SCExAO

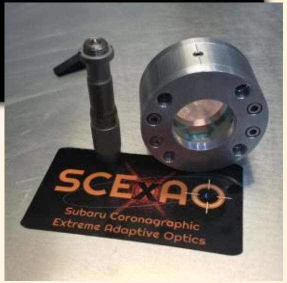
Subaru Coronagraphic Extreme Adaptive Optics

すばるコロナグラフ極限補償光学装置

SCExAO, a testbed enabling community-oriented wavefront sensing and control developments

Sebastien Vievard, Olivier Guyon, Julien Lozi, Vincent Deo, A. Sahoo, N. Skaf, N. Jovanovic, B. Norris, B. Mazin, A. Walter, P. Tuthill, T. Kudo, H. Kawahara, T. Kotani, M. Ireland, N. Cvetojevic, E. Huby, S. Lacour, T. D. Groff, J. Chilcote, J. Kasdin, F. Martinache, R. Laugier, J. Knight, S. Bos, F. Snik, D. Doelman, E. Bendek, R. Belikov, T. Currie, Y. Minowa, C. Clergeon, N. Takato, M. Tamura, J. Zhang, H. Takami, M. Hayashi

An International Collaboration



Subaru Telescope, National Astronomical Observatory of Japan

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Ananya Sahoo, Nour Skaf

VAMPIRES
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AO188
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K. Barjot
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R. Laugier
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D. Coutts

VVC
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E. Serabyn
G. Singh
J. Hagelberg
D. Defrère
D. Mawet

PyWFS /CACAO
J. Males
S. Cetre
L. Close
A. Sevin
D. Gratadour

MKIDS
B. Mazin
A. Walter
N. Fruitwala
A. Butler
S. Meeker
J. Massie
M. Strader
J. Van Eyken
K. Davis

FP WFS
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F. Cassaing
Bonnefois
J-F. Sauvage
M. Lamb

IRD/REACH
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T. Kotani
M. Ishizuka
T. Kudo
N. Jovanovic

SAPHIRA
D. Hall
S. Goebel
S. Jacobson
D. Atkinson
M. Chun
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GLINT
B. Norris
M. Martinot
T. Lagadec
N. Cvetojevic
S. Gross
A. Arriola
T. Gretzinger
P. Tuthill
M. Withford
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FPM DESIGN
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CHARIS
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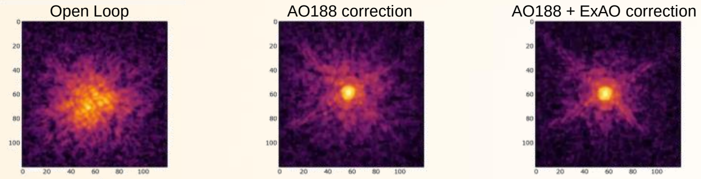
T. Groff
J. Chilcote
T. Brandt
M. Galvin
M. A. Peters

Science (+ SEEDs team)
T. Currie
M. Tamura
J. Zhang

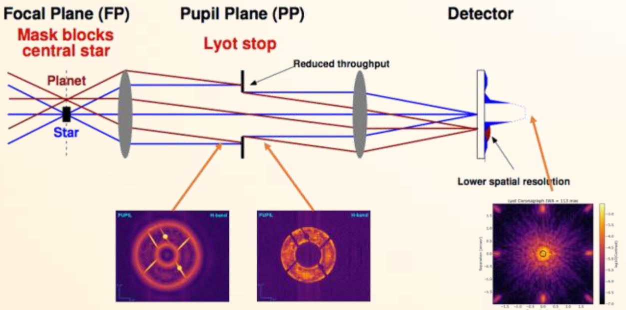
MACQUARIE University · l'Observatoire de Paris · Australian National University · PRINCETON UNIVERSITY · UCSB · HOKKAIDO UNIVERSITY · NAOJ National Astronomical Observatory of Japan · ONERA THE FRENCH AEROSPACE LAB · California Institute of Technology · Institute for Astronomy University of Hawaii · The University of Sydney · Observatoire de la CÔTE d'AZUR · AAO · THE UNIVERSITY OF ARIZONA · NASA JPL · Kyoto University · Universiteit Leiden Leiden Observatory

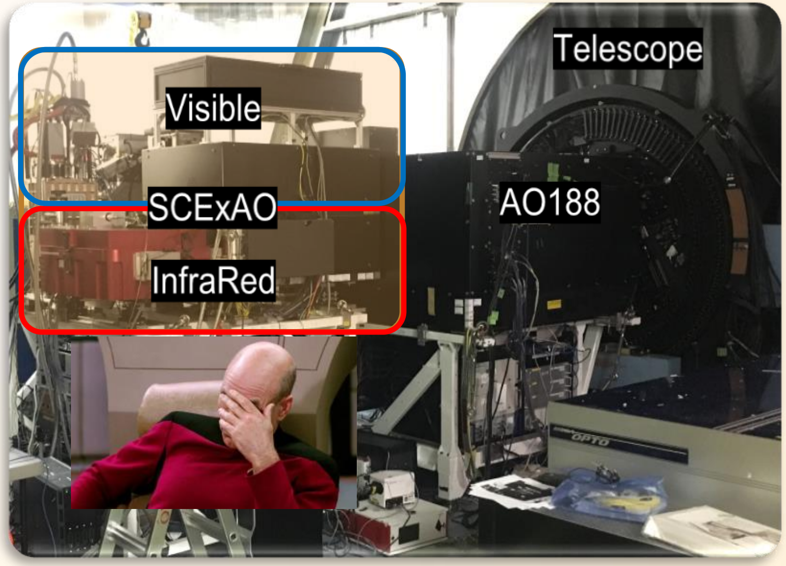
SCExAO : A high contrast instrument

- **SCExAO: Subaru Coronagraphic Extreme Adaptive Optics**
  - Extreme AO thanks to Pyramid wavefront sensor (PyWFS) → >80% Strehl (H-band)



  - Coronagraphs to suppress star light and reveal close circumstellar environment

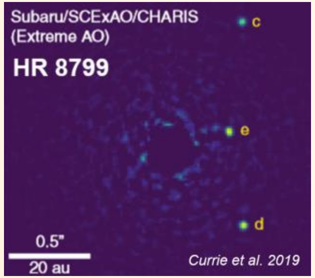


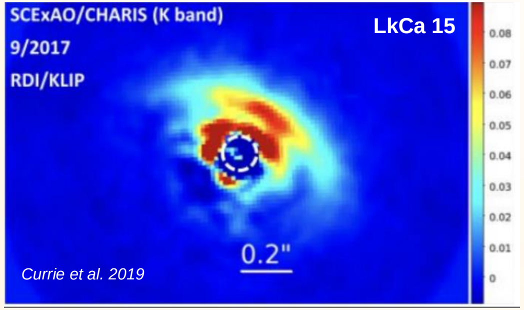


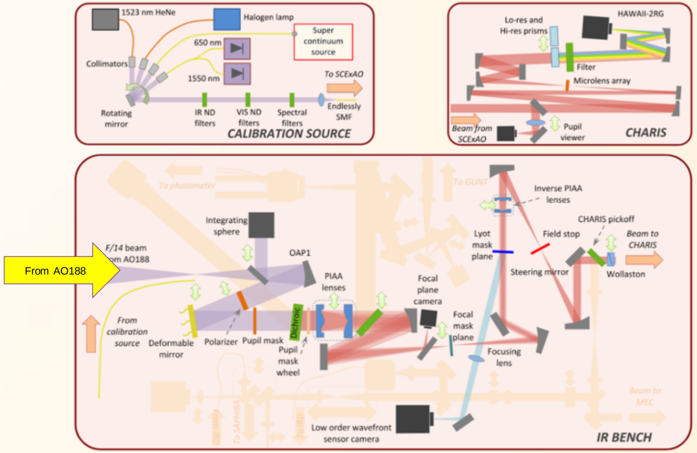
SCExAO on the IR Nasmyth focus of the Subaru Telescope

SCExAO : competitive commissioned science modules

- **SCEXAO: Subaru Coronagraphic Extreme Adaptive Optics**
  - ExAO + Coronagraphs for high contrast imaging
  - Science with SCExAO
    → Exoplanet/Disk detection and characterization with **CHARIS** Integral Field Spectrograph (Spectral bands J,H,K)







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- **SCEXAO: Subaru Coronagraphic Extreme Adaptive Optics**
  - ExAO + Coronagraphs for high contrast imaging
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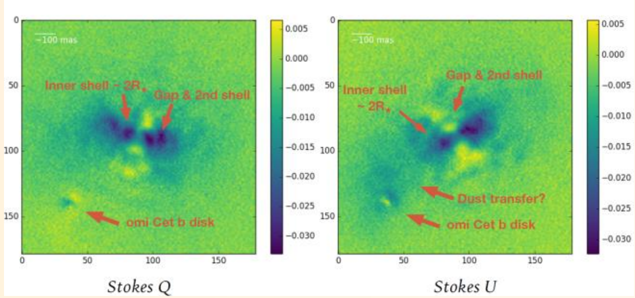
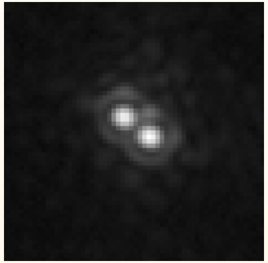
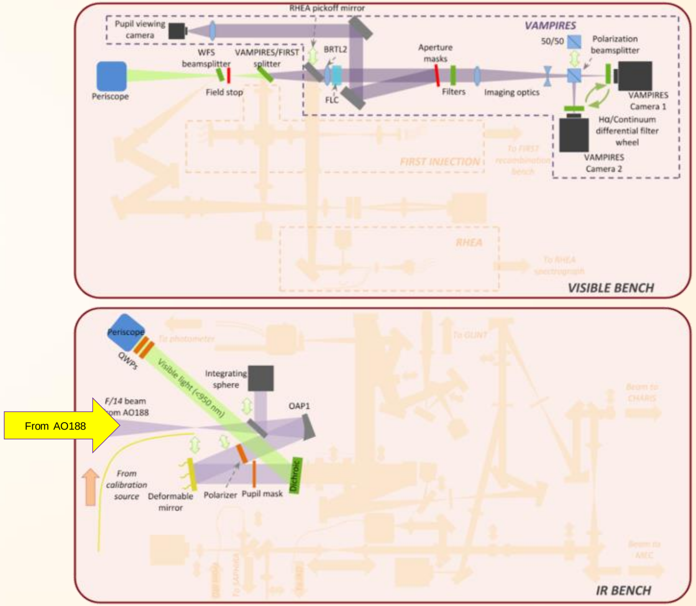
    → Exoplanet/Disk detection and characterization with **CHARIS** Integral Field Spectrograph (Spectral bands J,H,K)
    → Differential polarization (PDI) or H-α imaging of circumstellar environments with **VAMPIRES** (Visible)



PDI on omi Cet

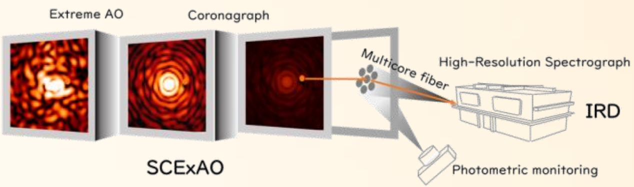


High Strehl @ 750nm
classic imaging
on Capella binary (~40mas separation)

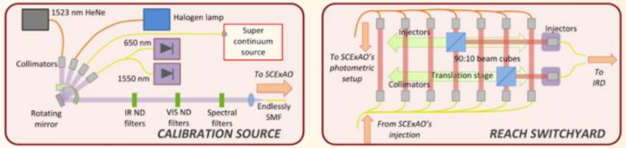


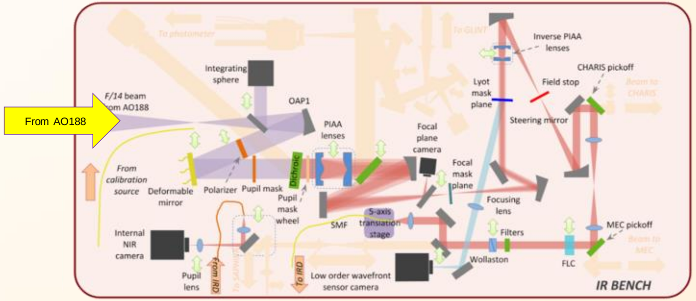
SCExAO : competitive commissioned science modules

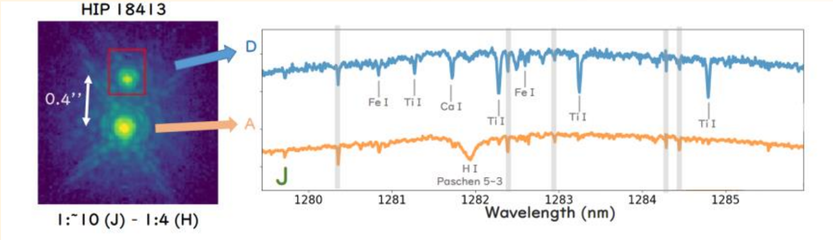
- **SCEXAO: Subaru Coronagraphic Extreme Adaptive Optics**
  - ExAO + Coronagraphs for high contrast imaging
  - <u>Science with SCExAO</u>
    → Exoplanet/Disk detection and characterization with **CHARIS** Integral Field Spectrograph (Spectral bands J,H,K)
    → Differential polarization or H-α imaging of circumstellar environments with **VAMPIRES** (Visible)
    → High dispersion coronagraphy with **REACH** (Spectral bands J,H,K) – using IRD instrument (R100 000)



Post-coronagraphic injection of companion light into a single-mode fiber feeding a high-resolution spectrographe





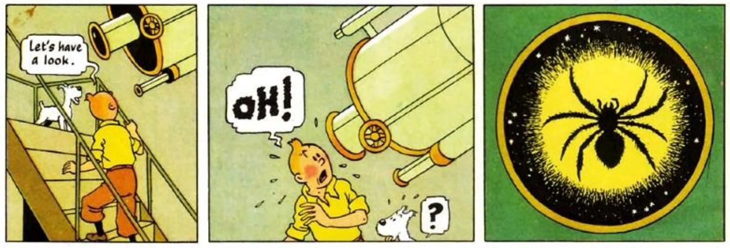


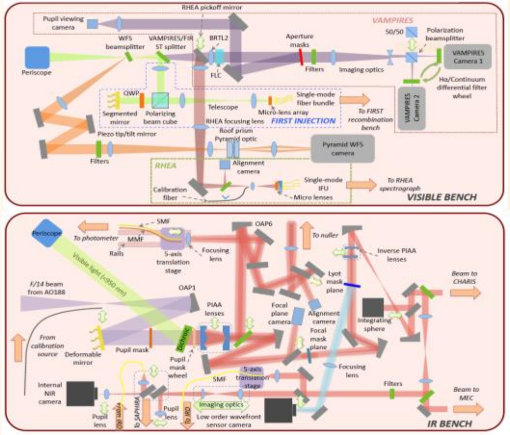
High-dispersion spectra of HIP18413 host star A and companion D obtained during engneering on-sky tests (without coronagraph)

SCExAO : instrumental limitations

- **Instrumental limitations to contrast performances:**
  - Island effect: due to the spider
    - → Differential Piston Effect, Petalling, Pupil fragmentation, Disconnectedness
    - → Low Wind Effect (LWE)
  - Non-Common Path Aberrations (NCPA)
    Differential aberrations between ExAO system and science detector

Tintin – The shooting star





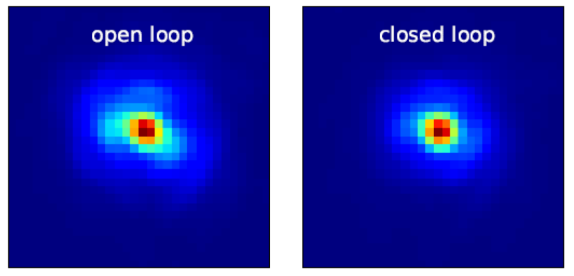
- **Modularity of SCExAO allows to easily integrate and test on-sky wavefront sensing and control techniques**
  → Visible cameras, IR Cred2 (x2), IR Cred1, IR MKIDS

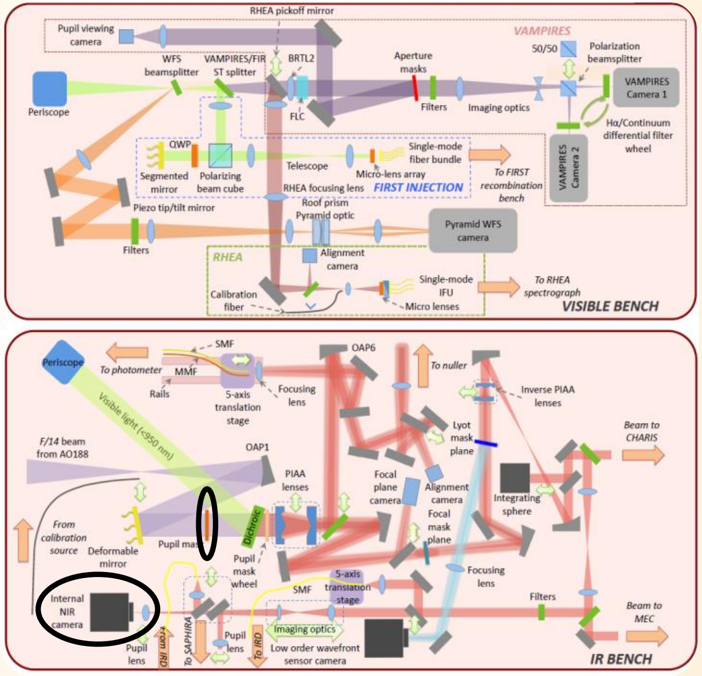
→ Collaborative effort to push back those limitations

(Some)
wavefront sensing developments
on SCExAO

SCExAO : wavefront sensing developments

- **Focal plane wavefront sensing**
  - Phase retrieval with asymmetric pupil mask
    → **Zernike Asymmetric Pupil wavefront sensor (ZAP)**
    On-sky : 37% gain in Strehl





M. N'Diaye et al., A&A, 2018

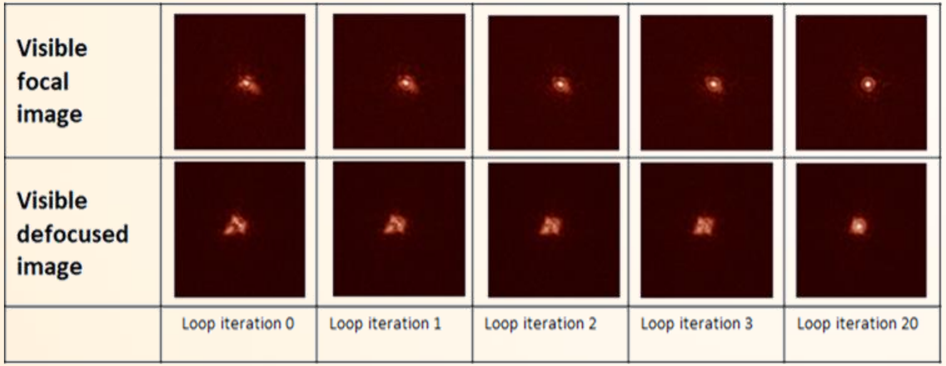
→ *C. Lopez now working on this (see talk 13/10)*

SCExAO : wavefront sensing developments

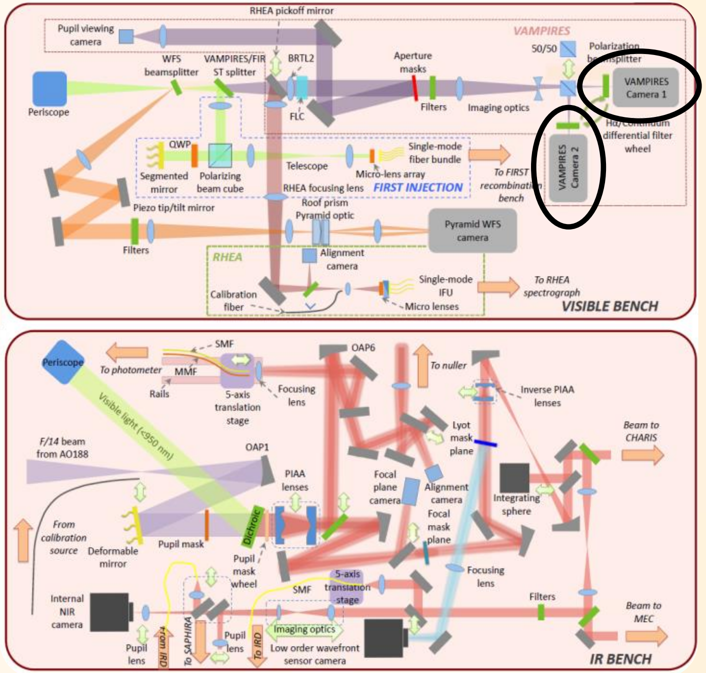
- **Focal plane wavefront sensing**
  - Phase retrieval with asymmetric pupil mask
  - Phase diversity

    → **Linearized Analytic Phase Diversity (LAPD)**

    Vievard et. al, 2020, Under review

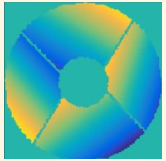


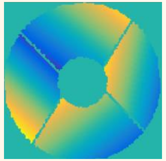
Loop closure on the SCExAO internal source
Applying a static LWE-like phase aberration map on the DM



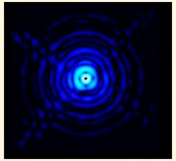
SCExAO : wavefront sensing developments

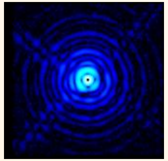
- **Focal plane wavefront sensing**
  - Phase retrieval with asymmetric pupil mask
  - Phase diversity
    - → Linearized Analytic Phase Diversity (LAPD)
    - → **Mono-plan phase diversity**


Random Piston/Tip/Tilt

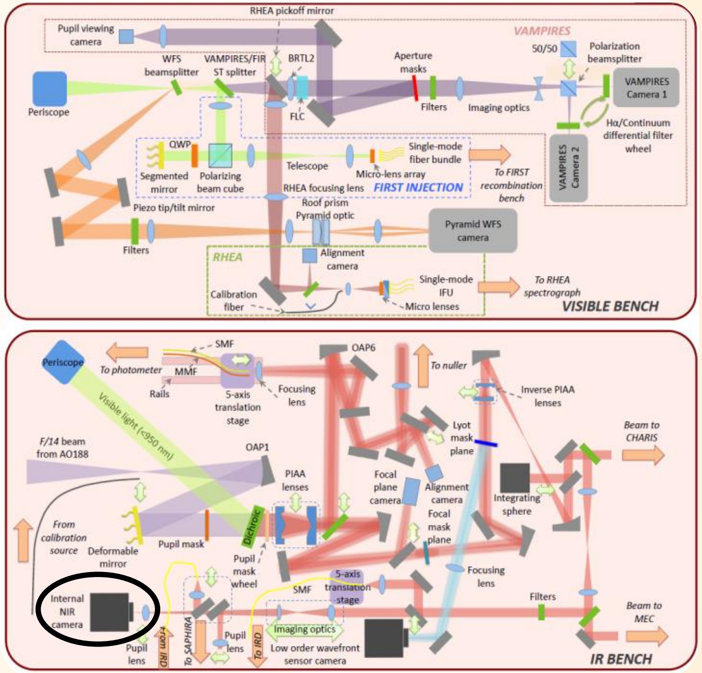

Estimated Piston/Tip/Tilt


Difference


PSF to correct


Estimated PSF

On internal source using one defocused image, *Masen Lamb*

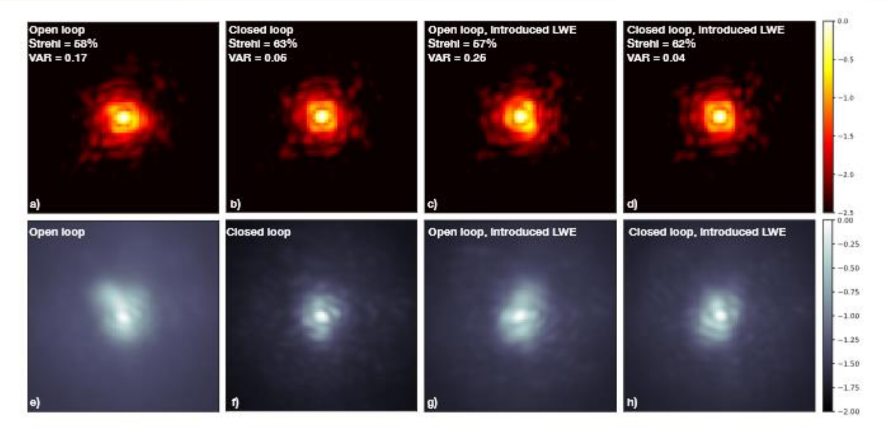


SCExAO : wavefront sensing developments

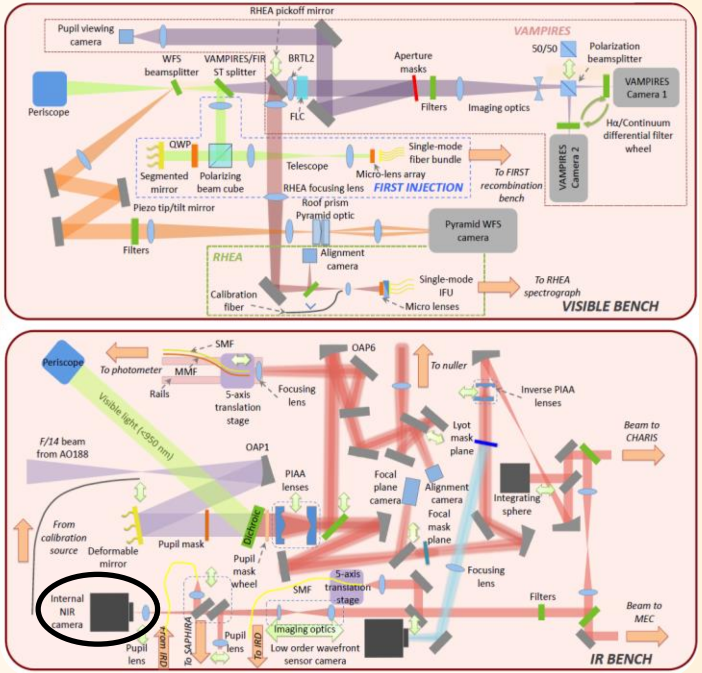
- **Focal plane wavefront sensing**
  - Phase retrieval with asymmetric pupil mask
  - Phase diversity
    → Linearized Analytic Phase Diversity (LAPD)
    → Mono-plan phase diversity
    → **Fast and Furious (sequential Phase Diversity)**

IR image
Used for correction

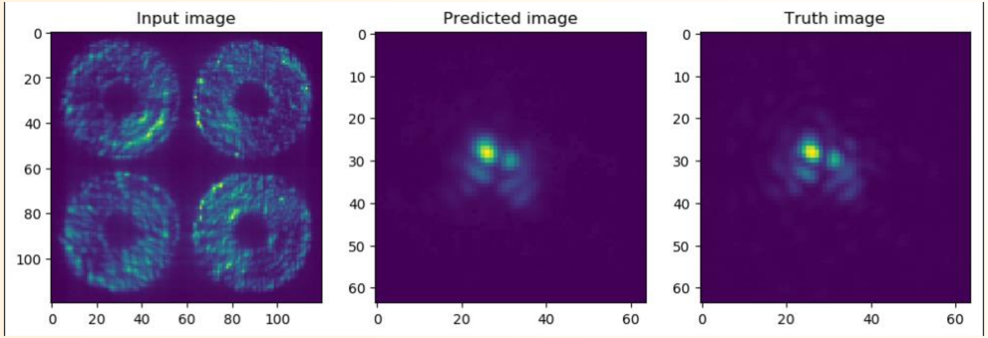
Vis image
Used for monitoring



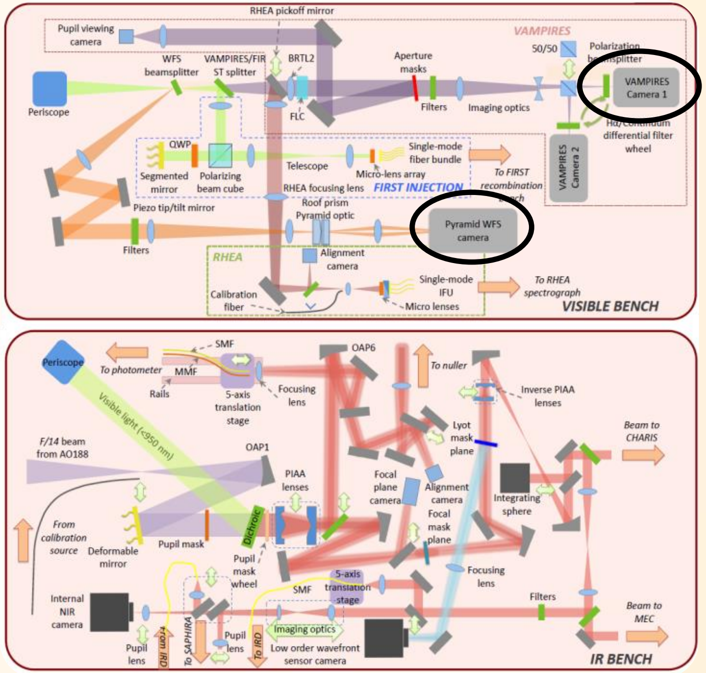
On-sky validation - S. Bos et al. (2020) – see talk 13/10



- **Focal plane wavefront sensing**
  - Phase retrieval with asymmetric pupil mask
  - Phase diversity
  - Neural Network
    → PSF reconstruction from PyWFS using Neural Network (NN)

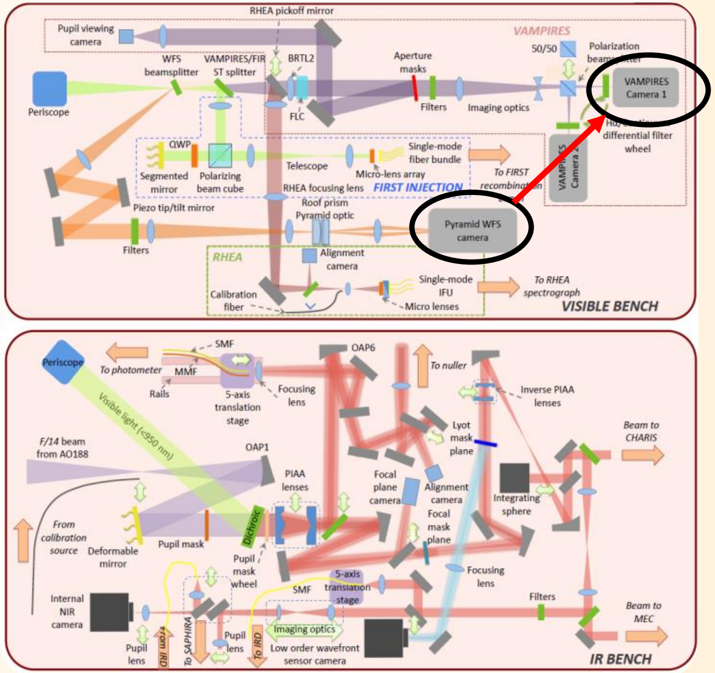


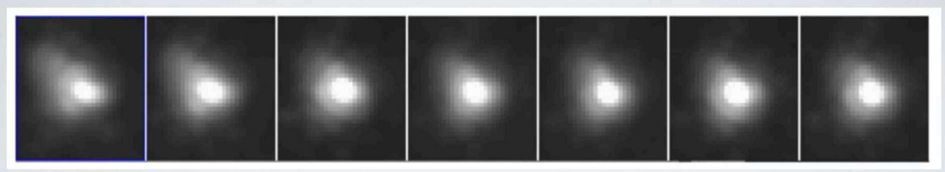
On-sky validation – B. Norris
From left to right: PyWFS telemetry ; predicted image from NN ; True image



SCExAO : wavefront sensing developments

- **Focal plane wavefront sensing**
  - Phase retrieval with asymmetric pupil mask
  - Phase diversity
  - Neural Network
  - Reinforcement learning
    → Direct Reinforcement Wavefront Heuristic Optimisation (DR WHO)





Evolution of PSF during reinforcement learning (21 minutes)
N. Skaf , see talk 14/10

SCExAO : wavefront sensing developments

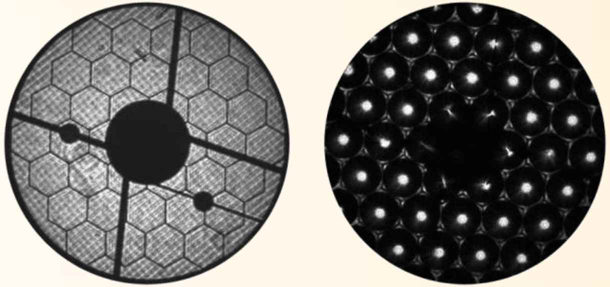
- Focal plane wavefront sensing

- **Interferometric/photonic approach to wavefront sensing**

→ Single telescope interferometers sample the pupil
and allow relative measurements between the sub-pupils

→ Coupled with a spectrometer, possibility to have
these measurements as a function of the
wavelength

→ Critical for fragmented (or segmented) pupils
→ Tackle down the Island Effect caused by the spiders
→ Co-phasing of segmented telescopes



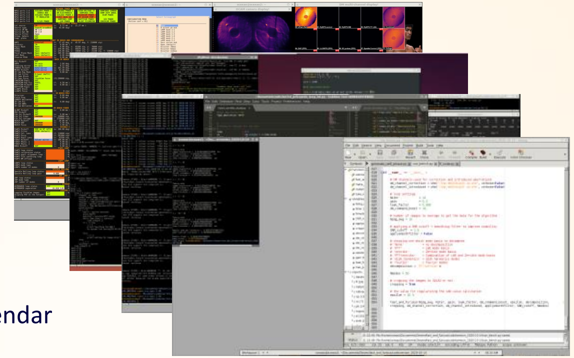
Sampling of the Subaru pupil
Injection into single-mode fibers using a micro-lens array

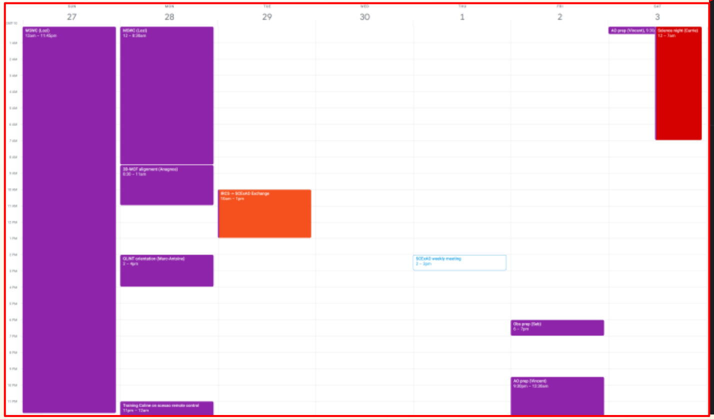
→ On SCExAO, hardware available for exploitation of interferometric/photonic data for WFS (*See B. Norris & K. Barjot talks 12/10*):
→ GLINT : On-chip Nulling interferometry and spectral dispersion in the IR
→ Photonic Lantern : Converts multiple modes from a multi-mode fiber (placed on the core of the PSF) into multiple single mode outputs in the NIR
→ FIRST : Pupil remapping using single mode-fibers (2 sets of 9) and spectral dispersion in the Visible

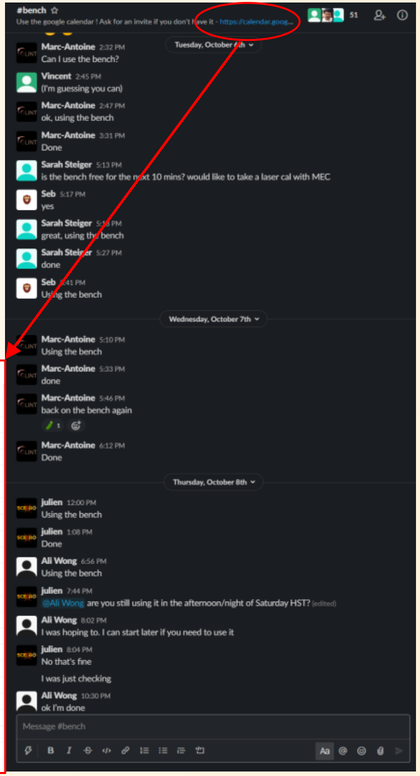
SCExAO : a host testbed for remote collaborators

SCExAO : international collaborative work (24/7)

- **SCExAO online 24/7**
  - → VNC viewer to connect to the instrument computers
    1 session for the instrument general control and multiple sessions for users (personal work space)
  - → Remote access (VPN)
  - → New users get training to operate what they need
    (easy communication with cameras/DM using shared memory → xaosim or pyMILK libraries)
  - → Coordination with others through Slack channel + online calendar



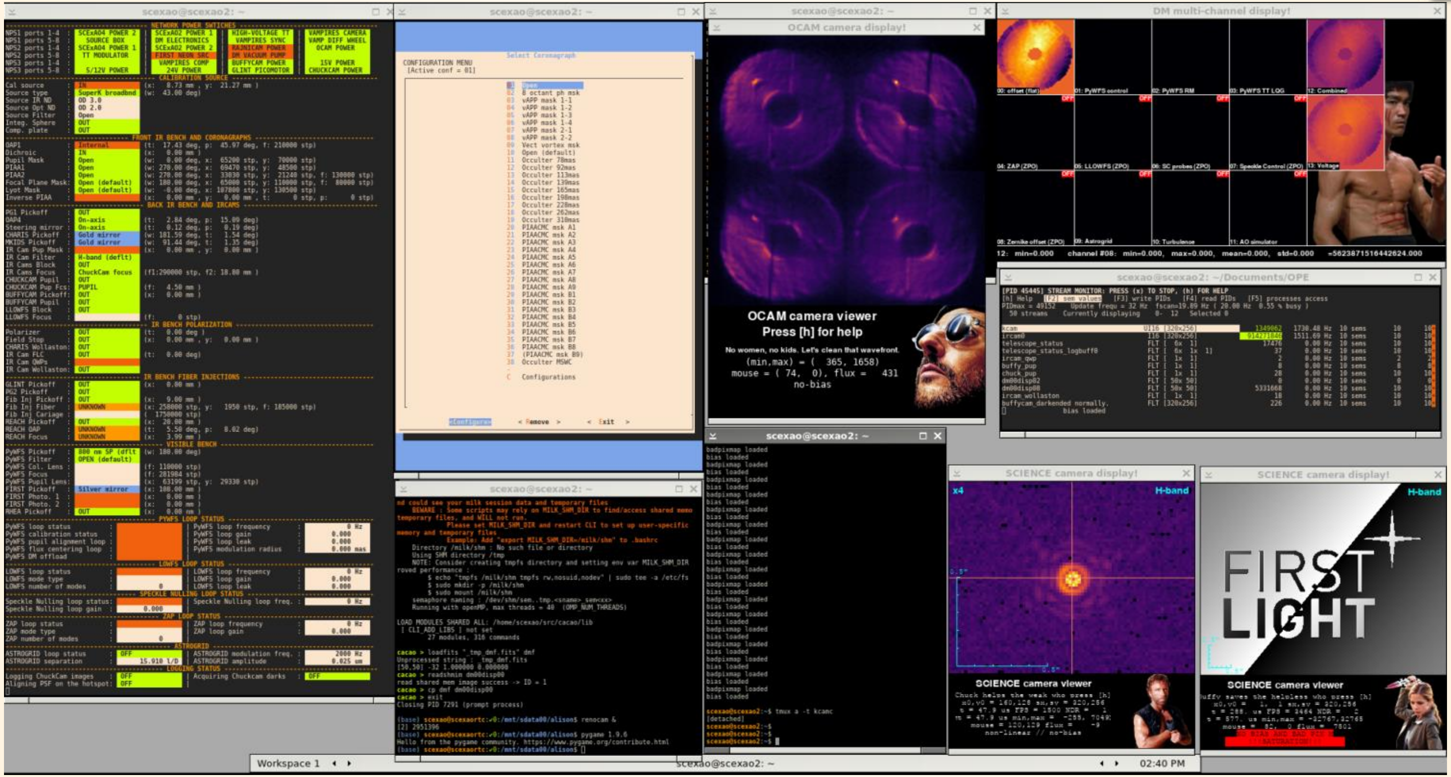




- **SCExAO core team ready to assist**
  - → Software (depending on luck)
  - → Hardware (drive to the summit)

- **Ready to go on-sky ?**
  - → ~ 7 nights of engineering per year

SCExAO : live demo now !



SCExAO : live demo now !

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SCExAO : Conclusion & future

- SCExAO is a unique instrument, able to simultaneously perform competitive science, while testing new technologies/algorithms routinely for future high-contrast imagers

- The framework allows for a large number of international collaborations

- Exciting upgrades to come:
  → CACAO will control SCExAO + AO188 deformable mirrors
  → AO188 will upgrade its DM (for a 64x64 Alpao)
  → New IR Pyramid Wavefront Sensor

- Talk to us ! We can't say no to new things !