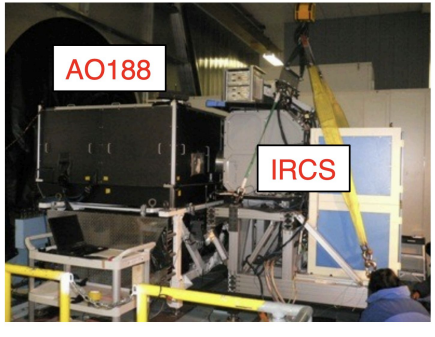
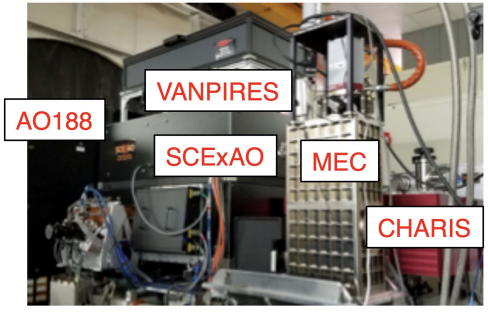
NsIR future roadmap

A discussion session at Subaru UM FY2023

Guyon, Hayano, Koyama, Ono, N. Tamura [chair]
(Committee for this discussion session)

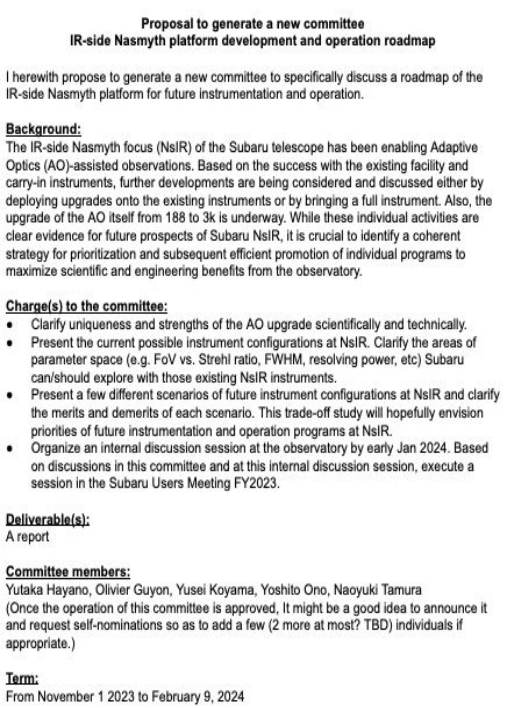
5 meetings + e-mail/Google slide discussions since Oct 2023
Observatory internal session on Jan 11 2024.





Scopes of this session

- Clarifications to the community
  - Current status of NsIR
    - AO188 + IRCS & ***PI-type*** instruments
    - Space as well as time is money.
  - Ongoing & near-term activities
    - AO upgrades with contributions from ***PI-type*** programs
    - More ***PI-type*** instruments
  - Current & upcoming capabilities
    - AO's capabilities, and AO+instrument capabilities
    - How well are the instruments exploiting the AO's capabilities?
    - How are they filling the functional parameter spaces?
- Discussions of future roadmap
  - How can we strategize the largely "bottom-up" situation from now?
  - What are science and technology areas Subaru should pursue?
  - How does the community think about all these?



Proposal to generate a new committee
IR-side Nasmyth platform development and operation roadmap

I herewith propose to generate a new committee to specifically discuss a roadmap of the IR-side Nasmyth platform for future instrumentation and operation.

Background:
The IR-side Nasmyth focus (NsIR) of the Subaru telescope has been enabling Adaptive Optics (AO)-assisted observations. Based on the success with the existing facility and carry-in instruments, further developments are being considered and discussed either by deploying upgrades onto the existing instruments or by bringing a full instrument. Also, the upgrade of the AO itself from 188 to 3k is underway. While these individual activities are clear evidence for future prospects of Subaru NsIR, it is crucial to identify a coherent strategy for prioritization and subsequent efficient promotion of individual programs to maximize scientific and engineering benefits from the observatory.

Charge(s) to the committee:
- Clarify uniqueness and strengths of the AO upgrade scientifically and technically.
- Present the current possible instrument configurations at NsIR. Clarify the areas of parameter space (e.g. FoV vs. Strehl ratio, FWHM, resolving power, etc) Subaru can/should explore with those existing NsIR instruments.
- Present a few different scenarios of future instrument configurations at NsIR and clarify the merits and demerits of each scenario. This trade-off study will hopefully envision priorities of future instrumentation and operation programs at NsIR.
- Organize an internal discussion session at the observatory by early Jan 2024. Based on discussions in this committee and at this internal discussion session, execute a session in the Subaru Users Meeting FY2023.

Deliverable(s):
A report

Committee members:
Yutaka Hayano, Olivier Guyon, Yusei Koyama, Yoshito Ono, Naoyuki Tamura
(Once the operation of this committee is approved, It might be a good idea to announce it and request self-nominations so as to add a few (2 more at most? TBD) individuals if appropriate.)

Term:
From November 1 2023 to February 9, 2024

Session agenda

Current and Near-Future NsIR AO & Instrumentation [50min]

- Introduction 5min [Tamura] (5min + Q&A 3min)
- Upgrades of AO and operation aspects [Ono] (13min + Q&A 3min)
- Current and future instrument lineup
  - With general purpose AO [Koyama] (10min + Q&A 3min)
  - Extreme AO [Guyon] (10min + Q&A 3min)

Discussions of future roadmap [25min]

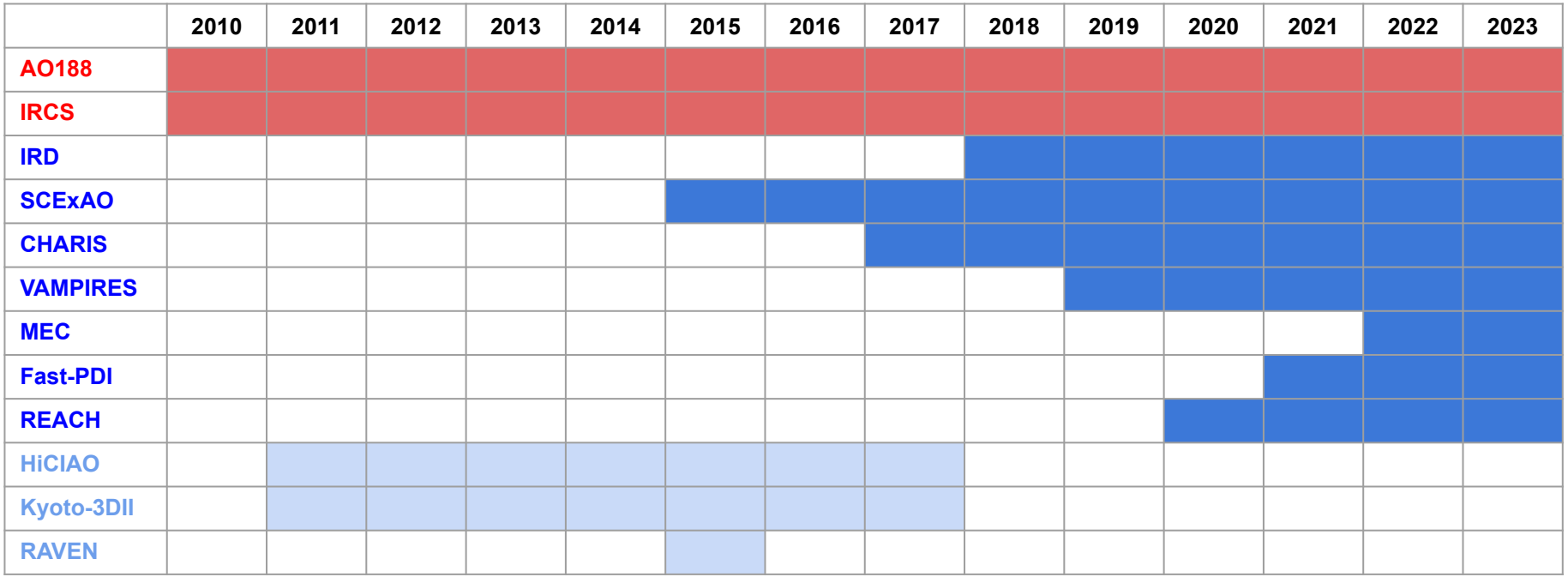
- Recap of the current situation with a few comments [Ono] (10min)
- Discussion 15min [moderated by N. Tamura]

P17: IRD, REACH, and K-REACH: Current Status and Upgrade Plans for Near-Infrared High-Dispersion Spectrometer (Takayuki Kotani)
P36: SCExAO/MEC: High speed ultra-low noise spectro-imaging in near-IR (Ben Mazin)
P37: SCExAO/FIRST: Interferometric spectro-imaging in visible light (Sébastien Vievard)
P38: SCExAO/fastPDI: Near-IR polarimetric imaging optimized for high contrast imaging (Tomoyuki Kubo)
P39: SCExAO/GLINT: Exoplanet detection at small angular separation with photonic nulling (Olivier Guyon)
P40: Upgrades to the visible-light high-contrast imager SCExAO: VAMPIRES (Miles Lucas)

History of NsIR platform

- AO platform
- Many PI-type instruments for science observation and technical validation

Science operation at NsIR



Near-future of NsIR platform (next ~ 5 yrs)

AO upgrade

- Improve the AO188 performance
- Technical validation for the future AO instruments

Operational upgrade

- Flexible beam switching system behind AO188
- Improve the operational efficiency

New PI-type instrument ideas

SCExAO-related upgrades (talked by Olivier Guyon)

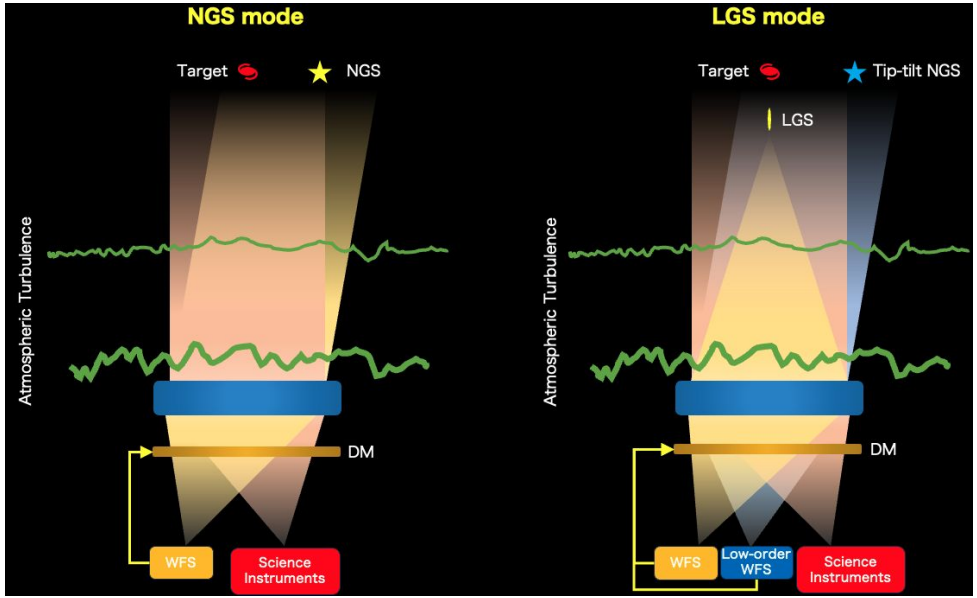
AO and Operational upgrades

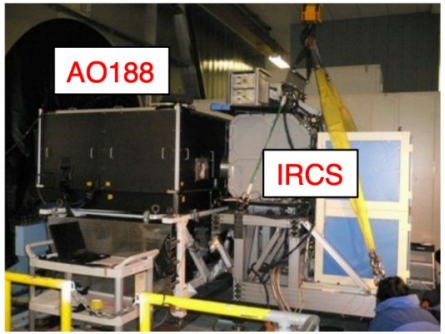
AO188

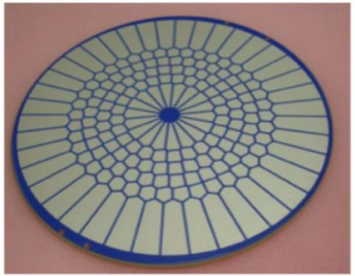
- 2nd-generation facility AO system
- **188-elements** WFS and DM
- Provide **diffraction-limited performance in the NIR wavelength** to the downstream instruments
- NGS (2008~) and LGS (2011~) modes

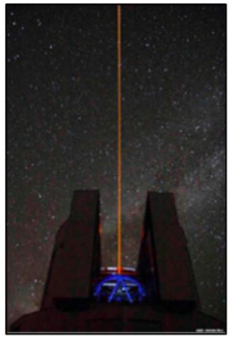
Planned Upgrade

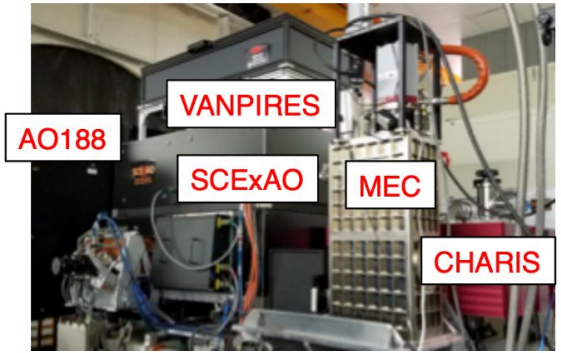
- NGS mode → **AO3K**
- LGS mode → **ULTIMATE-START LTAO**











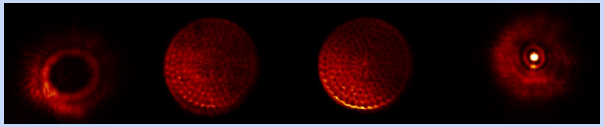
P11: AO3000 : Major update of AO188 (Yoshito Ono)

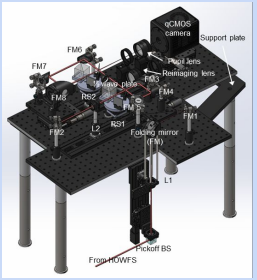
P12: A new visible wavefront sensor for AO3k (Kyohoon Ahn)

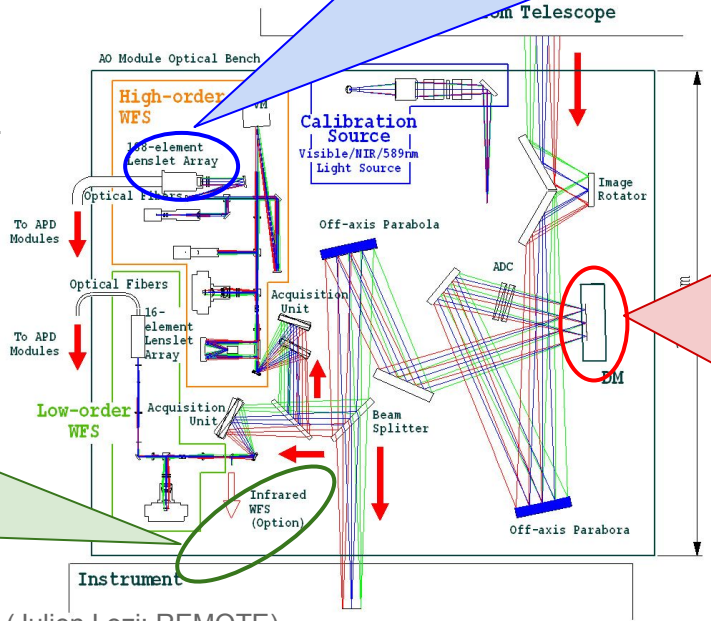
AO3k

- Increase the the number of DM actuators and WFS elements from 188 to **~3000**
  - New ALPAO DM
  - New visible and NIR WFSs
  - New real-time control system
- **Extremely high performance in NIR**
- **Diffraction-limited performance in visible**.
- Best correction capability in the world!

nICWFS: Visible curvature WFS that will be a replacement of the current curvature WFS.

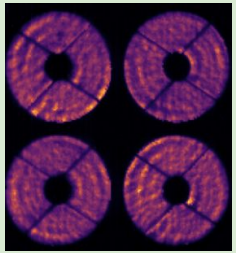


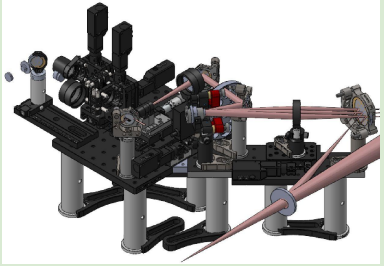




ALPAO DM3228
3228 active actuators

NIR WFS: Pyramid WFS working in NIR





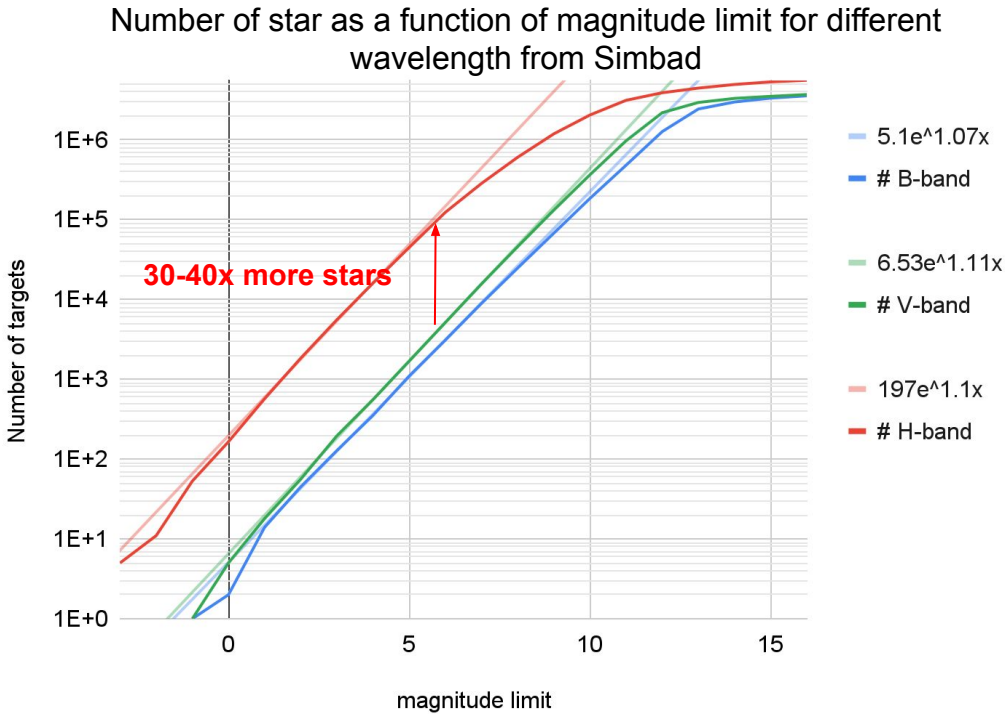
New Real-Time control system.
Common software platform with SCExAO

AO3k at Subaru: First on-sky results of the facility extreme-AO (Julien Lozi; REMOTE)

Another benefit from NIR WFS

- Performing **the wavefront measurement in NIR wavelength** provides **better sky-coverage** thanks for
  - well-corrected PSF in NIR
  - Better star availability especially in Galactic Center and the dust -obscured regions.

- NIR WFS is available from S24A (with AO188) as PI-type instrument
- PI is S. Nishiyama from Miyagi university of education and J. Lozi from SCExAO



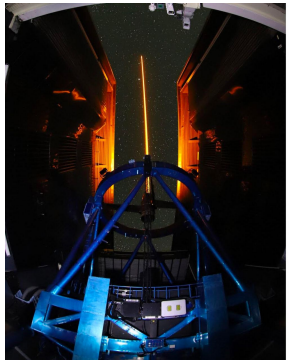
Made by Julien Lozi

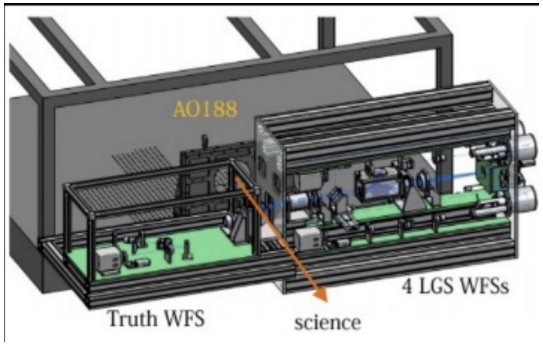
ULTIMATE-START project

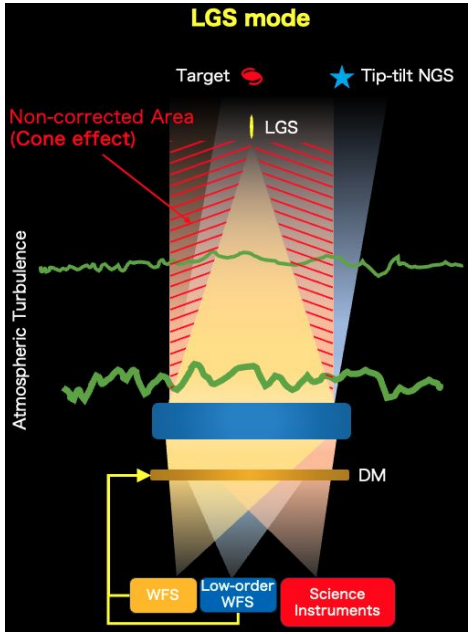
- PI-type instrument project led by Akiyama-san in Tohoku university
- Implementing **Laser-Tomography AO (LTAO)** system into AO3k
- Improving LGS-based AO performance using **the tomographic technique with the multiple LGSs.**

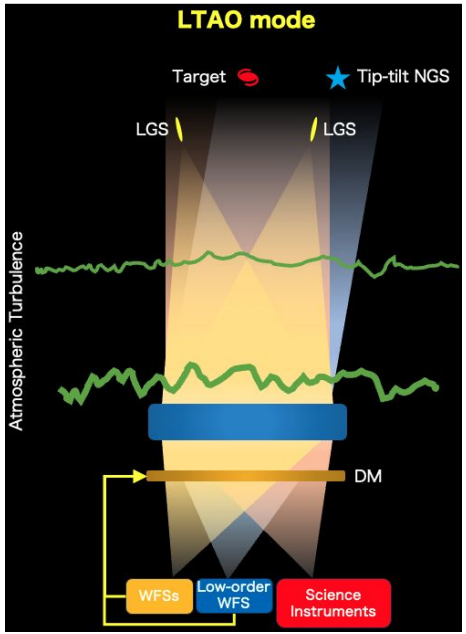
Key development

- LTAO WFS to be installed behind AO3k
- Upgrade the LGS system to generate 4 LGSs
- AO3k ALPAO DM3228



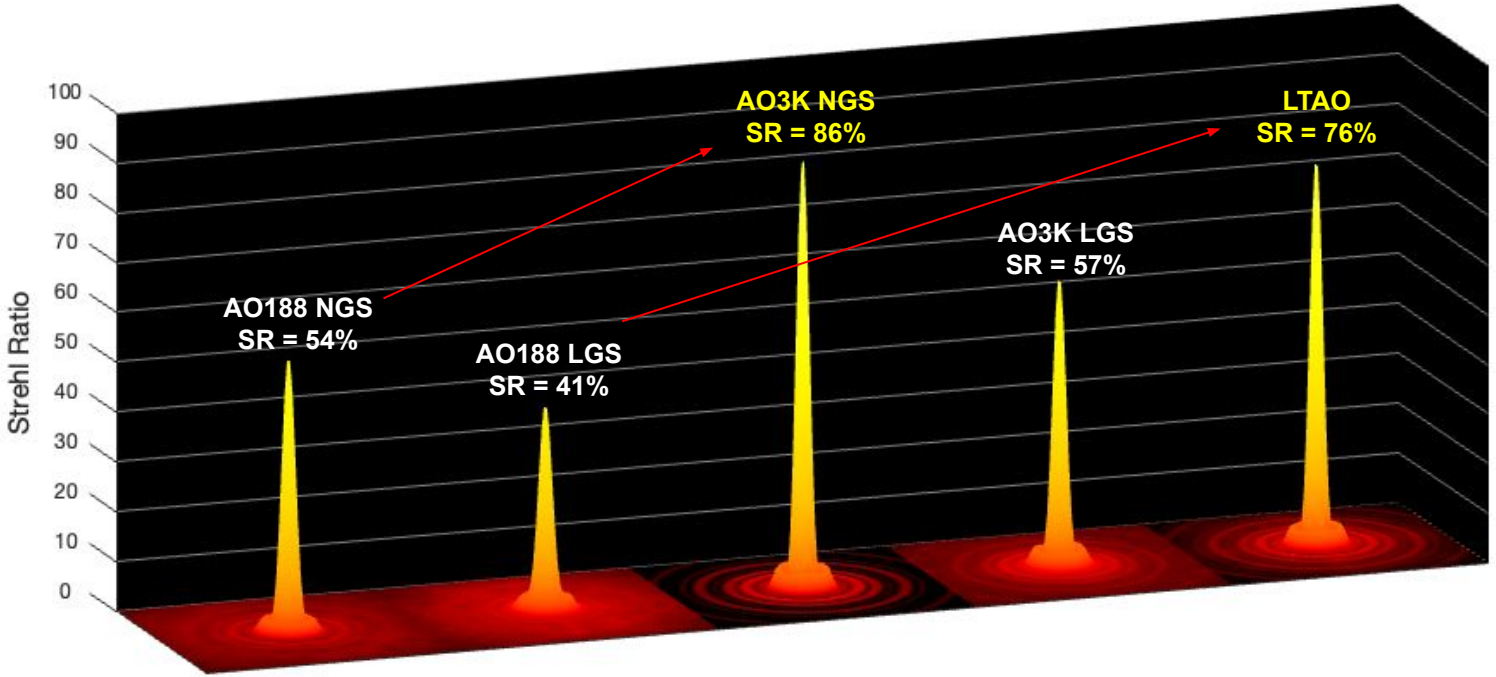






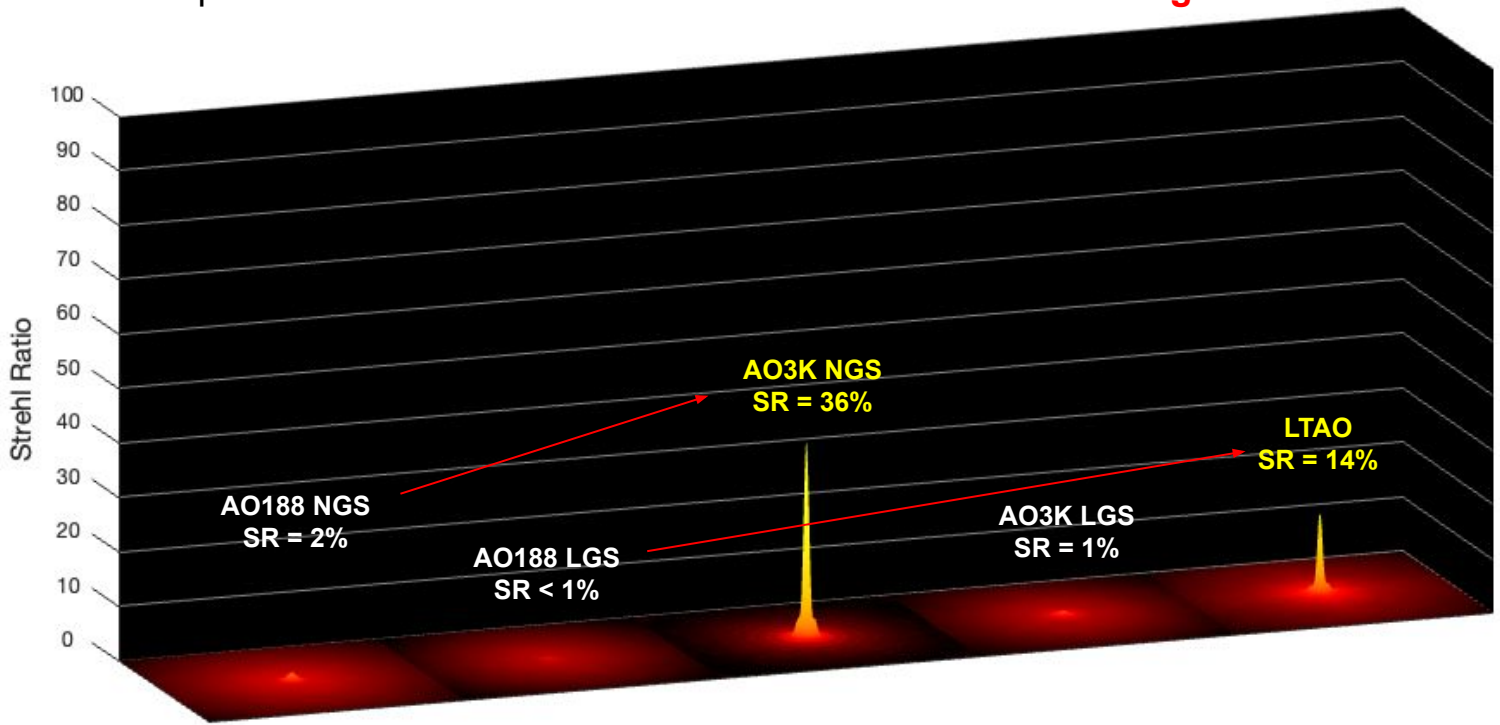
Simulated AO performance @K-band

- On-axis performance at median seeing condition assuming a bright on-axis guidestar
- AO3K/LTAO provides 1.5~2 times better SR compared to AO188
- Less speckle around PSF, good for high-contrast imaging.



Simulated AO performance @I-band

- On-axis performance at median seeing condition assuming a bright on-axis guidestar
- AO3K/LTAO provides a **diffraction-limited PSF in the visible wavelength**



Available AO modes in the near future

AO mode	Guidestar(s)	WFS	DM	Compatibility with the NsIR instruments			
				IRCS	IRD	SCExAO	New instrument behind NBS
NGS-based modes							
AO3k Visible	NGS (Vis)	nlCWFS	ALPAO DM3228	◯	◯	◯	◯
AO3k NIR	NGS (NIR)	NIR WFS		◯	×	◯	◯
LGS-based modes							
AO3k LGS	Single LGS Tip/Tilt NGS	nlCWFS Low-order WFS	ALPAO DM3228	◯	?	?	◯
LTAO	4 LGSs Tip/Tilt NGS	LTAO WFS Low-order WFS		◯	×	?	◯

See a poster by Yoshito Ono

Instrument exchange at NsIR

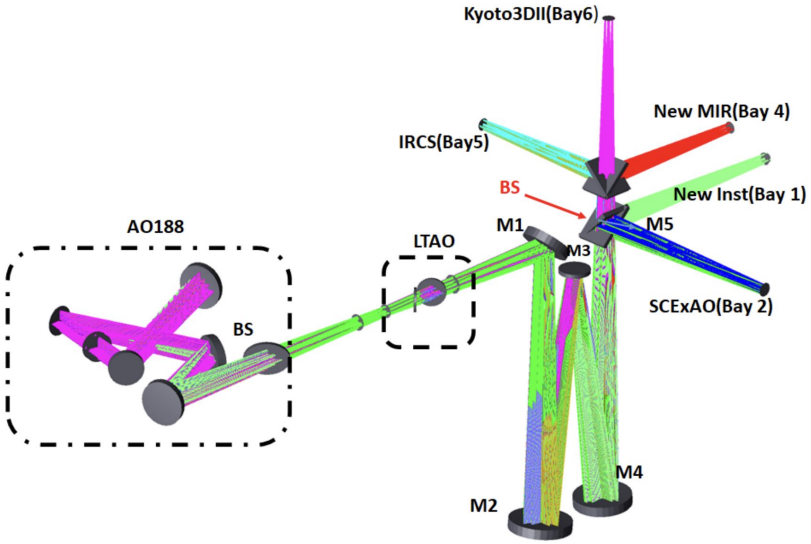
- The craining work is required for the instrument exchange behind AO188 (IRCS ⇄ SCExAO)
- Resource/Time consuming
  - **Takes ~2 hours with ~ 4 people every ~2 weeks**
  - Re-calibration between AO188 and the instruments after each crain work
- Risk to break something in the system during the craning work.
- Schedule constraint
  - No exchange between IRCS and SCExAO during night and weekend

Made by Sebastien Vievard

See. P03: Subaru Nasmyth Beam Switcher (Takashi Hattori)

Nasmyth Beam Switcher (NBS)

Automatic beam switching system to be installed behind AO188/AO3k for the **flexible instrument exchange at NsIR**, developed under collaboration with AAO.



Advantage

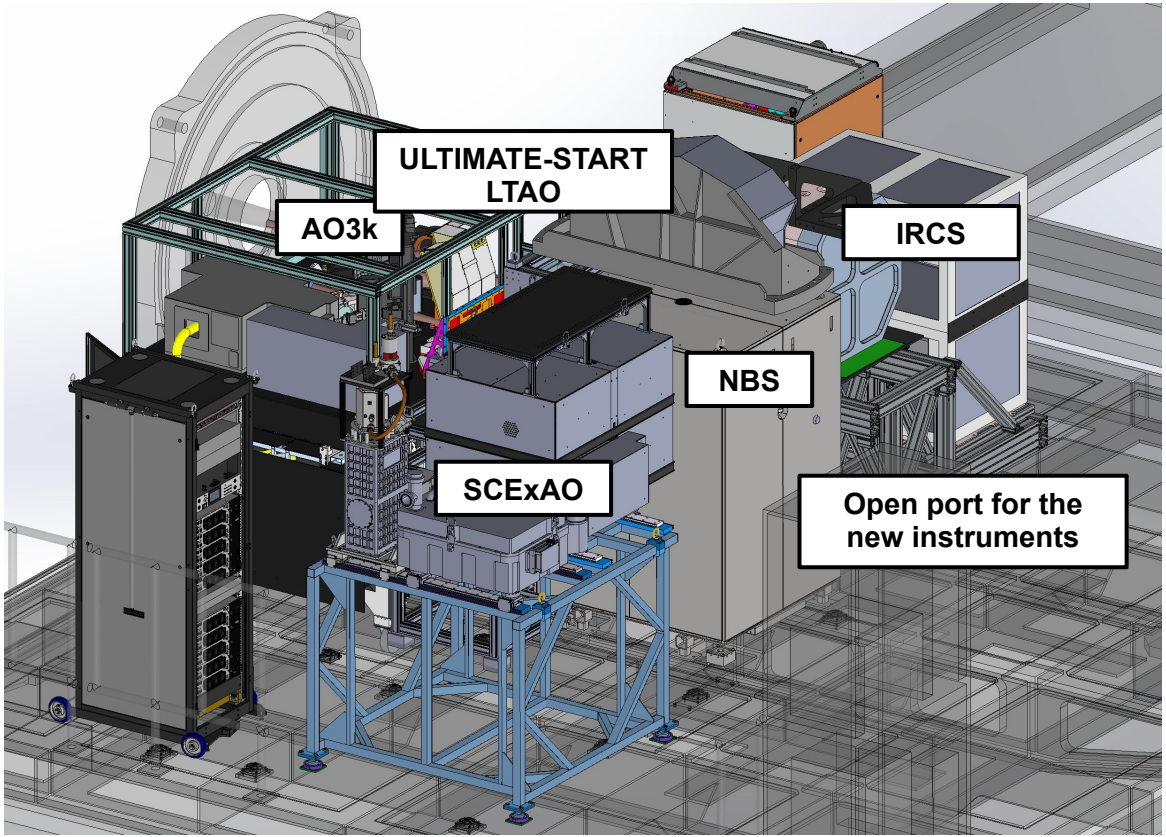
- Reduce the load/risk in the instrument exchange
- Improving the observation flexibility at NsIR
  - Instrument exchange during the night/weekend
  - Critical for flexible Queue / ToO observation
- New capabilities
  - Provide the AO-corrected light to several instruments at the same time
  - Open slots for new instruments

Disadvantage

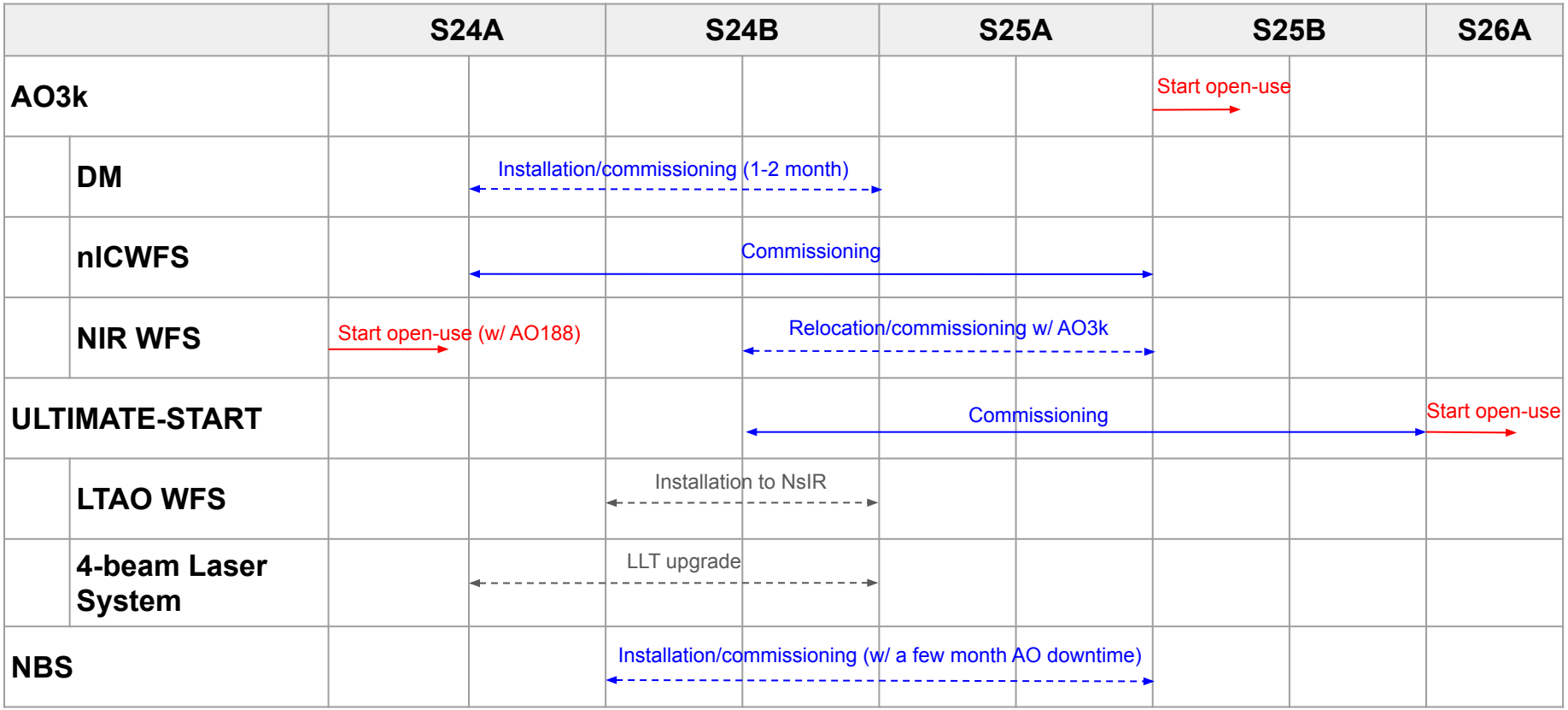
- Thermal background increase by **~10-20% in longer NIR** (estimated by Takagi-san)

	Kp	K	L	M
IRCS background increase (model)	1.10	1.18	1.17	1.12

Instrument configuration with NBS



(Tentative) Timeline for the near-future upgrades at NsIR

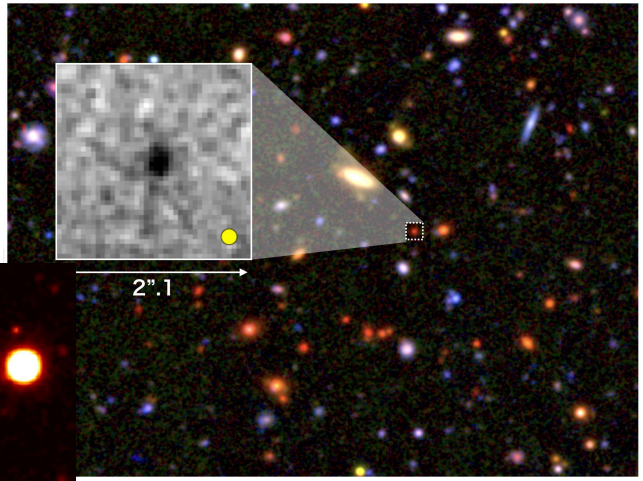


Science capability

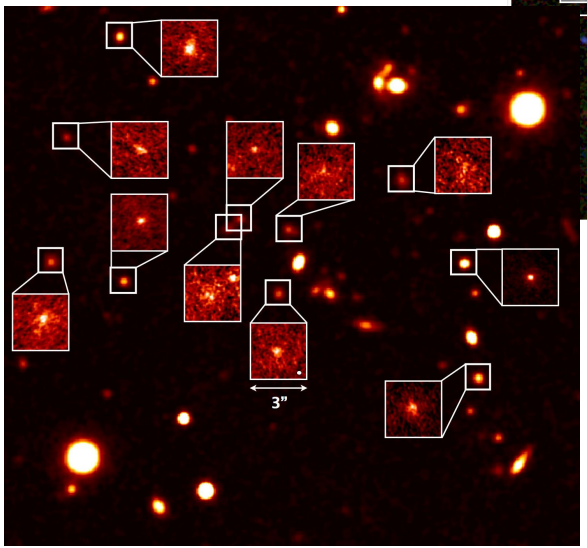
(for general users)

Science Highlights with current AO188 (examples)

Size, morphology, spatially-resolved view of high-z galaxies

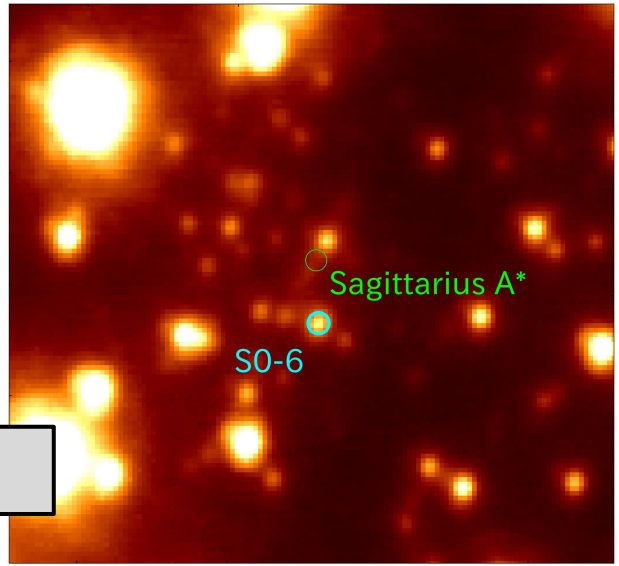


Kubo et al. (2018)



Suzuki et al. (2019)

Galactic Center

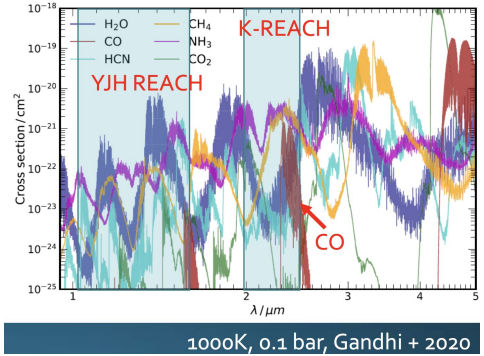


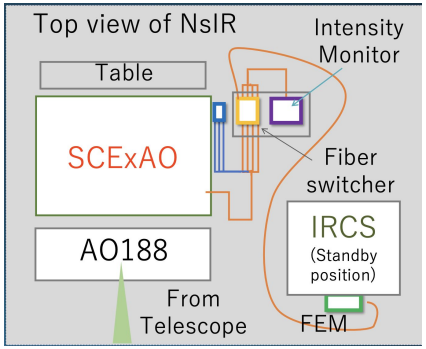
Nishiyama et al. (2023)

Upcoming PI-type instruments

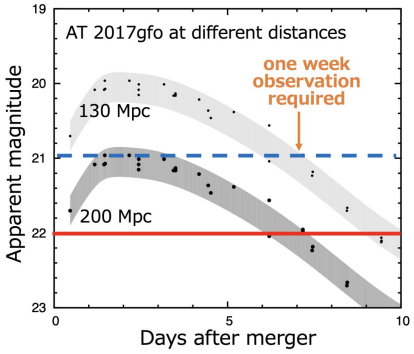
P16: NINJA: the wide-band spectrograph optimized for the Laser Tomography Adaptive Optics (Chihiro Tokoku)

K-REACH : Fiber-fed NIR high-resolution spectroscopy with SCExAO and IRCS





NINJA : LTAO-optimized Wide-field coverage single-object spectrograph



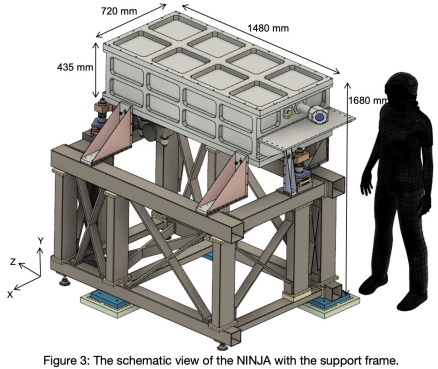
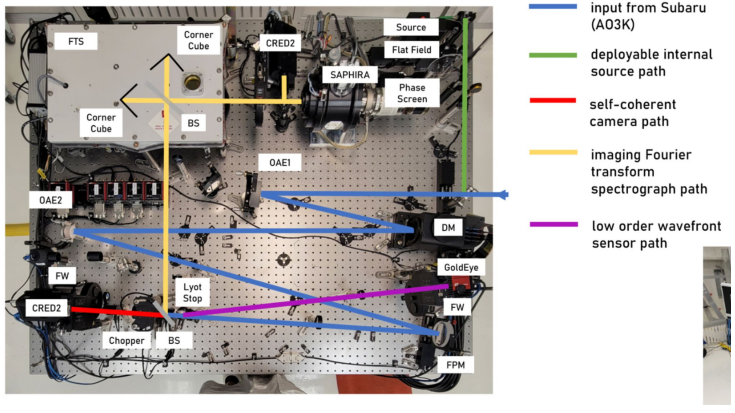
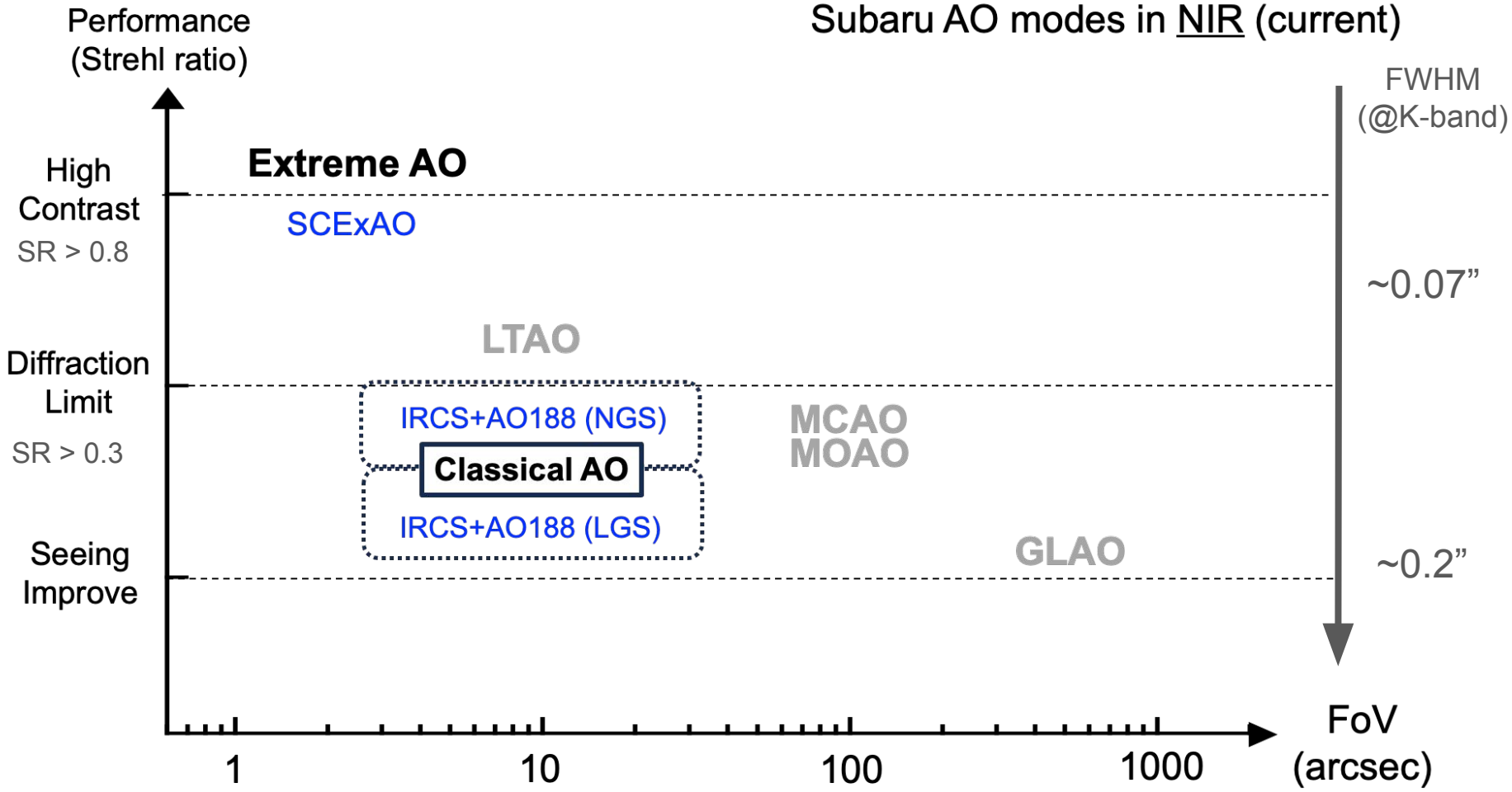
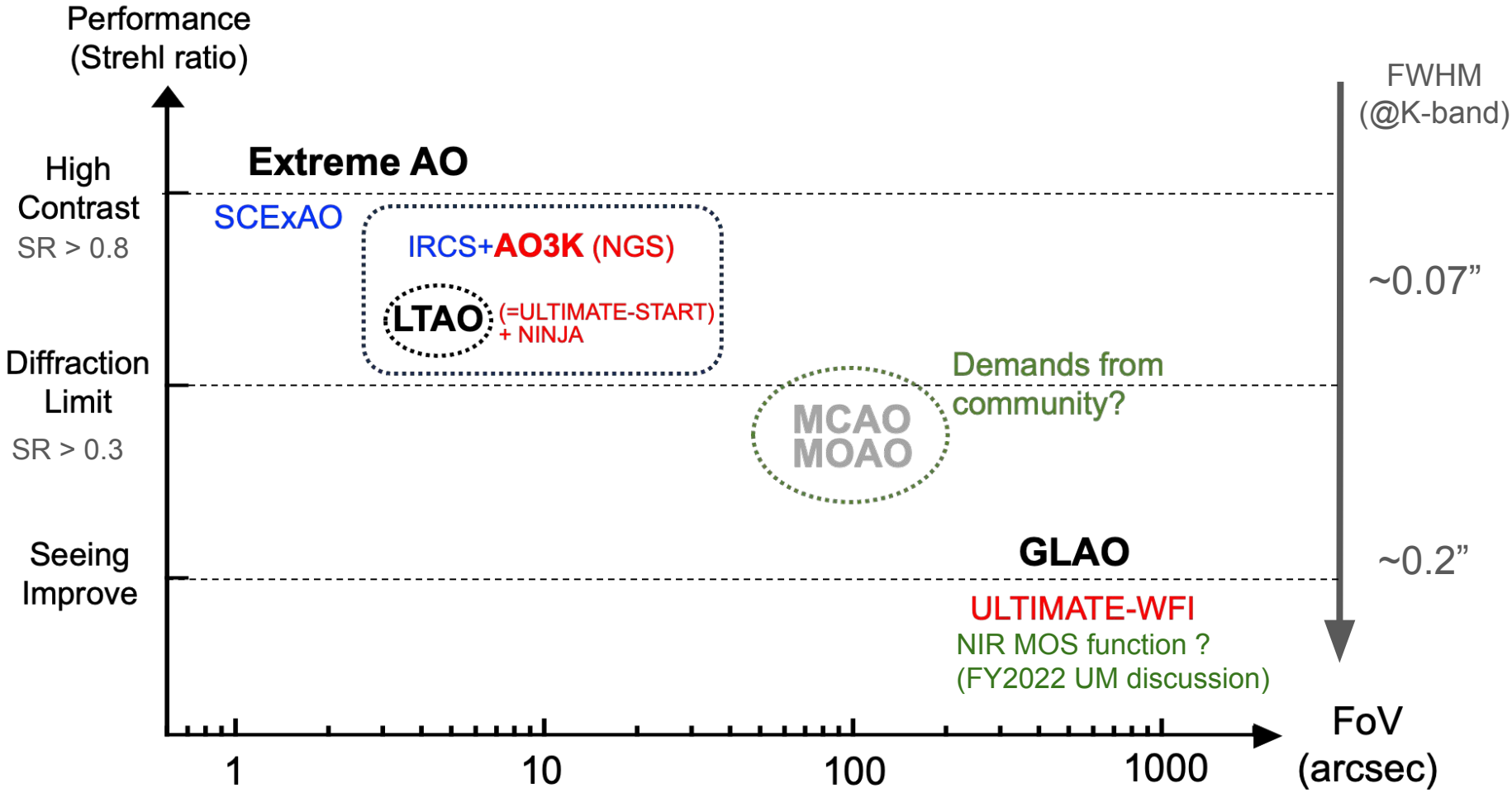


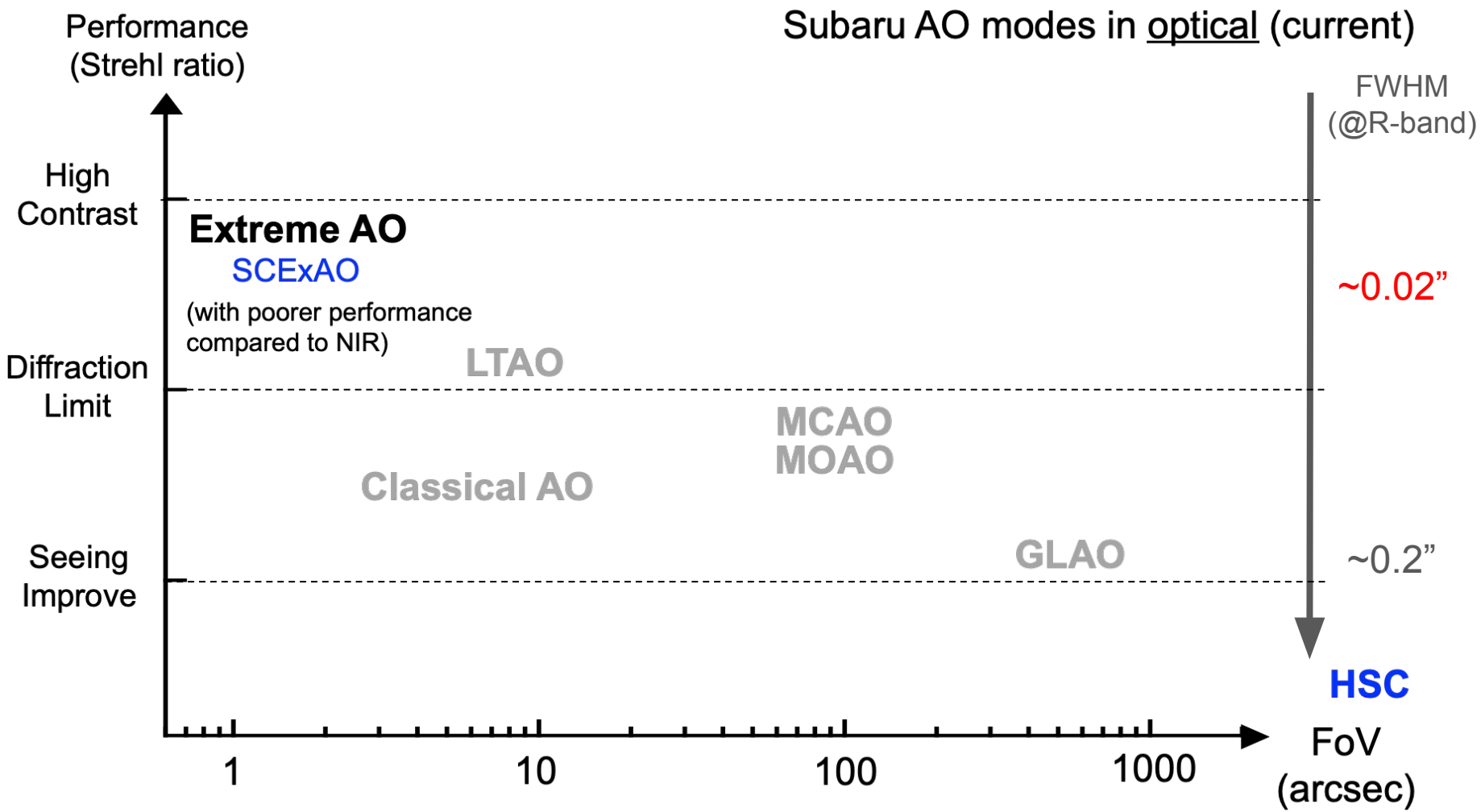
Figure 3: The schematic view of the NINJA with the support frame.

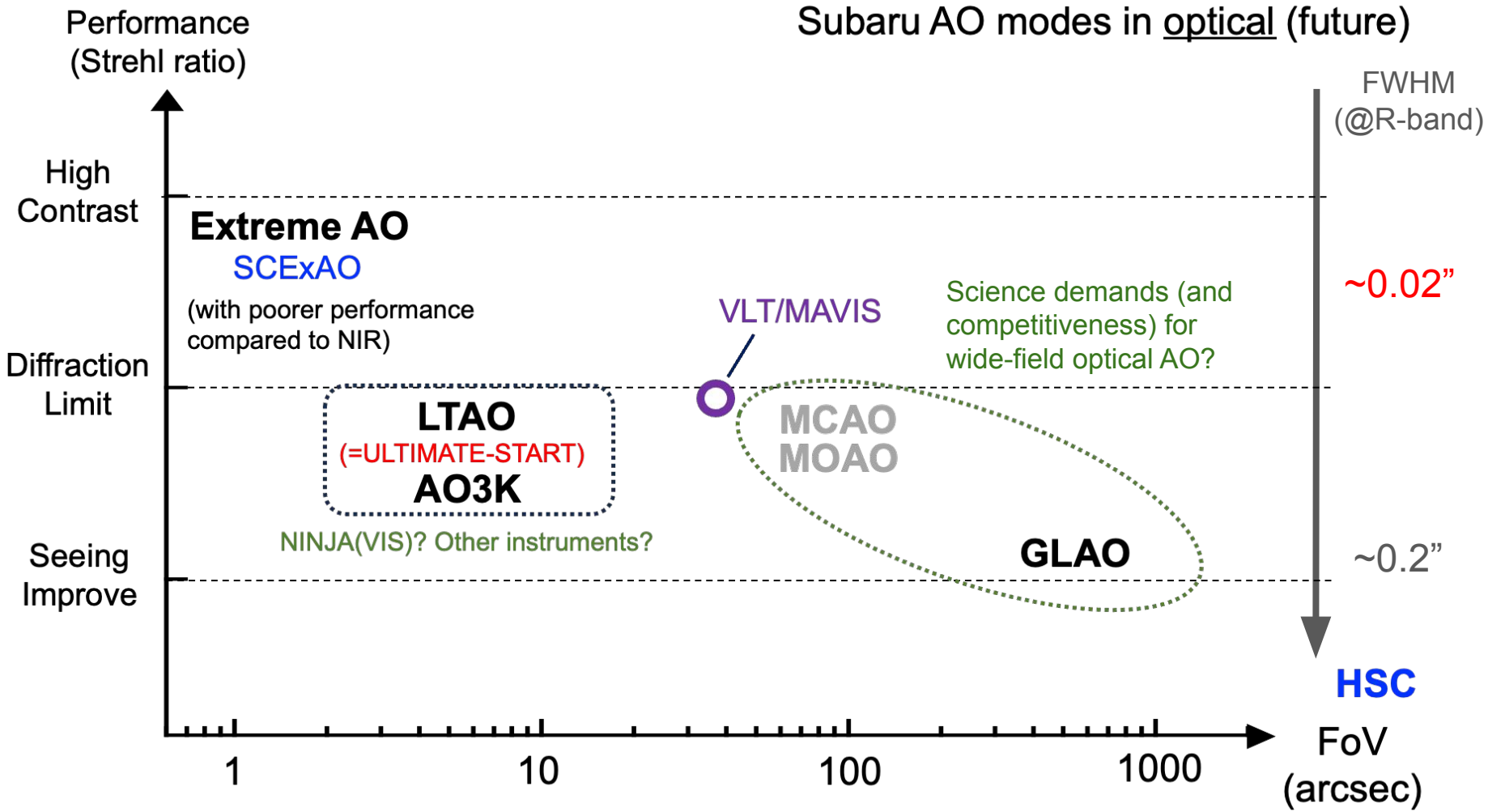
SPIDERS:
Speckle suppression demonstration +
NIR Fourier-transform spectrograph




Subaru AO modes in NIR (current)
Performance
(Strehl ratio)
FWHM
(@K-band)
High
Contrast
SR > 0.8
Extreme AO
SCExAO
~0.07”
LTAO
Diffraction
Limit
SR > 0.3
IRCS+AO188 (NGS)
MCAO
MOAO
Classical AO
IRCS+AO188 (LGS)
Seeing
Improve
GLAO
~0.2”
1
10
100
1000
FoV
(arcsec)


Performance
(Strehl ratio)
FWHM
(@K-band)
High
Contrast
SR > 0.8
Extreme AO
SCExAO
IRCS+AO3K (NGS)
LTAO
(=ULTIMATE-START)
+ NINJA
~0.07”
Diffraction
Limit
SR > 0.3
Demands from
community?
MCAO
MOAO
Seeing
Improve
GLAO
~0.2”
ULTIMATE-WFI
NIR MOS function ?
(FY2022 UM discussion)
1
10
100
1000
FoV
(arcsec)


Subaru AO modes in optical (current)
Performance
(Strehl ratio)
FWHM
(@R-band)
High
Contrast
Extreme AO
SCExAO
(with poorer performance
compared to NIR)
~0.02”
Diffraction
Limit
LTAO
MCAO
MOAO
Classical AO
Seeing
Improve
GLAO
~0.2”
HSC
1
10
100
1000
FoV
(arcsec)


Performance
(Strehl ratio)
Subaru AO modes in optical (future)
FWHM
(@R-band)
High
Contrast
Extreme AO
SCExAO
(with poorer performance
compared to NIR)
VLT/MAVIS
Science demands (and
competitiveness) for
wide-field optical AO?
~0.02”
Diffraction
Limit
LTAO
(=ULTIMATE-START)
AO3K
MCAO
MOAO
NINJA(VIS)? Other instruments?
GLAO
Seeing
Improve
~0.2”
HSC
1
10
100
1000
FoV
(arcsec)

Extreme-AO: Current and Future Instrumentation Line-up

Olivier Guyon, Subaru Telescope (guyon@naoj.org)

What is Extreme-AO ?

Extreme-AO refers to Adaptive Optics **optimized for extremely good correction** (high SR):

- Uses high number of elements (DM actuators), runs at high speed
- Optimized for bright targets, natural guide star only (m_R<~12)
- Small field of view (few arcsec)

Key capabilities:

- **High contrast imaging** (with coronagraph)
- **Diffraction-limited imaging in visible**
- Efficient and stable **injection in single-mode fibers** for spectroscopy

Main science cases:

- Exoplanet imaging and spectroscopy
- Circumstellar disks
- Planet formation
- Star formation
- Stellar evolution

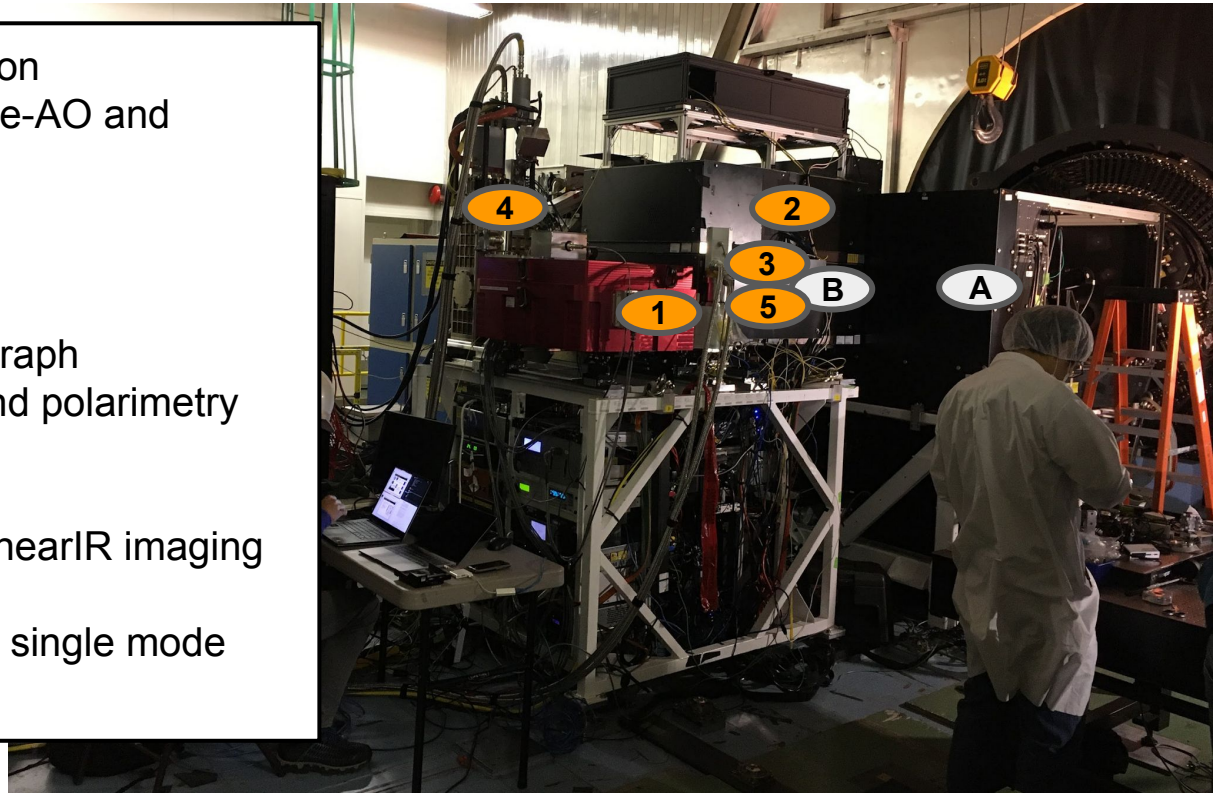
Current (2023) NasIR platform Extreme-AO configuration

[A] AO188 provides initial AO correction
[B] SCExAO system provides Extreme-AO and coronagraphy

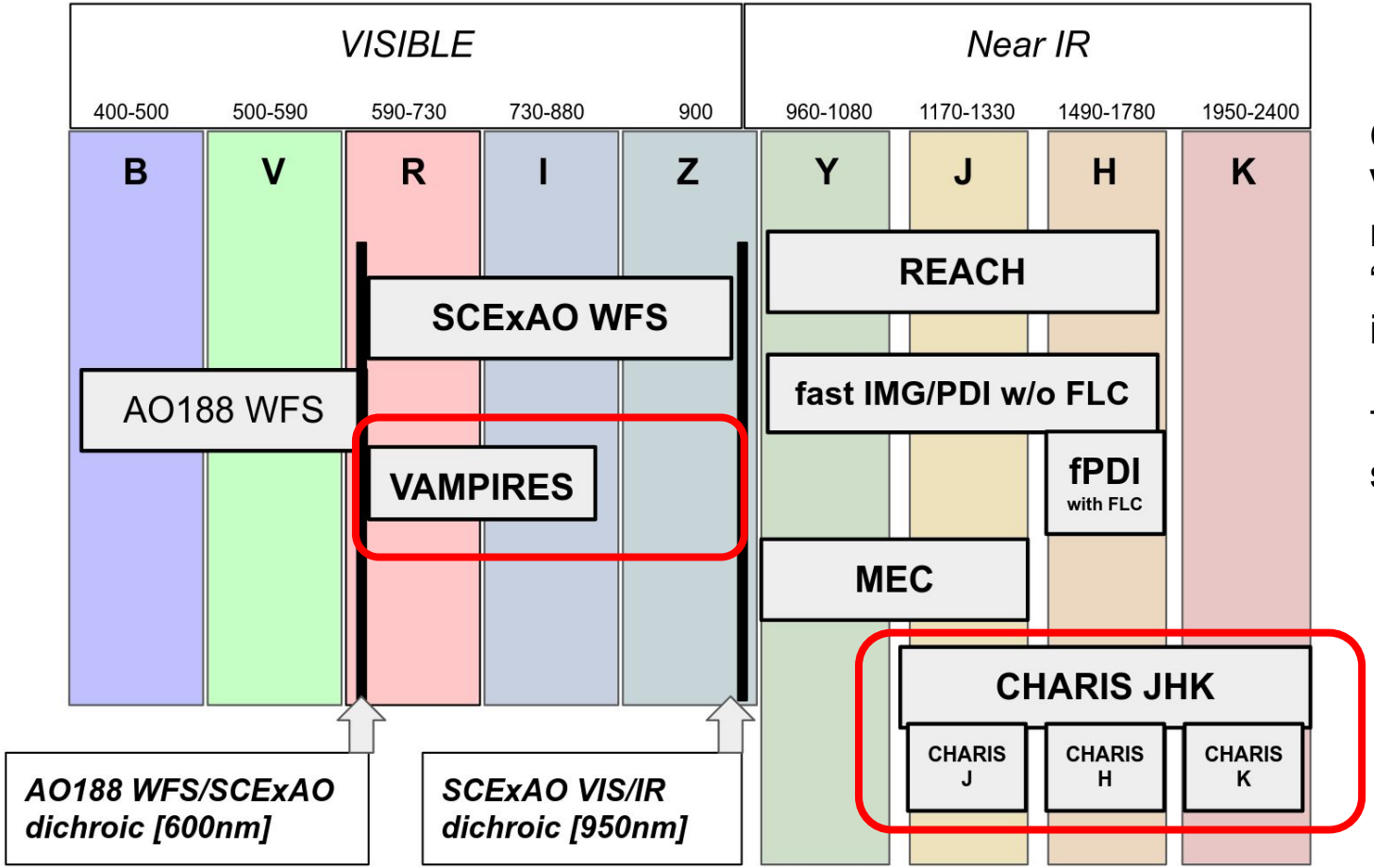
Open Use instruments :

[1] **CHARIS** near-IR imaging spectrograph
[2] **VAMPIRES** visible-light imaging and polarimetry

[3] **Fast-PDI** camera in nearIR
[4] **MEC** provides ultra-low noise fast nearIR imaging with energy resolution
[5] **REACH**: Near-IR light injected into single mode fiber for exoplanet spectroscopy



SCExAO-fed Instruments - Spectral Coverage

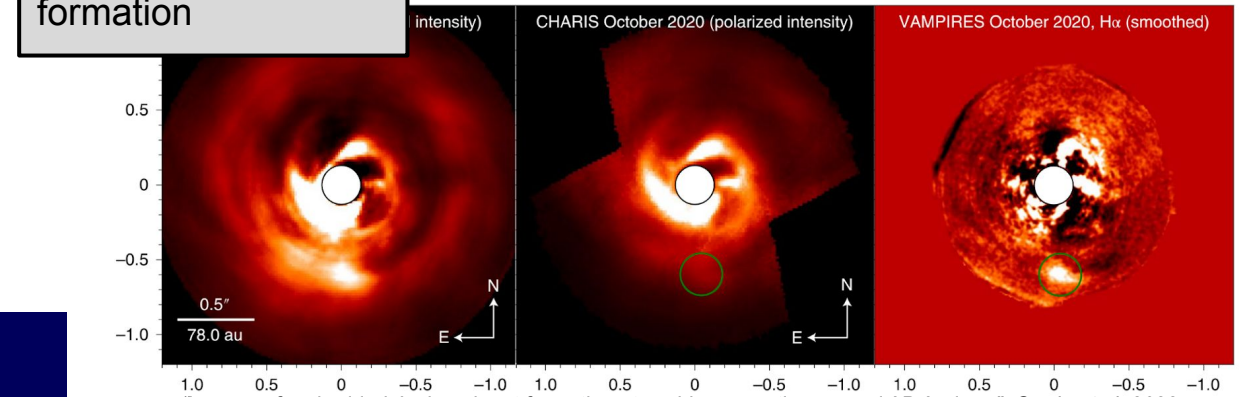


CHARIS & **VAMPIRES** are the main "general-purpose" instruments.

They are often used simultaneously

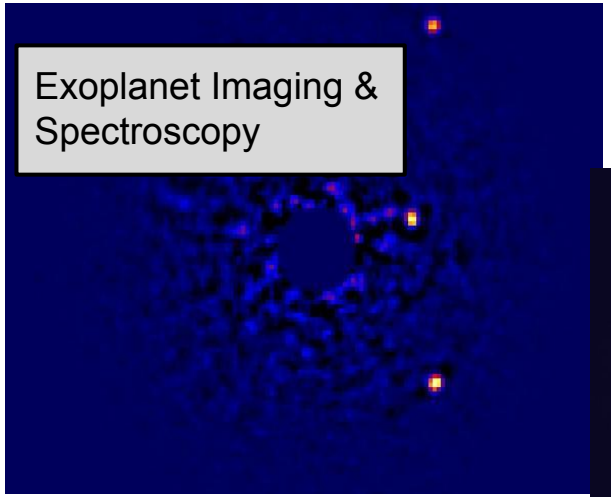
Key Science

Disks & planet formation

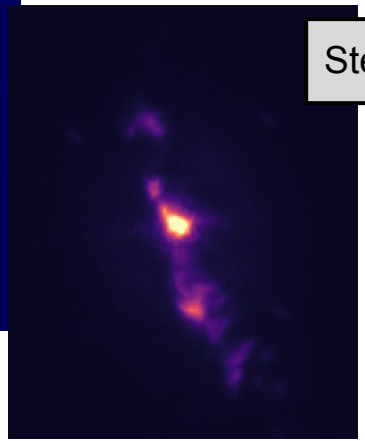


"Images of embedded Jovian planet formation at a wide separation around AB Aurigae", *Currie et al. 2022*

Exoplanet Imaging & Spectroscopy

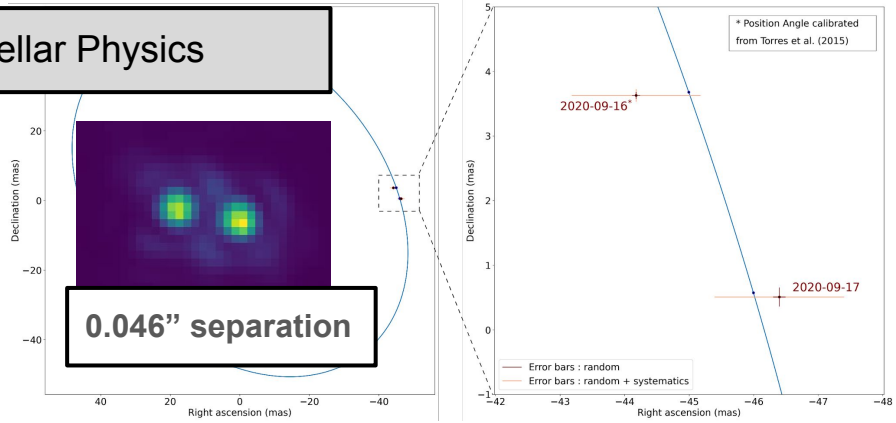


Inner 3 planets in HR8799 system



R Aquarii mass loss in Halpha
(Miles Lucas, UH)

Stellar Physics



"Single-aperture spectro-interferometry in the visible at the Subaru telescope with FIRST: First on-sky demonstration on Keho`oea (α Lyrae) and Hokulei (α Aurigae)", *Vievard et al. 2023*

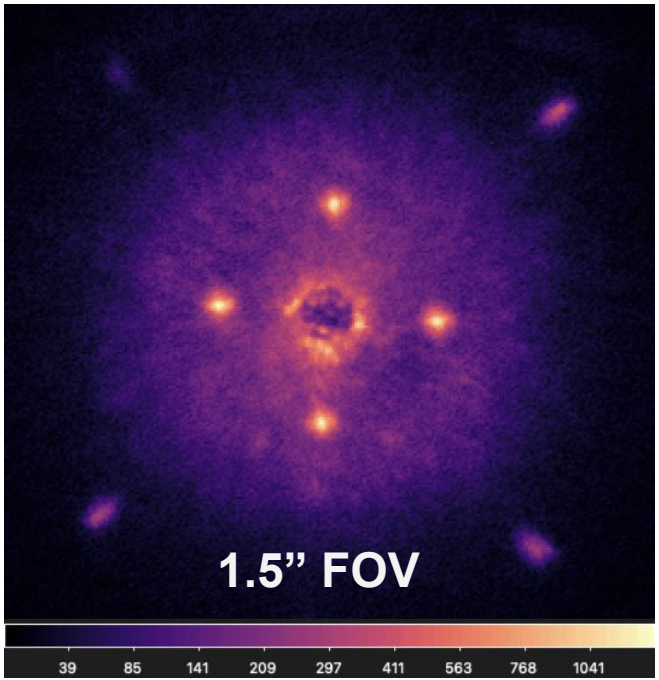
Visible Imaging with VAMPIRES

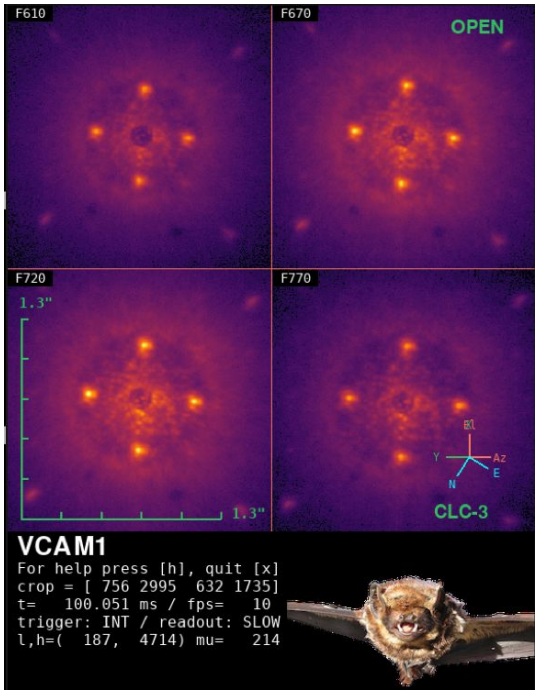
Visible light (600nm-800nm) key advantages:

- High angular resolution: FWHM = 0.015” at 600nm (vs. 0.04” in NIR)
- Access to Halpha emission, sign of accretion

Key science includes:

- Disk/planet interaction
- Circumstellar disks
- Evolved stars





Near-Future NasIR platform

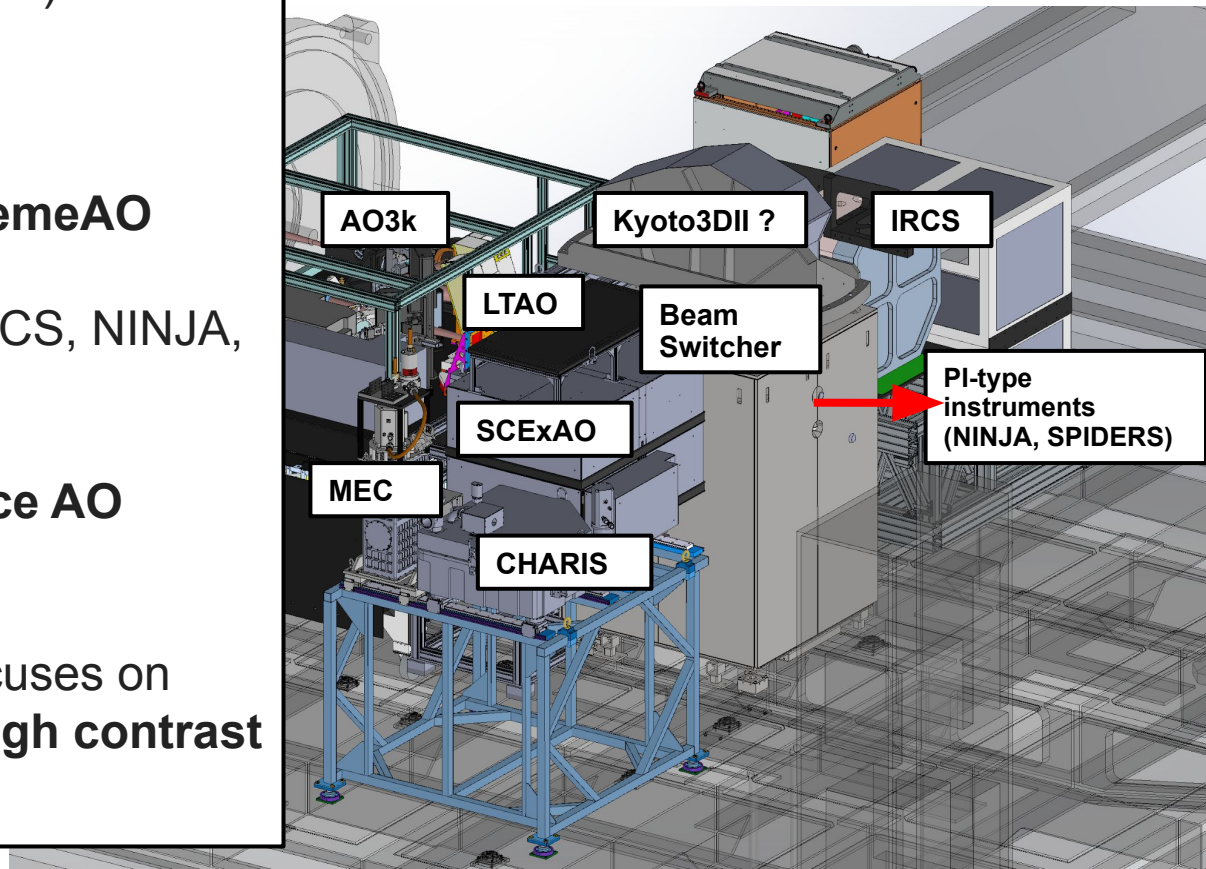
AO3k + Nas Beam Switcher (NBS)

Big changes:

AO3k/NGS+NBS provides **ExtremeAO level correction to all NBS-fed instruments** (IRD, SCExAO, IRCS, NINJA, SPIDERS)

LTAO extends **high-performance AO correction to nearly all-sky**

SCExAO's second-stage AO focuses on speckle control for **enhanced high contrast imaging**



Integrated NasIR platform instrumentation

AO3k (+ LTAO ?) + NBS + SCExAO will be integrated and operate as a single entity (enabled by new RTC on AO3k, and 3000-actuator DM and WFSing)

Integration between **spectrographs and SCExAO**: REACH (SCExAO-IRD), K-REACH (SCExAO-IRCS), ExoNINJA (SCExAO-NINJA), proposed visible RV spectrograph.

NBS will enable rapid switching (**queue** operation) between modes and **multi-instrument** simultaneous operation.

This is unique - there is no equivalent in the world. Subaru's NasIR 3-stage AO (ASM->AO3k->SCExAO) + NBS + instrumentation provides unmatched narrow-field diffraction-limited imaging & spectroscopy capabilities in VIS+NIR.

SCExAO plan over next ~5yr

Near-term (CY2024): **integration with AO3k and NBS, plan transition to CHARIS+VAMPIRES facility operation**. Significant performance boost, easier and more sustainable operation.

CHARIS (NIR) & VAMPIRES (VIS) will remain SCExAO's most productive instruments. Upgrades to SCExAO will continue to improve their performance. Main upgrades foreseen over next ~5yr: MEMs DM replacement within SCExAO (~2025), CHARIS detector upgrades (~2027 ?).

More **focused science modes** will continue to be supported and improved: fastPDI (disks in polarized light), MEC (deep contrast), REACH (HR spectroscopy).

New instruments/modes will be developed, and transition to open use when ready. Focused on:

- **Spectroscopic characterization** (ExoNINJA, SPIDERS & K-REACH in nearIR, RHEA/PL in visible)
- **Access to small angular separation** (GLINT in nearIR & FIRST in visible)
- [proposed] **Thermal-IR instrument** (3-5um) optimized for high contrast imaging, enabled by ASM
- [proposed] **Ultra-precise radial velocity in visible**

Long-Term Outlook: transition to ELTs

Exoplanet imaging & spectroscopy is best done on the largest telescopes. 8-m class telescopes cannot compete with 30-m class telescopes.

… but technology development & maturation is required to enable high-performance extreme-AO on 30-m class telescopes.

Extreme-AO @ Subaru is **prototyping the TMT-PSI exoplanet imaging instrument for TMT**. We can expect NAOJ's Extreme-AO activities to transition from Subaru to TMT.

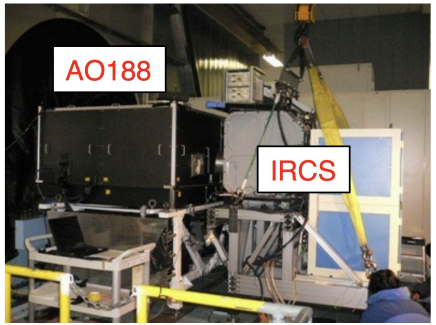
Note: 8-m class telescopes will remain excellent for ExAO-fed precision radial velocity

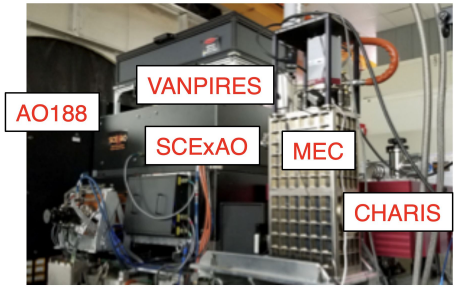
NsIR roadmap

Future of NsIR platform

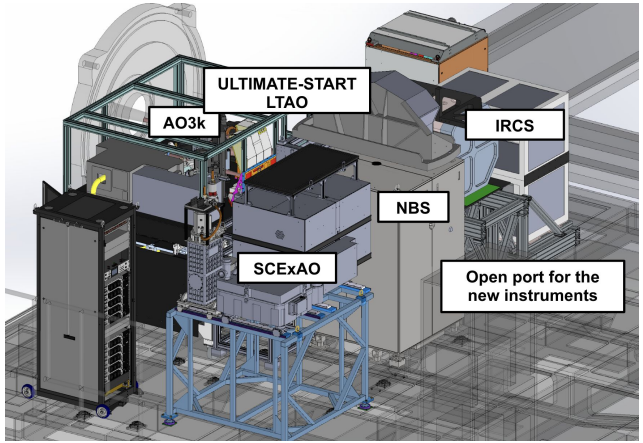
How do we realize it? What we want to/should do in the future?

Current





Near-future
(~5 years)



Future (2030s)

?

See P04: PI-type instrument activities at Subaru Telescope (Hirofumi Okita; talk by Hattori-san/Tamura-san)

PI-type instrument

Originally, PI-type instruments are expected to

- Focus mainly on PI's own science and development
- Short turnaround (<5yrs)
- 3-year operation term (w/ extensions if needed)

Some of the current PI-type instruments become more like "facility instrument" (E.g. CHARIS/VAMPIRES/IRD)

- Highly demanded by the community
- Not only for PI's own science but also for more general purpose
- Longer operation term

Slide from UM2015

Roles of the PI type instrument

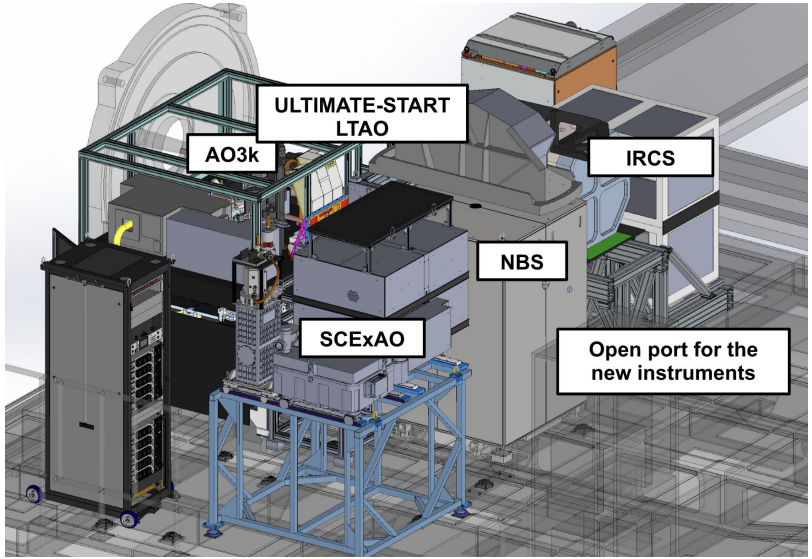
Subaru encourages to carry in the PI type instrument for:

1. Unique science capability
   - Complementary to the large facility instrument
   - Can be a single purpose science to pursue the PI's own science
2. Test bed of the latest technology for future instrument
3. Flexible operation compared to the large facility instrument
   - Short turnaround time (<5 yrs) from development to science output
   - Promote small scale development by University and provide a good educational ground for graduate students

How do we continue to support those "facility-like" PI-type instruments?

Necessity of Roadmap for NsIR platform

So far, the NsIR platform is developed with “bottom-up” way based on AO188 + PI-type instruments and there is no top-level scientific roadmap on it.



But…

- Limitations of the infrastructure (space, weight, and etc.) and resource to support the PI-type instruments.
- Coordination/Prioritization among existing/new instruments is required based not only on the technical feasibility but also on scientific roadmap

Beyond the near-future…

- There is no clear roadmap for the use of the NsIR platform in 2030s.
- Strong the scientific roadmap (Subaru 3?) will be necessary to make the Subaru/NsIR competitive
- In the meantime, supporting the PI-type instrument activity will be also the important role of the observatory.

Provisionally key elements for future roadmap

- **Securing long-term operations of high-demand PI-type instruments**
  - E.g. SCExAO/CHARIS, VAMPIRES & IRD look like good candidates.
  - Given collaborative efforts by Observatory and PI teams for “win-win” somehow.
- **Prioritizing the wavelengths *from red visible to blue NIR (e.g. from I to J)***
  - The number of Deformable Mirror elements is still too few to give diffraction limited AO performance to extremely large telescopes (ELT).
    - And it should take quite some time for technology to catch up with ELT.
- **Prioritizing *spectroscopic* capabilities over a larger FoV (~0.5-1 arcmin instead of ~10 arcsec) with**
  - Potentially 8m-class telescope will still be competitive by ***strategic*** instrumentation and investment of telescope time with assists by high-performance AO.
    - Including quick turnaround observations for time-domain sciences
  - MOS capability would be crucial for ***follow-up observation of ULTIMATE WFI imaging surveys***