SHARK-VIS
the new high-contrast optical imager for the LBT

Simone Antoniucci (INAF-OAR)
on behalf of the SHARK-VIS Team

F. Pedichini, G. Li Causi, M. Mattioli, R. Piazzesi, M. Stangalini, A. Terrer, V. Testa
Pair of synergetic high-contrast instruments (VIS+NIR) to use AO system of LBT (SOUL)

1.0-1.8 um coronagraphic imager spectrograph (LS, R~700)

0.4-0.9 um coronagraphic (fast) imager

VIS+NIR(+LBTI) → binocular (trinocular) mode
simultaneous observation window: 0.4-1.8 um (0.4-5.0 um)
SHARK-VIS: why, who, where, when

**Mission**
fast-track P.I. instrument to open LBT to AO science in the visible

**AO in the visible**
AO correction much more difficult than in the IR, but some advantages:
- low background
- fast, cheap, low-noise detectors
- higher resolution: $\lambda/D$ 15mas on a 8m telescope (same as ELT in the K band)
- bright line tracers (e.g. Hα)

**Core Team**
- Project, design, construction: AO group of INAF-OAR
  - F. Pedichini (PI), S. Antonucci (instrument scientist), M. Mattioli (project manager, system engineer), G. Li Causi (data reduction), R. Piazzesi (lab tests, software), A. Terreri (simulations, NCPA mitigation), V. Testa (data management, science), M. Stangalini (ASI)
  (simulations, post-processing)

**Science**
Science Team: 70+ people from 15 institutes; main science topics: accreting exoplanets and brown dwarfs, YSO jets and disks, Solar System minor bodies, evolved stars, AGNs

**Operations**
Shipped to LBT by Summer 2020; First Light by end of 2020
SHARK-VIS precursor: the ForeRunner

- Ultra-simplified version of SHARK-VIS: basic optics + fast low-noise camera

- ANDOR sCMOS imager, 200x200 pix, 3.73mas/pix, 1.5e^- RON
- 1kHz frame rate (1ms DIT)

- Diffraction-limited PSF at 630nm: 18 mas FWHM

- Gliese 777 (mag R=5.7)
Fast-imaging data

1000 raw frames: 1ms DIT

Re-centered frames

Sum of re-centered frames

Sum of not recentered frames (as in a long exposure)

target: Gliese 777 (mag R=5.7)
frames: 1 ms DIT (1kHz rate)
filter: $\lambda = 630 \text{ nm, } \Delta \lambda = 40 \text{ nm}
obs: 20 minutes of data

seeing=0".8-1".2, strong wind
LBTI-AO: 550 modes corrected, 990 Hz

residual aberrations and jitter
speckles mean life is few ms
speckles are frozen in single frames

use innovative ad-hoc post-processing techniques
- final (re-centered) image: 18mas FWHM core
- achieved contrast: $2 \times 10^{-5}$

Talk by G. Li Causi
SHARK-VIS: the instrument

1kHz science camera: sCMOS/EM-CCD

Calibration Source

Shutter

ABS (PSF stabilizer)

entrance dichroics (5 dichroics)

Triplet ADC

detector wheel SDI Filters, 2x lens

pupil, mask, filter wheels: filters, stops, coro, wollastons

1kHz guide camera

guide splitter (5 splitters)

~60cm 100 kg
## SHARK-VIS in a nutshell

<table>
<thead>
<tr>
<th><strong>spectral range</strong></th>
<th>400-900 nm</th>
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</thead>
<tbody>
<tr>
<td><strong>angular resolution</strong></td>
<td>15 mas in V band</td>
</tr>
<tr>
<td><strong>pixel scale</strong></td>
<td>6.5 mas/pixel</td>
</tr>
<tr>
<td><strong>max frame rate</strong></td>
<td>1 kHz</td>
</tr>
<tr>
<td><strong>field of view</strong></td>
<td>10&quot; x 10&quot; (1&quot;.3 x 1&quot;.3 at 1 kHz)</td>
</tr>
<tr>
<td><strong>coronagraphs</strong></td>
<td>Lyot and Gaussian (50, 100, 200 mas IWA)</td>
</tr>
<tr>
<td><strong>xAO system</strong></td>
<td>SOUL (SCAO)</td>
</tr>
<tr>
<td><strong>observing modes</strong></td>
<td>(coro) classical imaging &amp; dual-band imaging</td>
</tr>
<tr>
<td><strong>filters - BB</strong></td>
<td>B, V, R, V*, I, z</td>
</tr>
<tr>
<td><strong>filters - NB</strong></td>
<td>Hα, [OIII]λ5007, …</td>
</tr>
<tr>
<td><strong>filters - dual-band (NB)</strong></td>
<td>Hα+Cnt, [OI]λ6300+Cnt, …</td>
</tr>
<tr>
<td><strong>performance goal</strong></td>
<td>contrasts &lt; 10^{-4} at 100 mas and below</td>
</tr>
<tr>
<td><strong>future upgrades</strong></td>
<td>IFU module (R=5000-10000)</td>
</tr>
<tr>
<td><strong>extras</strong></td>
<td>PSF stabilization, multiple dichroics, fast-imaging → innovative post-processing techniques, northern hemisphere</td>
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</table>

- 50 km @5au, 2au @150 pc
- 4 mas/pixel in 2x mode
- no derotator (pupil-stabilized)
- Strehl R ~10% at mag R~12-13
- free slots still available
- SDI technique
- ELVIS project
Observe faint objects really close to bright source (contrasts $\ll 10^{-3}$)

Need to remove starlight $\rightarrow$ subtract star (continuum) PSF

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<tr>
<th>technique</th>
<th>info</th>
<th>SHARK</th>
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<tr>
<td>coronagraphy</td>
<td>physically block out light from central star</td>
<td>✔</td>
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<tr>
<td>SDI - spectral differential imaging</td>
<td>subtract image at different lambda (e.g. line &amp; continuum filters)</td>
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<td>ADI - angular differential imaging</td>
<td>subtract median PSF constructed from non de-rotated frames</td>
<td>✔</td>
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<td>RDI - reference differential imaging</td>
<td>subtract a reference (re-scaled) PSF</td>
<td>✔</td>
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<tr>
<td>PDI - polarimetric diff. imaging</td>
<td>subtract orthogonal polarizations (enhance polarized light)</td>
<td>✗</td>
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<tr>
<td>PCA</td>
<td>principal component analysis</td>
<td>✔</td>
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<tr>
<td>Deconvolution</td>
<td>e.g. multi-frame blind deconvolution</td>
<td>✔</td>
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<tr>
<td>SFADI, SFI, RQA, ...</td>
<td>techniques for fast-imaging</td>
<td>✔</td>
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High-contrast techniques

Observe faint objects really close to bright source (contrasts $<< 10^{-3}$)

need to remove starlight $\rightarrow$ subtract star (continuum) PSF

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Talk by G. Li Causi

Astrofisica di frontiera con AO italiana - Roma 17/02/2020 - SHARK-VIS @LBT
Resolved (spectroscopic) binary $\alpha$ And
16 mas separation (0.5 au @30 pc)
one of the highest-angular resolution direct images ever taken

Mattioli+ 2019
Imaging of known low-mass companions to test procedures and optimize reduction algorithms (first detections in the visible).

HD 8375 B
R=5.8, 198 mas, 2e-3

v450 And B
R= 7.7, 304 mas, 1.7e-3
SHARK-VIS papers

High Contrast Imaging in the Visible: First Experimental Results at the Large Binocular Telescope
F. Pedichini1,2, M. Stangalini1,2, F. Ambrosino1, A. Puglisi3, E. Pinna3, V. Bailey4, L. Carbonaro3, M. Controne1, J. Christou5, S. Esposito3, L. Ferrari2, A. Fiore3, L. Galli1, A. M. Hill5, P. M. Hinz5, and L. Sabatini1

Recurrence Quantification Analysis as a Post-processing Technique in Adaptive Optics High-contrast Imaging
M. Stangalini1,2,3, G. Li Causi1,2, F. Pedichini1,2, S. Antoniucci1,2,4, M. Mattioli1,2, J. Christou5, G. Comolli3, D. Hope5, S. M. Eelkema1,2, R. Fiorenza3, and V. Testa1,2

SPADI: The Speckle-free Angular Differential Imaging Method
Gianluca Li Causi1,2,3, Marco Stangalini1,2, Simone Antoniucci1,2,4, Fernando Pedichini1,2, Massimiliano Mattioli1,2, and Vincenzo Testa1,2

Speckle statistics in adaptive optics images at visible wavelengths
Marco Stangalini,2,3, Fernando Pedichini,2,3,3,3, Enrico Pinna,3,3, Julian Christou,2 John Hinz,2 Alfio Puglisi,3,3, Vanessa Bailey,2 Mauro Centrone,2 Dario Del Muro,2 Simone Esposito,2,3, Fabrizio Fiore,2,3 Emanuele Galli1,2, Phil Hinz,2 and Amali Vaz2

First Direct Imaging Detection of the Secondary Component of α Andromedae with the LBT/SHARK-VIS Pathfinder Experiment
M. Mattioli1,2, F. Pedichini1,2, S. Antoniucci1,2, G. Li Causi1,2,3, R. Piazzesi1,2, M. Stangalini1,2, V. Testa1,2, A. Vaz4, E. Pinna3,5, A. Puglisi3,5

SHARK-VIS has already produced papers mostly based on 20 min ForeRunner data
- 4 refereed papers + 1 in preparation
- 1 research note
- 15+ technical papers and proceedings
Contrast curves (5σ) of ForeRunner test observations (seeing 1\".0-1\".2)
→ final contrast depends on reduction technique
→ indicated noise limit assumes perfect star PSF subtraction

R mag 5.7, Bandwidth 40nm, 20 min, DIT 1ms

R mag 7.7, Bandwidth 10nm, 10 min, DIT 2.5ms
Contrast curves (5σ) of ForeRunner test observations (seeing 1\(^{\prime\prime}\) 0.0-1\(^{\prime\prime}\) 2).

**SHARK-VIS vs ForeRunner**
- x4 bandwidth with ADC (BB observations)
- coro
- SDI (dual-band NB observations)
- new post-processing methods
- 0-noise detector (EM-CCD)
- SOUL vs FLAO (same Strehl Ratio as FLAO but on 2 mag fainter objects)

R mag 5.7, Bandwidth 40nm, 20 min, DIT 1ms

R mag 7.7, Bandwidth 10nm, 10 min, DIT 2.5ms

![Graph showing contrast vs separation for SHARK-VIS and ForeRunner](attachment:image.png)
**xAO high-resolution in the visible**

<table>
<thead>
<tr>
<th>telescope</th>
<th>instrument</th>
<th>AO</th>
<th>status</th>
<th>λ range (nm)</th>
<th>obs. modes</th>
<th>extra</th>
<th>hem</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLT</td>
<td>SPHERE/ZIMPOL</td>
<td>SCAO</td>
<td>active</td>
<td>500-900</td>
<td>img/pol/DBI</td>
<td>SPHERE+ upgrade?</td>
<td>S</td>
</tr>
<tr>
<td>Magellan</td>
<td>MagAO/VisAO</td>
<td>SCAO</td>
<td>active</td>
<td>500-900</td>
<td>img/DBI</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>VLT</td>
<td>MUSE</td>
<td>LTAO</td>
<td>active</td>
<td>480-930</td>
<td>ifs (R~2500)</td>
<td>narrow-field mode</td>
<td>S</td>
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<tr>
<td>Subaru</td>
<td>SCexAO</td>
<td>SCAO</td>
<td>experim.</td>
<td>&lt; 950</td>
<td>img</td>
<td></td>
<td>N</td>
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<tr>
<td>LBT</td>
<td>SHARK-VIS</td>
<td>SCAO</td>
<td>2020</td>
<td>400-900</td>
<td>img/DBI</td>
<td>fast cadence</td>
<td>N</td>
</tr>
<tr>
<td>VLT</td>
<td>MAVIS</td>
<td>MCAO</td>
<td>2026</td>
<td>450-950</td>
<td>img/spec</td>
<td>FoV 30&quot;×30&quot;</td>
<td>S</td>
</tr>
</tbody>
</table>
Observing with SHARK-VIS: FPS

SHARK-VIS
Focal Plane Simulator
web interface

→ ETC
→ SV observation simulator
→ returns expected PSF profile
→ returns theoretical noise limit (ideal star subtraction)
→ returns estimate of final contrast limit
→ generates OBs
# SHARK-VIS science cases

<table>
<thead>
<tr>
<th>Primary cases</th>
<th>sep./resolution</th>
<th>contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accreting planets and BDs</strong></td>
<td>down to 50 mas</td>
<td>$\leq 10^{-3}$</td>
</tr>
<tr>
<td><strong>Jets from young stellar objects</strong></td>
<td>&lt;70 mas</td>
<td>$\leq 10^{-3}$</td>
</tr>
<tr>
<td>Minor bodies and moons of the Solar System</td>
<td>~15 mas</td>
<td>$&gt;10^{-2}$</td>
</tr>
</tbody>
</table>

## Other cases

<table>
<thead>
<tr>
<th></th>
<th>sep./resolution</th>
<th>contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disks around YSOs and debris disks</td>
<td>&lt;1000 mas</td>
<td>$\leq 10^{-4}$</td>
</tr>
<tr>
<td>Substellar companions</td>
<td>down to 50 mas</td>
<td>$\leq 10^{-3}$</td>
</tr>
<tr>
<td>AGN morphology (BH feeding &amp; feedback)</td>
<td>&lt;300 mas</td>
<td>$\leq 10^{-3}$</td>
</tr>
<tr>
<td>Envelopes of evolved stars (AGBs, post-AGBs)</td>
<td>&lt;1000 mas</td>
<td>$\leq 10^{-3}$</td>
</tr>
<tr>
<td>Close binaries</td>
<td>down to 15 mas</td>
<td>$&gt;10^{-2}$</td>
</tr>
<tr>
<td>Microlensing events</td>
<td>~15 mas</td>
<td>$&gt;10^{-2}$</td>
</tr>
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</table>

## Pathfinder

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<tr>
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<th>sep./resolution</th>
<th>contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflected-light planets</td>
<td>down to 50 mas</td>
<td>$\leq 10^{-6}$</td>
</tr>
</tbody>
</table>
Accreting planets and BDs: Hα imaging

SHARKs: direct imaging of wide orbit (> 5au) young giant planets → clues on planet formation

SHARK key project: survey of Taurus-Auriga (d=150 pc, 5-10 au ⇔ 35-70 mas)

bulk of giant planets should form at separations 5-10 au (core-accretion)
accretion can be revealed in Hα

first accreting planets PDS70 b,c observed in Hα with Magellan/VisAO (b) and VLT/MUSE (b,c)
Accreting planets and BDs: Hα imaging

**SHARKs**: direct imaging of wide orbit (> 5au) young giant planets → clues on planet formation

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First accreting planets PDS70 b,c observed in Hα with Magellan/VisAO (b) and VLT/MUSE (b,c)

**PDS 70-like observation** (mag R~11); SV setup:
- Hα+Cnt DB imaging, DIT 3-10 ms
- I, z BB imaging, DIT 3-10 ms
- 2h+ total integration to maximise field rotation
Jets from YSOs

formation+collimation of YSO jets
feedback on disk
angular momentum removal

probe jet base (<10 au ⇔ <70 mas @ 150 pc)
imaging in Hα and [OI]

**Antoniucci**+ 2016

**Antoniucci**+ in prep.

**SPHERE/ZIMPOL**

**[O I] 6300 Å**

**DG Tau**

**Z CMa**

**Antoniucci**+ 2016
Jets from YSOs

formation+collimation of YSO jets feedback on disk angular momentum removal

probe jet base (<10au ⇔ <70mas @150pc) imaging in Hα and [OI]

DG Tau observation (mag R~11.7); SV setup:
- Hα+Cnt DB imaging
- [OI]+Cnt DB imaging
- DIT 5-10 ms

Antoniucci+ 2016

Z CMa

SPHERE/ZIMPOL
[OI] 6300Å

DG Tau observation (mag R~11.7); SV setup:
- Hα+Cnt DB imaging
- [OI]+Cnt DB imaging
- DIT 5-10 ms

Antoniucci+ 2016

SPHERE/ZIMPOL
[OI] 6300Å

Antoniucci+ in prep.
SV Lab: a short tour
SHARK-VIS in the lab
SHARK-VIS in the lab
SV Lab: on-sky target simulator

SV Lab: AO target simulator

→ star+planet injector
→ tunable separation and contrast
→ phase screen to reproduce residual aberrations after AO correction (encoded from ForeRunner real on-sky data)
Take-home messages

- **SHARK-VIS** is the new xAO **visible high-contrast imager** for the LBT (400-900 nm)
- angular resolutions down to 15mas
- **fast-cadence approach** → additional innovative post-processing algorithms
- shipped before summer, **first light in 2020**

- unique potential for breakthrough science (**accreting exoplanets, YSO jets and disks, minor bodies of Solar System, AGNs, evolved stars, ...**)
- synergy with SHARK-NIR and LMIRCAM → **bi- and tri-nocular mode**

- **SHARK-VIS** is a **precursor for AO-science in the visible** and a technological platform (**procedures, techniques and algorithms**).
Open to community interested in AO observations with SHARK
Discussion and organization of key science programs, presentation of new science cases

Website: https://indico.ict.inaf.it/e/shark-science-meeting
Contact: V. D’Orazi (OAPd) and S. Antoniucci (OAR)
Thank You