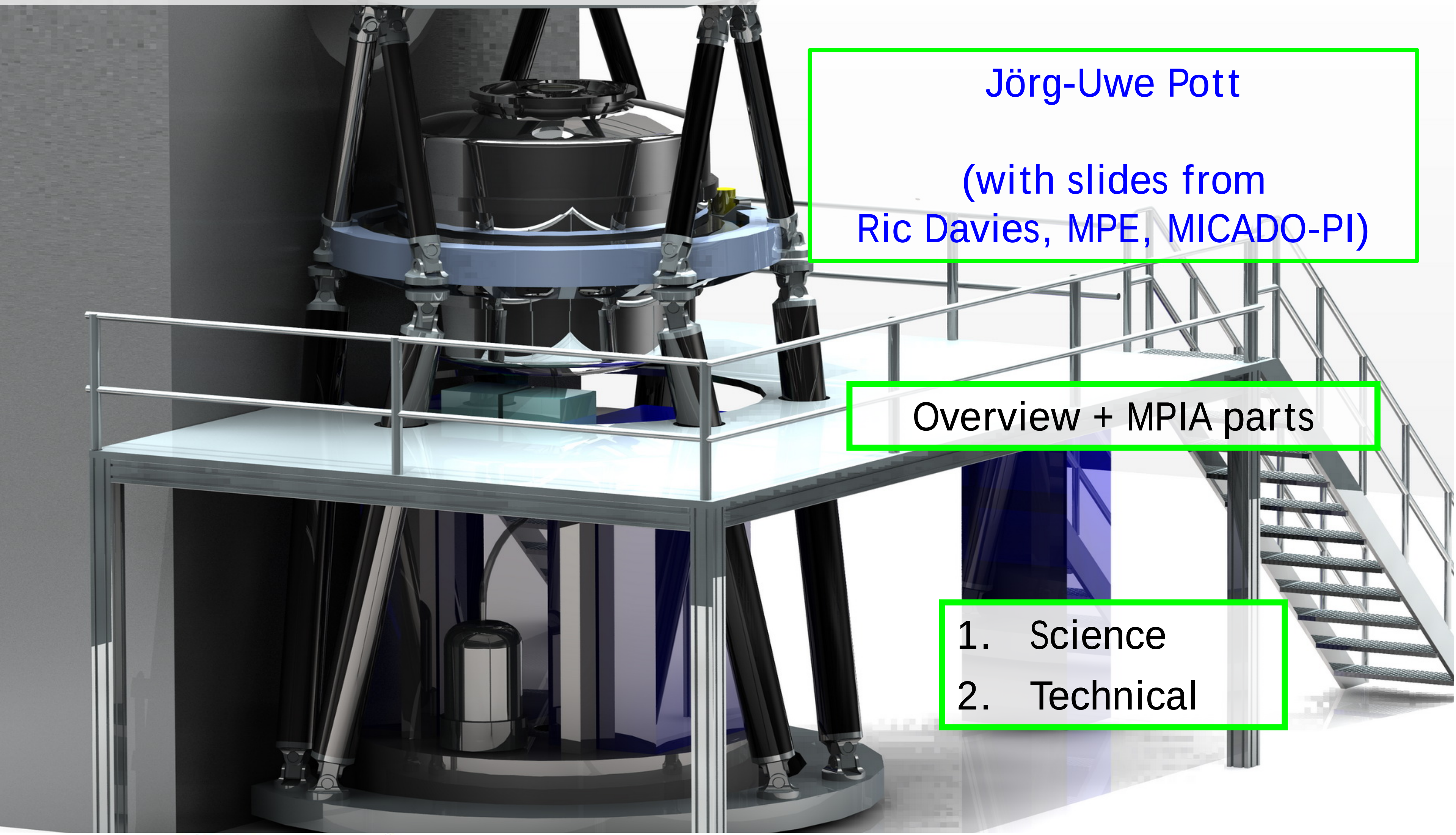
MICADO: First Light Imager for the E-ELT

Jörg-Uwe Pott

(with slides from
Ric Davies, MPE, MICADO-PI)

Overview + MPIA parts

1. Science
2. Technical

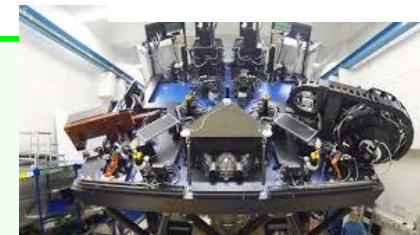


Key Capabilities – 5 of our instruments in 1

- **Imaging**
  - 0.8-2.4μm with >30 broad/narrow filters
  - 1.5 & 4mas pixels for 19 & 51” FoV at 6-12mas
  - Similar sensitivity to JWST, and 6× better resolution


JWST

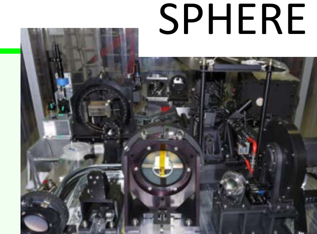
- **Astrometric imaging**
  - 50μas precision across full field
  - 10μas/yr = 5km/s at 100kpc after 3-4 years
  - bring precision astrometry into mainstream


LINC-NIRVANA

- **Spectroscopy**
  - ideal for compact sources
  - fixed configuration for 0.8-1.45μm & 1.45-2.4μm
  - R ~ 8000 across slit, higher for point sources


LUCI

- **High Contrast imaging**
  - focal plane coronagraph & lyot stop
  - angular differential imaging
  - small inner working angle


SPHERE

- **Time Resolved Astronomy**
  - windowing for frame rates up to ~100Hz


ASTRALux

Key Capabilities

- Imaging
  - cosmic star formation history: resolved stellar populations
  - structure of high-z galaxies on 100pc scales
  - nuclei of nearby galaxies (stellar cusps, star formation, BHs

- Astrometric imaging
  - stellar motions within light hours of Sgr A*
  - IMBHs in stellar clusters & dwarf galaxies
  - Milky Way formation: proper motion of clusters & dwarf galaxies

- Spectroscopy
  - ages, metallicities, masses of first elliptical galaxies at z=2-3
  - spectra of first supernovae at z=1-6
  - redshifts, velocities, metallicities of SFGs at z=4-6

- High Contrast imaging
  - Giant/massive planets at a few AU around nearby stars
  - Direct detection of planets discovered via RV measurements

- Time Resolved Astronomy
  - Pulsars & magnetars
  - Accreting white dwarfs
  - Compact binary systems
  - Transits & occultations

Spatially Resolved Stellar Populations in Nearby Galaxies

Science Goal is galaxy evolution: to understand *why*, *when*, & *where* stars formed in galaxies

- Observe galaxies at different epochs & track evolution of the samples
- Infer the past star formation history from relic populations in local galaxies

- HST has been very successful: optical colours, wide field, stable PSF

- In sparse fields, the limit is *sensitivity -> JWST*
- In crowded fields, the limit is *resolution -> MICADO*
- *Key goal for ELTs* is to reach Virgo cluster – large sample of 'normal' ellipticals

What will the E-ELT be able to detect?

H_{AB} ~ 31mag for isolated sources after several hours.

from Deep+ 11 & Greggio+ 12:

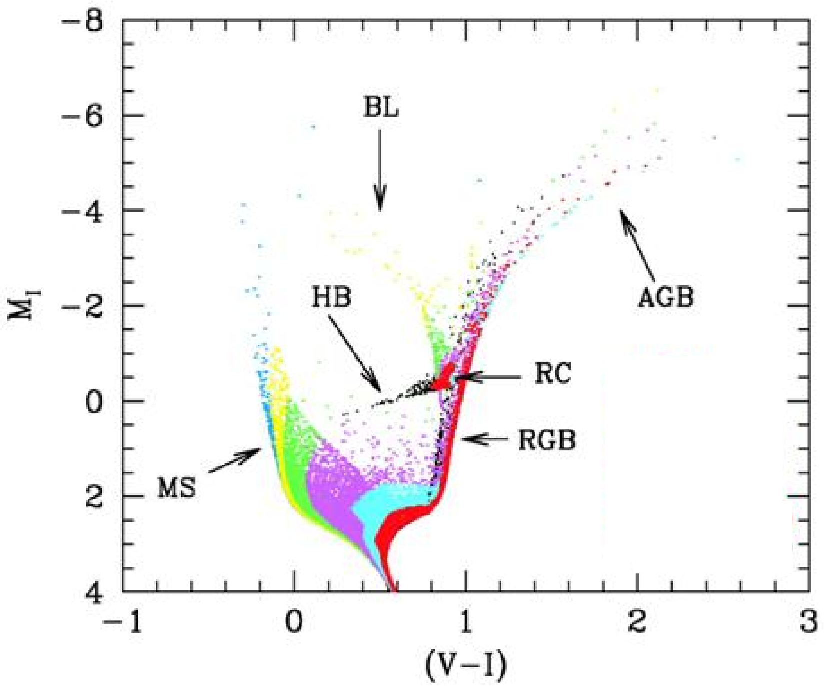
old Main Sequence Turnoffs out to ~2 Mpc
Local Group, Sculptor & M81 groups:
several large spirals

Horizontal Branch out to ~10 Mpc
Cen A: closest peculiar elliptical
Leo Group: closest normal elliptical (NGC3379)

Red Giant Branch
Virgo Cluster: many large galaxies

tip of Red Giant Branch & luminous variable stars out to >100Mpc

- **< 0.1 Gyr**
- **0.1 – 0.4 Gyr**
- **0.4 – 1.0 Gyr**
- **1.0 – 3.0 Gyr**
- **3.0 – 6 Gyr**
- **6 – 10 Gyr**
- **10 – 13 Gyr**



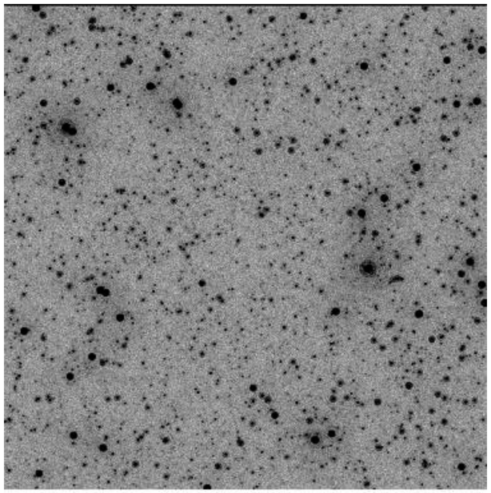
Aparicio & Gallart (2004)

Anticipating the ELTs

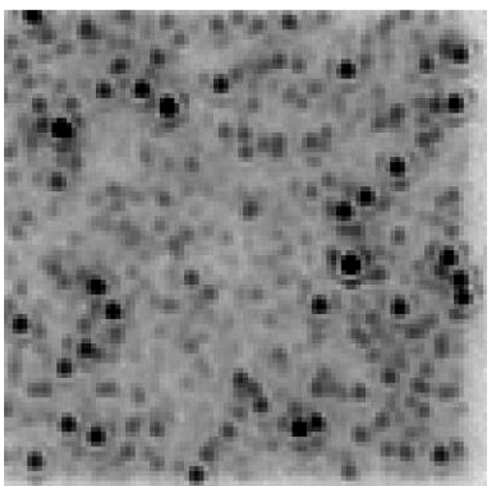
Resolution gives an effective sensitivity gain wrt JWST – cf. 3mag for MAD vs ISAAC.

Can probe tip of RGB out to Virgo (δ_{Virgo} = +12.5°, zd at transit is 37°)

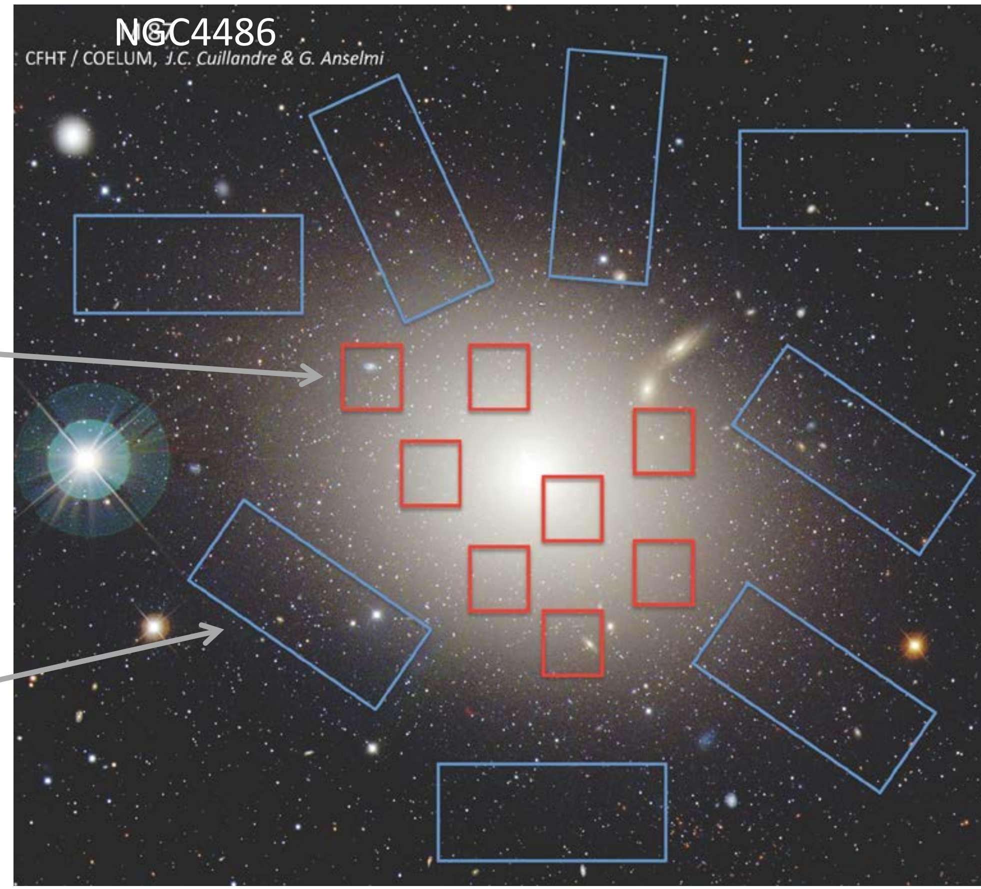
5-hr K-band simulated exposures



MICADO @ E-ELT



NIRCAM @ JWST



Galaxies at High Redshift

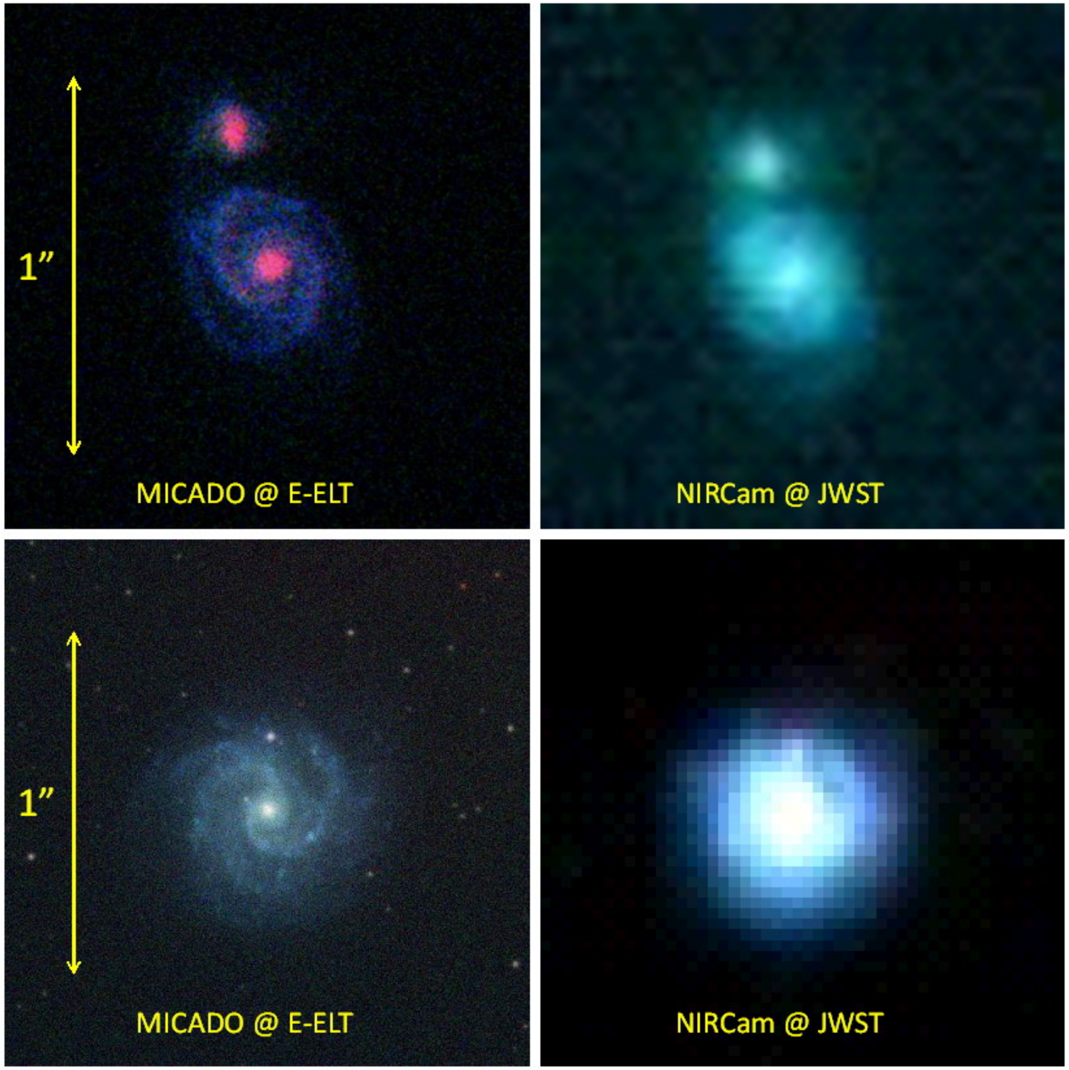
JWST will select samples & measure basic galaxy properties

MICADO will trace stellar continuum & provide detailed structure

HARMONI will give kinematics & emission line distribution (but more limited spatial sampling)

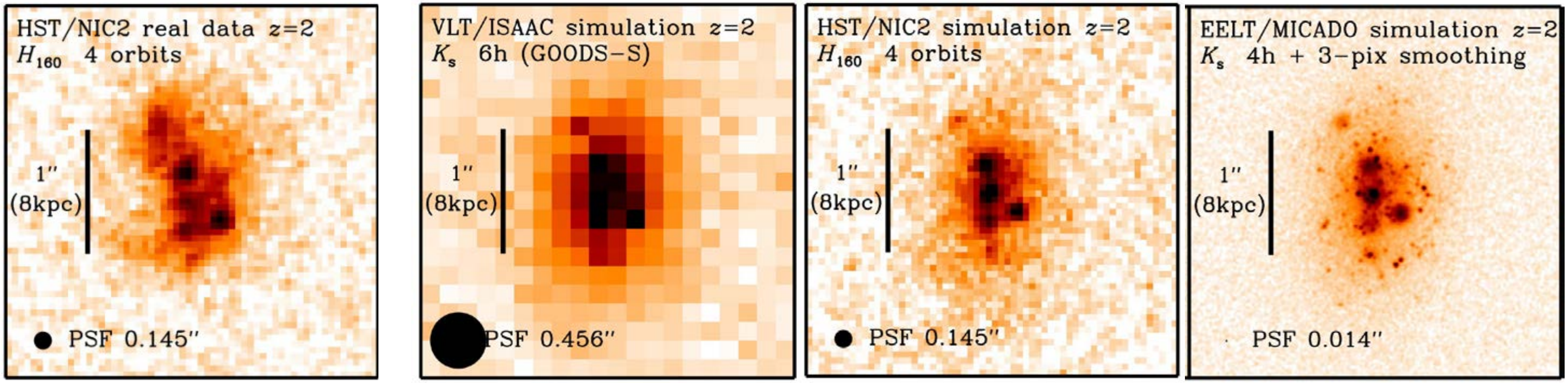
ALMA will trace molecular component

All are needed to answer:
What are the physical processes driving their evolution?



combined JHK images of local templates (BVR bands) shifted to z=2 (top) and z=1 (bottom), with R_{eff}=0.5" and Mv=-21. 5hrs integration.

Galaxies at High Redshift

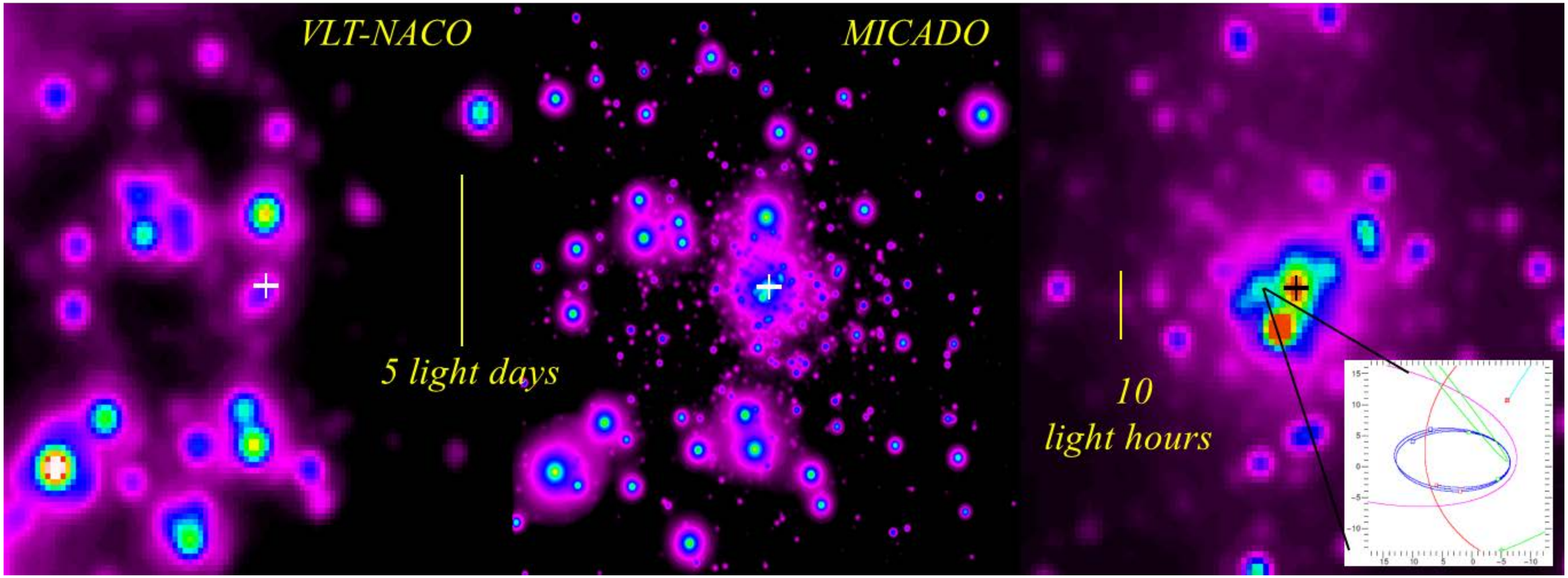


simulation of a large bright disk galaxy at z = 2.3 ($R_{1/2}$ = 5 kpc, K_{AB} = 21.3), showing that one can measure sizes, distribution and luminosity functions of compact clusters to K_{AB} ~ 28.5

spectroscopy: - metallicity, extinction, stellar populations, outflows (AGN)
- relations between mass, SFR, metallicity

Galactic Centers near & far

- Unique laboratory to explore strong gravity around the closest massive black hole
- Crucial guide for accretion onto BHs & co-evolution of star clusters and AGN



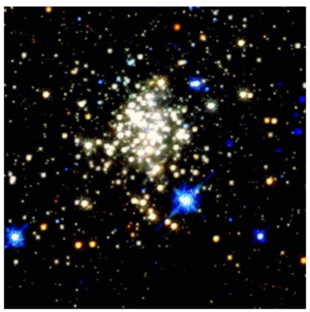
- sensitivity >5mag fainter, resolution & astrometry 5x better than NACO@VLT
- density profile, luminosity function to $<1M_{sun}$, shape of IMF
- orbits of stars closest to BH: prograde & retrograde precession
- proper motions of ~1000 stars: phase-space clumping (disks)

spectroscopy: - 3D orbits, stellar types, spectral properties of accretion events

Intermediate Mass Black Holes

- In globular clusters & nearby dwarf galaxies
- Milky Way has ~150 GCs, typical central dispersion ~10km/s -> 50μas/yr at 40kpc

Arches
M_{BH}~1000M_{sun}?
(Portegies Zwart et al. 06)



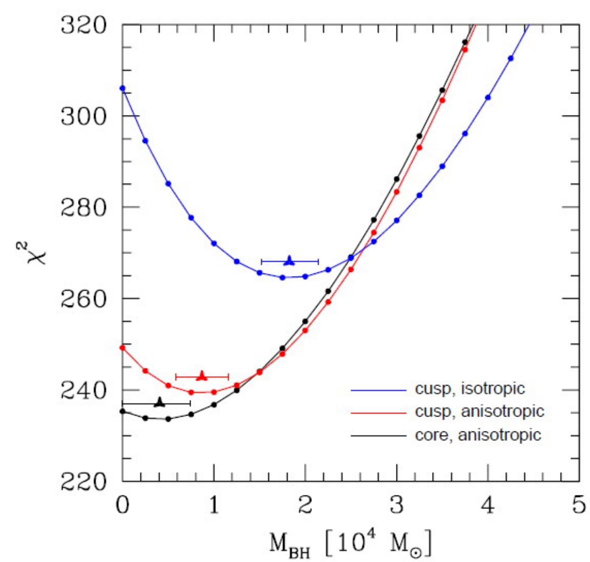
IRS 13
M_{BH}~1300M_{sun}?
(Maillard et al. 04)

ω Cen:
M_{BH}~10000M_{sun}?
(Noyola+ 08)

Andersen+ 09, van der Marel+ 09

ω Cen

- more than 50000 stars, 4-yr baseline, ε ~100μas/yr
- proper motions -> small but significant anisotropy
- shallow cusp models require M_{BH}~$2\times10^4 M_{sun}$
- core profile models require no central dark mass !



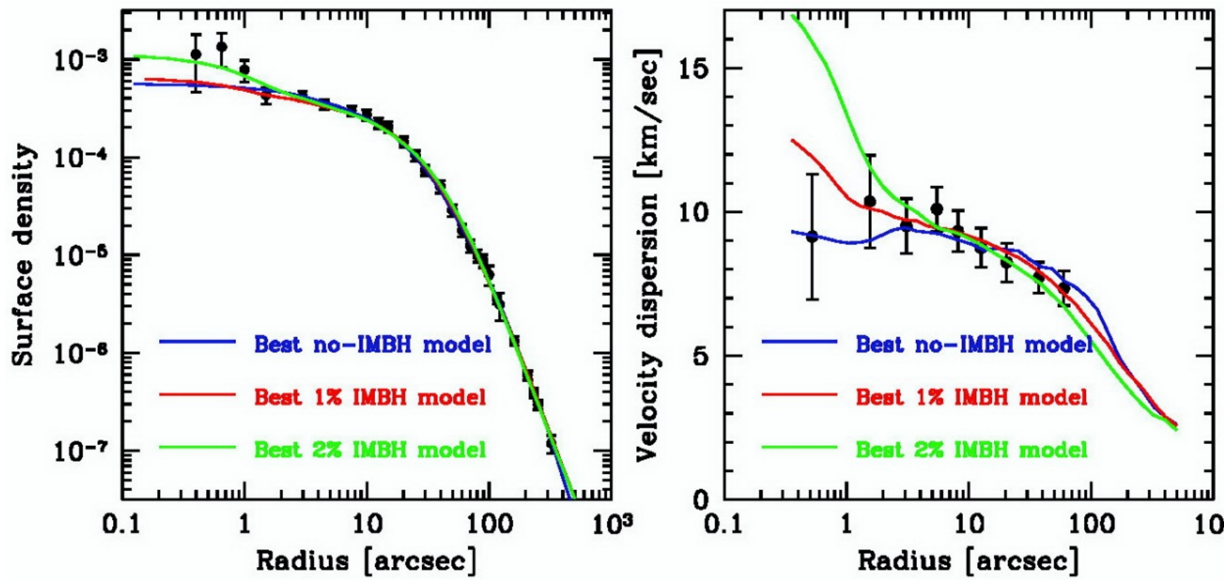
Intermediate Mass Black Holes

Feldmeier+ 13: NGC5286

Jeans models:
$M_{BH} \sim (1.5 \pm 1.0) \times 10^3\ M_{sun}$

N-body simulations:
$M_{BH} \sim (4 \pm 2) \times 10^3\ M_{sun}$

(0.9% of cluster mass)



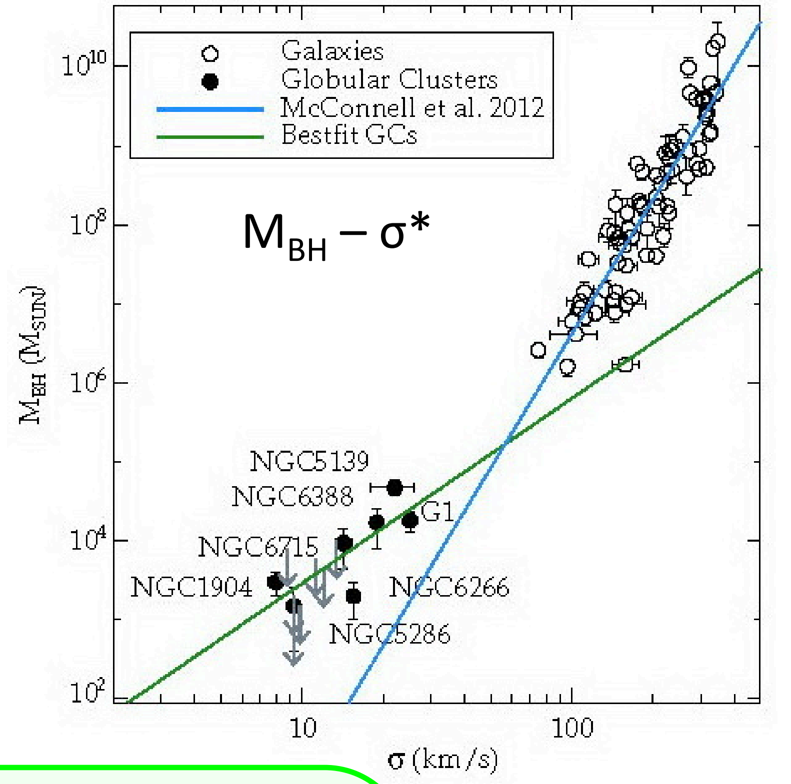
"our detection is at the 1- to 1.5σ level…
Detection of IMBHs in Galactic globular clusters remains a challenging task…"

Kamann+ 14: M3, M13, M92 3σ upper limits $\sim 10^4\ M_{sun}$

"A massive black hole is required in none of the three clusters to explain the observed kinematics"

Intermediate Mass Black Holes

Lützgendorf+ 13



NGC6388: $17 \pm 9 \times 10^3$ M_{sun} (Lützgendorf+ 11)

NGC6715: $9.4 \pm 5.0 \times 10^3$ M_{sun} (Ibata+ 09)

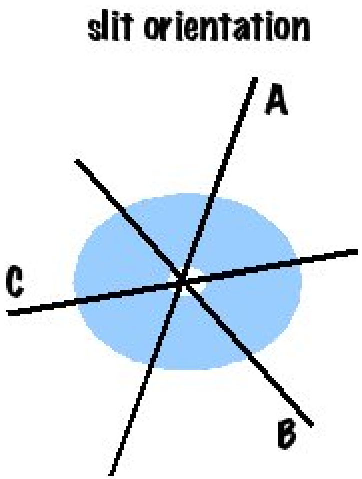
NGC5139 (ω Cen) & NGC5286 we've already seen.

- Are BH masses in clusters over-estimated?
- Should we expect them to lie on the $M_{BH} - \sigma^*$ for ellipticals & galaxy bulges?
- (is there even a single meaningful $M_{BH} - \sigma^*$ relation?)

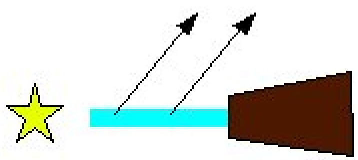
Need resolution & sensitivity of MICADO to address this robustly

Spectroastrometry technique:

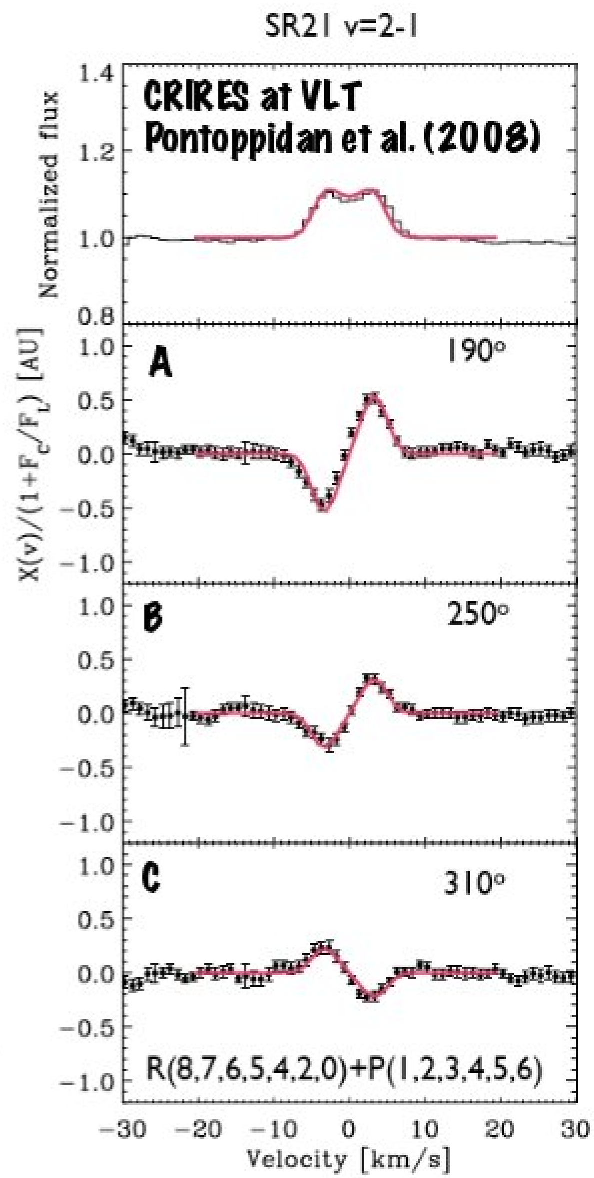
High Resolution (R~100000) + AO
Spectro-astrometry



Better constrains on the
☺ inner disk inclination
☺ inner gas dynamics



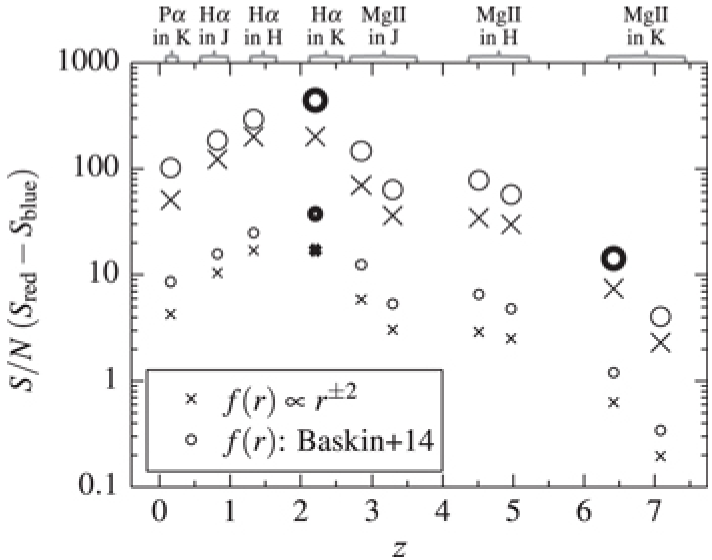
This particular work:
study of the GAS inside
the gap of transitional disks.



[Slide from A. Carmona]

Spectroastrometry of AGN

Stern+ 15



SPATIALLY RESOLVING THE KINEMATICS OF THE QUASAR BROAD-LINE REGION

- Measure spatial offset in spectral feature
- BLR motion is not completely random

- Patzer price -> KoCo soon

- BLR-SMBH relation for high-mass and high-z quasars
- Gauge reverberation mapping BLR geometry model factors
- Constrain kinematics of BLR (-> formation scenarios)

Need resolution & sensitivity of MICADO

Global overview of the instrument

- Shown in ‘stand-alone’ phase.
- Same mount structure as when under MAORY.

Design spaces:

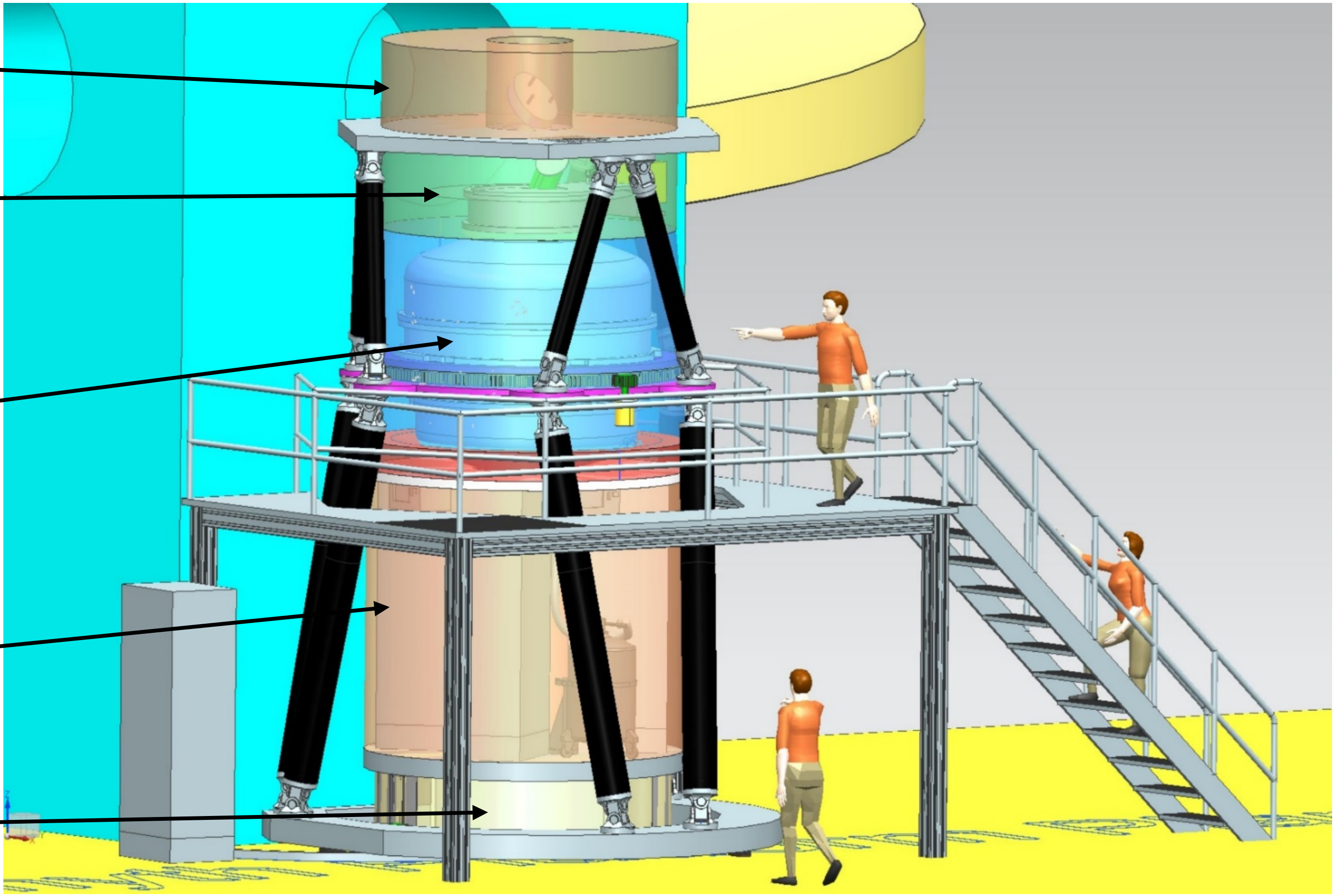
Fold mirror & calibration unit

SCAO (+ MAORY NGS-WFS)

Cryostat & derotator

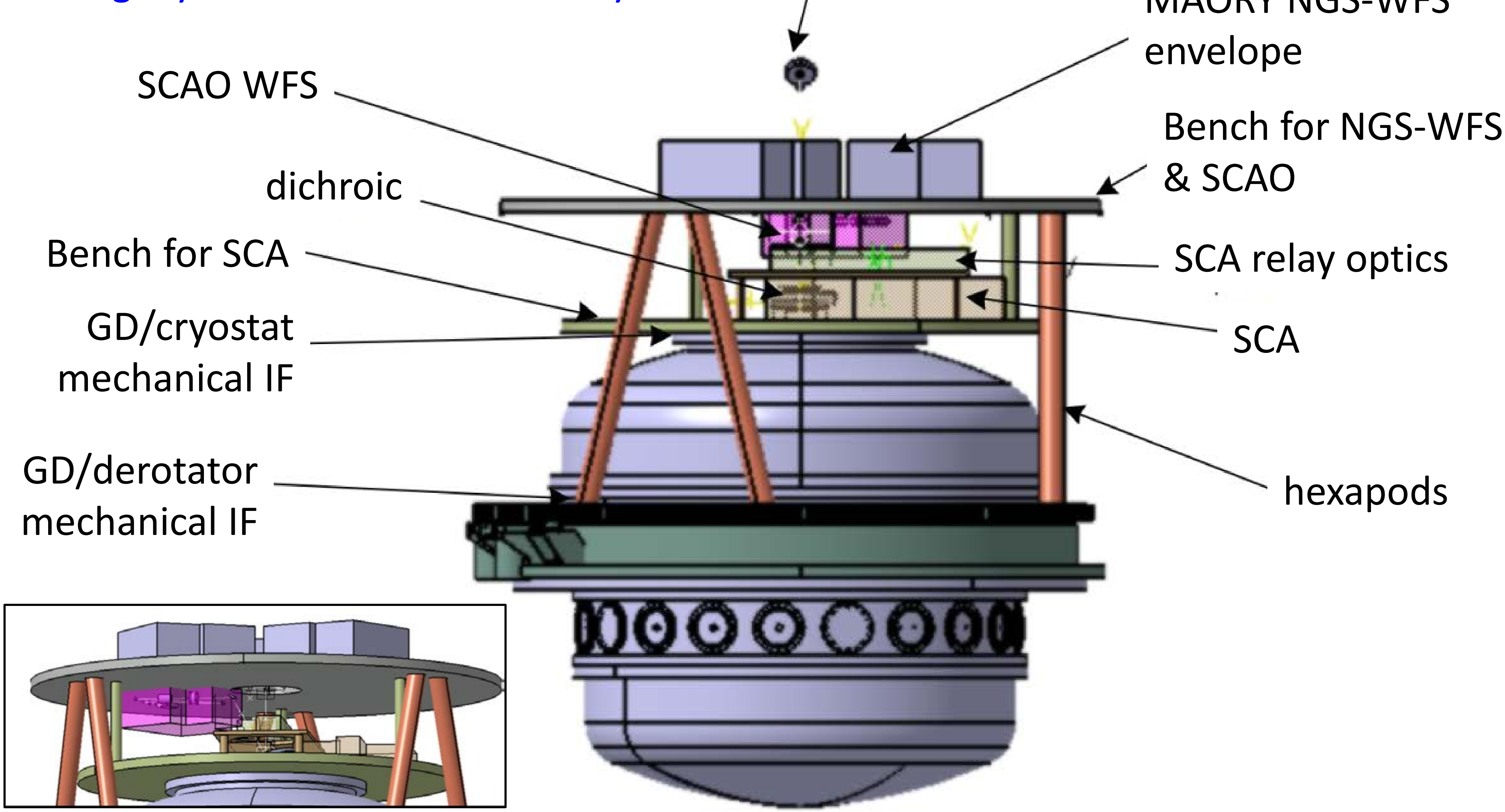
Electronics (co-rotating)

Cable-wrap

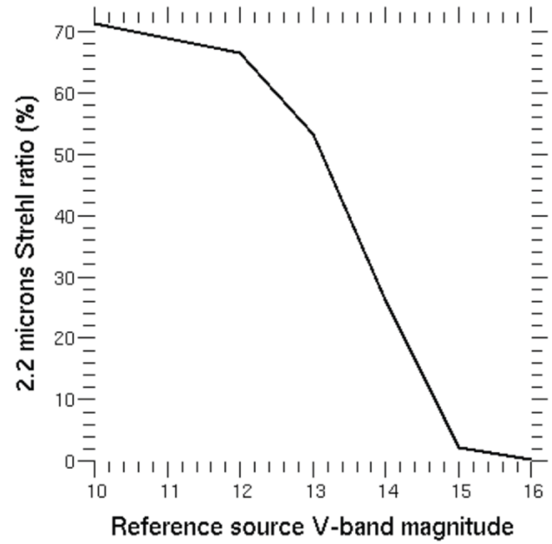


MICADO cryostat & NGS WFS assembly

- WFS module ('Green Doughnut') is a key interface between MICADO and MAORY.
- Houses MAORY infrared NGS-WFS *and* SCAO (+SCA = SCAO calibration assembly).
- Rigidly mounted to MICADO cryostat.



SCAO performance



Based on end-to-end GPU simulations

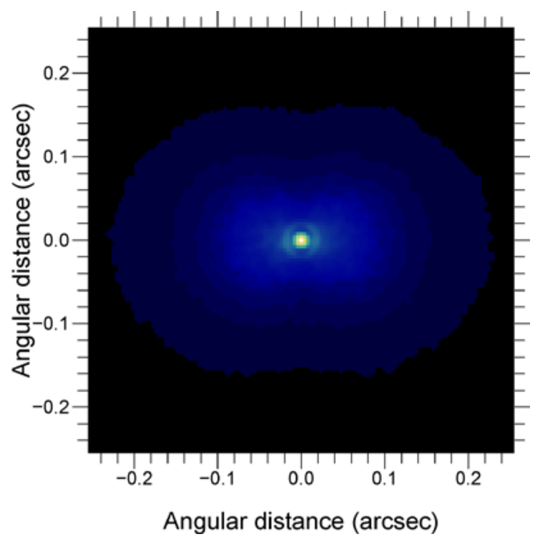
Maximum strehl

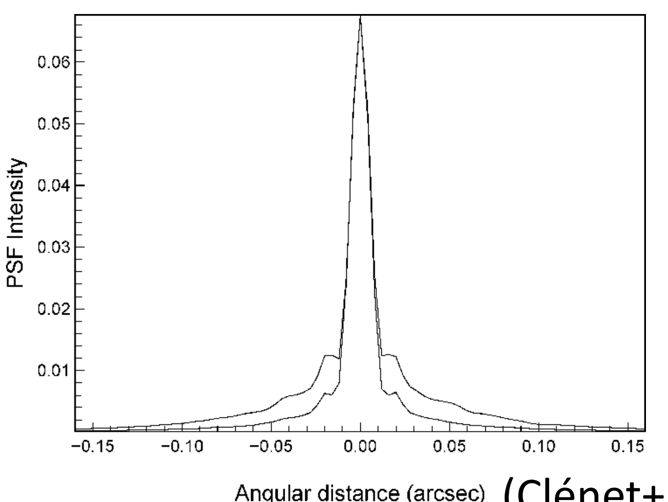
- Limited by M4 and telescope WFE budget
- Residual tip-tilt ~3mas

Anisoplanatism

- Different to 8-m telescopes, because E-ELT diameter is comparable to L_0.
- Although Strehl ratio is low, PSF retains a diffraction limited core even far off-axis

PSF with radial & transverse cuts, 30” off-axis, for realistic L_0 profile (K-band Strehl ~6%)





(Clénet+ 13, 14)

MPIA key contributions

DEROT: Instrument / WFS de-rotator
Lead: Santiago Barboza

MCA: Micado calibration assembly
Lead: Gabriele Rodeghiero
Includes M7

FPAA: 3x3 array of 4k FPAs
Lead: Peter Bizenberger

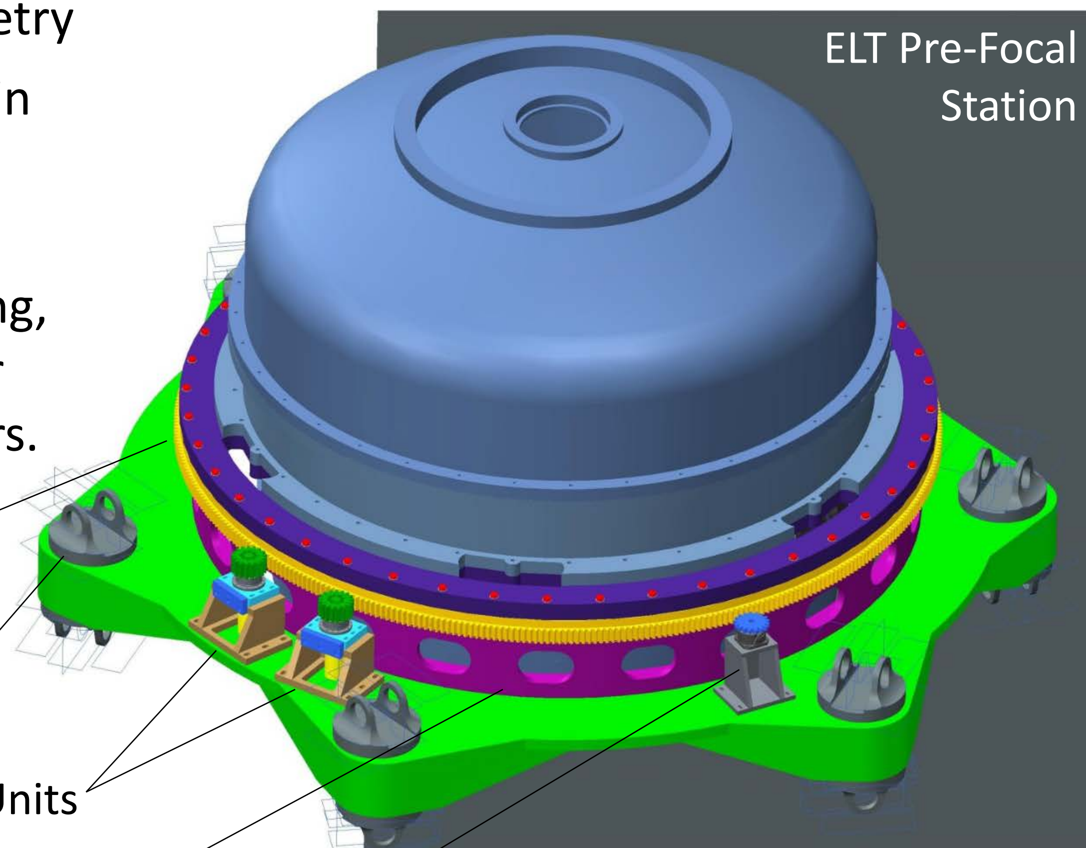
Vibration control: enlarge the science phase space of SCAO
Lead: Martin Glück

Instrument science, systems engineering, project control
JUP, Friedrich Müller, Ralph Hofferbert, technical departments

De-rotating the cryostat

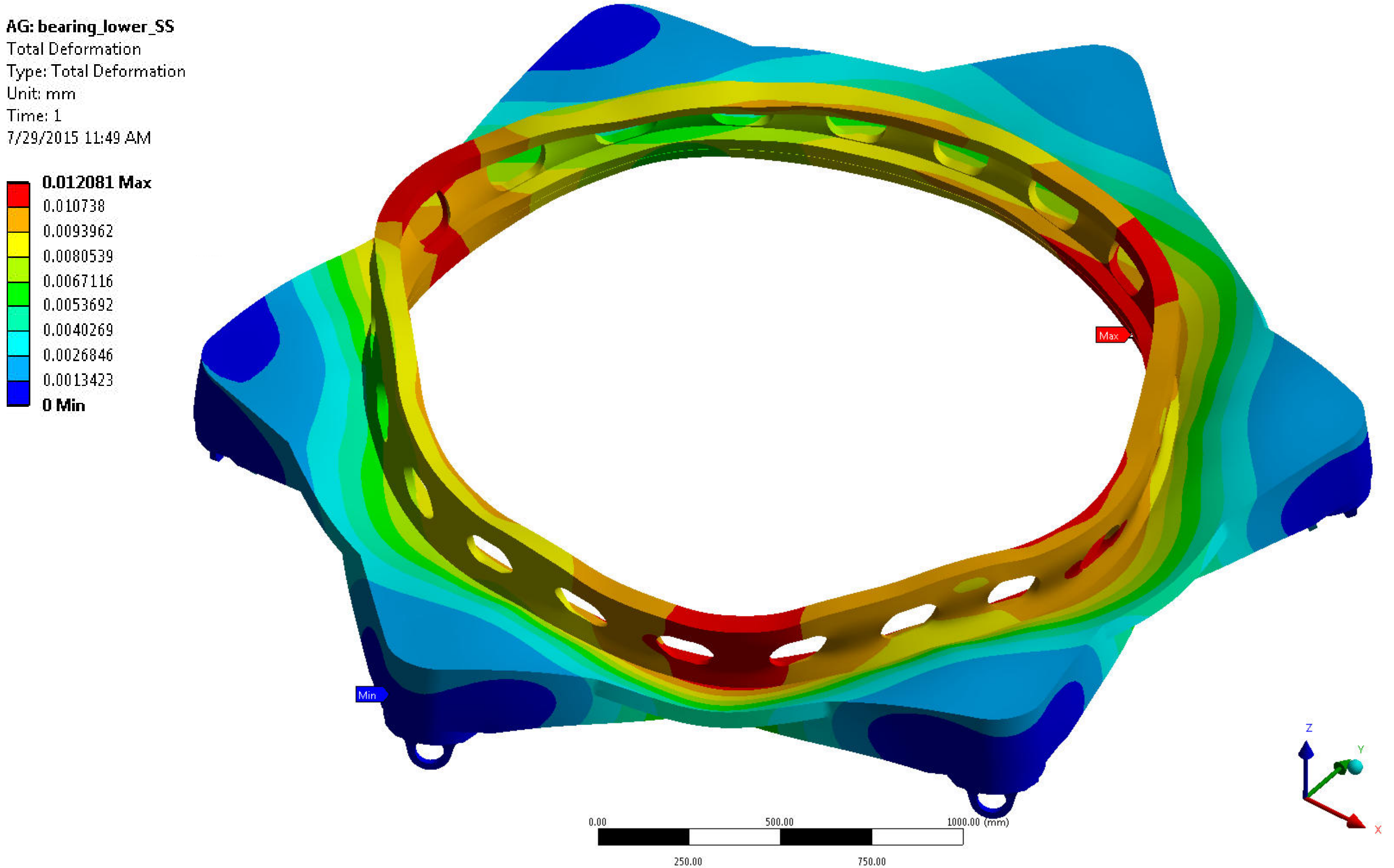
Challenge: control ~3000 kg rotation to a few arcsec precision

- Goal: limit the rotation uncertainty within a PSF during exposure to get precise astrometry & photometry
- Maximum radial/axial runout in 50-100μm range
- Requires advanced technical solutions: e.g. precision bearing, stiff interfaces, minimal motor jitter, precise position encoders.



Support Structure Preliminary FEA

- Total deformation

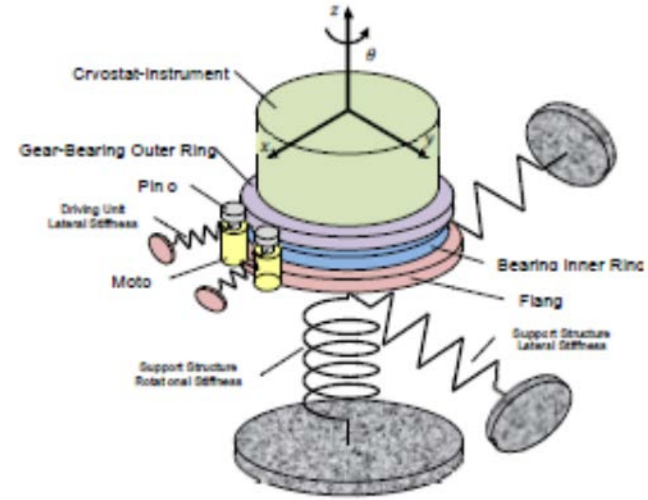


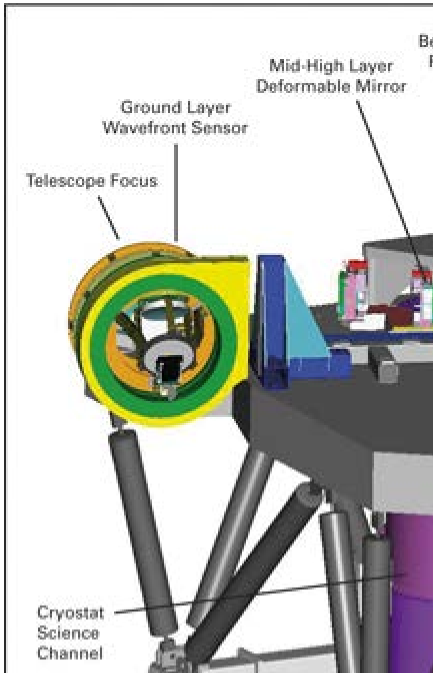
Derotator

Next steps in house

- End-to-end modeling in software to break down the system requirement to individual specifications
  - Bearing friction
  - Interface flatness and stiffness
  - Motor parameters
  - …
  - Collaboration with DSI, Uni Stuttgart

- Test-stand, to verify
  - Position encoding, and motor control concepts
  - End-to-end model
  - Use the heritage of LINC-NIRVANA GWS

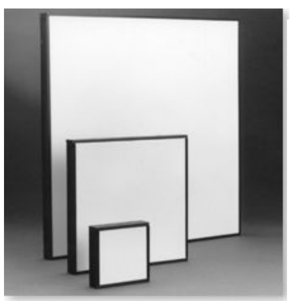




MICADO camera calibration

Flat field

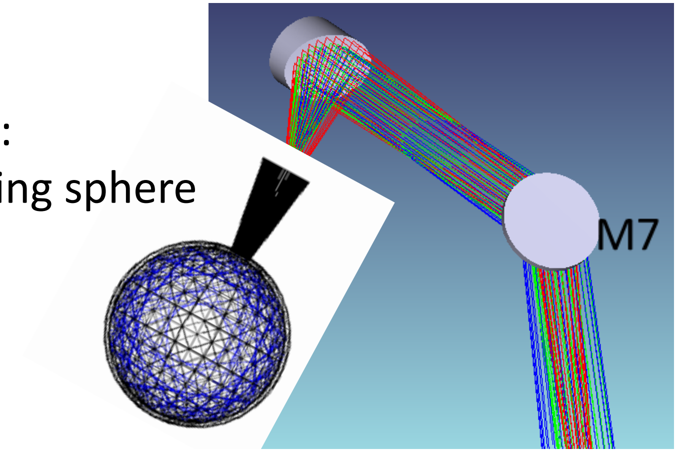
- Goal is 0.1% detector calibration
- Requires homogeneous illumination of the pupil and focal plane
- Avoid large, expensive optics, and focus on short-scale (pix2pix) variations



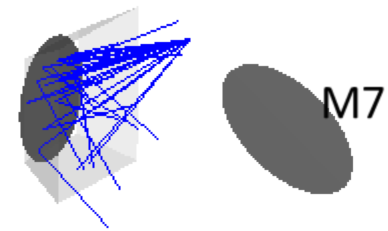
Spectralon or Infragold*

* Reflectance >94% above 1000 nm
$R_{@800} = 0.911$, $R_{@900} = 0.925$

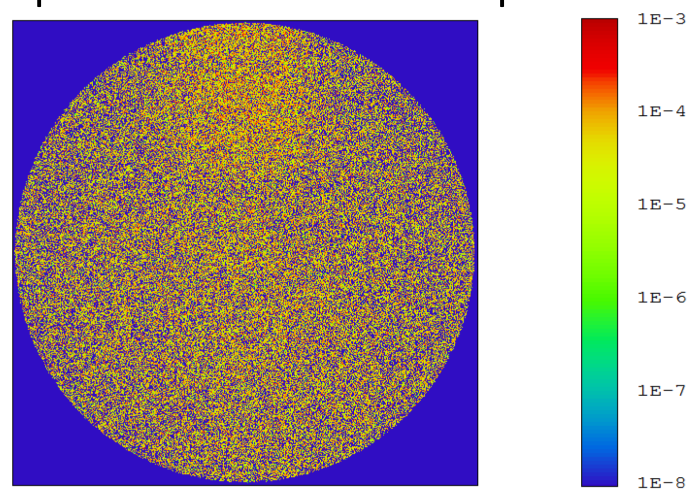
Option1:
Integrating sphere



Option2:
Spectralon Diffusor



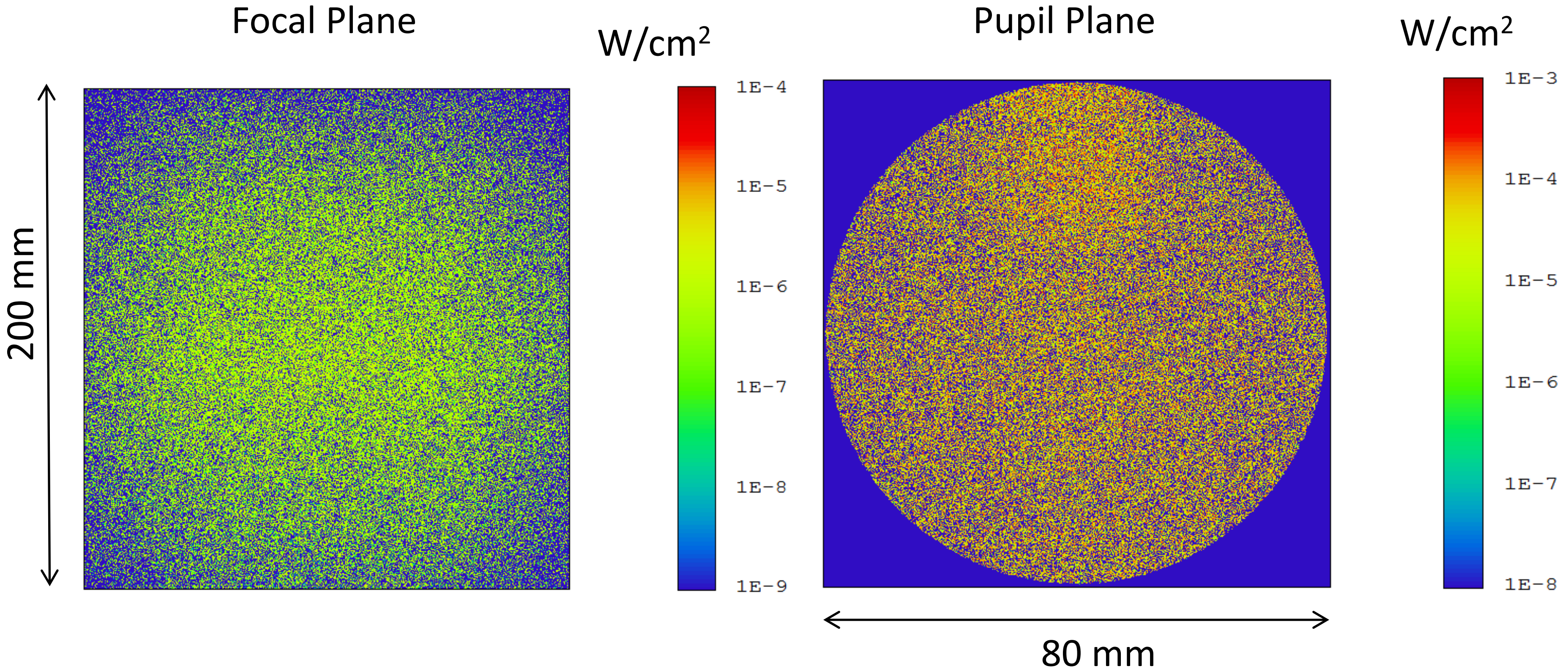
Pupil plane illumination for Opt2:



Detector Image: Incoherent Irradiance

E-MCD-556C50E6
29/09/2015
Detector 38, NSCG Surface 1: pupil plane
Size 81.000 W X 81.000 H Millimeters, Pixels 1000 W X 1000 H, Total Hits = 172365
Peak Irradiance : 6.7545E-004 Watts/cm^2
Total Power : 2.2051E-003 Watts

Diffuse illumination

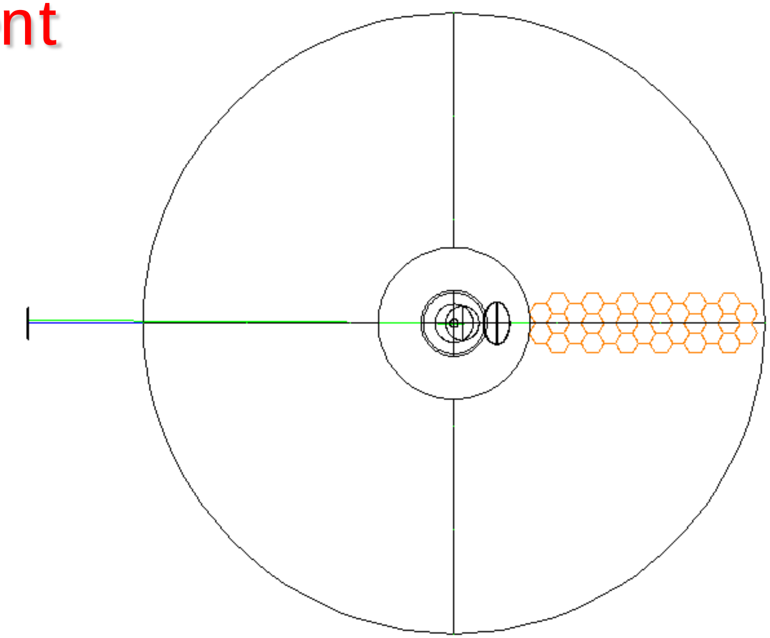


- Optimization steps
  - Iterated requirements: is local calibration enough
  - Use several alternating light sources to distinguish source related illumination pattern from MICADO flat field effects

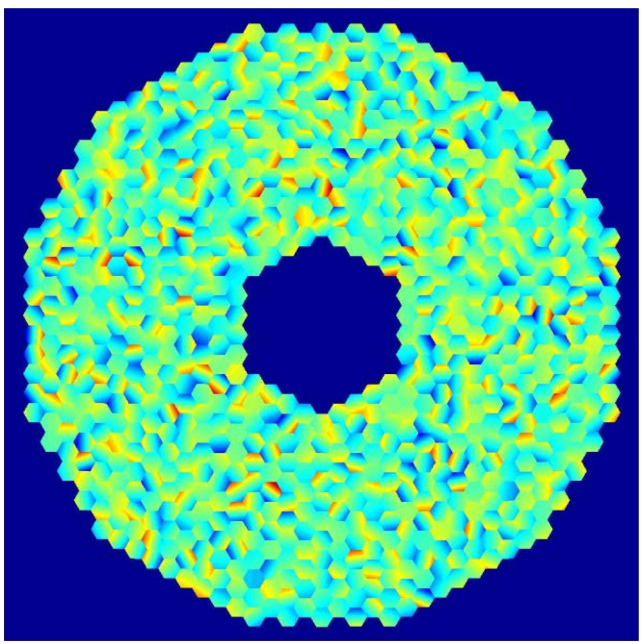
Astrometry error budget assessment

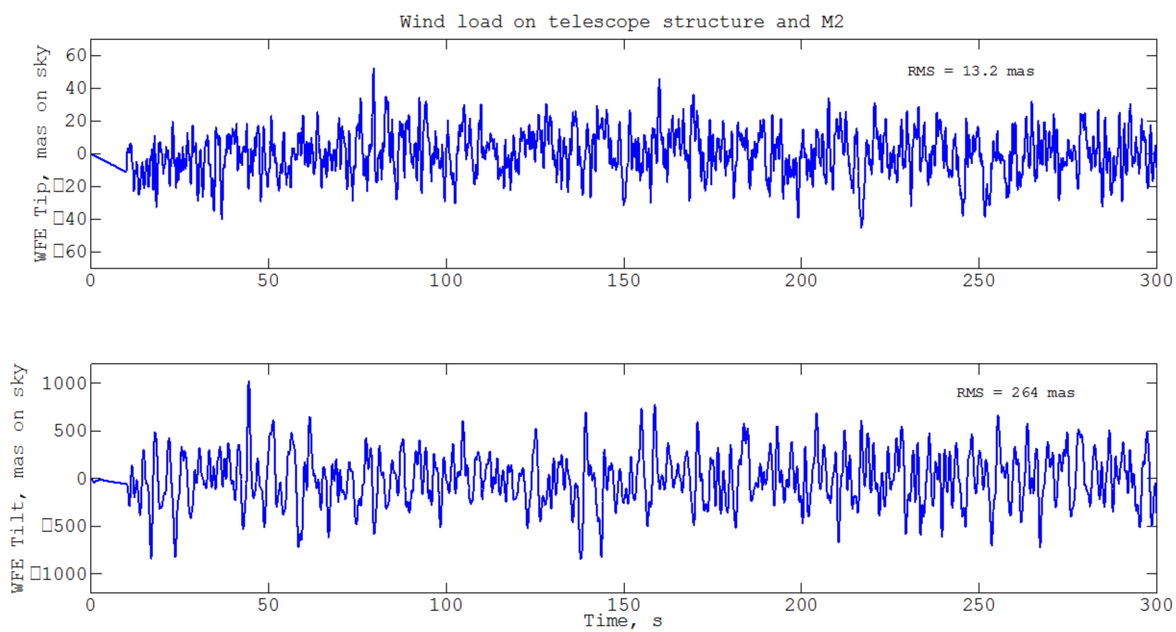
Contributions from:

- Telescope mirrors and structure
  ESO TEL_INS_IF dataset
- Atmospheric perturbations
- Instrumental distortions



RMS WFE: 37 nm

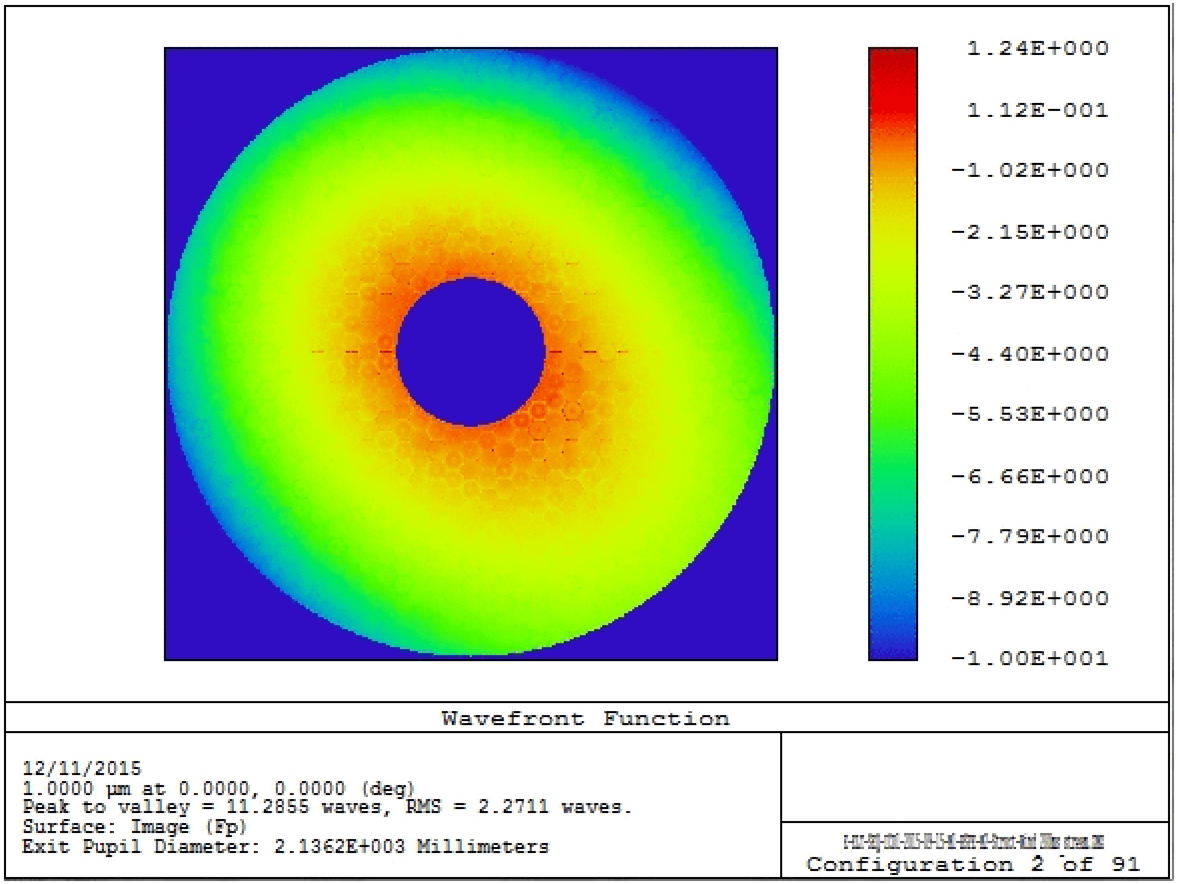




Astrometry error budget assessment

Goal model and separate astrometric stability of

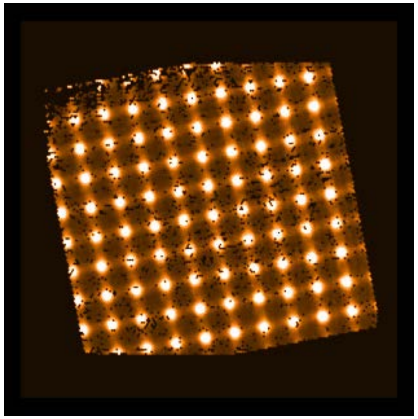
- the E-ELT (M1-M5)
- MICADO / MAORY RelayOptics
- Camera



Astrometric calibration mask

Idea is to put a precise pinhole mask
- in the ext focal plane of the EELT (ie infront of the RO)
- In the entrance focal plane of MICADO (ie between RO and CAM)

- To create an artificial reference star grid on the detector



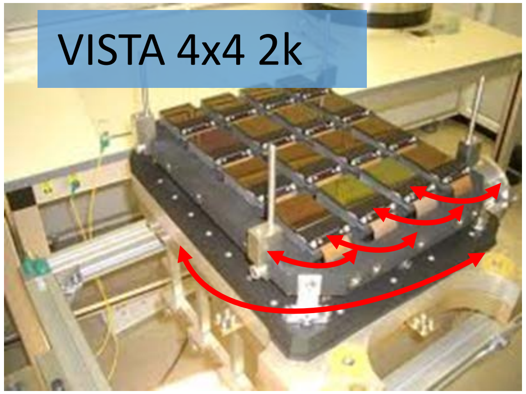
- To calibrate the RO+CAM
- To check rotation effects of

- Idea is simple, the realization is not, since extreme requirements (10^{-7} relative precision) needs to be guaranteed in observatory conditions (variable temperature), and without optical impact on the beam

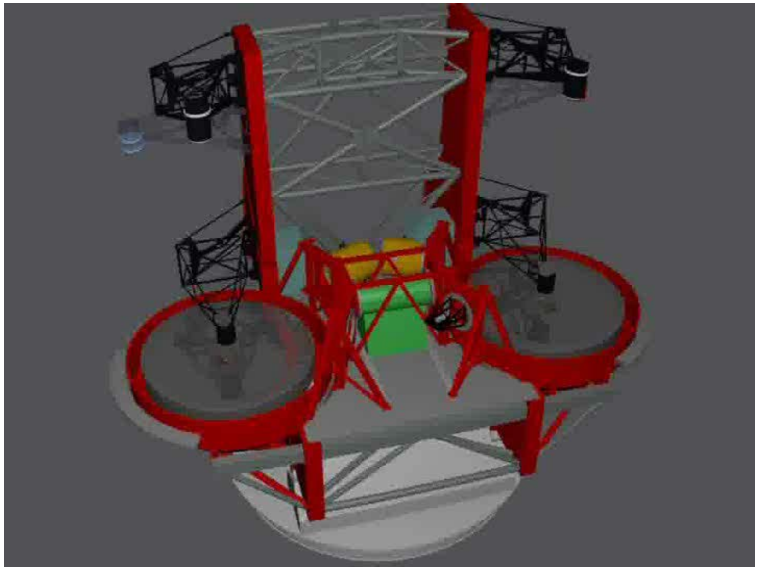
Detector alignment

MICADO tries to combine increased angular precision with increased field-of-view
-> OoM jump in relative precision between largest and smallest dimension over current technology

-> precise inter detector alignment, and detector array positioning in the cold



Updates on vibration suppression



Remember my last ATT

Apply and extent our work for LBT-IF

- Use YAO AO software as sandbox, implement:
    - M2 vibration according to ESO
    - realistic accelerometer readings
    - M4/M5 transfer functions
    - Robust feedfordward control

- Team-up with COMPASS project (LESIA)
    - Implement the above YAO vibration toolbox in COMPASS GPU-base framework to allow for E-ELT scale simulation in little time
    - Estimate benefit of vibration suppression for AO performance (also in the non-diffraction limited regime for faint NGS observations)

Accelerometer based vibration supression for MICADO

Observing *faint* stars with MICADO SCAO


Pic:NASA

Increasing the exposure time for higher WFS SNR

AO Bandwidth is decreased

(0 dB cut off Frequency closed loop)

$$G(s) = K_i\, e^{-T_C}\,\frac{(1 - e^{-T_S})}{T^2 s^2}$$

$$E(s) = \frac{1}{1 + G(s)}$$

$T_s = 1\ ms, T_C = 2\ ms, K_i = 0.25, f_c = 36\ Hz$

$T_s = 10\ ms, T_C = 2\ ms, K_i = 0.25, f_c = 6\ Hz$

Fast structure vibrations are difficult to compensate

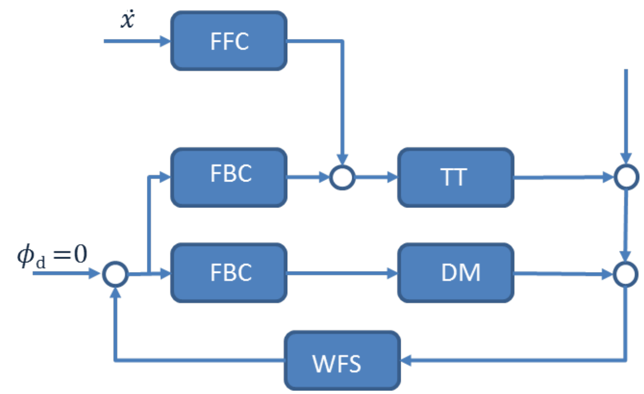
MICADO M2 first eigenfrequency nearby 7 Hz (ESO report)

Goal: Increase AO rejection Bandwidth with accelerometer based feedforward control on Tip-Tilt mirror M5

Simulating vibration effects on AO sytem

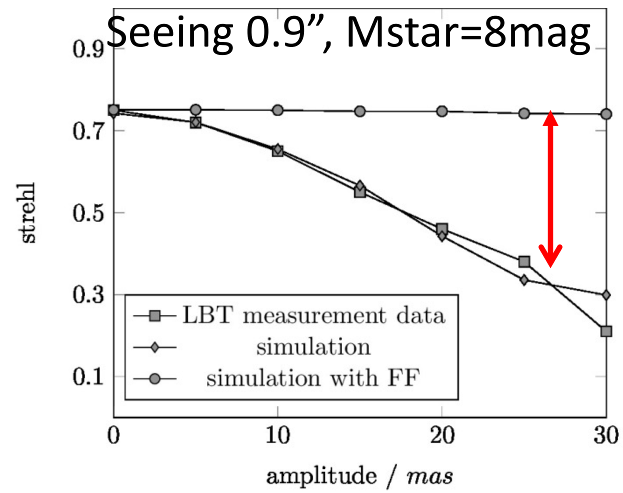
Simulation in YAO

- Enlarged with accelerometer based feedforward control
    - simulation accelerometer signals
    - Reconstruction mirror displacement



Verification of the Simulation and results

- Using measurement data from FLAO/LBT (comissioning report 2011)
- First results of an ideal FF control on an TT mirror
- Test implementation at LBT



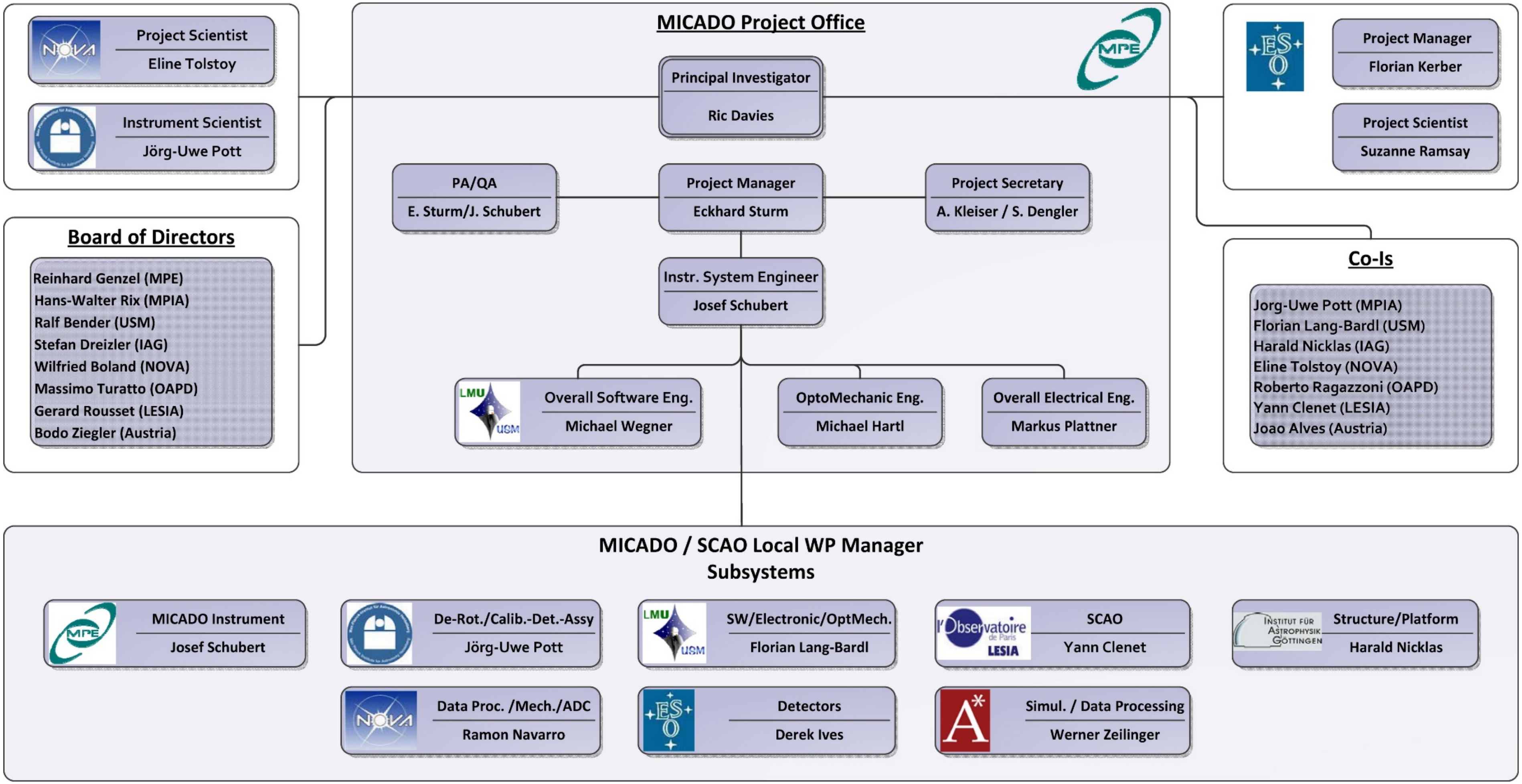
TT residual at 13 Hz

Verify in the lab and at LBT

Next steps

- Investigations on faint stars (brightness, exposure time)
- Laboratory setup for investigating the FF control on a tip-tilt mirror

Project Organisation



Work Breakdown

WPNr Phase Code Le Leve Leve Leve empty HW SubSys Institute Name

MICADO System

WP #	Phase	WP Code	Description	HW Reference	Sys. (S) Sub Sys (SS)	Resp.	Responsible Person
			MICADO System Task WP				
MPE 1	B/CD/E1/E2	ProjOffi	**MICADO System Management**	M 0.0.0.0		MPE	Eckhard Sturm
		ProjAdm	Project Administration	M 0.0.0.0	S	MPE	Eckhard Sturm
		ContrAdm	Contract Administration	M 0.0.0.0	S	MPE	B. Scheiner
		SubcoAdm	Consortium and Subcos Administration	M 0.0.0.0	S	MPE	Eckhard Sturm
		PC-Admin	Project Control	M 0.0.0.0	S	MPE	Eckhard Sturm
		CostCon	*Financial Control and Cost Engineering*	na	S		
		SchedCon	*Planning & Schedule Control*	na	S		
		ConfiCon	*Configuration Management & Control*	na	S		
		DocuCon	*Documentation Management & Control*	na	S		A. Kleiser
		RiksMan	Risk Management and Security	M 0.0.0.0	S	MPE	J. Schubert
		Ops_Mgm	Management Operations and Logistic	M 0.0.0.0	S	MPE	Eckhard Sturm
		ProcMgmt	Procurement Management & Control	M 0.0.0.0	S	MPE	E. Kuhwald
MPE 2	B/CD/E1/E2	PI	PI and Project Lead	M 0.0.0.0	S	MPE	Ric Davies
		Sci	**MICADO Science**	M 0.0.0.0			
MPE 3	B/CD/E1/E2	SciPerf	Science and Performance	M 0.0.0.0	S	MPE	Ric Davies
MPE 4	B/CD/E1/E2	SciPerf	Science Cases Development	M 0.0.0.0	S	MPE	R. Genzel/ N. Förster Schreib
MPE 5	B/CD/E1/E2	PA	**MICADO Product Assurance**	M 0.0.0.0		MPE	E. Sturm/ J. Schubert
		PA-Admin	PA and Safety Management	M 0.0.0.0	S		
		QA	Quality Assurance (incl. Procurement PA)	M 0.0.0.0	S		
	B/CD	Engin	**MICADO System Engineering**			MPE	Josef Schubert
MPE 6		SE_DeCon	MICADO SE and Coordination	M 0.0.0.0	S	MPE	Josef Schubert
		Syst_Eng	*MICADO SE & Coordination (SAMI+MAORY+ ELT)*	na	S		
		Req_Eng	*MICADO Requirements & Verification Engineering*	na	S		
		AIV_Eng	*MICADO Performance & Budgets*	na	S		
		I/F_Def	*MICADO Interfaces Engineering & Control*	na	S		
		OpsAnaly	*MICADO Operational Design Analyse*	na	S		
		DataPro	*MICADO Configuration Design & Analysis*	na	S		
		Budgets	*MICADO Performance & Budgets*	na	S		
MPE 7		Syst_Eng_M	MICADO Overall Mechanical SE	M 0.0.0.0	S	MPE	M. Haug
		Syst_Eng	*Mech. SE & Coordination (SAMI+MAORY+ ELT)*	na	S		
		DataPro	*Mech. Configuration Design & Analysis*	na	S		
		I/F_Def	*Mech. Interfaces Engineering & Control*	na	S		
		AIV_Eng	*Mech Requirements & Verification Engineering*	na	S		
		AIV_Eng	*Mech. Budgets*	na	S		
MPE 8		Syst_Eng_O	MICADO Overall Optical SE	M 0.0.0.0	S	MPE	Michael Hartl
		Syst_Eng_O	*Optical SE & Coordination (SAMI+MAORY+ ELT)*	na	S		
		DataPro	*Optical Configuration Design & Analysis*	na	S		
		I/F_Def	*Optical Interfaces Engineering & Control*	na	S		
		Req_Eng	*Optical Requirements & Verification Engineering*	na	S		
		AIV_Eng	*Optical Performance & Budgets*	na	S		
MPE 9	B/CD	Syst_Eng_E	MICADO Overall Electronic SE	M 4.0.0.0	S	MPE	Markus Plattner
		Syst_Eng	*Electr. SE & Coordination (SAMI+MAORY+ ELT)*	na	S		
		DataPro	*Electr.l Configuration Design & Analysis*	na	S		
		I/F_Def	*Electr. Interfaces Engineering & Control*	na	S		
		Req_Eng	*Electr. Requirements & Verification Engineering*	na	S		
		AIV_Eng	*Electr. Budgets*	na	S		
see USM 7	B/CD/E1/E2	S/W Eng	MICADO Overall SW SE (OSS + SOS)	M 5.0.0.0	SS	USM	M.Wegner (J.S)

Work Breakdown & FTE distribution

- Germany (58%)

  MPE project office, cryostat, cold optics, systems engineering

  IAG support structure, cable wrap

  USM spectrograph module, electronics, control software

  MPIA instrument scientist, derotator, focal plane array, instrument calibration

- France (18%)

  LESIA/GEPI/IPAG SCAO (WFS assembly, RTC, control software, calibration), coronagraphic mode

- Netherlands (11%)

  NOVA project scientist, ADC, filters, wheels & mask, imaging/astrometry pipeline

- Italy (1%)

  INAF-OAPD miscellaneous small contributions

- Austria (12%)

  A* simulator, spectroscopic pipeline, PSF reconstruction

- ESO detectors: procurement, characterisation, control

Timeline

Date	Milestone	Comments
2015, Oct	Kick-Off	Preliminary Design Phase (B) begins with a 1.5-year baseline & interface consolidation phase.
2017, Apr	System Requirements Internal Review	Once the system baseline is defined, the design will be developed more fully over the following 1.5 years
2018, Oct	**Preliminary Design Review**	Following this review, the project can begin the Final Design Phase (C).
2020, Oct	**Final Design Review**	Following this review, project will enter Manufacturing, Assembly, Test, and Integration Phase (D).
2022, May	MAIT Mid-term Meeting	Progress will be formally assessed half-way through the MAIT Phase.
2023, Oct	PAE Document Review (= Test Readiness Review, start of PAE process)	This will take place 6 months before the scheduled date for the European Acceptance Review, to confirm the instrument is ready to begin formal testing during that period
2024, Jun	**Preliminary Acceptance Europe**	This will take place once testing is completed and the reports are written. The instrument will be shipped to the observatory once this review is passed.
From 2025	**Provisional Acceptance in Chile**	Telescope technical first light with ~480 segments early 2024; Telescope commissioning with all segments from Dec 2024; MICADO commissioning 1 with SCAO module; MICADO commissioning 2 with MAORY.

First step done: Kick-off in Vienna, ATT done, more to come…

Date	Milestone	Comments
2015, Oct	Kick-Off	Preliminary Design Phase (B) begins with a 1.5-year baseline & interface consolidation phase.
		the system baseline is defined, the design will be …oped more fully over the following 1.5 years
		…wing this review, the project can begin the Final Design …e (C).
		…wing this review, project will enter Manufacturing, …nbly, Test, and Integration Phase (D).
		…this review is passed.
		…cope technical first light with ~480 segments early 2024; …cope commissioning with all segments from Dec 2024; …DO commissioning 1 with SCAO module; …DO commissioning 2 with MAORY.


MAX-PLANCK-INSTITUT FÜR ASTRONOMIE

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Institutsmeldungen › 2015_10_07_MICADO

Startschuss für die E-ELT-Kamera MICADO: eine neue Ära der Präzisionsastronomie

Die MICADO-Kamera am E-ELT tritt in die Designpha…

7. Oktober 2015

Für die MICADO-Kamera, das Instrument mit dem da… Extremely Large Telescope (E-ELT) seine ersten Bild… beginnt eine neue Phase: In einer gemeinsamen Abs… (Memorandum of Understanding) auf der „Kick-off"-… bestätigten die Partner in Deutschland, Frankreich, … Österreich und Italien ihre Teilnahme am Projekt. Zw… 18. September, hatten das Konsortium und die Europ… Südsternwarte (ESO), die das Teleskop baut, den en… Kooperationsvertrag unterzeichnet. Nach diesen Me… Projekt nun in die Designphase ein. Als erste, dedizie… E-ELT wird MICADO beugungsbegrenzte Abbildungen… Wellenlängen (Wärmestrahlung) mit dem Riesentele…

MICADO, die „Mu… for Deep Observa… European Extrem… (E-ELT), ein Teleskop mit 39 Metern Spiegeldurchmesser, konzipiert. Dieses revolutionäre Teleskop wird das größte optische bzw. Nah-Infrarot-Teleskop der Welt sein und etwa 15 Mal mehr Licht sammeln als die heute existierenden größten optischen Teleskope. Die MICADO-Kamera wird beugungsbegrenzte Abbildungen bei Nah-Infrarot-Wellenlängen ermöglichen und eine neue …

Danke
für die Aufmerksamkeit