SHARK@LBT
SYSTEM FOR CORONAGRAPHY WITH HIGH ORDER ADAPTIVE OPTICS FROM R TO K BAND

Isabella Pagano and Jacopo Farinato on behalf the SHARK Team

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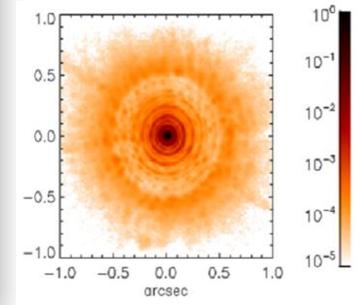
1) INAF PADOVA 2) INAF ROMA 3) INAF-ARCETRI 4) INAF CATANIA 5) IPAG
6) STEWARD OBSERVATORY – ARIZONA (USA) 7) MPIA 8) UNIVERSITY OF PADOVA
9) UNIVERSITY OF CATANIA 10) INAF-TORINO 11) INAF-PALERMO
12) AIX MARSEILLE UNIVERSITÉ, LAM 13) ESO

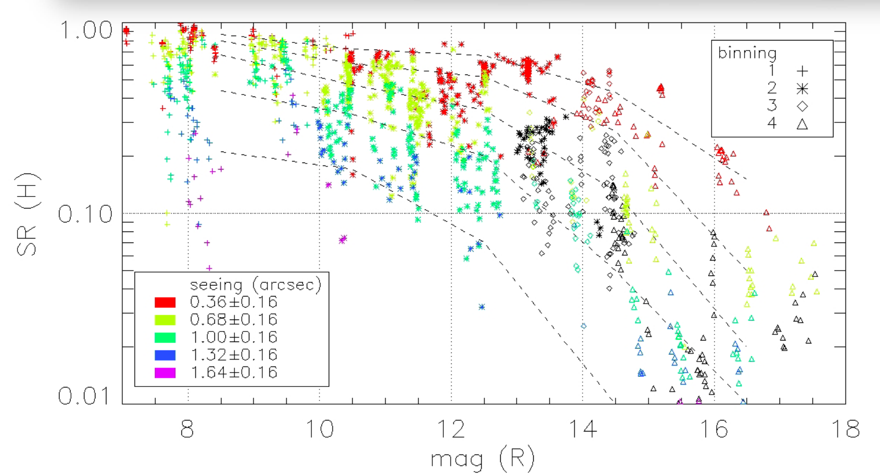
Why SHARK

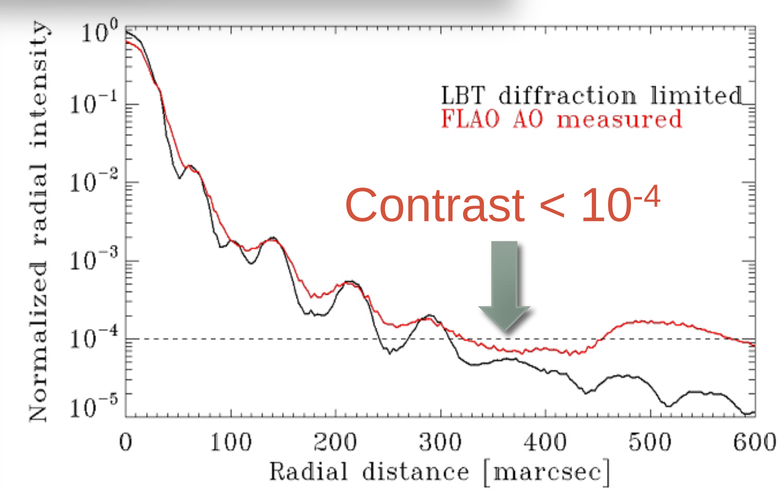
- ✓ Extreme AO correction in the **NIR** region with **SR > 95%** ➔ best PSF subtraction with or without coronagraph ➔ increasing target S/N.
- ✓ Very good **SR > 40%** in the **optical R-I bands** ➔ new window for high angular resolution (**~17 mas**) at a single telescope, comparable to what achievable at LBT by **NIR** interferometry.



H band
w/o coronograph

SHARK is the **VIS** & **NIR** coronographic imager that will make use of the LBT excellent AO performances!



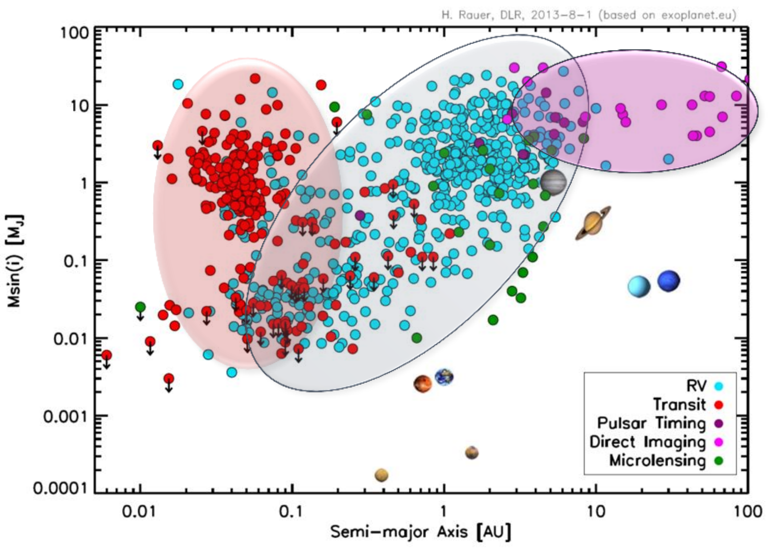


Outstanding SHARK science

- ✓ **Direct imaging of close giant planets**
  investigating the main evolutionary stages:
  - ✓ **Young planets**, from early phases of growth (the first few million years) when these are hot, surrounded by disks, and can be revealed thermally at T> 300 K in NIR and in Halpha (VIS channel)
  - ✓ **Old giant planets**, very close (< 5-10 pc) and bright, whose reflected light could be detected for separations of the order of 100-200 mas in the visible, where greater is their emission, and also in the NIR if very cloudy.
- ✓ **Disks around Young Stars and their Jets**
  - ✓ High-contrast images of circumstellar disks with optical/near-IR coronagraphy and polarimetric differential imaging
  - ✓ Coronagraphic imaging of stellar jets
  - ✓ 2D maps of Jets
- ✓ **AGNs and QSOs**

Exoplanets: the contest

Direct imaging allows to detect giant planets at larger separations (> 5-10 AU), complementing information from RV and transits.



~3% of known planets discovered by direct imaging

Why they matter?

- Diversity
  - Different formation mechanism
  - Different evolution
  - Athmospheric characterization

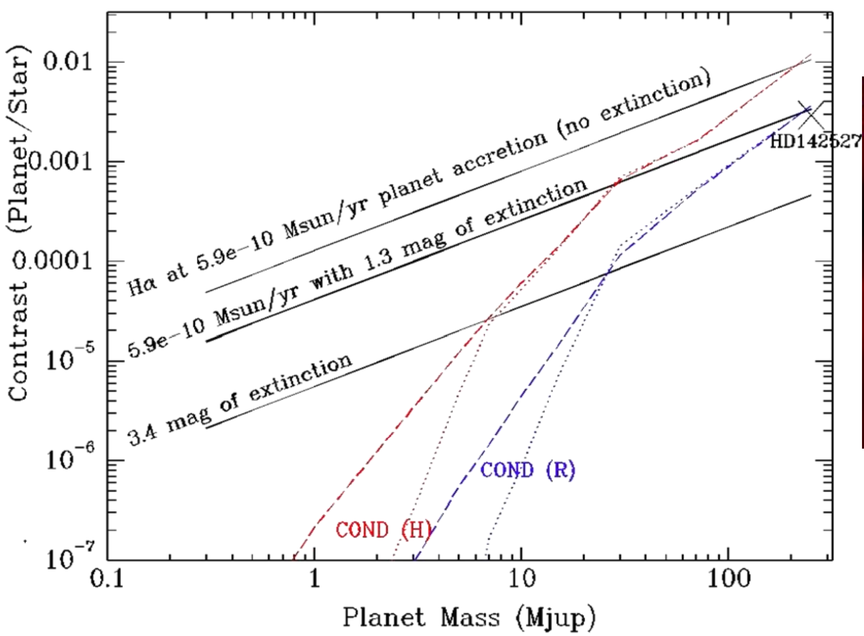
Accreting planets

- ✓ The satellite system of Jupiter are strongly suggestive of formation from circumplanetary disk.
- ✓ Disks and/or accretion signatures have been observed around young brown dwarf.

Very young planets are expected have their own accretion disk.

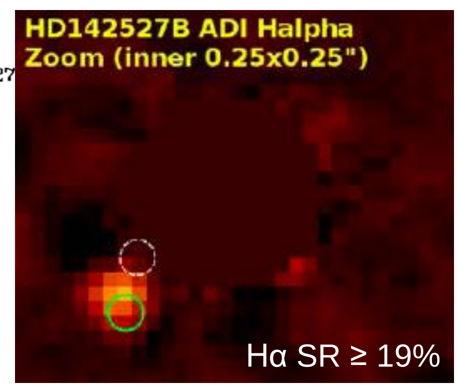
Clues on formation mechanism for planets in wide orbits:

- ✓ planet-planet scattering unlikely to preserve disks, formation at wide separation favoured if accretion observed.



Close et al 2014

a ~12 AU

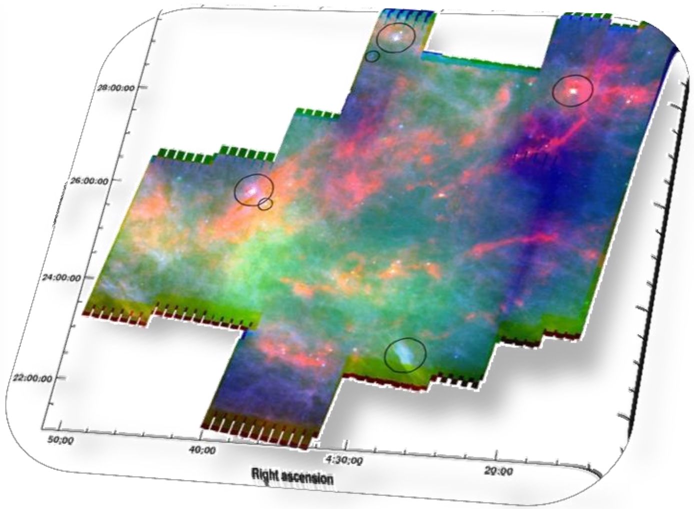


Accretion can be observed in Hα where for such planets contrast is higher than at other wavelengths.

Accreting planets

Targets

- ✓ Taurus-Auriga star forming region (140 pc, ~1-2Myr); about 350 members were identified, 130 of which brighter than R=15 (typically 10-13).
- ✓ This is northern and then badly accessible with SPHERE and GPI (no Hα @GPI).



Mooley et al. 2013

Binocular Asset

- ✓ The VIS channel should be used for narrow band imaging in Hα to reveal signatures of accretion.
- ✓ The NIR channel will be used to reveal planet thermal emission.
- ✓ The simultaneous observations will allow to highly mitigating the issue of variability.

Requirements

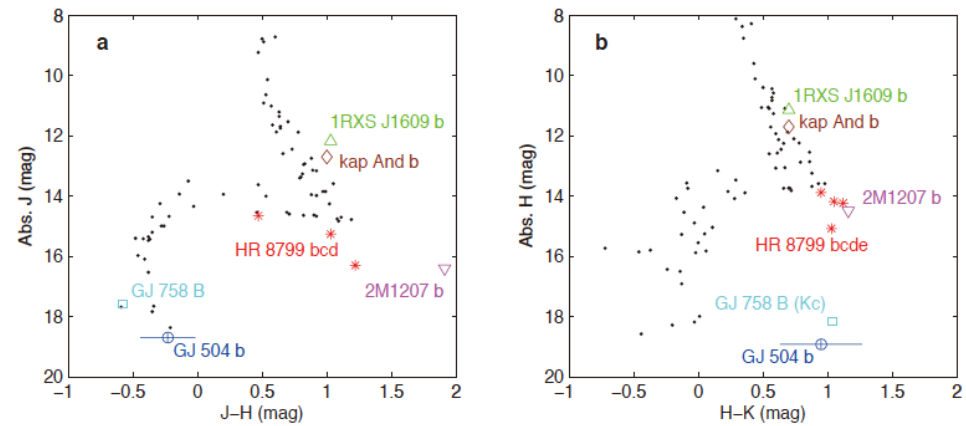
- ✓ **IWA** ≤ 100 mas; **FoV** ~10x10 arcsec ; **Mode**: imaging + coronagraph;
- ✓ **Filters:** Narrow band in the visible (Hα + continuum outside band; width TBD); Broad band in NIR (JHK).
- ✓ **Typical integration time**: 1 hour.
- ✓ **Nights requested**: ~20-30 nights (assuming 100-150 objects to be observed, TBC)

Photometric and spectroscopic characterization of known planet

SHARK can extend to optical the SED of planets already detected in **NIR**

- ✓ Typically ~4/6 mag fainter in optical (**I/R**) than in **NIR**
  ➔ Call for **high-SR imaging**

Kuzahara et al. 2013



Science goal

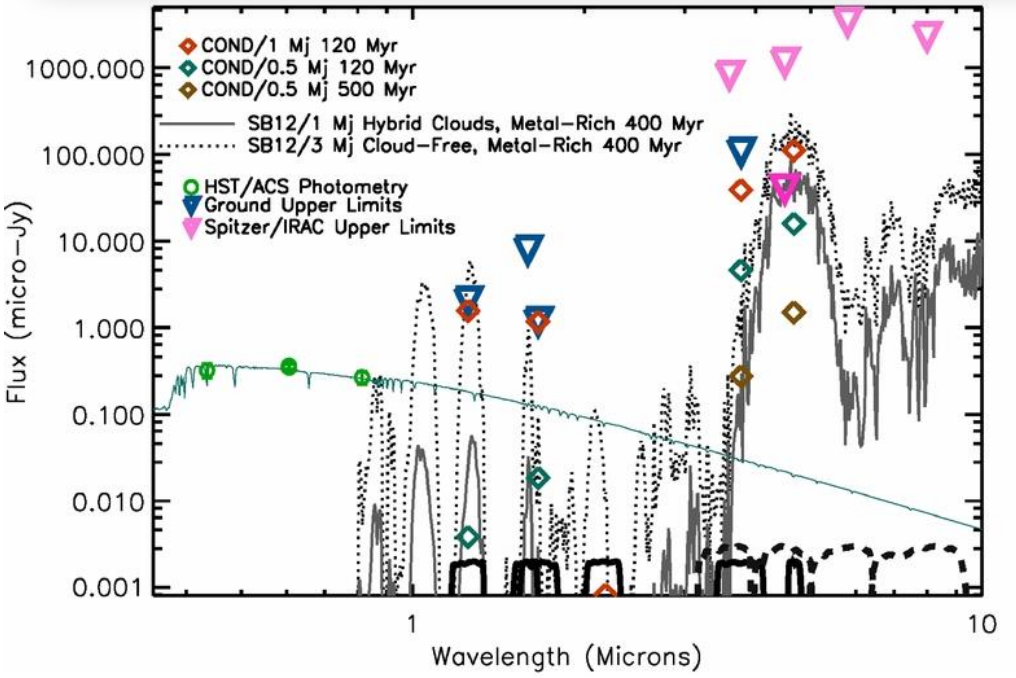
- ✓ Planet characterization and comparison with the atmospheres of highly-irradiated transiting planets.
- ✓ Shed light on L-T transition and on the characteristics of brown dwarfs and giant planets, which are expected to somewhat overlap but also significantly differ in terms of chemistry of the atmospheres and mechanisms of clouds formation (Mandushev et al. 2014).

Requirements

- ✓ Spectroscopic modes available (better in NIR). IFU is preferable but long-slit acceptable.
- ✓ Resolution: R~30: for spectral classification (e.g. L vs T); R>100: for molecular bands identification.
- ✓ Field stabilized mode required (optical derotator?).
- ✓ Coronagraph (we can accept a rather large IWA).
- ✓ Night requested: **~10 nights**

Photometric and spectroscopic characterization of known planet

✓ Optically-bright planets, such as **Fomalhaut b**, can be identified with SHARK.



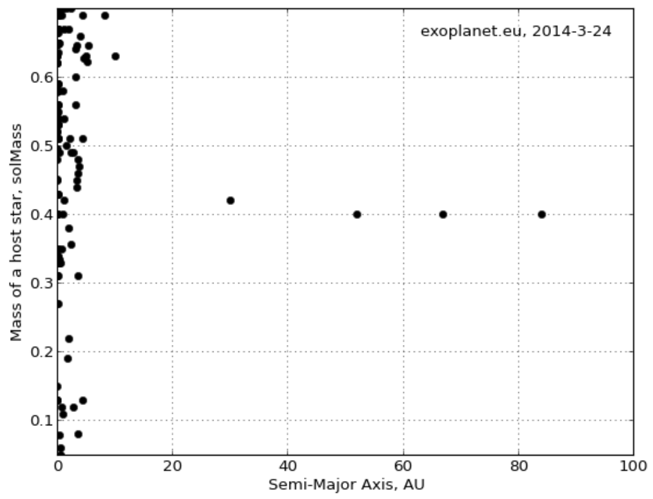
Currie et al 2012

Scattered light by dust surrounding the planet?

(Galicher & Marois 2013)

Planets in wide orbits of low mass stars

- ✓ A special niche for SHARK is offered by the LBT AO at faint mag, especially with AO upgrade: wide planets orbiting low mass stars.
- ✓ SPHERE and GPI will be mostly limited to solar-type and early-type stars.



Targets:

- ✓ Several members of young moving groups (age 10-100 Myr) were recently identified, with special effort for low-mass stars (see e.g. Schlieder et al. 2012, AJ 144, 109; Gagnè et al. 2013; arxiv 1312.5864; Riedel et al. 2014 arxiv 1401.0722).

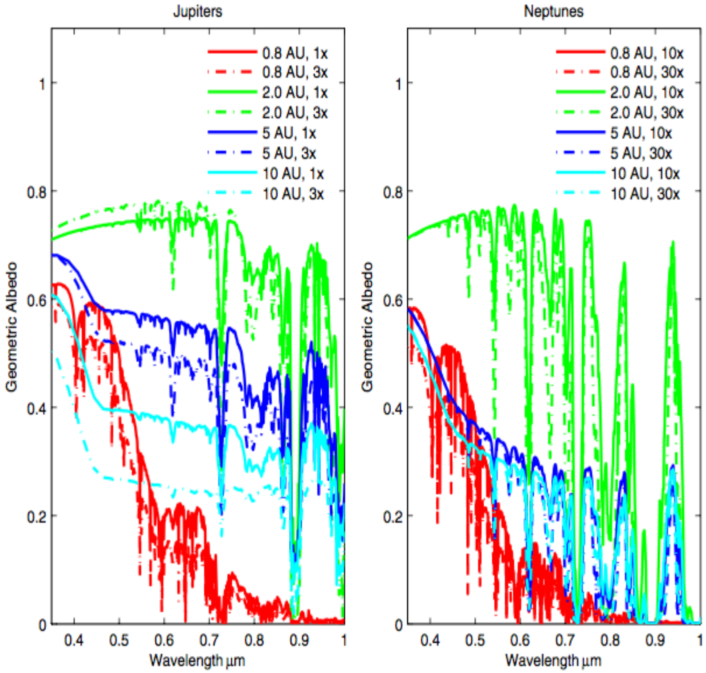
Requirements

- ✓ **IWA** ≤ 100 -150 mas; **FoV** ~10x10 arcsec ; **Mode**: imaging + coronagraph;
- ✓ **Filters:** Broad band in NIR (JHK), VIS TBD
- ✓ **Typical integration time**: 1 hour.
- ✓ **Nights requested**: ~10-20

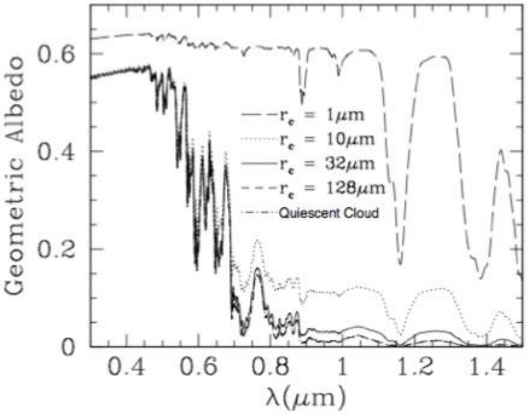
A Pathfinder to detection of reflected light from giant planets

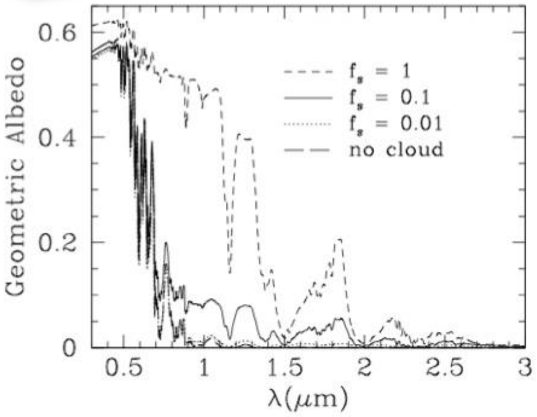
- ✓ The presence of water clouds increases the planetary albedo due to Mie scattering which is essentially independent of wavelength

Cahoy et al. 2010



Fortney et al. 1999





Geometric albedo is function of wavelength and of the distance from the parent star

- ✓ Planets with M ~ 0.5-4 MJ orbiting around stars (A-G) at a separation of 1-3 AU because of water clouds may reach a large albedo in the optical and NIR bands
- ✓ If within 10 pc from us, these could be detected in both VIS and IR.

A Pathfinder to detection of reflected light from giant planets

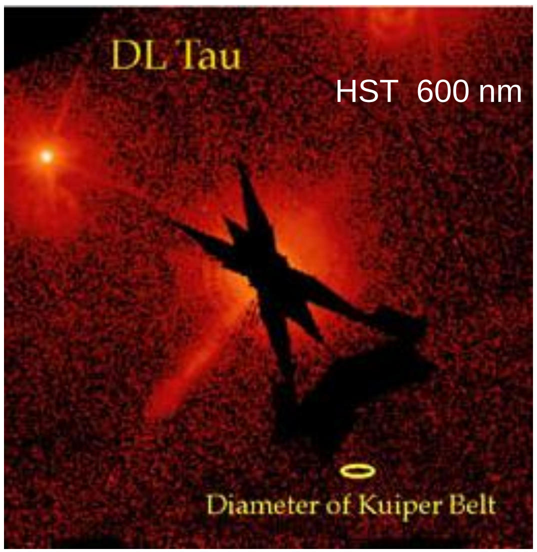
Requirements

- ✓ VIS possibly down to 0.65 micron
- ✓ 20 mas resolution and achievable SR (40%) in the VIS ➔I coronagraphic detection at >4-5 λ/D ➔ separations of the order of 100 mas, i.e. 1 AU at 10 pc.
- ✓ Observations at longer wavelengths both in the optical and in the J, H bands at separations between 100-300 mas can allow the characterization of the reflection spectra and consequently of the atmosphere structure and composition.
- ✓ **Nights requested**: ~10 for a pilot program

Disks around Young Stars and their Jets

- ✓ High-contrast images of circumstellar disks with optical/near-IR coronagraphy and polarimetric differential imaging
- ✓ Coronagraphic imaging of stellar jets

Narrow-band images of jets reveal the generation mechanism and its feedback on the star/disk



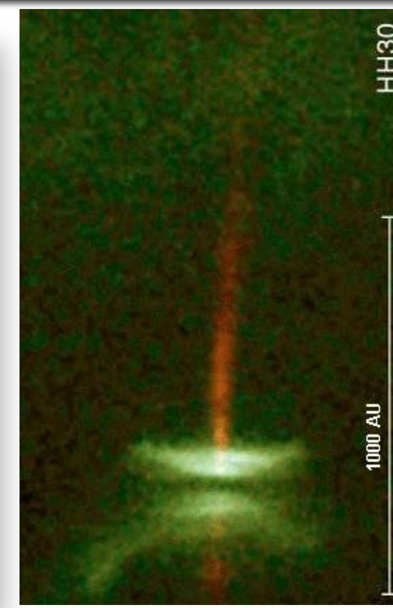
Grady et al 2004

Goal

- ✓ understand dynamic role of jets in shaping the disk structure

Requirements

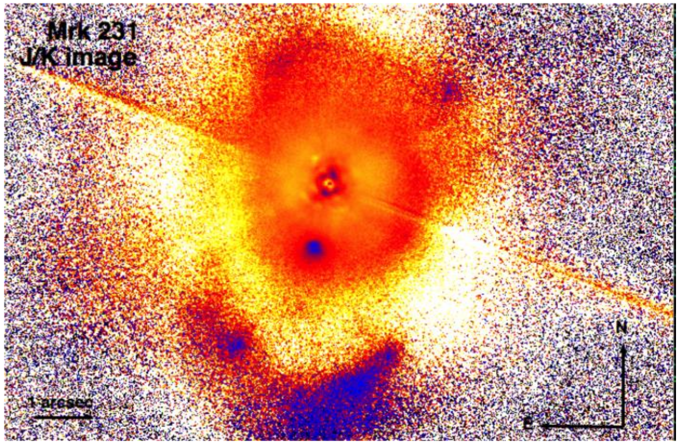
- ✓ Binocular VIS (IFU) & NIR (img + cor)
- ✓ IWA<4λ/D; FoV ~ 10”x10”; SR > 45% Mv=10-13
- ✓ Exp. Time: 30m-1h on source
- ✓ Nights: 3 nights for a starting project



Wood et al. 2001

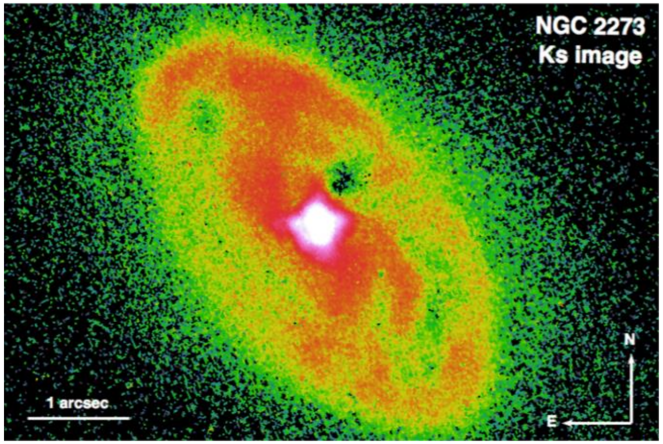
- ✓ HST coronagraph: stop radius (>300mas) too large to probe the innermost regions of disks and jets in T Tauri stars.
- ✓ SHARK coronagraph: size down to 100mas, sampling 50mas ➔ down to 5-10 AU in nearby star formation regions.

AGNs and QSOs



see Fiore talk @ this meeting

- ✓ Discover and fully characterize the AGN close pairs;
- ✓ Constrain the Black Hole feeding mechanism (e.g. SN driven winds vs gravitational asymmetries) in local Seyfert galaxies

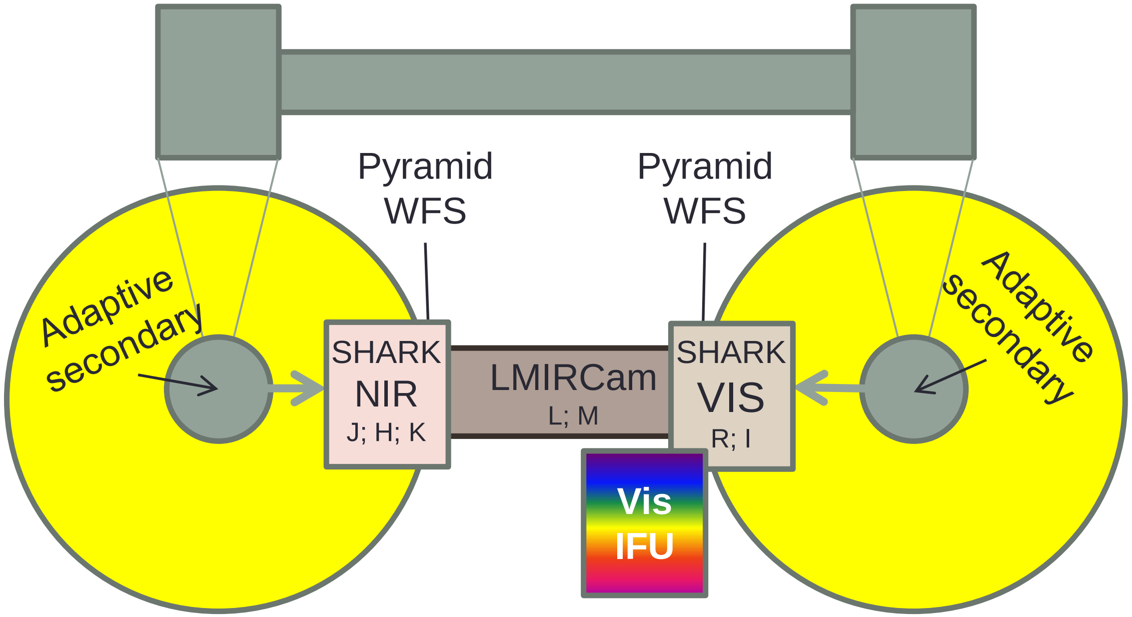


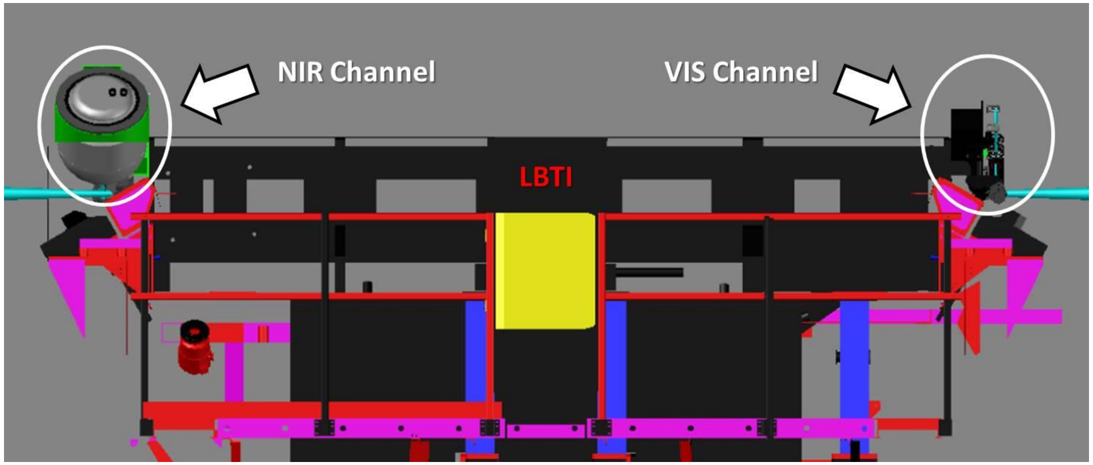
- ✓ Trace, in bright quasars, molecular outflows powerful enough to clean the inner kpc and quench the star formation (SF)
- ✓ Color maps and IFU follow-up of SF regions in the galaxy nucleus and disk to constrain the SF rate, the age, and the metallicity.
- ✓ Constrain fundamental physics.

Requirements

- ✓ Binocular VIS and NIR both imaging and coronagraphic modes.
- ✓ Coronagraphs with 2<λ/D<8; FoV of 5”x5” and ~20”x20” for DLAs and AGN inner morphology.
- ✓ IFU for follow-up measurements of ionization, SF, and metallicity parameters.
- ✓ The achievable SR (H-band, average seeing 0.8”) for AGN with the current FLAO capabilities ranges from 50% for the brightest targets to 30% for I=15 mag.
- ✓ Nights: 5 nights for a starting project

SHARK location: at the entrance of LBTI



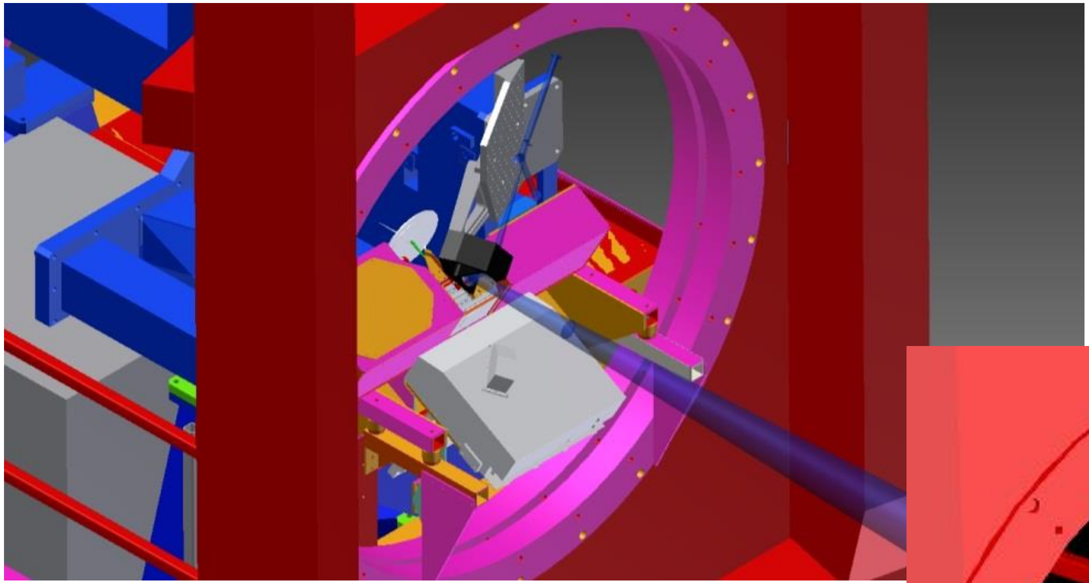


Even if it is a 2nd generation instrument, it can coexist with the 1st generation, with an impact as soft as possible (simplicity, small dimension, only partially overlapping wavelength range).

In fact, SHARK basic features are:

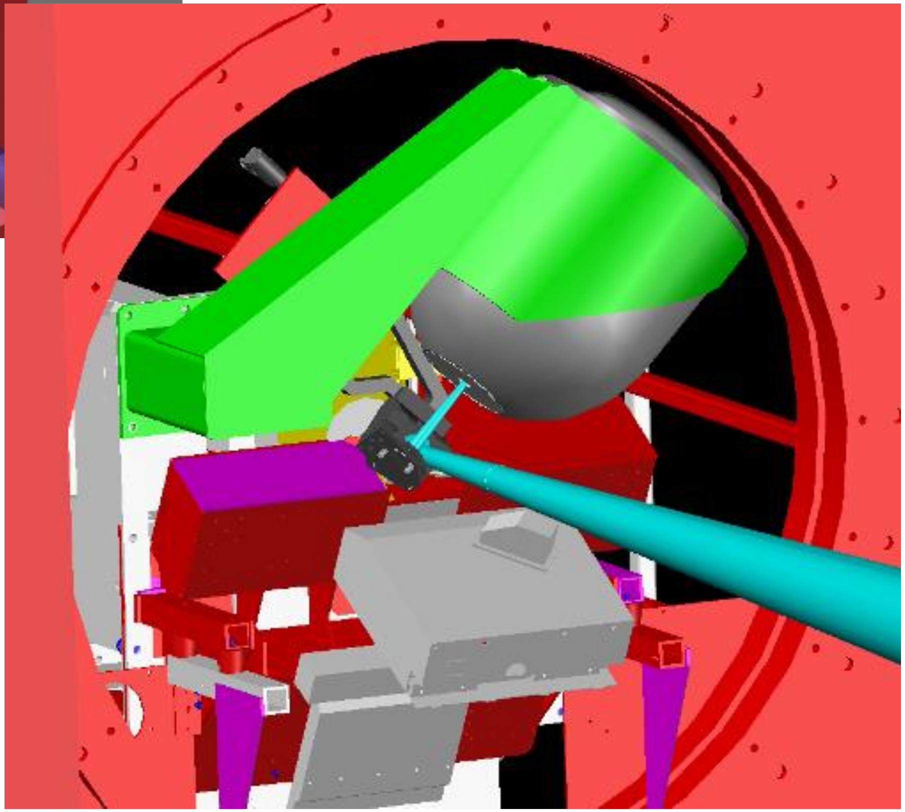
- ✓ NIR Coro-Camera (J,H,K)
- ✓ VIS Coro-Camera (R,I)
- ✓ VIS Spectrograph

The VIS & NIR Channels location

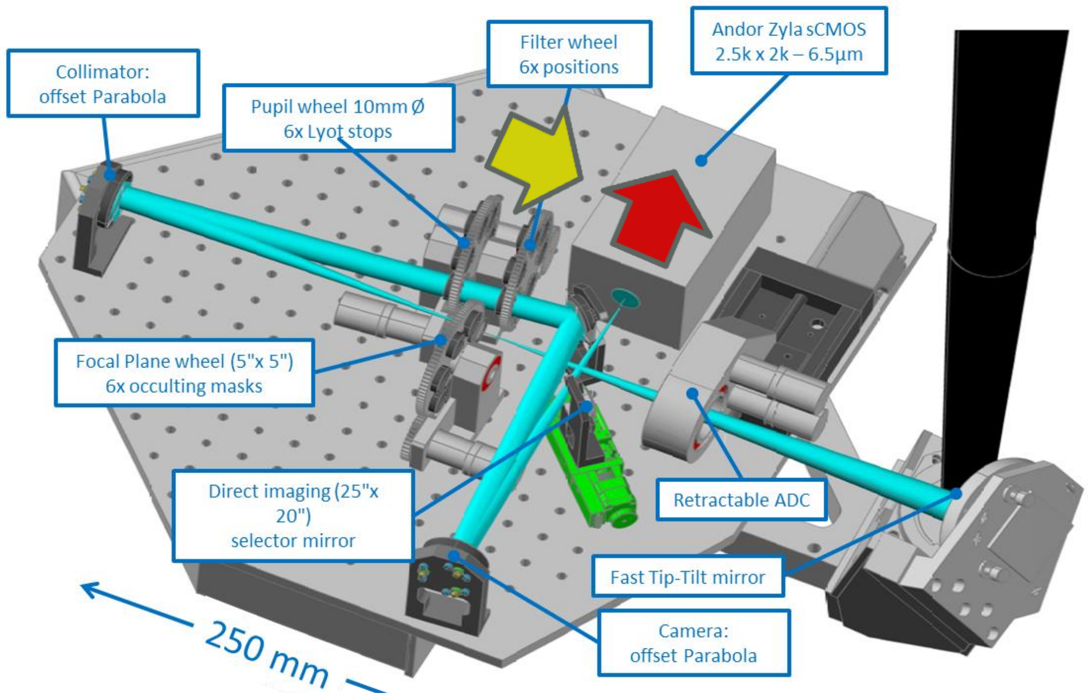


VIS Channel

NIR Channel



The VIS Channel



SPECIFICATION

Direct Imager

- ✓ Field of view = (20x25)" or (8x10)"
- ✓ Sampling 4÷10 mas /pixel
- ✓ ADC bandwidth 600 ÷ 900 nm

Coronagraph

- ✓ Field of view = (5x5)"
- ✓ Sampling 4÷10 mas /pixel
- ✓ Focal plane 6 x occulter
- ✓ Pupil plane 6 x stops/apodizers

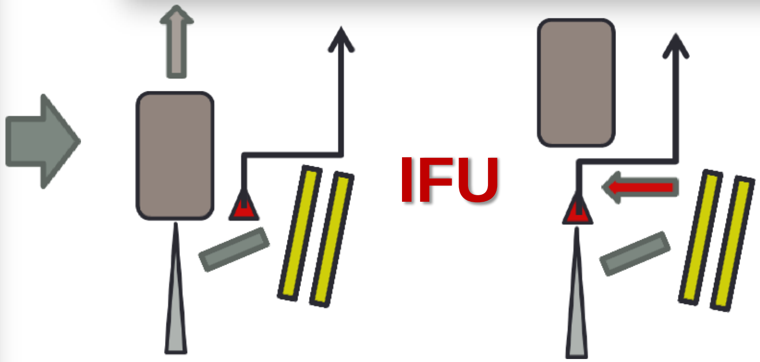
Detector

- ✓ Fast sCMOS imager 1 e- r.o.n.
- ✓ Exposure 10e-4 ÷ 30 s

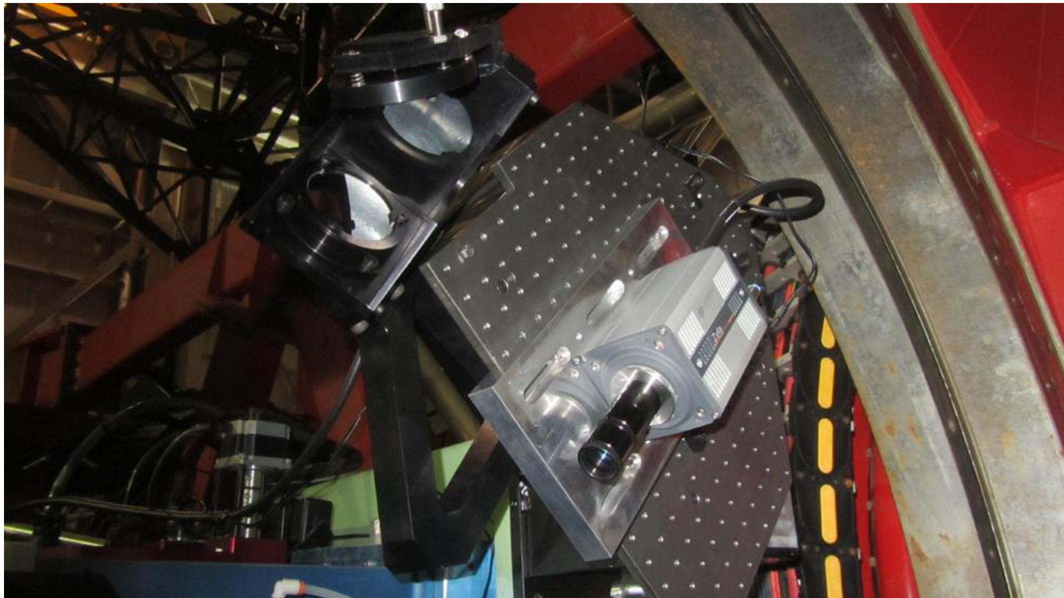
IFU OPTION

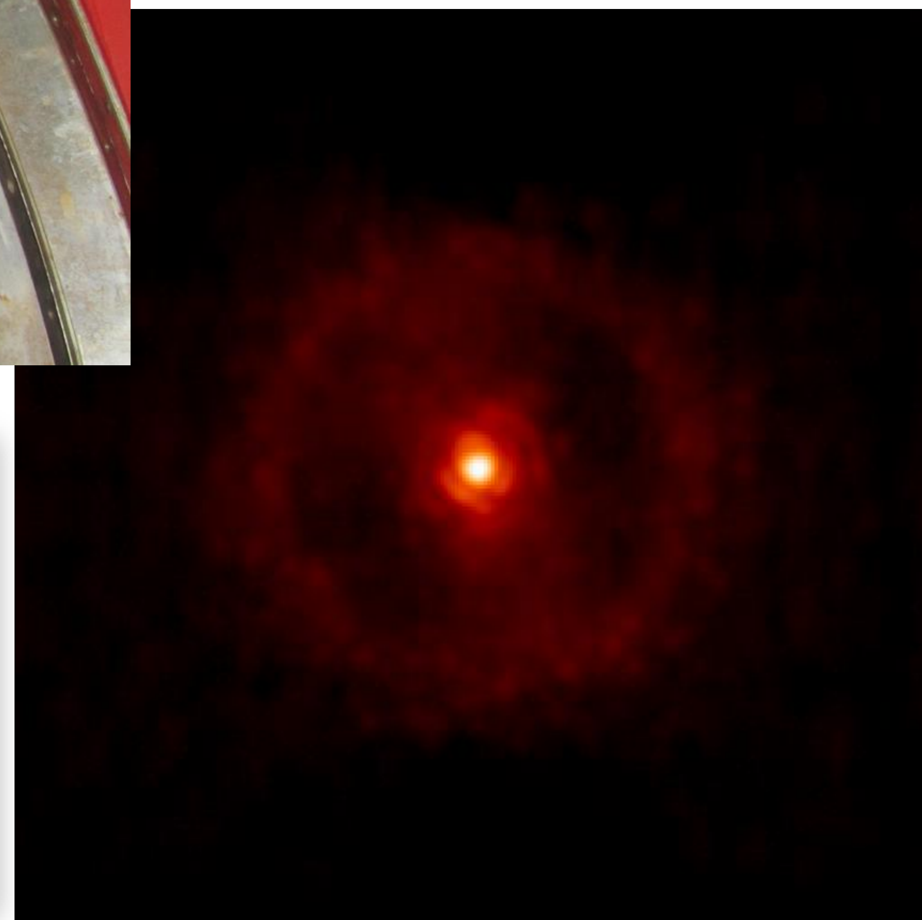
It is foreseen to study and develop an IFU based on optical fibers bundle to interface the V_SHARK focal plane to a slit spectroscope to obtain multi spectral images of a small subfield.

- ✓ Resolution of spaxel 40-80 mas
- ✓ Spaxel field 2 x 2 arcsec
- ✓ Number of spaxel 20 x 20
- ✓ Spectral resolution 200 ÷ 2000
- ✓ Wavelenght range 550 ÷ 950
- ✓ Fiber core 30 ÷ 60 micron



The SHARK VIS arm forerunner experiment





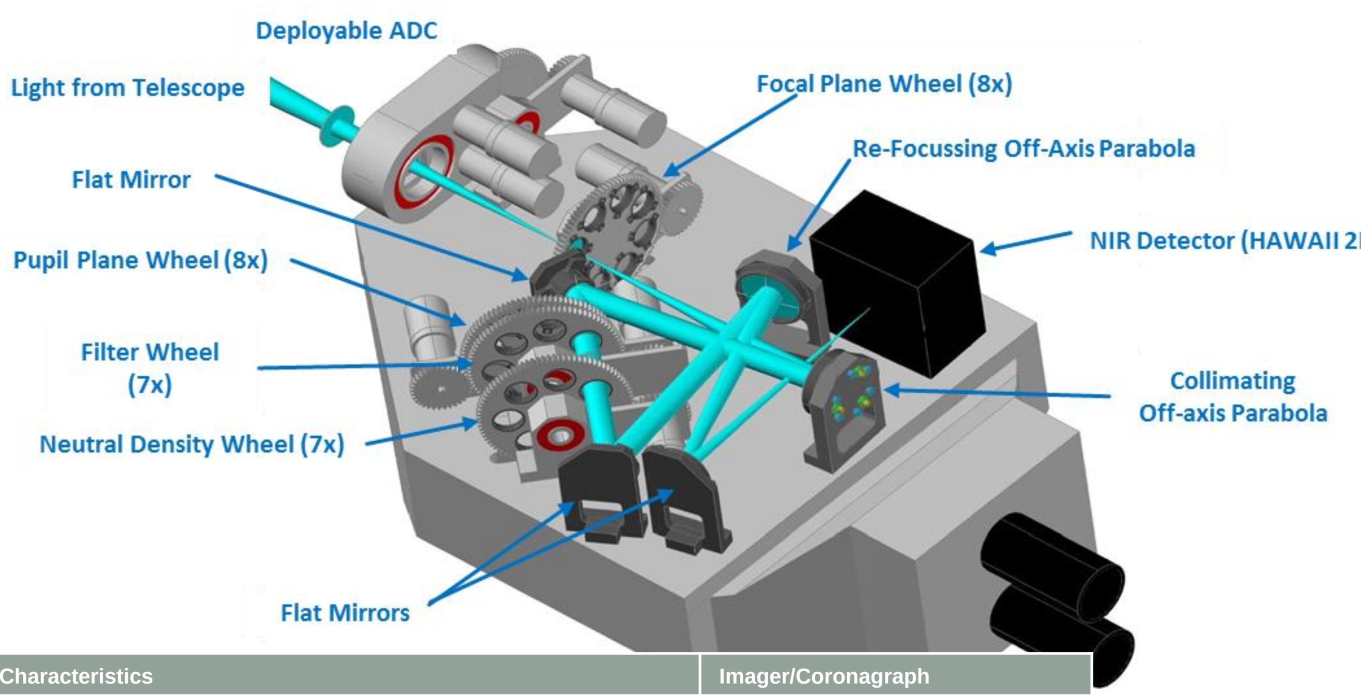
Unfortunately bad weather

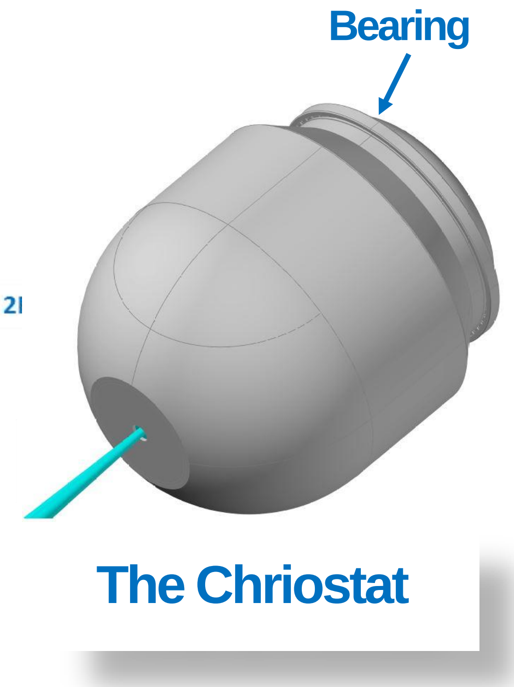
Still, very useful for PSF characterization with simulated seeing (0.8”)

NCP quite high (dichroic too tightened?)

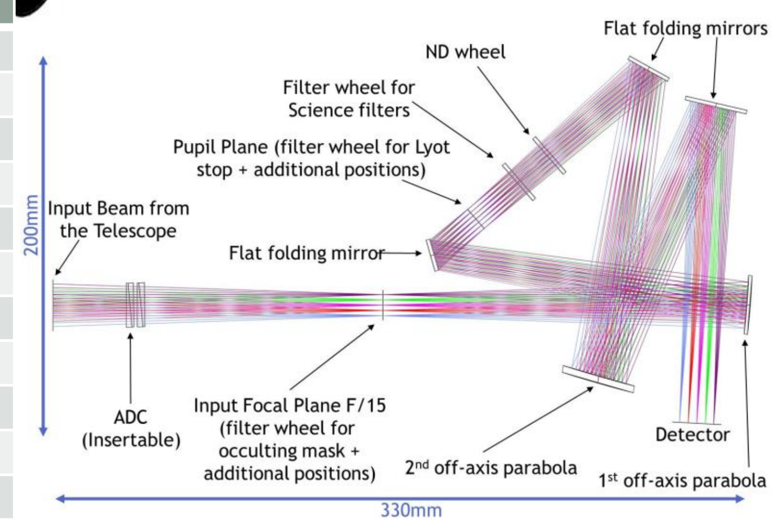
It would be very valuable to make an on-sky test, to have a real VIS PSF

The NIR Channel

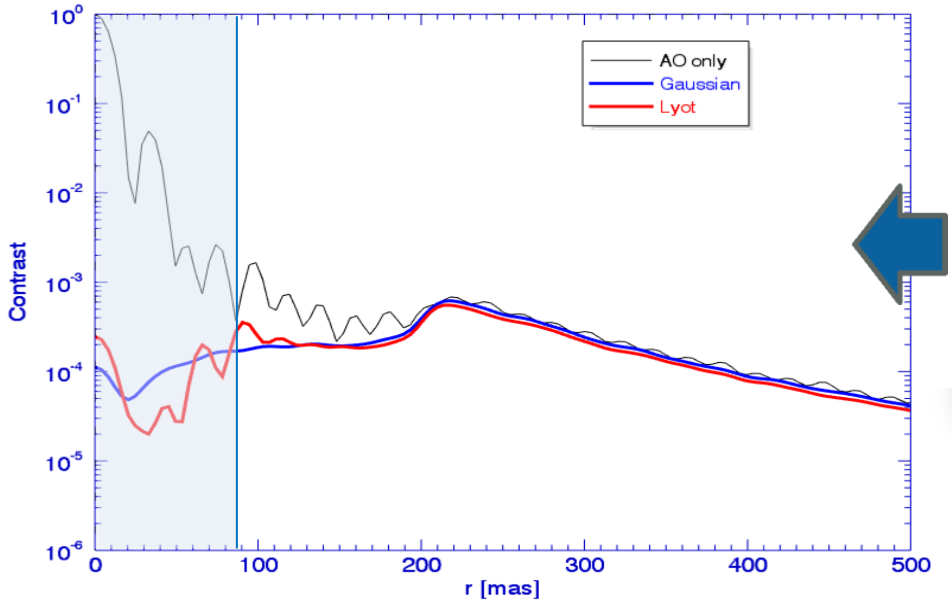




Characteristics	Imager/Coronagraph
Field of View [arcsec]	19.2 x 19.2
Wavelength Range [µm]	1.1-2.4
Sampling J Band [marcsec/pix]	19
E.E. @ 37 mas (J Band Diffraction Limit PSF)	>83%
Intrinsic Optical Quality (0°-25° Zenithal Distance - NO ADC) [SR]	>99.8%
Intrinsic Optical Quality (30° Zenithal Distance with ADC) [SR]	>97.8%
Intrinsic Optical Quality (45° Zenithal Distance with ADC) [SR]	>97.7%
Coronagraph type	Lyot (+ TBD)
Filters	TBD (J,H,K + Narrow Bands)
Polarimetric filters	TBD
Long Slit + GRISM or VPh Spectroscopy	TBD

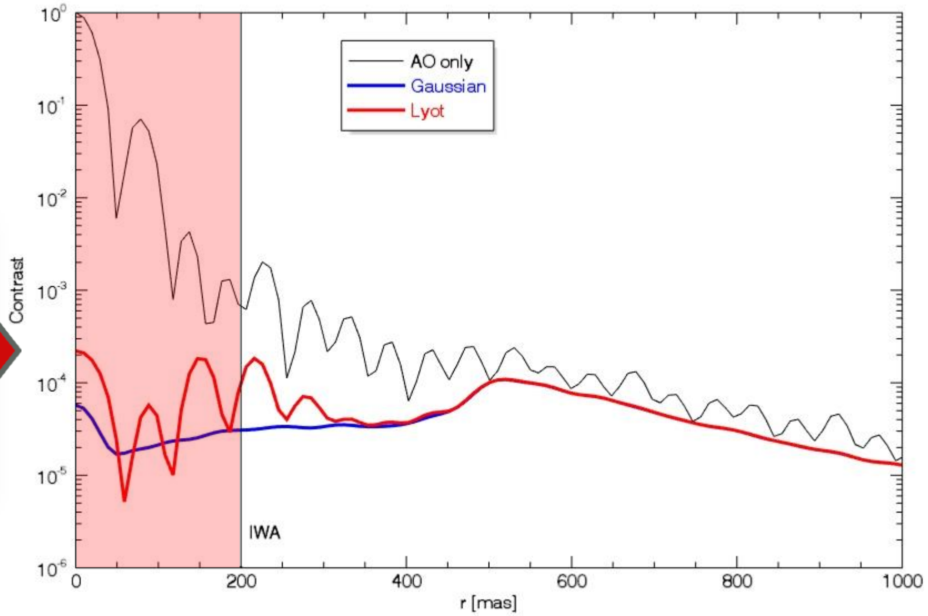


Simulated Contrast Performance



Expected contrast using coronagraphs with 90 mas IWA (~5λ/D). Simulation performed at 675nm, 50nm bandwidth using FLAO residual turbulence at 0.4 arcsec seeing.

Expected contrast using coronagraphs with 200 mas IWA (~5λ/D). Simulation performed in H Band, using FLAO residual turbulence at 0.4 arcsec seeing.



Critical issues on the Shark design

- ✓We do have a baseline design for the coronagraph, but we have a design which is flexible enough to accommodate other coronagraphs (IWA issue)
- ✓Tracking of the PSF movements
- ✓Tracking of the Pupil movements
- ✓Minimization and characterization of the non common path aberrations
- ✓Rejection of the quasi-static speckle

The Team

- ✓INAF Padova (NIR Channel Opto-Mechanics)
- ✓INAF-Rome (VIS Channel)
- ✓INAF-Catania (IFU)
- ✓INAF-Arcetri (AO Interaction and CRYO part)
- ✓Steward Observatory (LBTI interfaces, NIR detector, alternative CORO design)
- ✓IPAG (alternative CORO design)
- ✓ESO (alternative CORO design)
- ✓Science team (INAF Padova, INAF Roma, INAF Arcetri, INAF Catania, IPAG, Steward Observatory , MPIA, University of Padova, University of Catania, INAFTorino, INAF Palermo, Aix Marseille Université (LAM), ESO
- ✓A Board of supervisor (both from Science group and from Instrument experts)

Well identified and shared responsibilities, with reasonable required manpower

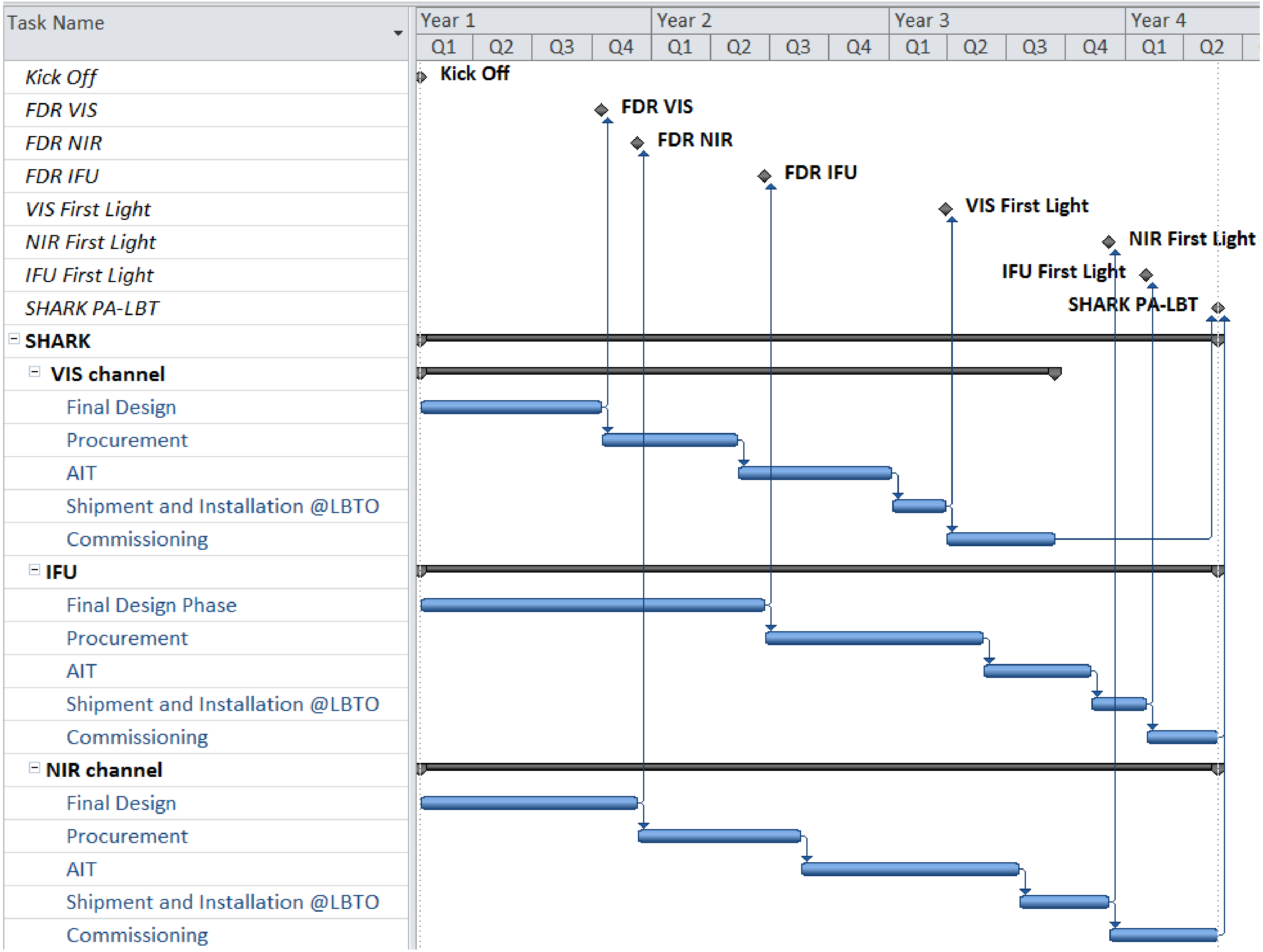
A total of ~30 FTEs for the project completion (not considering management)

Schedule Milestones

We do have a very aggressive (success oriented!) schedule (which supposes a certain cash flow shown later), the main milestones of which are:

- ✓VIS on Sky in about 2 years from T0
- ✓NIR on SKY in about 2.5 year (HAWAII II delivery?)
- ✓VIS IFU on Sky in about 2.5 years

Schedule


Task Name
Kick Off
FDR VIS
FDR NIR
FDR IFU
VIS First Light
NIR First Light
IFU First Light
SHARK PA-LBT
SHARK
VIS channel
Final Design
Procurement
AIT
Shipment and Installation @LBTO
Commissioning
IFU
Final Design Phase
Procurement
AIT
Shipment and Installation @LBTO
Commissioning
NIR channel
Final Design
Procurement
AIT
Shipment and Installation @LBTO
Commissioning
Year 1
Year 2
Year 3
Year 4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Kick Off
FDR VIS
FDR NIR
FDR IFU
VIS First Light
NIR First Light
IFU First Light
SHARK PA-LBT

Cost

ITEM	Cost
NIR	870K€
VIS	240K€
IFU VIS	380K€
TOTAL HW	~1500K€

ITEM	Cost
HW	1500K€
Travels	310K€
Contracts	470K€
TOTAL	~**2.3M€**
TOTAL (contingency 10%)	~2.5M€

Cash Flow (SHARK funding scheme K€)

SHARK project	1st year	2nd year	3rd year	4th year	TOTAL
HARDWARE	480	710	250	100	1540
TRAVELS	30	55	100	120	305
CONTRACTS	88	187	132	66	473
TOTAL	**598**	**952**	**482**	**286**	~2300
TOTAL + CONT.					~2500

Statement on Open Use

We intend SHARK to be a facility instrument, and thus to offer it to the whole LBTO community, beyond the partners involved in our proposal.

Conclusions

- ✓ **We do have an outstanding science case, probably the most popular of the last years, plus several very interesting cases which require binocularity and coronagraphy (we did not touch the NON-Coro and the single eye science)**

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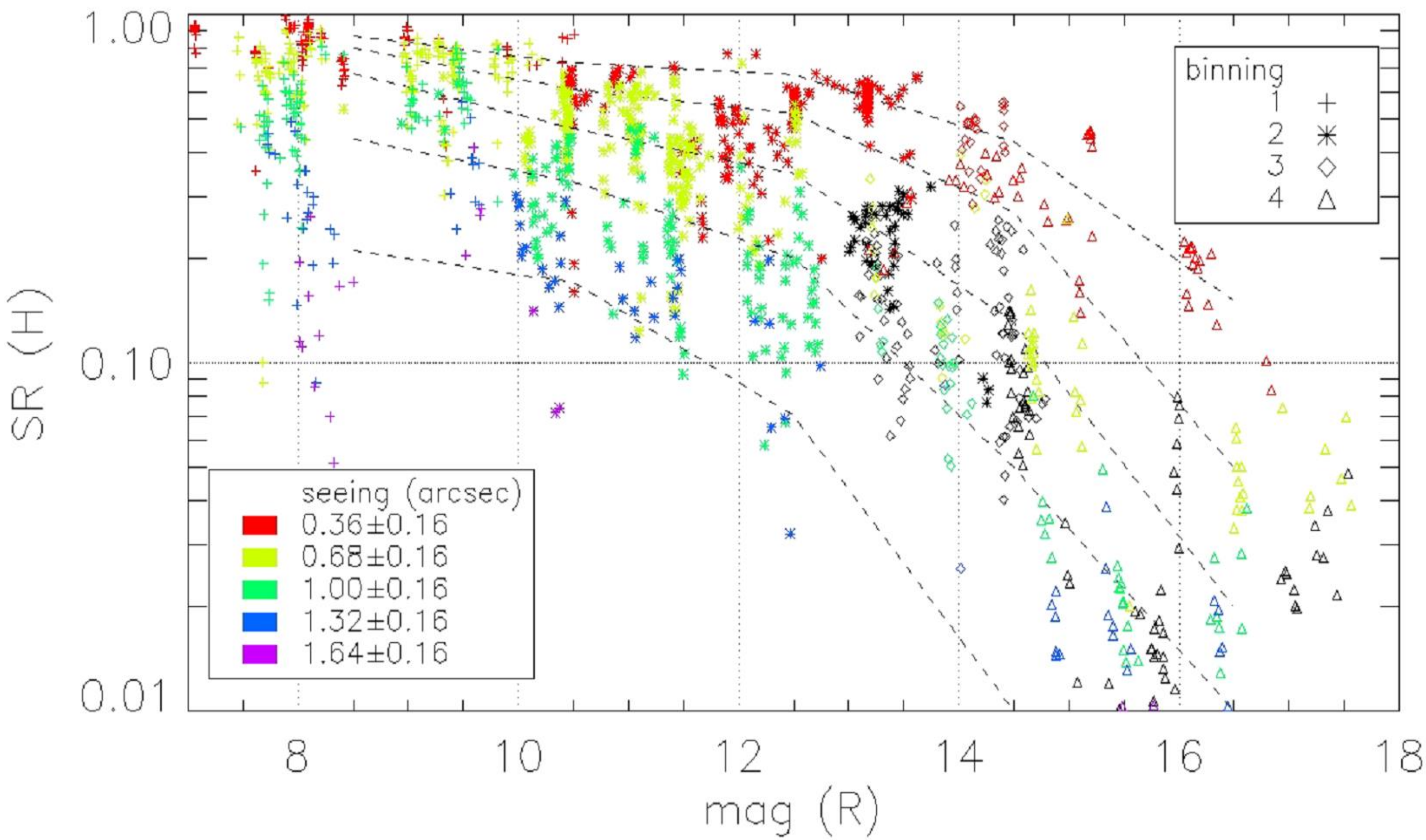

Conclusions

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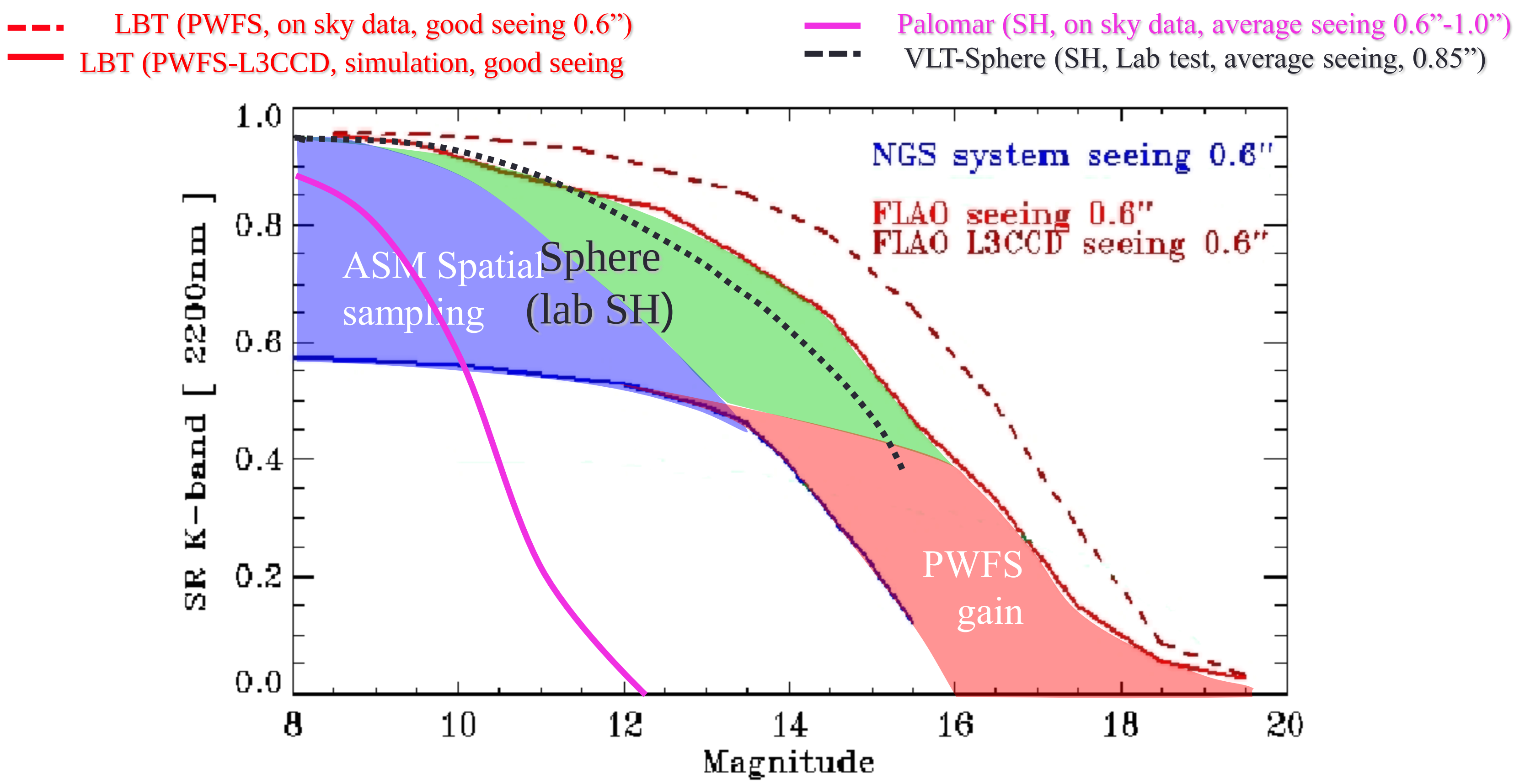

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Laird Close' famous sentence: "with the SHARK VIS arm, wherever you point it's a paper!"

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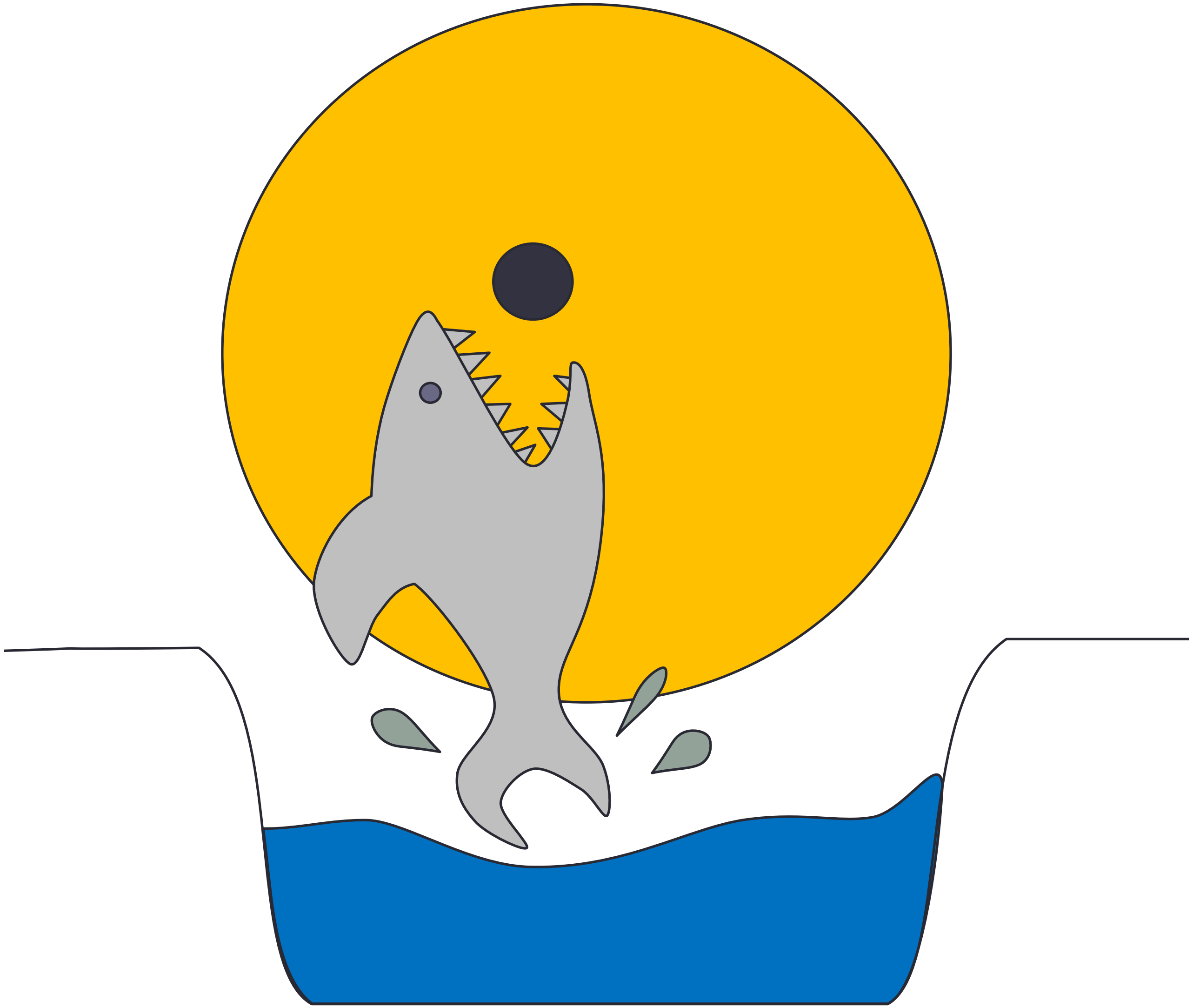
- ✓SHARK is very simple, small and close to the WFS (NCP and flexure minimization)
- ✓SHARK is a 2nd generation instrument which can coexist with the 1st generation
- ✓**SHARK is "cheap" and potentially "fast" (depending on the cash flow and also multiplying by the Christian Veillet factor 1.5)**

… so, why not?



Critical issues on the Shark design

- ✓We do have a baseline design for the coronagraph, but we have a design which is flexible enough to accommodate other coronagraphs (IWA issue)
- ✓Tracking of the PSF movements
- ✓Tracking of the Pupil movements
- ✓Minimization and characterization of the non common path aberrations
- ✓Rejection of the quasi-static speckle

IWA Issue

Coronagraph type	Specifications			State of art	
	IWA (λ/D, ±0.1)	$\mathcal{T}^{a}$ (%)	Parameters	Laboratory tests	Sky observations
FQPM	0.9	82.4	–	vis. / near IR / mid IR	near IR
AGPM	0.9	82.7	$lp^{\beta} = 2$	–	–
AIC	0.4	50.0	–	vis. / near IR	near IR
Lyot	3.9	62.7	$d = 7.5\lambda/D$	vis. / IR	vis. / IR
APLC	2.4	54.5	$d = 4.7\lambda/D$	vis. / near IR	near IR
APRC	0.7	74.5	$d = 1.06\lambda/D$	–	–
BL4	4.0	22.4	$\epsilon = 0.21$	vis.	–
BL8	4.0	13.8	$\epsilon = 0.6, m = 1, l = 3$	vis.	–

Martinez et al., 2008

- ✓ FQPM: Four Quadrant Phase Mask (Rouan et al. 2000; Riaud et al. 2001)
- ✓ AGPM: Annular Groove Phase Mask (Mawet et al. 2005)
- ✓ AIC: Achromatic Interferometric Coronagraph (Gay et al. 1997; Baudoz et al. 2000)
- ✓ Lyot: Lyot 1939
- ✓ APLC: Apodized Pupil Lyot Coronagraph (Aime et al. 2002; Soummer et al. 2003a,b)
- ✓ APRC: APodized Roddier Coronagraph (i.e. Dual zone) (Soummer et al. 2003a,b)
- ✓ BL4: Band-Limited 4th order (Kuchner & Traub 2002)
- ✓ BL8: Band-Limited 8th order (Kuchner et al. 2005)

- ✓ VVC: Vector Vortex Coronagraph (Mawet et al. 2005, Mawet et al. 2011)
- ✓ PAP: Pupil Apodizer on the Pupil (Verinaut et al. 2012)
- ✓ APCMLC: Apodized Pupil Complex Mask Lyot Coronagraphy (Guyon et al. 2010)
- ✓ SLLC: Stop Less Lyot Coronagraphy (N'Diaye et al. 2008; Vigan et al. 2012)

We do have in the SHARK team expertise to design and provide alternative coronagraphic techniques with the goal of having a few choices matching as much as possible the requirements of the different science cases.

- ✓ **Alexis Carlotti (Apodizer in the PP)**
- ✓ **Laird Close**
- ✓ **Johanan Codona (Phase Mask in the PP)**
- ✓ **Olivier Guyon**
- ✓ **Phil Hinz**
- ✓ **Christophe Verinaud (Apodiz. in the PP)**

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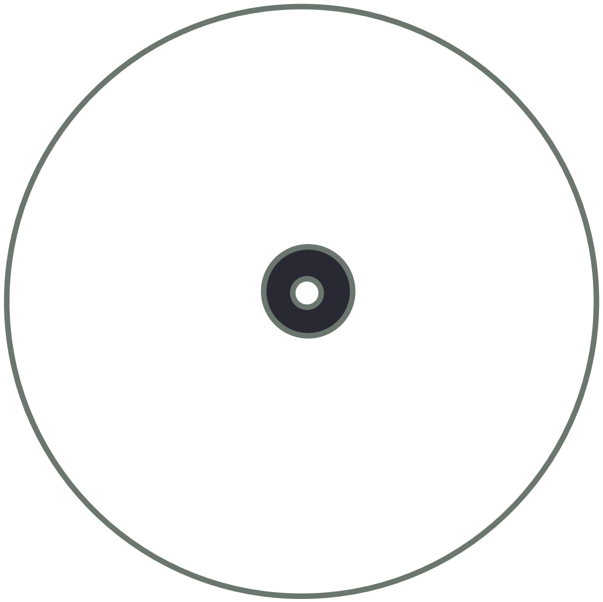
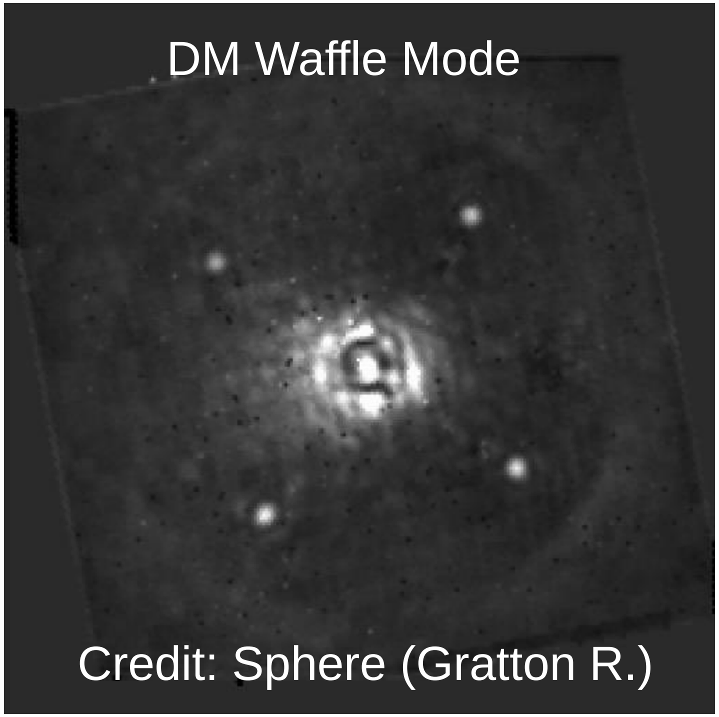
Tracking of the PSF Movements

- ✓ No additional TT sensor foreseen
- ✓ Two possibilities (both OK for tracking also during the exposure):
- ✓ Occulting mask in the focal plane with a semitransparent circle in the center (OK for Lyot, not for Coronagraphs which do not need an occulter on the FP)
- ✓ Create four artificial spot onto the focal plane (outside the science FoV) by introducing a waffle mode in the DM



Semi-transparent central dot



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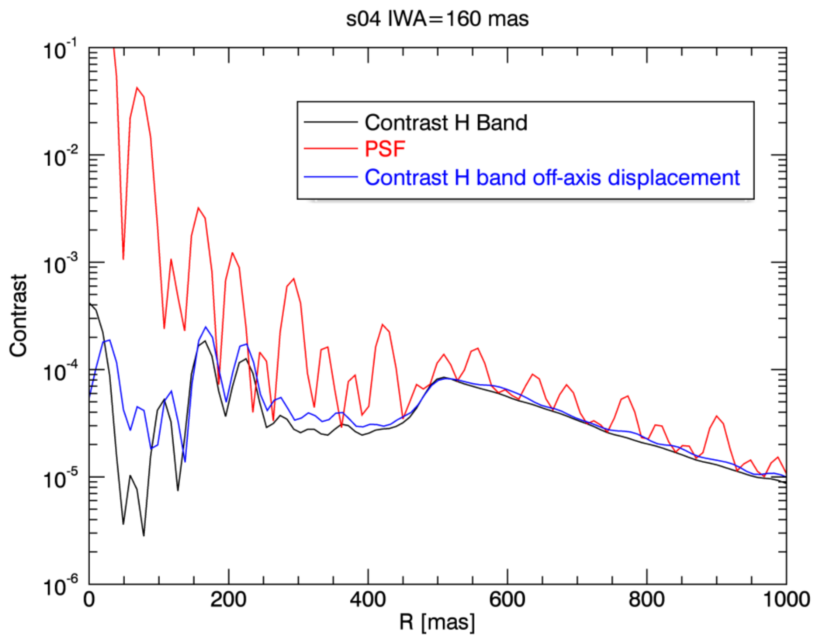
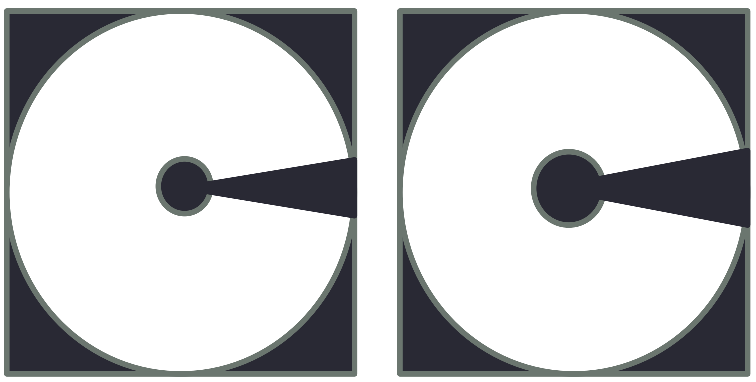
Tracking of the Pupil Movements

In the current design, nothing is foreseen to look at the pupil movements (but minimizing them by design). For example, a shift of 0.1mm (strongly conservative case) during the exposure does not seem to have a strong impact on the contrast (preliminary simulations).

To account for pupil rotations, there might be two ways (OK only between different Exposures):

- ✓ Add a pupil plane mask with "slightly" undersized spiders
- ✓ Use the huge ASM focus adjustment to defocus the image and adjust the rotator angle accordingly





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Minimization of the NCP aberrations

By design the system is:

✓Small

✓Light

✓Compact

✓Close to the WFS

Daytime characterization through the LBTI Source Light

Compensation of the pyramid variable gain with online measurement of the WFS sensitivity

For the VIS arm, we are evaluating the possibility to have an internal DM which should be used for closing an internal loop with the science camera to avoid the offload of the NCP to the pyramid sensor

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Rejection of the quasi-static speckle

The major source of noise limiting high-contrast imaging is caused by quasi-static speckles. Instrumental speckles (due mostly to optical quality and misalignment errors) average to form a fixed pattern, which can be calibrated to a certain extent, but their temporal evolution limits this possibility (mechanical and thermal deformation during the exposure).

The **Angular Differential Imaging (ADI)**, utilized by most of the Coronagraphs, is a technique to minimize this effect.

A sequence of images is acquired with the telescope close to the Meridian while the instrument field derotator is switched off. This keeps the instrument and telescope optics aligned and allows the field of view to rotate with respect to the instrument. For each image, a reference point-spread function (PSF) is constructed from other appropriately selected images of the same sequence and subtracted to remove quasi-static PSF structures. All residual images are then rotated to align the field and are combined.

ADI Technique