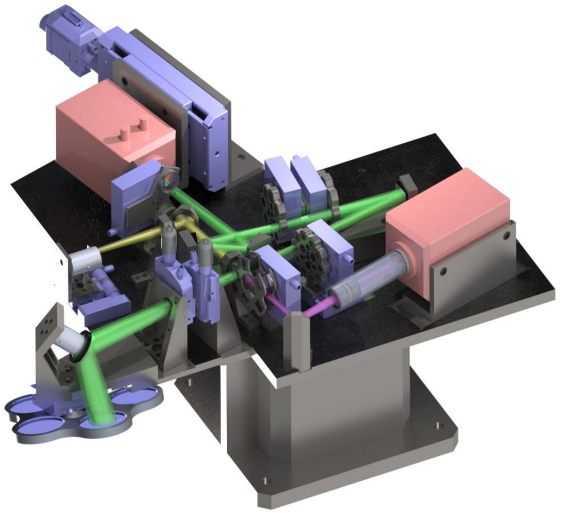


# SHARK-VIS

*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. Terreri, V. Testa**

# SHARK(s) @LBT

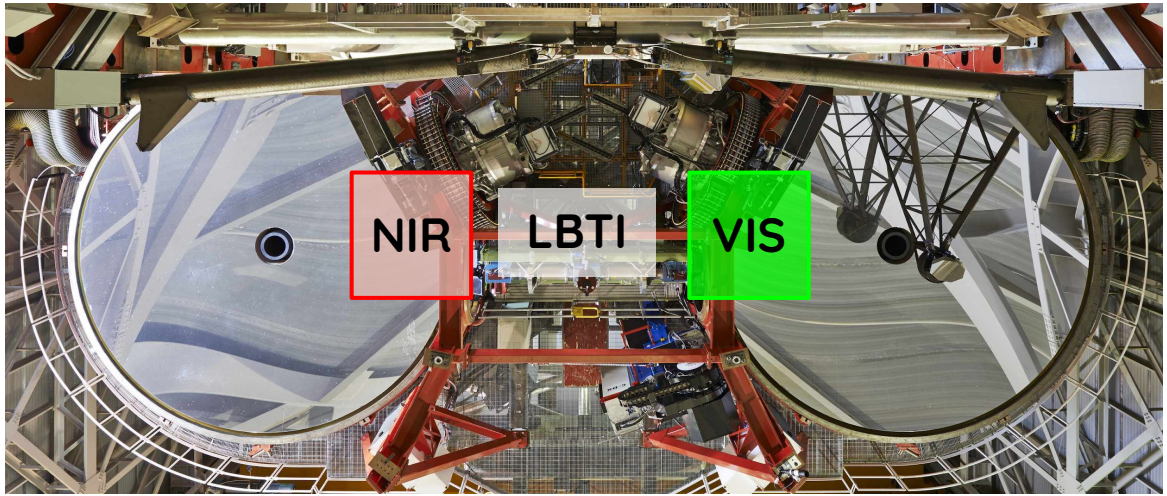
**S**ystem for coronagraphy with **H**igh order **A**daptive optics from **R** to **K** band

Pair of synergetic high-contrast instruments (VIS+NIR) to use AO system of LBT (SOUL)

OAPd **NIR**

shark-nir

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




**VIS** OAR

shark-vis

0.4-0.9 um coronagraphic (fast) imager

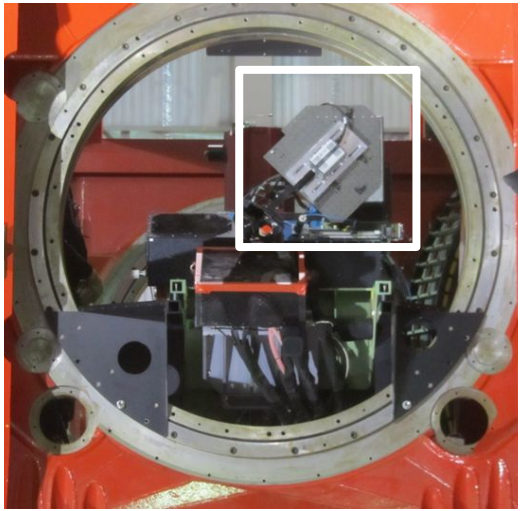
VIS+NIR(+LBTI) → **binocular (trinocular) mode**
simultaneous observation window: 0.4-1.8 um (0.4-5.0 um)

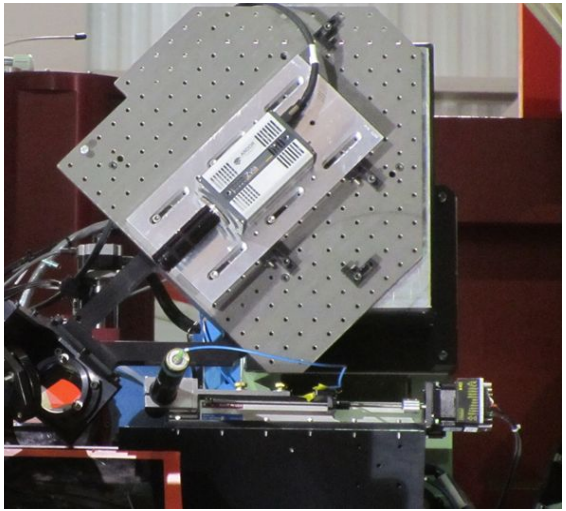
# SHARK-VIS: why, who, where, when

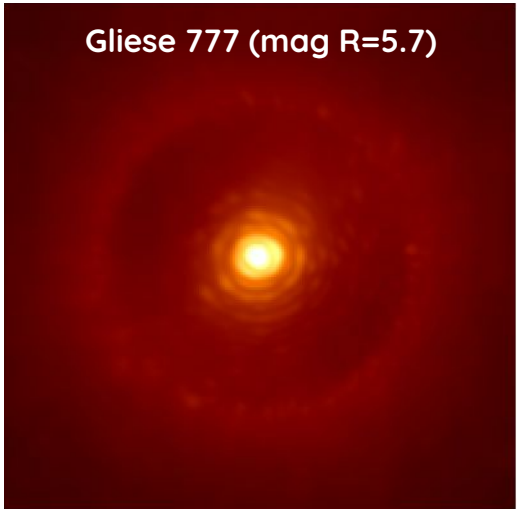
| | |
|---|---|
| Mission | fast-track P.I. instrument to open LBT to AO science in the visible |
| AO in the visible | AO correction much more difficult than in the IR, but some advantages:<br>→ low background<br>→ fast, cheap, low-noise detectors<br>→ **higher resolution:** λ/D **15mas on a 8m telescope** (same as ELT in the K band)<br>→ bright line tracers (e.g. Hα) |
| Core Team | Project, design, construction: **AO group of INAF-OAR**<br>**F. Pedichini (PI), S. Antoniucci** (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, 1.5$e^-$ RON
**1kHz frame rate (1ms DIT)**

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

# Fast-imaging data

1000 raw frames: 1ms DIT

Re-centered frames

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

Sum of re-centered frames

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

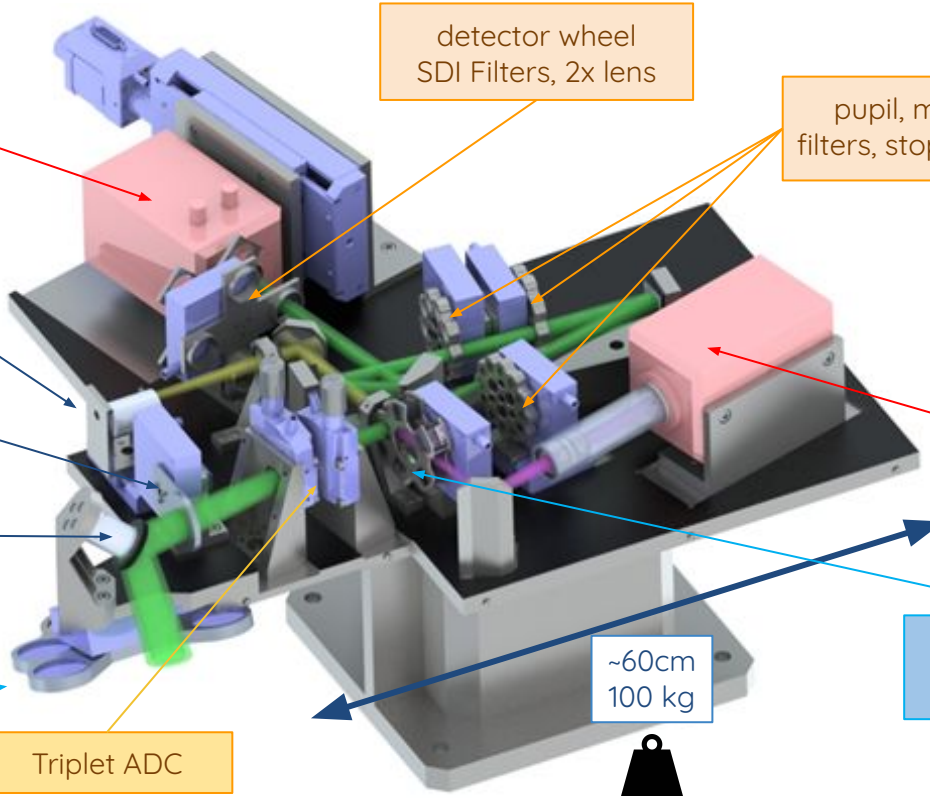
seeing=0".8-1".2, strong wind
LBTI-AO: 550 modes corrected, 990 Hz

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



# SHARK-VIS in a nutshell

| | | |
|---|---|---|
| spectral range | 400-900 nm | |
| **angular resolution** | **15 mas in V band** | 50 km @5au, 2au @150 pc |
| pixel scale | 6.5 mas/pixel | 4 mas/pixel in 2x mode |
| max frame rate | 1 kHz | |
| field of view | 10" × 10" (1".3 × 1".3 at 1 kHz) | no derotator (pupil-stabilized) |
| coronagraphs | Lyot and Gaussian (50, 100, 200 mas IWA) | |
| xAO system | SOUL (SCAO) | Strehl R ~10% at mag R~12-13 |
| **observing modes** | **(coro) classical imaging & dual-band imaging** | |
| filters - BB | B, V, R, V*, I, z | |
| filters - NB | Hα, [OIII]λ5007, … | free slots still available |
| **filters - dual-band (NB)** | **Hα+Cnt, [OI]λ6300+Cnt, …** | SDI technique |
| **performance goal** | **contrasts < $10^{-4}$ at 100 mas and below** | |
| future upgrades | IFU module (R~5000-10000) | ELVIS project |
| extras | PSF stabilization, multiple dichroics, fast-imaging → innovative post-processing techniques, northern hemisphere | |

# High-contrast techniques

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

need to remove starlight → subtract star (continuum) PSF

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

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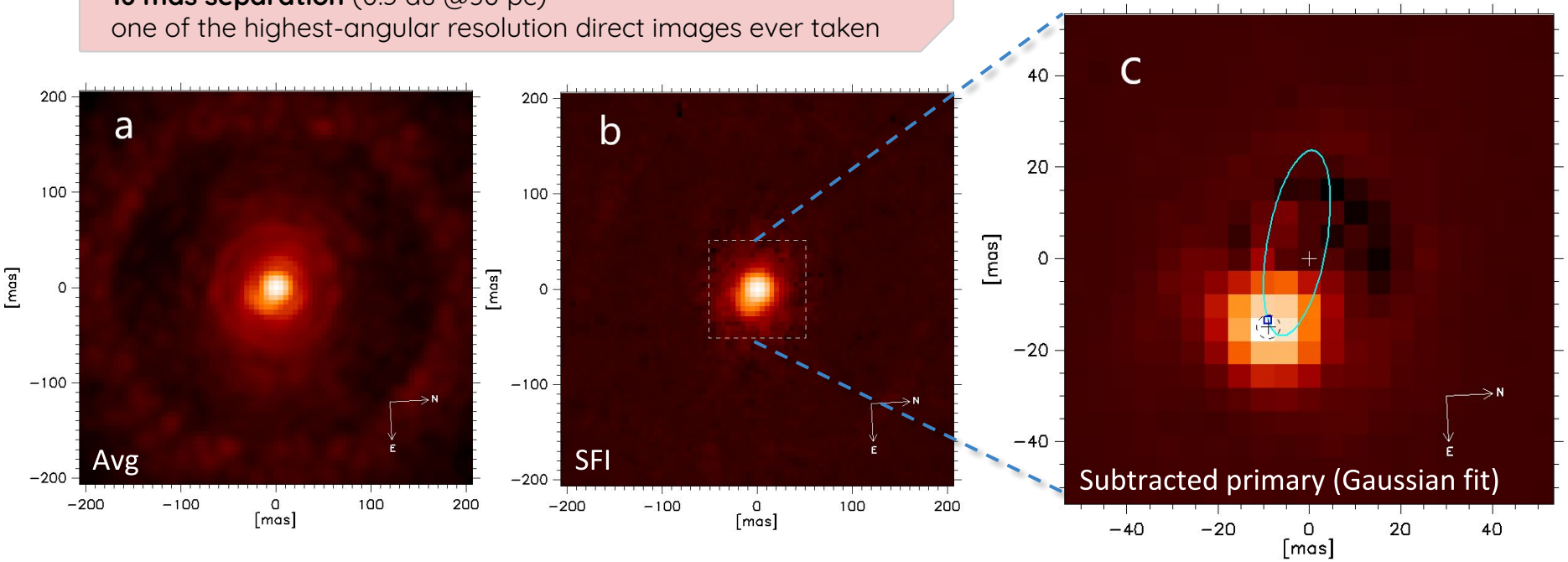
| **SFADI, SFI, RQA, ...** | techniques for fast-imaging | ✓ |

**talk by G. Li Causi**

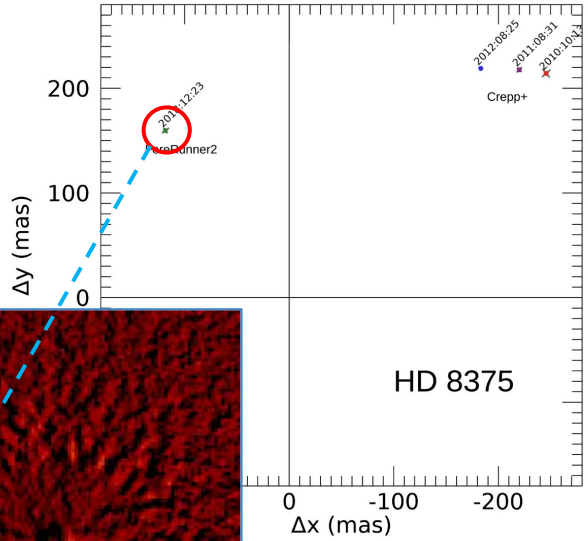
# SHARK-VIS: ForeRunner images

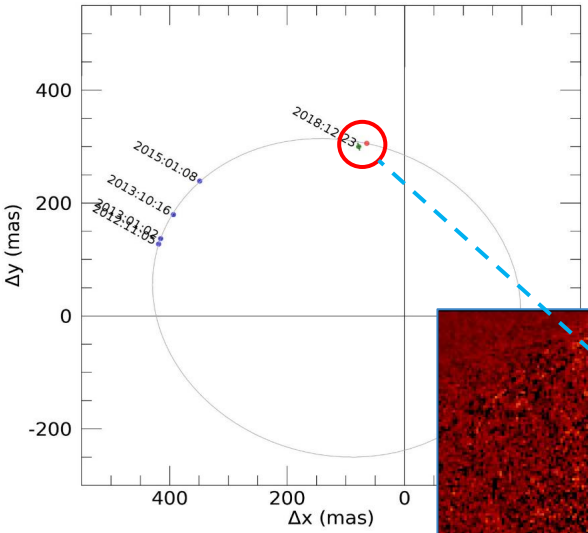
Resolved (spectroscopic) binary **α And**
**16 mas separation** (0.5 au @30 pc)
one of the highest-angular resolution direct images ever taken

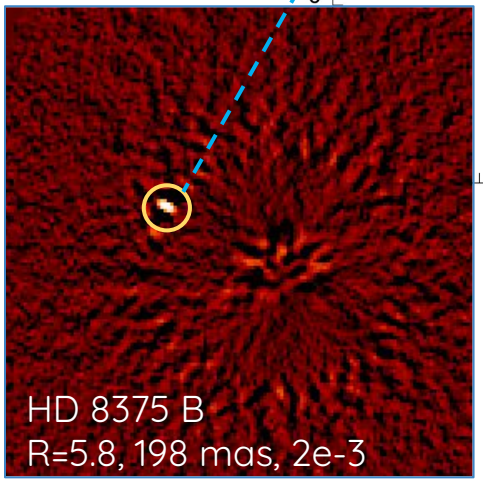
*Mattioli+ 2019*



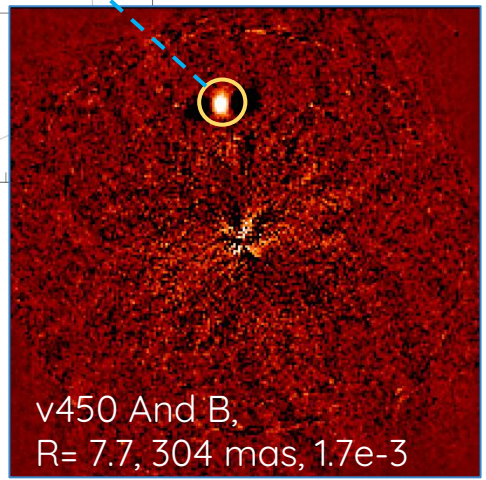
# SHARK-VIS: ForeRunner images



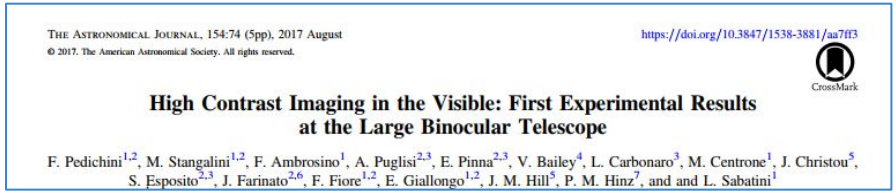




imaging of known low-mass companions to test procedures and optimize reduction algorithms
(first detections in the visible)



# SHARK-VIS papers



The Astronomical Journal, 154:74 (5pp), 2017 August https://doi.org/10.3847/1538-3881/aa7ff3
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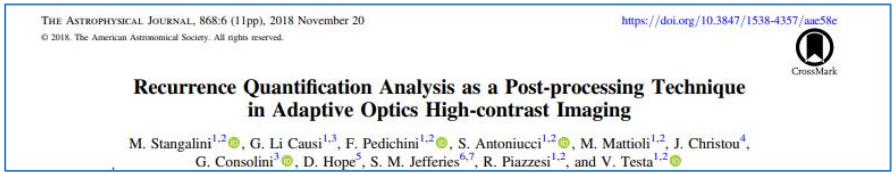
**High Contrast Imaging in the Visible: First Experimental Results at the Large Binocular Telescope**

F. Pedichini[1,2], M. Stangalini[1,2], F. Ambrosino[1], A. Puglisi[2,3], E. Pinna[2,3], V. Bailey[4], L. Carbonaro[3], M. Centrone[1], J. Christou[5], S. Esposito[2,3], J. Farinato[2,6], F. Fiore[1,2], E. Giallongo[1,2], J. M. Hill[5], P. M. Hinz[7], and and L. Sabatini[1]



The Astrophysical Journal, 868:6 (11pp), 2018 November 20 https://doi.org/10.3847/1538-4357/aae58e
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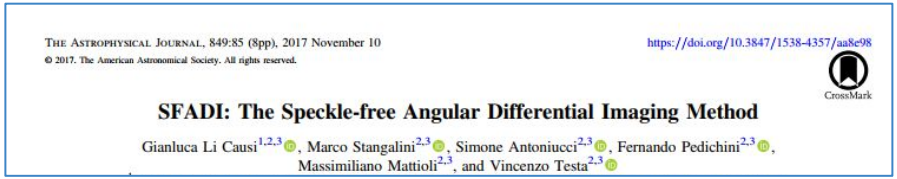
**Recurrence Quantification Analysis as a Post-processing Technique in Adaptive Optics High-contrast Imaging**

M. Stangalini[1,2], G. Li Causi[1,3], F. Pedichini[1,2], S. Antoniucci[1,2], M. Mattioli[1,2], J. Christou[4], G. Consolini[3], D. Hope[5], S. M. Jefferies[6,7], R. Piazzesi[1,2], and V. Testa[1,2]



The Astrophysical Journal, 849:85 (8pp), 2017 November 10 https://doi.org/10.3847/1538-4357/aa8e98
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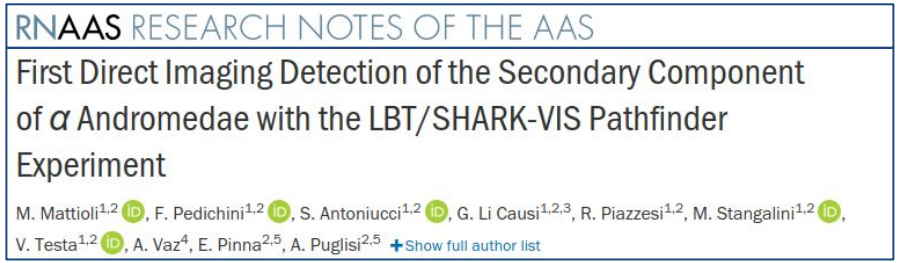
**SFADI: The Speckle-free Angular Differential Imaging Method**

Gianluca Li Causi[1,2,3], Marco Stangalini[2,3], Simone Antoniucci[2,3], Fernando Pedichini[2,3], Massimiliano Mattioli[2,3], and Vincenzo Testa[2,3]

Journal of Astronomical Telescopes, Instruments, and Systems 3(2), 025001 (Apr–Jun 2017)

**Speckle statistics in adaptive optics images at visible wavelengths**

Marco Stangalini,[a,b,*] Fernando Pedichini,[a,b] Enrico Pinna,[b,c] Julian Christou,[d] John Hill,[d] Alfio Puglisi,[b,c] Vanessa Bailey,[e] Mauro Centrone,[a] Dario Del Moro,[f] Simone Esposito,[b,c] Fabrizio Fiore,[a,b] Emanuele Giallongo,[a,b] Phil Hinz,[g] and Amali Vaz[g]



RNAAS RESEARCH NOTES OF THE AAS

**First Direct Imaging Detection of the Secondary Component of α Andromedae with the LBT/SHARK-VIS Pathfinder Experiment**

M. Mattioli[1,2], F. Pedichini[1,2], S. Antoniucci[1,2], G. Li Causi[1,2,3], R. Piazzesi[1,2], M. Stangalini[1,2], V. Testa[1,2], A. Vaz[4], E. Pinna[2,5], A. Puglisi[2,5] +Show full author list

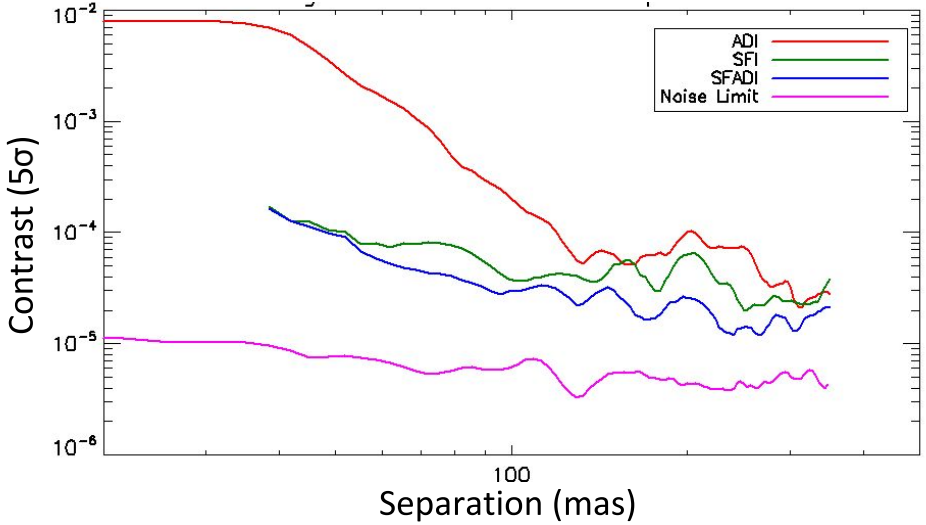
SHARK-VIS has already produced papers mostly based on 20 min ForeRunner data

- **4 refereed papers** + 1 in preparation
- **1 research note**
- **15+ technical papers** and proceedings

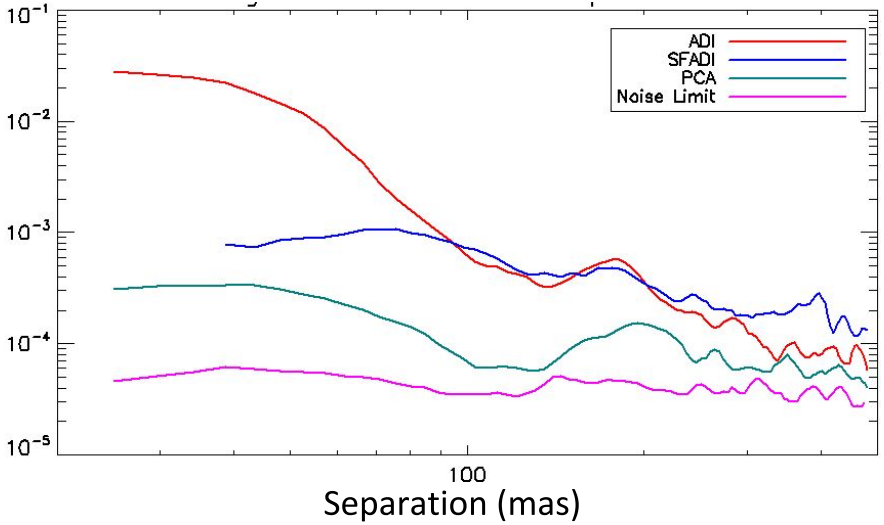
# Performance

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



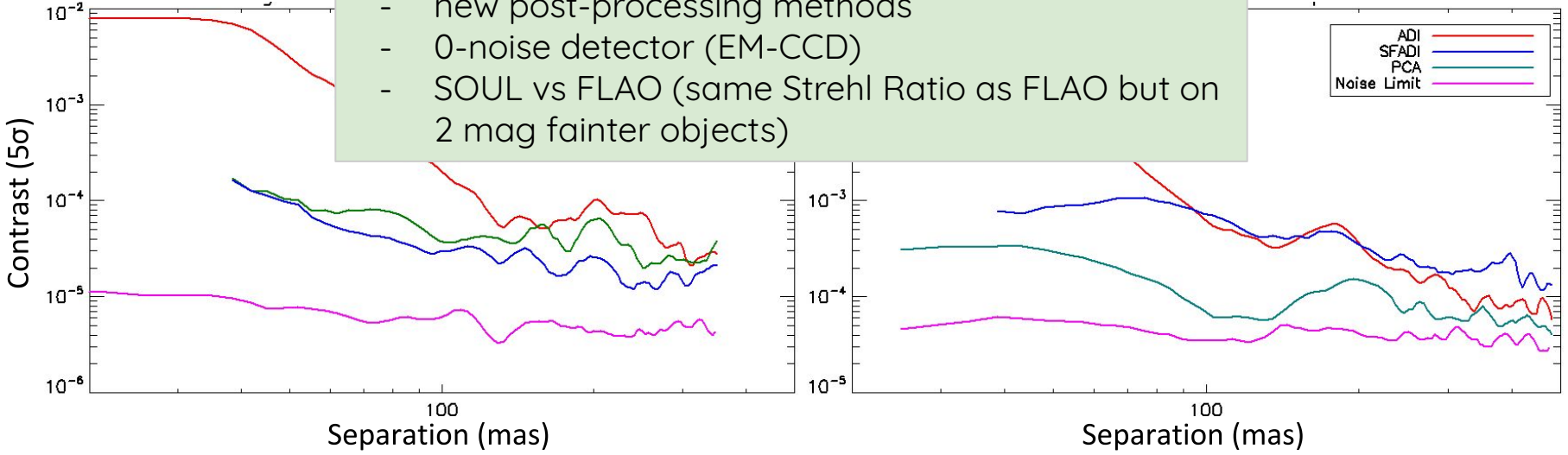
# Performance

Contrast curves (5σ) of ForeRunner test observations (seeing 1" 0-1" 2)

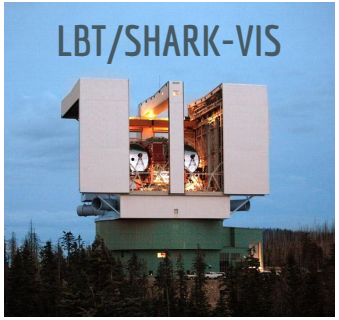
R mag 5.7, Bandv … 0 min, DIT 2.5ms

**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)



# xAO high-resolution in the visible

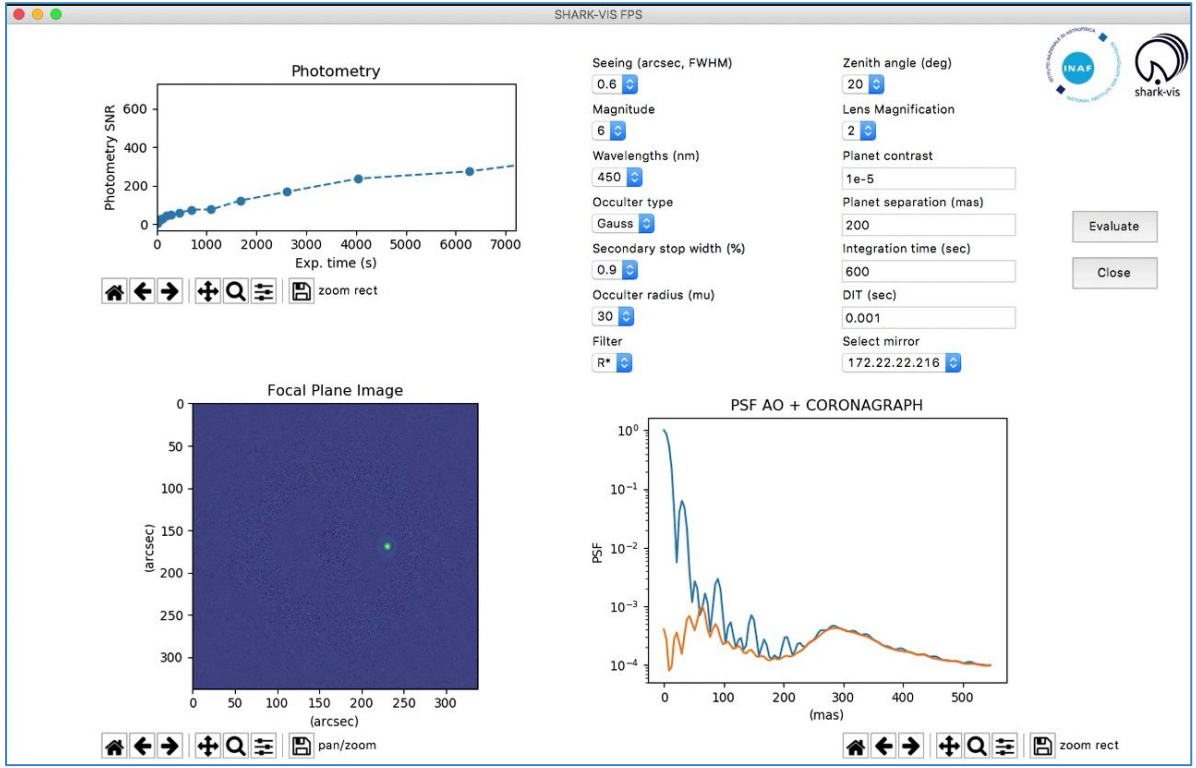






| telescope | instrument | AO | status | λ range (nm) | obs. modes | extra | hem |
|---|---|---|---|---|---|---|---|
| VLT | **SPHERE/ZIMPOL** | SCAO | active | 500-900 | img/pol/DBI | SPHERE+ upgrade? | S |
| Magellan | **MagAO/VisAO** | SCAO | active | 500-900 | img/DBI | | S |
| VLT | **MUSE** | LTAO | active | 480-930 | ifs (R~2500) | narrow-field mode | S |
| Subaru | **SCexAO** | SCAO | experim. | < 950 | img | | N |
| LBT | **SHARK-VIS** | SCAO | 2020 | 400-900 | img/DBI | fast cadence | N |
| VLT | **MAVIS** | MCAO | 2026 | 450-950 | img/spec | FoV 30"×30" | S |

# 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

| | sep./resolution | contrast |
|---|---|---|
| **Primary cases** | | |
| **Accreting planets and BDs** | down to 50 mas | $\leq 10^{-3}$ |
| **Jets from young stellar objects** | <70 mas | $\leq 10^{-3}$ |
| Minor bodies and moons of the Solar System | ~15 mas | $> 10^{-2}$ |
| **Other cases** | | |
| Disks around YSOs and debris disks | <1000 mas | $\leq 10^{-4}$ |
| Substellar companions | down to 50 mas | $\leq 10^{-3}$ |
| AGN morphology (BH feeding & feedback) | <300 mas | $\leq 10^{-3}$ |
| Envelopes of evolved stars (AGBs, post-AGBs) | <1000 mas | $\leq 10^{-3}$ |
| Close binaries | down to 15 mas | $> 10^{-2}$ |
| Microlensing events | ~15 mas | $> 10^{-2}$ |
| **Pathfinder** | | |
| Reflected-light planets | down to 50 mas | $\leq 10^{-6}$ |

**next talks**

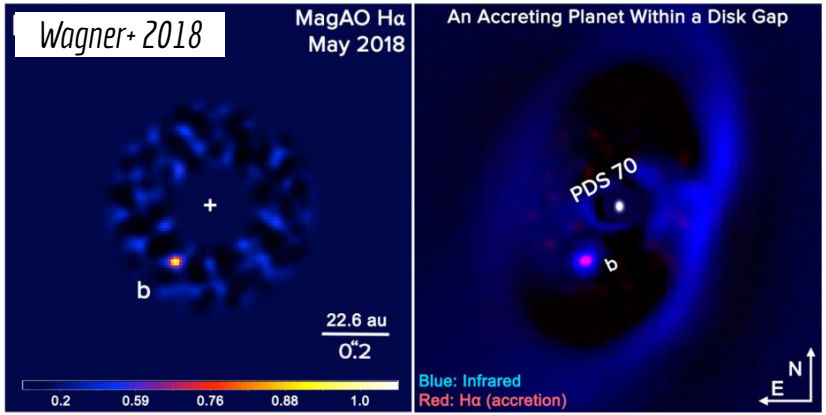
# Accreting planets and BDs: Hα imaging

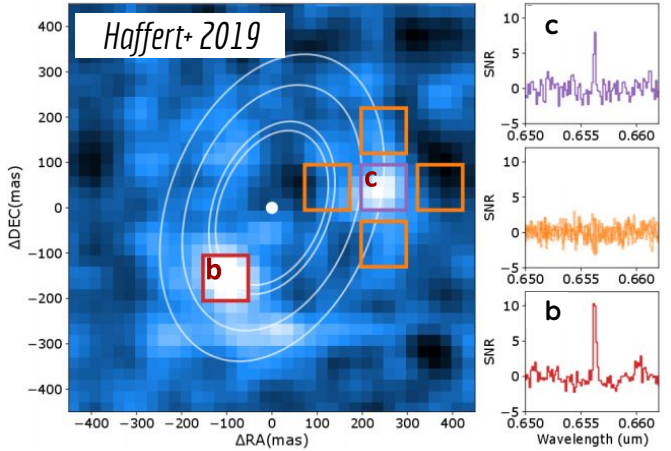
**SHARKs: direct imaging of wide orbit (> 5au) young giant planets → clues on planet formation**
**SHARK key project**: survey of Taurus-Auriga (d=150 pc, 5-10 au ⇔ 35-70 mas)

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

**SHARK-VIS!**

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



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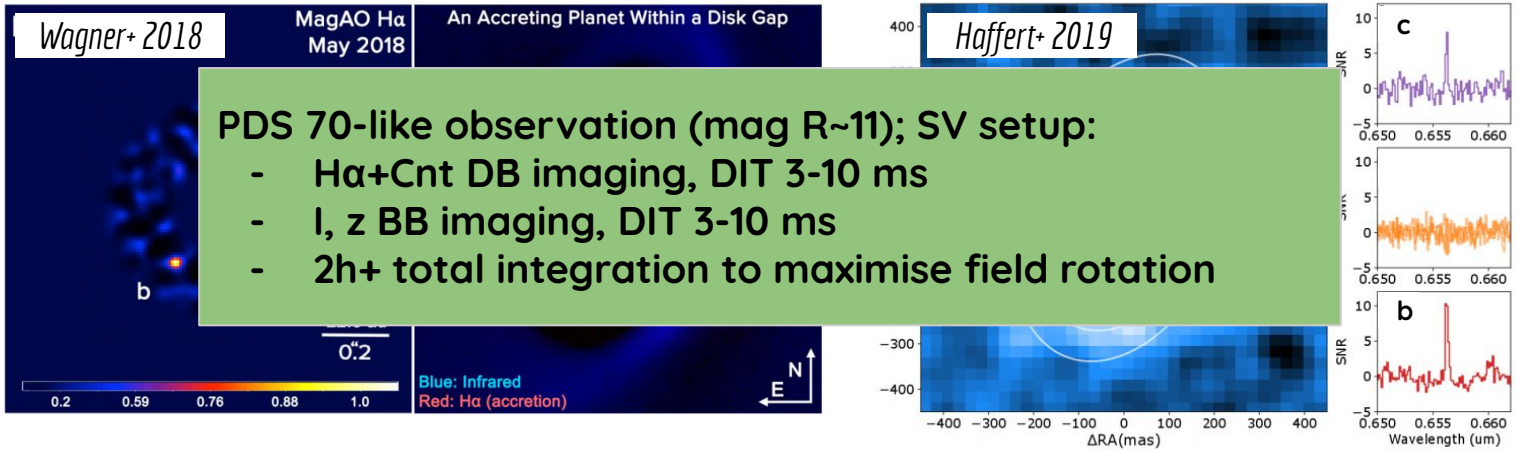
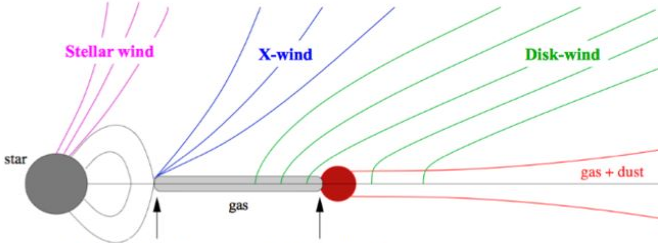



**PDS 70-like observation (mag R~11); SV setup:**

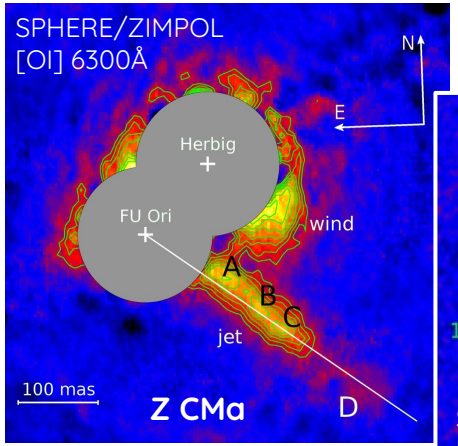
- **Hα+Cnt DB imaging, DIT 3-10 ms**
- **I, z BB imaging, DIT 3-10 ms**
- **2h+ total integration to maximise field rotation**

# Jets from YSOs



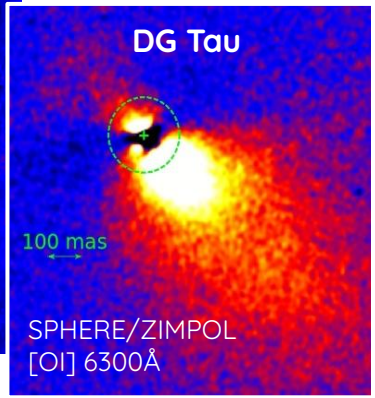

formation+collimation of YSO jets
feedback on disk
angular momentum removal

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

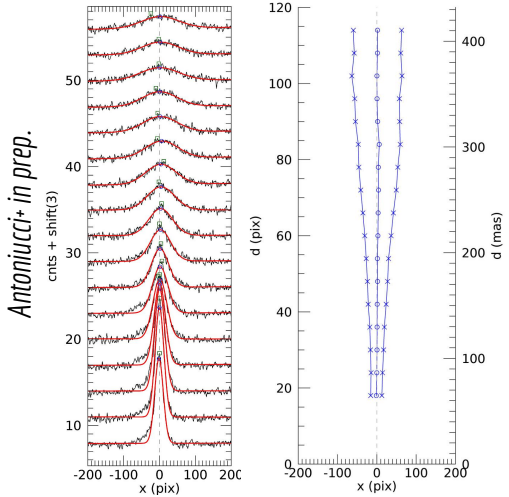



Antoniucci+ 2016

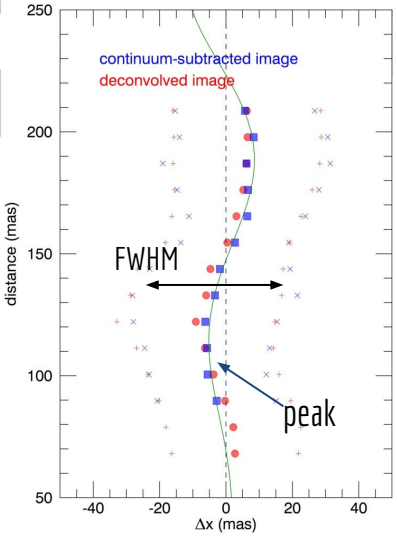
Antoniucci+ in prep.

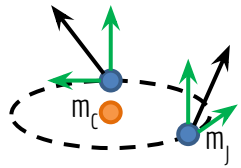



Antoniucci+ in prep.

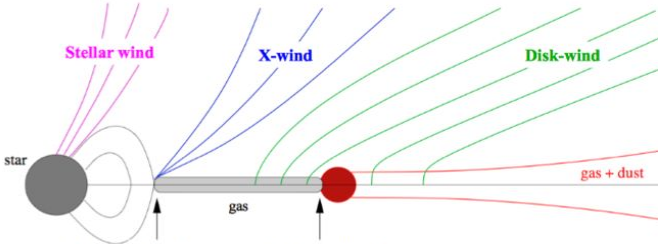



Antoniucci+ 2016



# Jets from YSOs




formation+collimation of YSO jets
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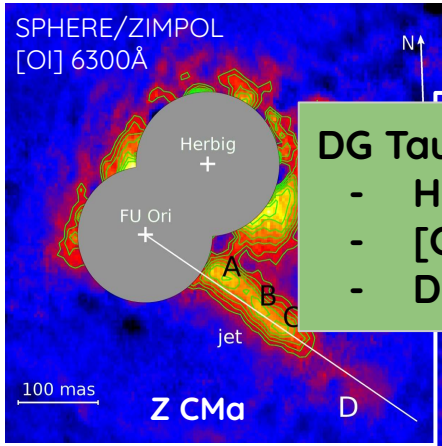
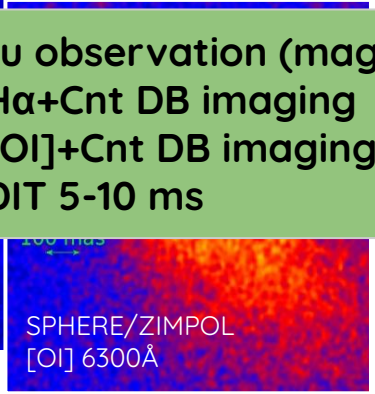
probe jet base (<10au ⇔ <70mas @150pc)
imaging in Hα and [OI]

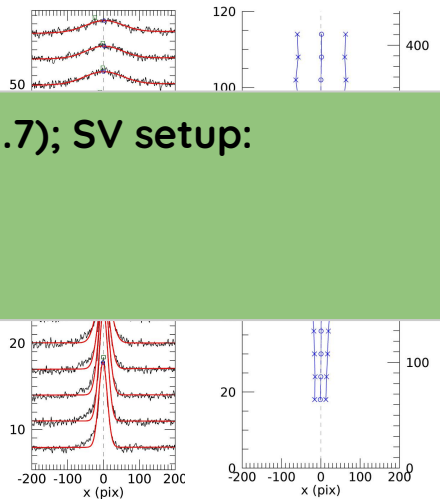



Antoniucci+ 2016

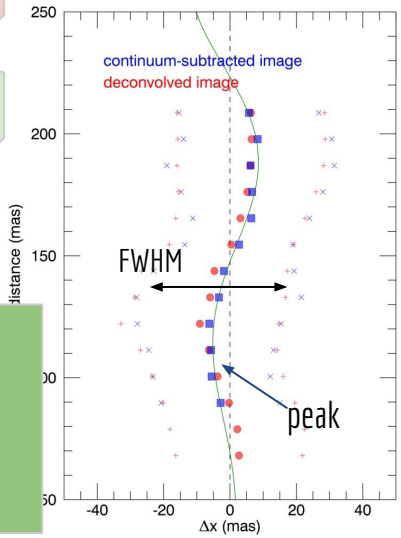
Antoniucci+ in prep.

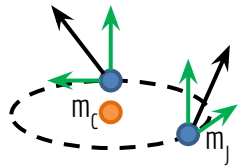



**DG Tau observation (mag R~11.7); SV setup:**
- **Hα+Cnt DB imaging**
- **[OI]+Cnt DB imaging**
- **DIT 5-10 ms**

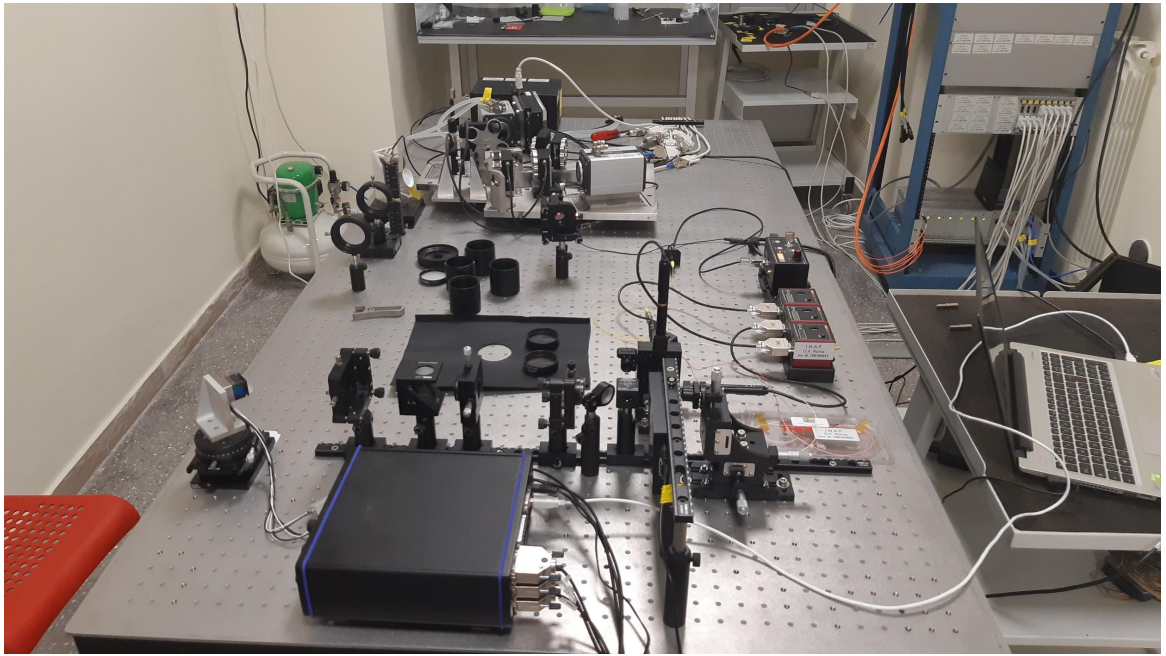



Antoniucci+ 2016

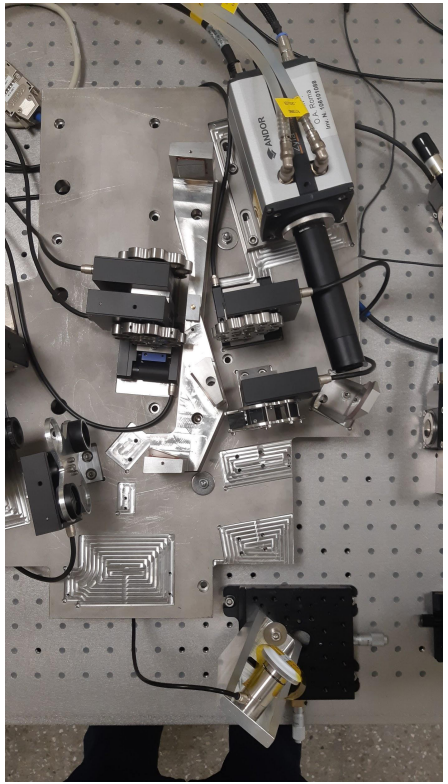


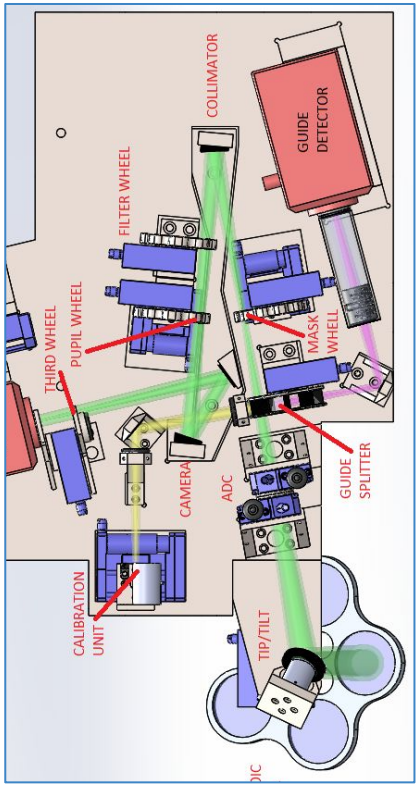



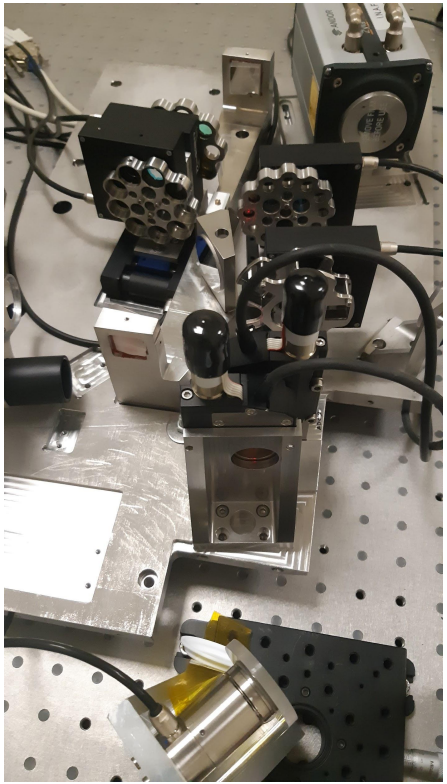
# SV Lab: a short tour

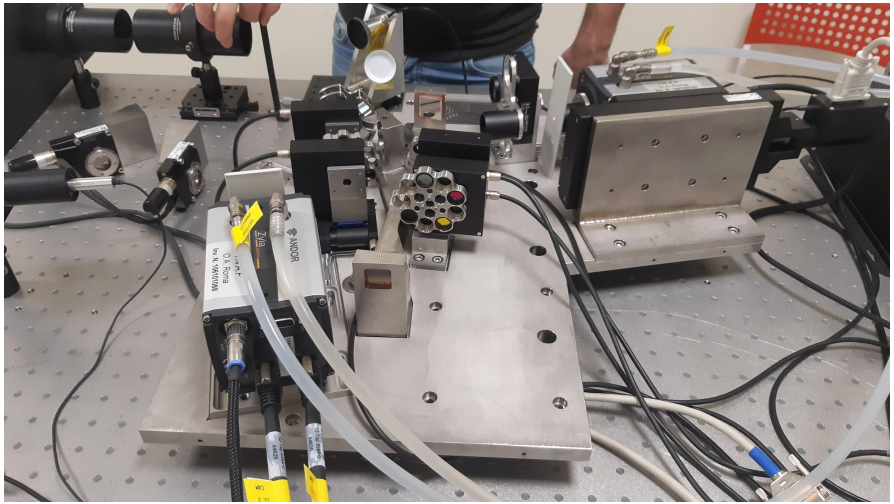
# SHARK-VIS in the lab

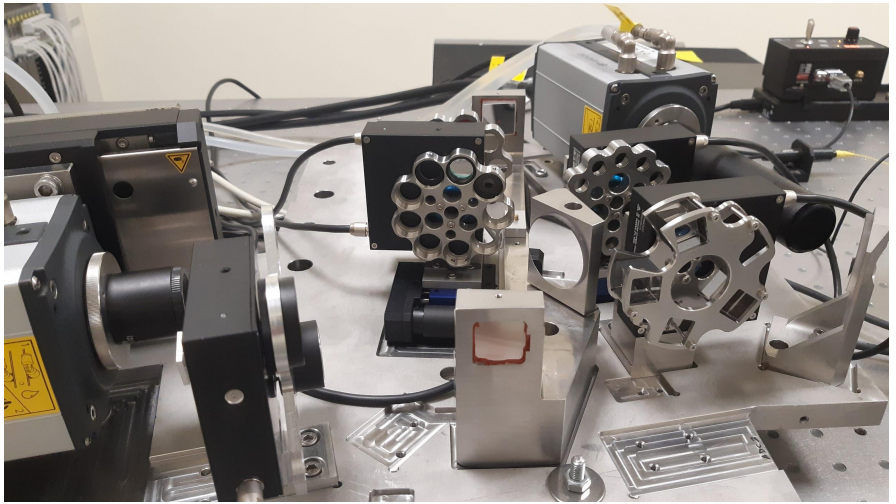




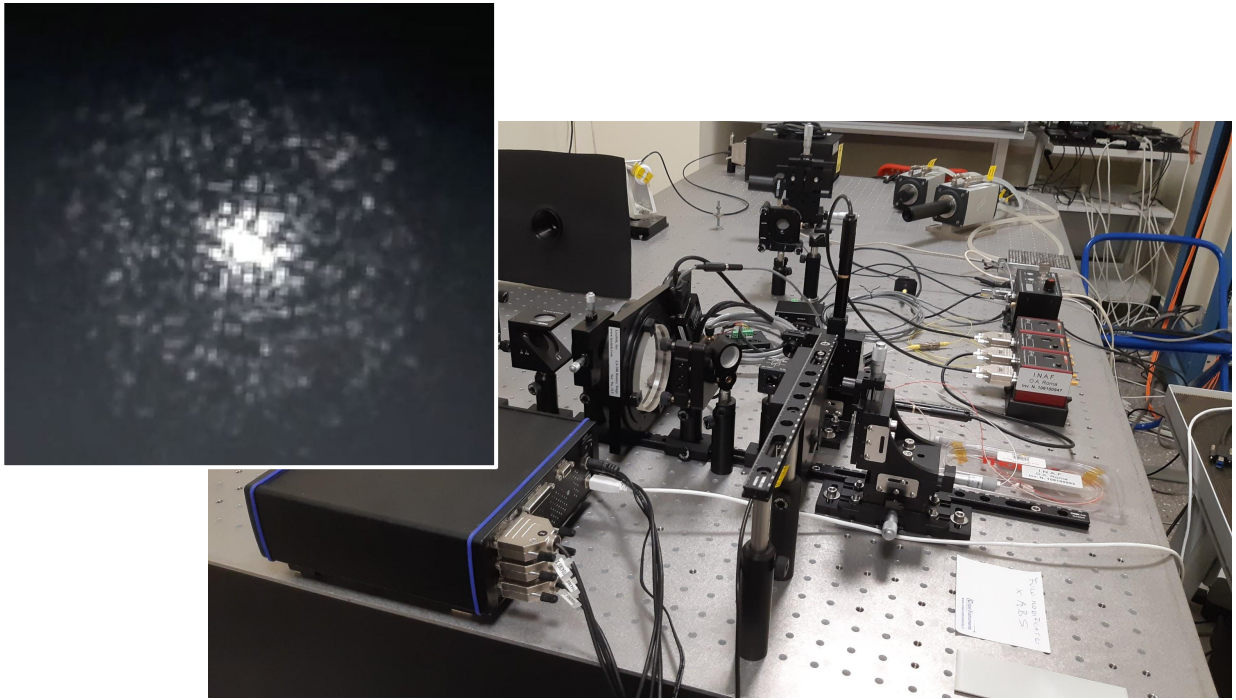



# SHARK-VIS in the lab



# 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)**

# SHARK Science Meeting


6-8 April 2020
INAF Headquarters, Monte Mario, Rome
Europe/Rome timezone

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