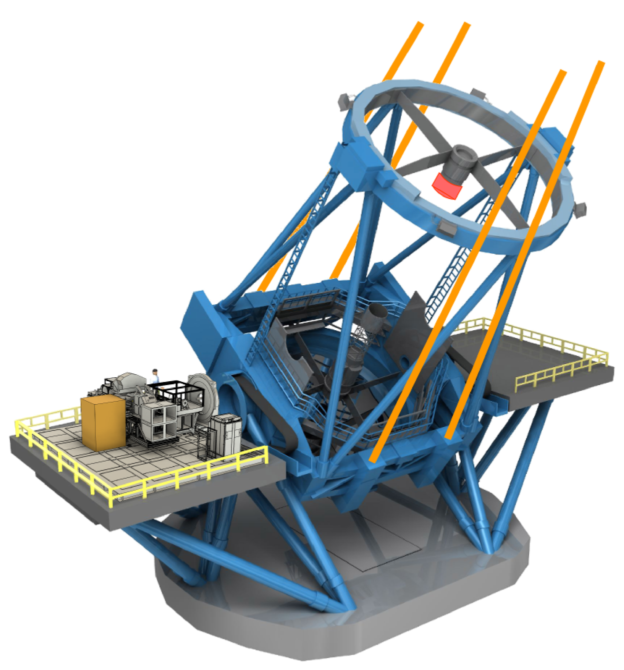


NINJA : Subaru Optical-to-NIR spectrograph optimized for LTAO

Chihiro Tokoku, Shinobu Ozaki, Takashi Moriya, Kenshi Yanagisawa, Kentaro Motohara, Masami Ouchi, Nozomu Tominaga, Masayuki Tanaka (National Astronomical Observatory of Japan), Yoshito Ono, Yosuke Minowa, Yutaka Hayano,Yusei Koyama, Sadman Ali (Subaru Telescope), Masaomi Tanaka, Masayuki Akiyama (Tohoku University), Tohru Nagao, Yoshiki Matsuoka (Ehime University), Kosuke Kushibiki, Shogo Homan, and Akino Yasuda (University of Tokyo), and Michitoshi Yoshida ((National Astronomical Observatory of Japan),

INTRODUCTION

Near-INfrared and optical Joint spectrograph with Adaptive optics (NINJA) is a new wide-band spectrograph for the Laser Tomography Adaptive Optics (LTAO), being proposed as a visiting instrument for the Subaru Telescope.

In the ULTIMATE-Subaru project [1], in addition to the key priority function of the wide-field Ground Layer AO (GLAO), LTAO capability is also planned to be developed to achieve narrow field observations with near diffraction-limited resolution not only in the NIR bands but also in the visible (> 0.6 µm). Taking full advantage of LTAO, NINJA realizes a highly efficient, broadband, medium-resolution spectroscopy for point sources.

In the first phase, a LTAO mode will be implemented to the Subaru as a part of the upgrades of the existing AO system, AO188 [4][5], by adding a new LTAO wavefront sensor (WFS) system which will be installed into behind AO188 and upgrading of the existing laser guide star (LGS) system to add four-beam configuration to generate 4 LGSs for the LTAO mode. Those development for the LTAO mode is being proceeded in the framework of the ULTIMATE-Subaru Tomography Adaptive optics Research experimenT (ULTIMATE-START) project [6][7]. At the same time, Subaru Nasmyth Beam Switcher (SNBS)[8] will also be newly introduced to switch the light downstream of AO188 and LTAO to multiple instruments and to allow multiple instruments work simultaneously. In the second phase, when the ULTIMATE- Subaru GLAO system is available and AO188 is decommissioned, the LTAO system will be upgraded to be compatible with Adaptive Secondary Mirror (ASM).

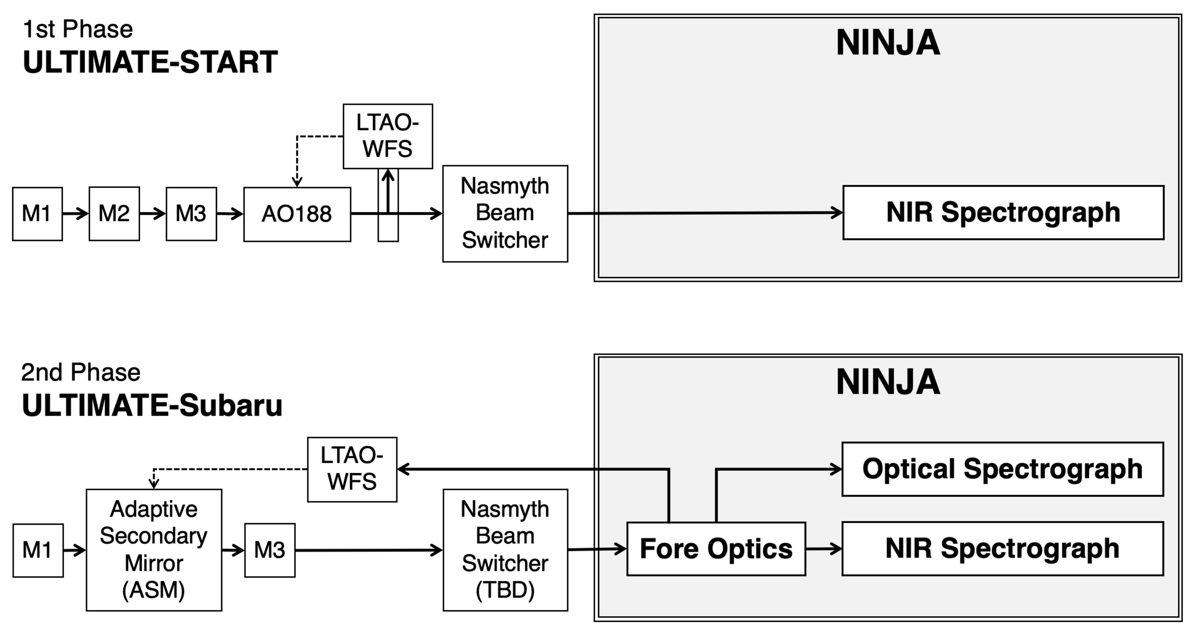


Figure 1 : Conceptual optical diagram of NINJA, the telescope (M1, M2, and M3 represent the primary mirror secondary mirror, and tertiary mirror, respectively), and the AO systems in two phases, before and after installation of the ASM. Solid arrows show the optical paths and dash arrows show the feedback control lines of the AO system.

SCIENCE OBJECTIVES

The main scientific objective of NINJA is to reveal origins of elements through observations of kilonovae as well as supernovae. Especially, through the observations of the kilonova AT2017gfo followed by a double neutron star merger discovered by the gravitational wave event GW170817, it has been confirmed that r-process elements are synthesized in double neutron star mergers [9]. However, AT2017gfo remains to be the only kilonova identified with gravitational waves. Many more observations of kilonovae are required to understand the general nucleosynthesis properties of double neutron-star mergers. In order to estimate how much r-process elements are synthesized in a double neutron star merger, it is required to conduct spectroscopic observations in the optical and NIR of a kilonova at least for a week after its merger. Indeed, VLT/X-Shooter spectra of AT2017gfo that covered the optical and NIR simultaneously played essential roles in revealing its nucleosynthesis signatures [10][11]. During the O5 of the gravitational wave observatories starting in 2027, about 50 neutron star mergers out to 200 Mpc are expected to be discovered by gravitational wave events in a year. **To conduct spectroscopic follow-up observations of kilonovae at 200 Mpc for a week after the mergers, we require a spectrograph with a limiting magnitude of 22 mag in the NIR** (Figure 2). By reaching 22 mag with NINJA, we can significantly increase the observational constraints on the nucleosynthesis in neutron-star mergers during O5 and obtain general nucleosynthesis properties in neutron star mergers.

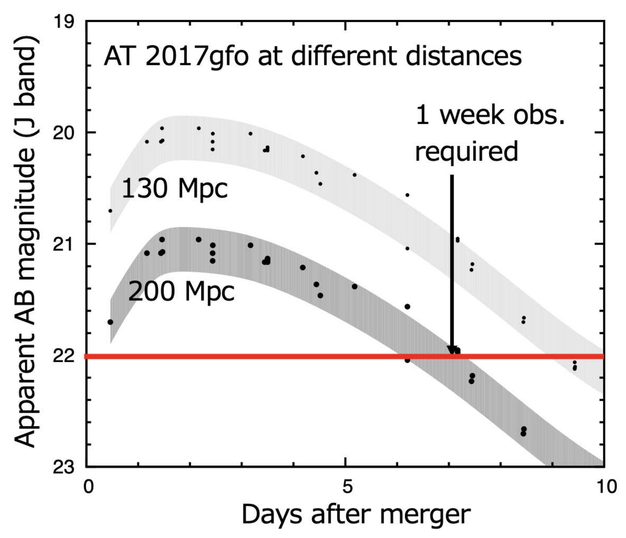
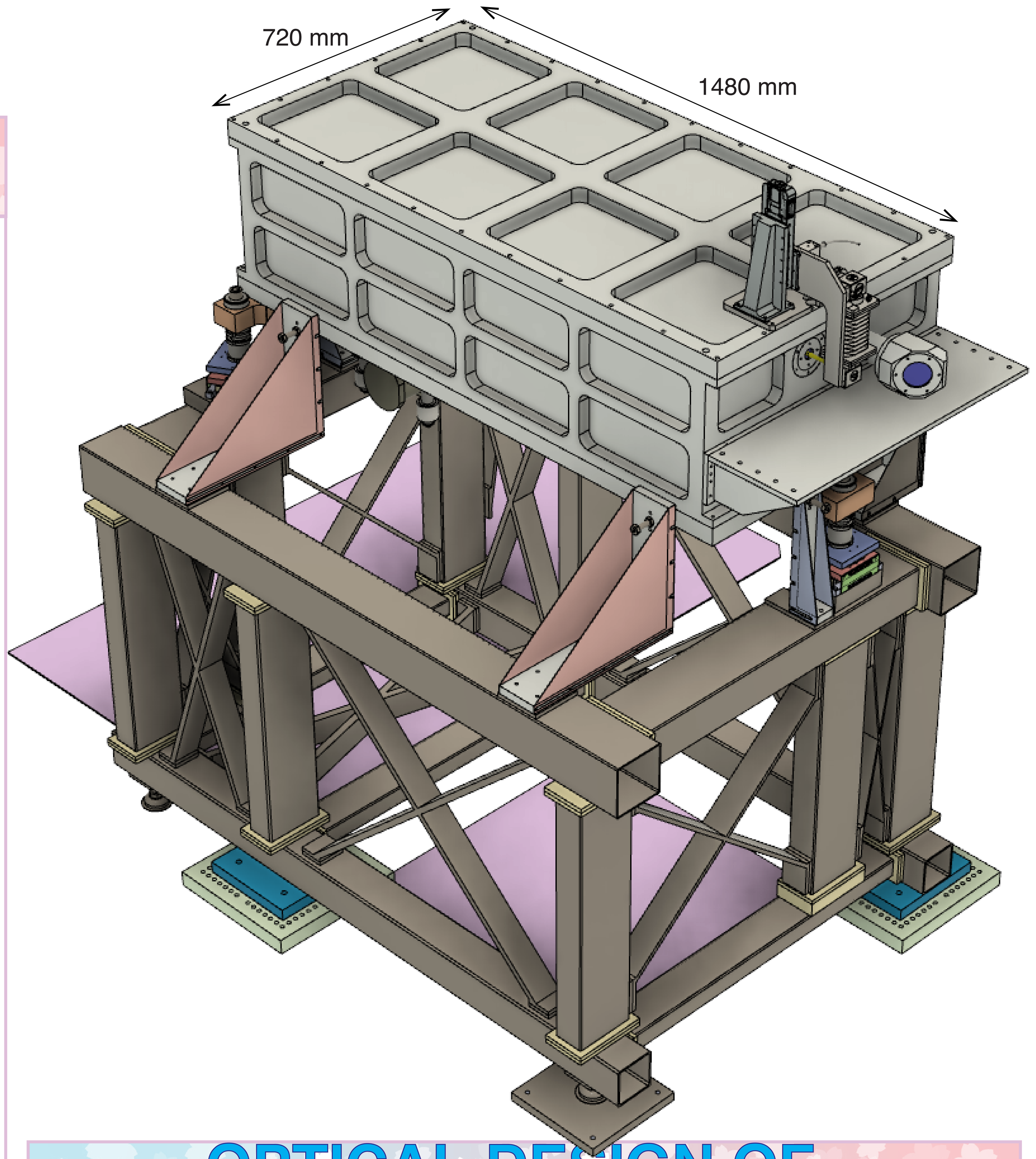


Figure 2 : Expected J -band light curves of kilonovae at 130 Mpc and 200 Mpc. In order to observe a kilonova at 200 Mpc for one week after its merger, limiting magnitude deeper than 22mag is necessary.



OPTICAL DESIGN OF NIR SPECTROGRAPH

The optical layout of the NINJA NIR spectrograph is based on white pupil layout proposed by Baranne [11] (Figure 3). A grating is used in a quasi-Littrow configuration. A collimator and cross-dispersing prisms are used in double path. A concave field mirror transfers a pupil image around the first element of a camera lens system. Efficiency of the spectrograph is estimated to be ~43% not including the detector.

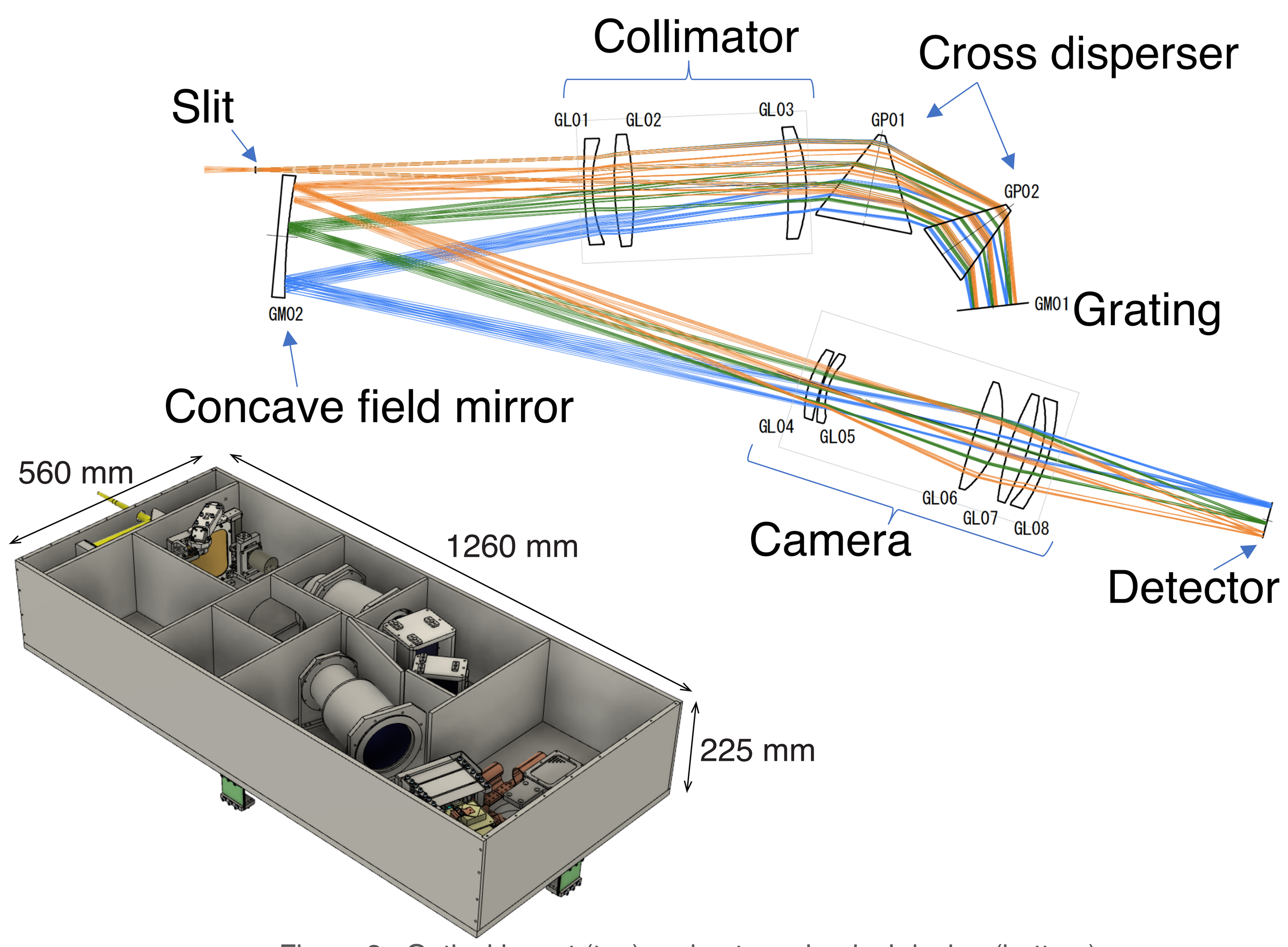


Figure 3 : Optical layout (top) and opt-mechanical design (bottom).

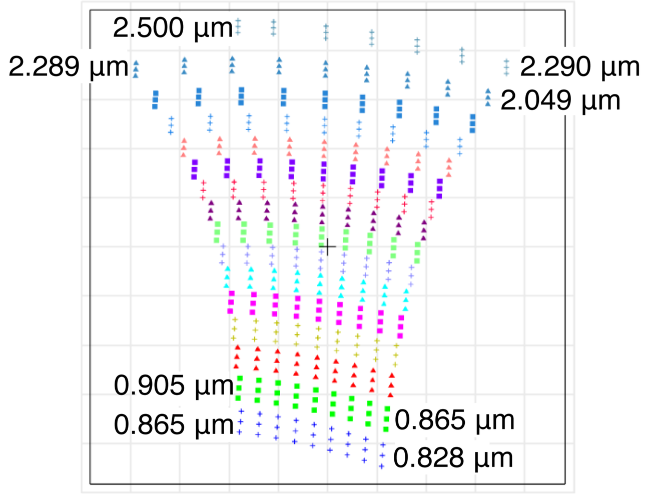


Figure 4 : Simulated Echelle format. The black solid square shows the detector area of the HAWAII-2RG.

Table 1 : NIR spectrograph parameters

Wavelength coverage	0.83 – 2.5 µm
Input F ratio	13.9
Slit width	0.35″ (0.19 mm) Nominal 0.21″, 0.5″, 0.7″ Options
Slit length	5″ (2.7 mm)
Collimator focal length	597.7 mm
Pupil diameter	43.0 mm
Camera focal length	181.3 mm
Grating line density	56 lines/mm
Grating braze angle	33 degrees
Detector format	2048 x 2048 pix
Pixel size	18 µm/pix
Sampling for 0.35″ slit width	3.3 pix
Spectral resolving power	R~3,300 (with 0.35″ slit)

LTAO PERFORMANCES IN NIR

Figure 6 shows a simulated performance of the LTAO mode in NIR at the Subaru telescope as a function of wavelength. The LTAO mode can realize almost diffraction-limited resolution in the wide wavelength range from the visible to NIR. The LTAO performance highly depends on off-axis separation of NGS and decreases with larger separation (Figure 5). However, we can achieve FWHM < 0.1" at wavelength > 0.6 µm even with a NGS of 60" off-axis.

Simulation Conditions:
- Median condition with 7-layers model
- On-axis performance
- 1x1 visible NGS WFS
  ※ the LGS focus drift should be monitored with a different camera.
- NGS separation = 40″
- NGS magnitude = 16 mag in R
- No instrumental PSF is included
- Optimal tomographic reconstructor with assuming a perfect turbulence profile information

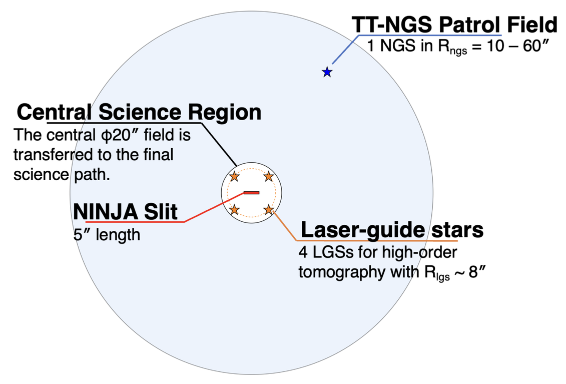


Figure 5 : Field configuration of LTAO.

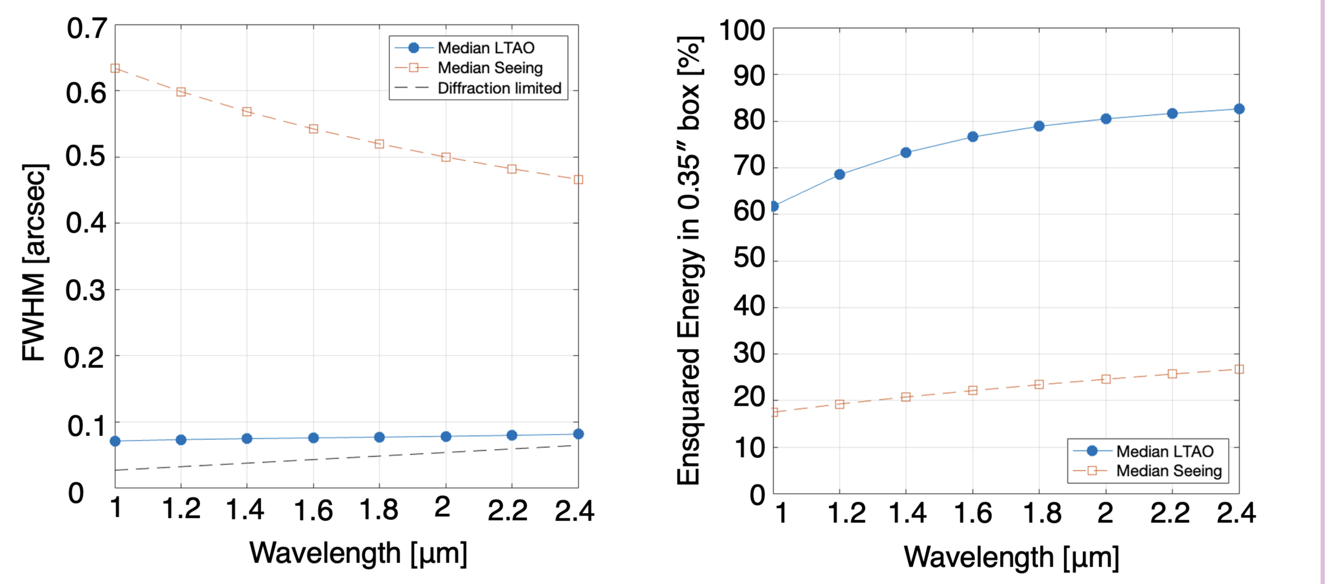


Figure 6 : Simulated performance of LTAO (FWHM vs Wavelength, EE vs Wavelength)

DEVELOPMENT PLAN

The first light of NINJA NIR spectrograph is set at early 2025.

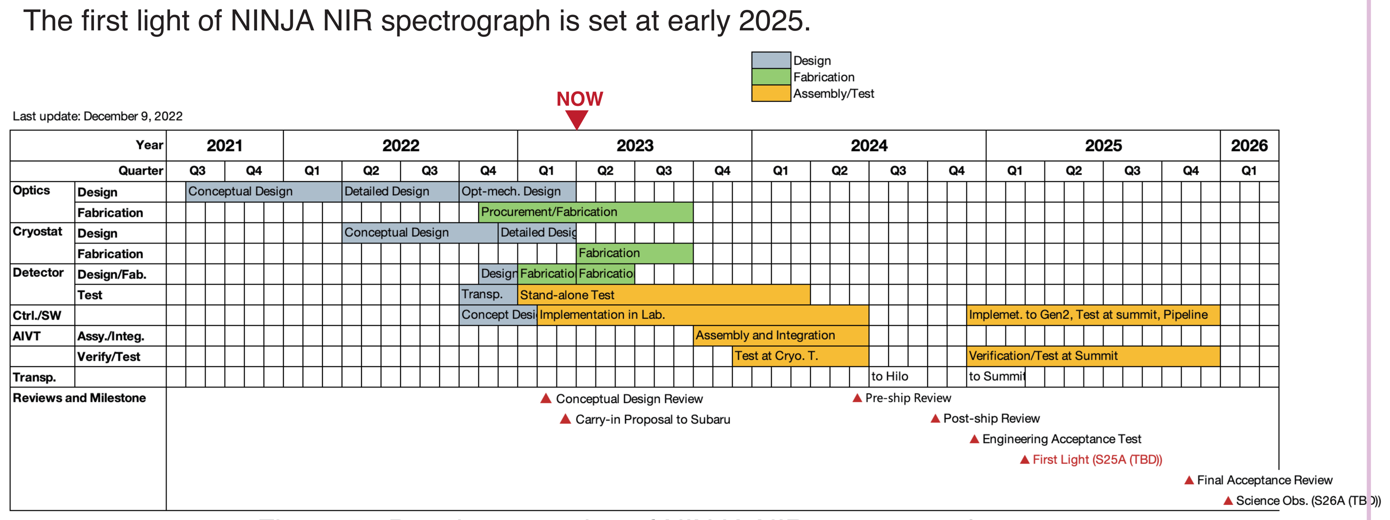


Figure 7 : Development plan of NINJA NIR spectrograph.

ACKNOWLEDGMENTS

This work was supported by Japan Society for the Promotion of Science (JSPS) KAKENHI, Grant-in-Aid for Scientific Research (S), Grant Number 21H04997. Part of the development is supported by the Advanced Technology Center, National astronomical observatory of Japan.

REFERENCE

[0] Tokoku, C. et al., "NINJA : an LTAO assisted optical and near-infrared spectrograph of Subaru Telescope Proc. of SPIE Vol. 12184 121847R-1 (2022)
[1] UILTIMATE-Subaru website. https://ultimate.naoj.org/english/index.html.
[2] Minowa, Y., "ULTIMATE-Subaru: GLAO preliminary design overview," Proc. SPIE, 12185, Adaptive Optics Systems VIII 12185, 12185–73 (2022).
[3] Ono, Y. et al., "Overview of ao activities at subaru telescope" , Proc. SPIE 11448, Adaptive Optics Systems VII, 11448, 114480K (2020).
[4] Hayano, Y., "Current status of the laser guide star adaptive optics system for subaru telescope," Proc. SPIE 7015, Adaptive Optics Systems 7015, 701510 (2008)
[5] Hayano, Y., "Commissioning status of subaru laser guide sta adaptive optics system," Proc. SPIE 7736, Adaptive Optics Systems II, 7736, 77360N (2010).
[6] Akiyama, M., "ULTIMATE-START: Subaru tomography adaptive optics research experiment project overview" , Proc. SPIE 11448, Adaptive Optics Systems VII 11448, 114481O (2020).
[7] Terao, K., "ULTIMATE-START: current status of the subaru tomography adaptive optics research experiment project," Proc. SPIE, 12185, Adaptive Optics Systems VIII 12185, 12185–250 (2022).
[8] Zheng, J. R., "Optical system design for subaru nasmyth beam switcher," Proc. SPIE, 12182, Phasing and Alignment 12182, 12182–160 (2022).
[9] Tanaka, M. et al., "Kilonova from post-merger ejecta as an optical and near-Infrared counterpart of GW170817" , PASJ, Vol.69, 102 (2017)
[10] Watson, D. et al., "Identification of strontium in the merger of two neutron stars" , Nature, Vol. 574, 497-500 (2019)
[11] Pian, E. et al., "Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger" , Nature, Vol. 551, 67-70 (2017)
[12] Baranne, A., "Equipement spectrographique du foyer coude du telescope de 3,60 metres etude de faisabilite d'un spectrographe universel," ESO/CERN Conference on Auxiliary Instrumentation for Large Telescopes, P.227 (1972).