ESO Technology Development Programme & future plans

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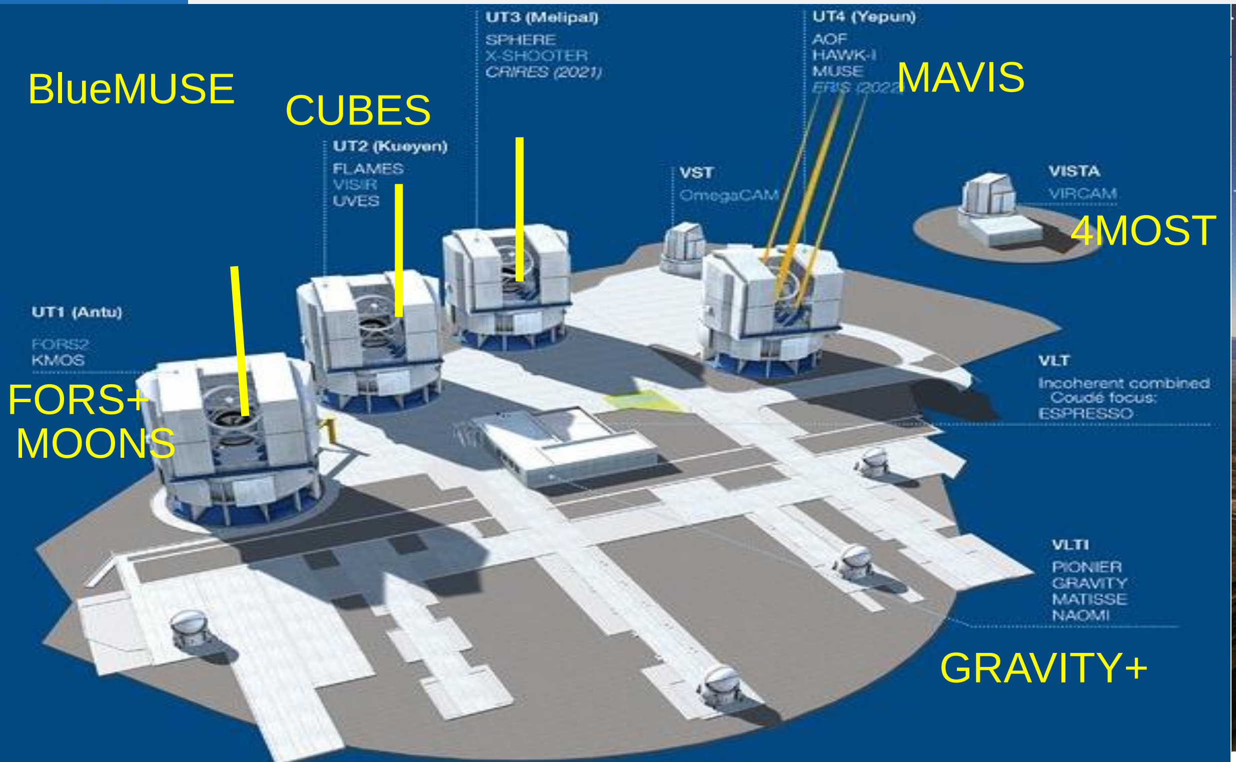
European Southern Observatory

ESO context & infrastructure



Very Large Telescope & VLT Interferometer in operation

- 4x 8-m & 4x1.8m telescopes + interferometric mode
- 2 survey 2 & 4m class telescopes
- Continuous renewal of instruments and improved capabilities ***requiring new technologies***

- 39m diameter, primary mirror, 798 high precision segments re-aligned to ~0.0001 mm in real-time
- Science: exo-earths, deep universe, resolved populations, open window to the unknowns
- Timeline 2014-2027; ESO capital cost: 1300MEUR
- Large effort to build 1st and 2nd generation instruments ***requiring new technologies***

Technology development approach

- Innovative technologies for telescope subsystems are developed within the construction project: Phase A-B-C largely in collaboration with industry➔ see slides of **Roberto Tamai**
- In few cases, pathfinder projects on smaller telescopes were used to prepare for larger telescope needs: i.e VLT to ELT
- Some innovative technologies with TRL 5-6+ are also developed within instrument construction in collaboration with institutes few example also provided in the slides of **Suzie Ramsay**
- Low TRL technologies are covered by a dedicated Technology development programme with strong collaboration with institutes: **my presentation**

Purpose of the ESO Tech. Dev. Programme

The requirement to not only develop but secure the technology for the future means that only **rarely** will a TecDev project take the form of a **conventional procurement from industry or institutes**. Usually, a **collaborative approach** will be required to ensure that the intellectual property developed in the project is either transferred to ESO in a meaningful way, or some other scheme is used to ensure the technology will be available and further developed over the period of time that it is required by ESO.

On-going Technology Development projects

Project name/Description	Project Manager	Status	Start date	Completion date
FIAT detector test bench for ELT IR detectors	R.Guzman	completed	~~2015~~	~~Q4 2021~~
Cryo-amplifiers for advanced ALMA receivers	Gie Han Tan	active	2017	4Q 2022
LGS Systems R&D (WP1-2-3) closed with reporting and WP(4-5) active	D.Bonaccini W.Hackenberg	active	2016	4Q 2023
Advanced reflective coatings	R.Holzloehner	Active	2019	Q2 2022
Large Saphira Detector 512x512	M. Engelhardt G. Finger	Active	2018	Q2 2022
New Generation of Controller II	L. Mehrgan D. Ives	Active	2020	1Q ‘24
Development of deformable mirrors for future ESO projects Phase 2 (WP1-2-3 and now -4)	P.-Y. Madec S. Stroebele	Active	2020	2023
Curved science CCD detector	M. Engelhardt O. Iwert	Active	2Q ‘21	2Q’24
PCS Technology Development Phase 2	M.Kasper	Active	2020	End 2022
Laser Frequency Combs for blue and IR	O. Pfühl	Active	Q42021	1Q ‘24
ATTRACT phase 2	A. Williams	Active	2021	4Q 2024
XAO DM Phase 3: 128x128 DM prototype for PCS	P.Y Madec S. Stroebele	Active	Q1 2022	2024

In orange: directly relevant for ELT

Future Technology Development projects

Project name/Description	Project Manager	Status	Start date	Projected completion date
ATTRACT 3 (Submitted to EC)	A Williams	OK DT	3Q22	2026
Advanced Graphics Processing Unit (GPU) technology for ALMA correlators	G. H. Tan	To be submitted to DT	2Q ‘22	1Q ‘24
OPTICON22 (PCS R&D, DM dev, VLTI) to be submitted to the EC April ‘22	N. Hubin M. Kasper A. Merand	Discussed with DT	3-4Q ‘22	3-4Q ‘26
SAXO+ Adaptive Optics as part of the PCS roadmap	M. Kasper (TBC)	Draft agreement	2022 ?	1Q ‘25
Pyxel simulator (awaiting DT decision and FTE allocation…)	E. Georges	Postponed by DT	??	??
ALFA large IR arrays development testing (2Kx2K)	D. Ives (TBC)	exploration	??	??
CMOS technology for science detectors	E. Georges O. Iwert (TBC)	exploration	??	2023-4?
2Kx2K (TBC) Large SAPHIRA detector with ESA/ Leonardo	TBC	exploration	2022	2025
LGS Monostatic tip-tilt sensing – delay method	D.Bonaccini (TBC)	After CaNaPy Commissioning	2023	2024
Dynamic Refocusing at EELT scale	D.Bonaccini and S.Rabien (MPE)	With WLGSU-WHT at ORM	2022	2023

Phase 1 of the DM technology development

- 2 types of DMs considered
  - Compact DM (open loop AO: MOAO and Dual AO):
    - Development and manufacturing of a prototype DM
  - Extreme AO DM (XAO):
    - Increase Technology Readiness Level, demonstrated by breadboards
    - Prepare for a second development phase to reach the level of a prototype DM

- Fixed price Call for Tender for 2 parallel developments

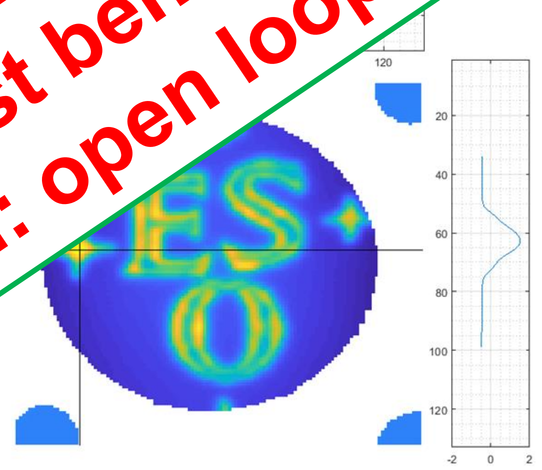
- 3 contracts were signed in May and June 2016
  - ALPAO - Compact DM
  - ALPAO - XAO DM
  - IOF-PI – XAO DM (Fraunhofer institute Jena, Physik Instrumente)

- All contracts completed by end of 2019➔ Phase 2

Outcome of the Compact DM Phase 1

- ALPAO Compact DMs
  - Design, manufacturing, test a … LESIA) of a 64x64 actuator DM (3228 actuators - 96 mm pupil d… ke, speed, compactness… OK
  - Stability with time (… nd gravity (reference plate) to be improved: major…
  - Thermal m… e improved

3228 a…
6 nm rm…



Successful de-risking activity beneficial to
- **MAVIS: 2 DMs**
- **GRAVITY+: 4+1DMs**
- **MICADO test bench**
- **HARMONI: open loop DM?**

Identification of the Phase 2 project needs

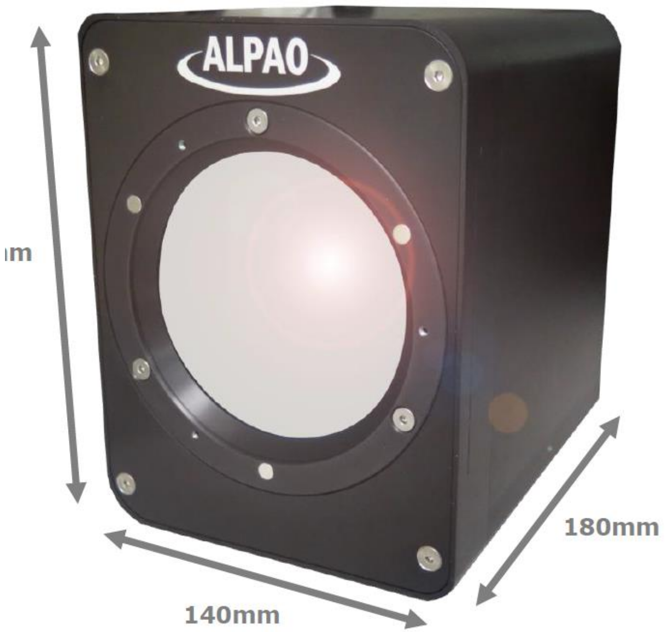
Following discussions with stakeholders, following needs have been identified

VLT/ELT short/mid term — ELT long term

	MAVIS	GRAVITY+	HARMONI	MOSAIC	PCS
Number of actuators	54x54	40x40	28x28	32x32	128x128
Actuator pitch	1.5 mm	2.5 mm	1.5 mm	1.5 mm	1.5 mm
Pupil diameter	80 mm	100 mm	40 mm	50 mm	190 mm
Control frequency	1 kHz	1 kHz	500 Hz	1 kHz	4 kHz
Stroke (TBC)	5 µm	10 µm	10 µm	5 µm	2 µm
Resolution	-	-	-	-	0.1 nm
Stability with time	N/A	N/A	Yes	Yes	N/A
Stability with temperature	Yes	Yes	Yes	Yes	Yes
Stability with gravity	Partly	Partly	Yes	Yes	Partly
Low power consumption	N/A	N/A	N/A	N/A	N/A
…					

Deformable Mirror Development Phase 2

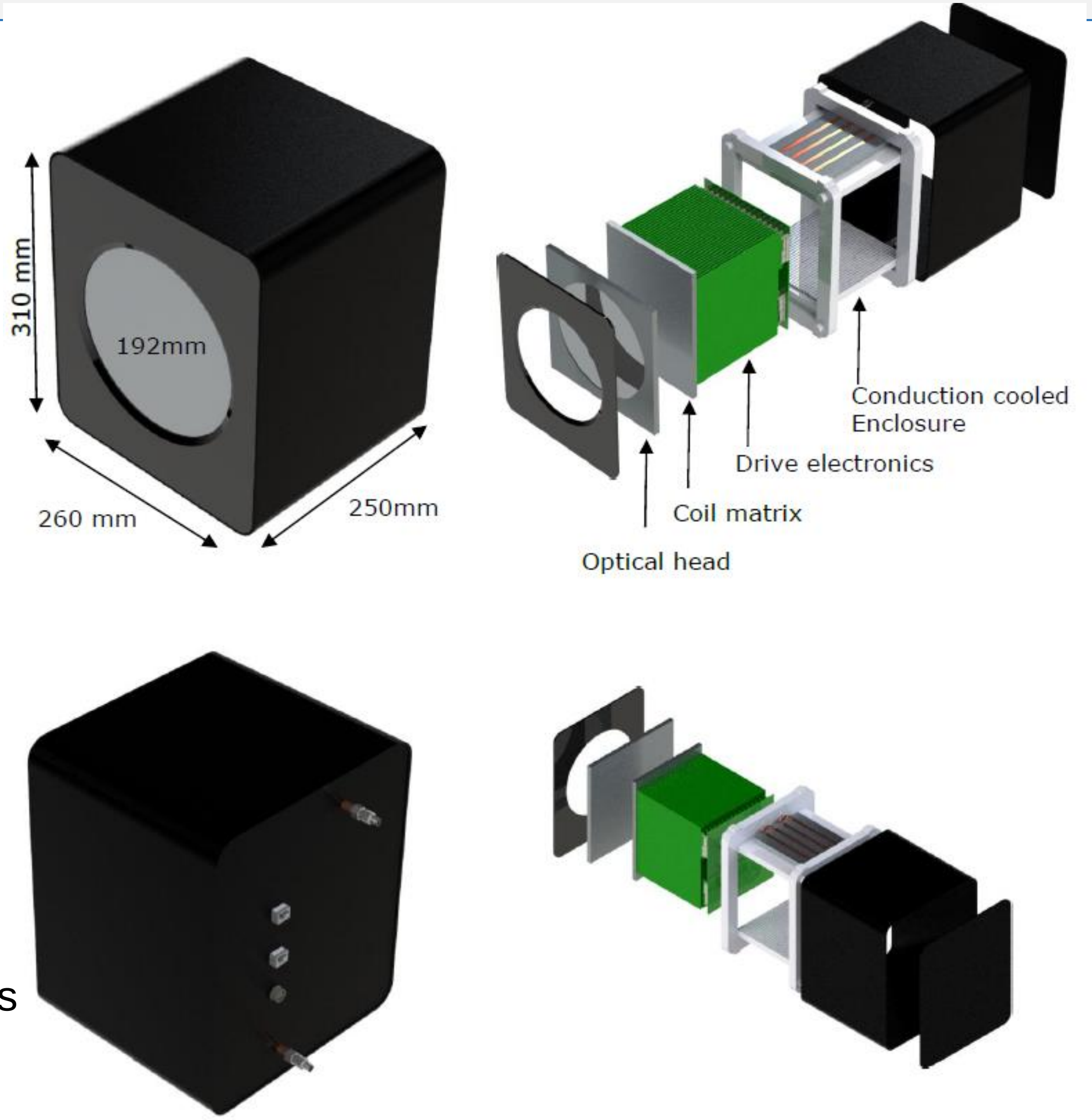
- Phase 2: follow-up of the Compact DM Phase1 developments
- Goal: design, manufacture, test high stability DM prototypes
  - High stability vs time (creep), temperature and gravity
  - 100 mm diameter – 2.5 mm pitch (GRAVITY+) and/or 1.5 mm pitch (MAVIS); 1 kHz control frequency, HARMONI?
- Phase 2 contract negotiated with ALPAO (WP1-5)
  - DM design fully and test bench development fully funded by Tech Dev. WP1-3)
  - WP4-5: GRAVITY+ and MAVIS high stability DM Prototypes
- Collaboration with MPE signed to co-fund WP1-3; G+ motivation
- WP4-5: MAVIS project, MPE-G+



3228 actuators deformable mirror produced during Phase 1 (used by MICADO test bench); one additional unit procured by Subaru→ TMT-PFI

Phase 3 PCS scale 1 DM Development started

- ➢ scale 1 DM prototype for ELT PCS 128x128 act.
- ➢ Initial development WPs to be launched 10 ‘22
- ➢ Full prototyping 128^2 pending availability of funds
- ➢ Started discussion with TMT Planetary System Imager (PSI) team for collaboration
- ➢ Started discussion also with NASA and ESA
- ➢ Horizon Infratech 2022 to be submitted: PCS WP: 1.3ME for DM development



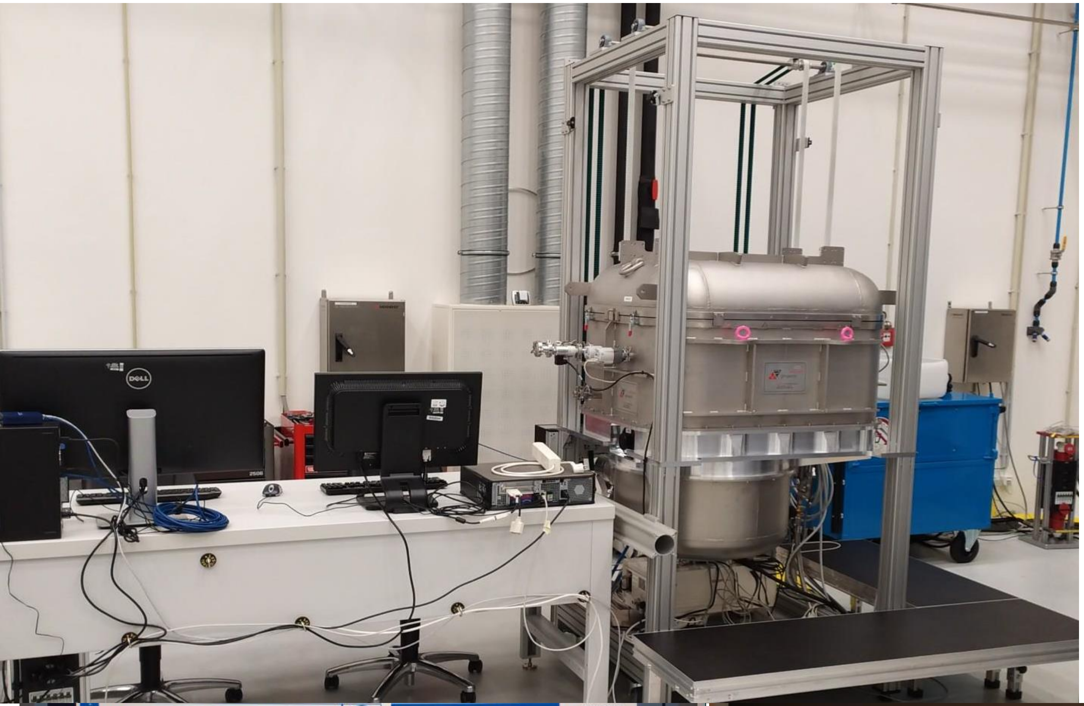
DM Conceptual Design- ALPAO (Phase 1)

- Very compact design, thanks to the embedded control electronics
- Large cable bundles replaced by a single high-speed fiber

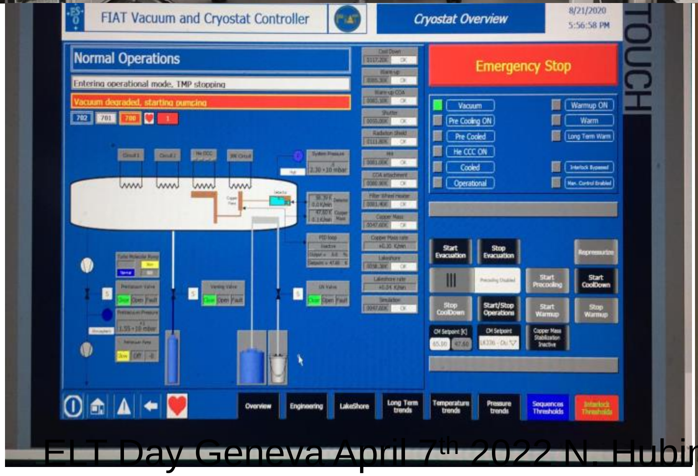
PCS Deformable Mirror: Key requirements

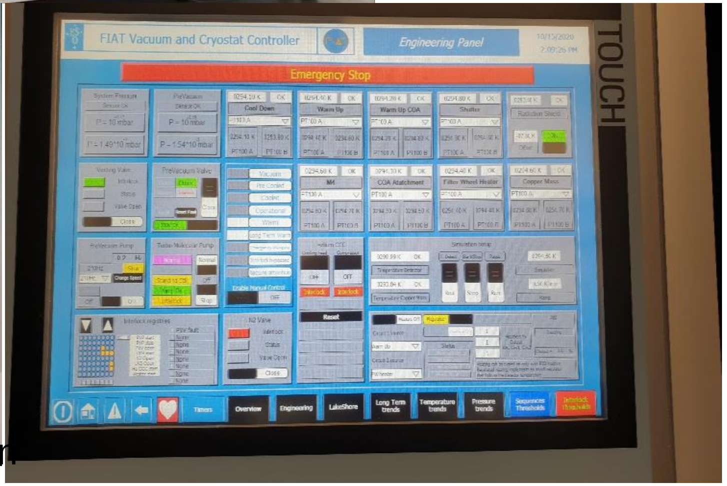
- Application is eXtreme AO for High Contrast Imaging (PCS)
  - Actuator count: 10800 to 20000
  - DM diameter: 150mm to 450mm
  - Small stroke settling time: 50nm to ±10% within <150µs, goal <100µs
  - Stroke: > 3µm
  - Resolution: 0.1nm goal 0.06nm! ~15Bit
  - Hysteresis: <5%
  - Few non-functioning actuators can be tolerated

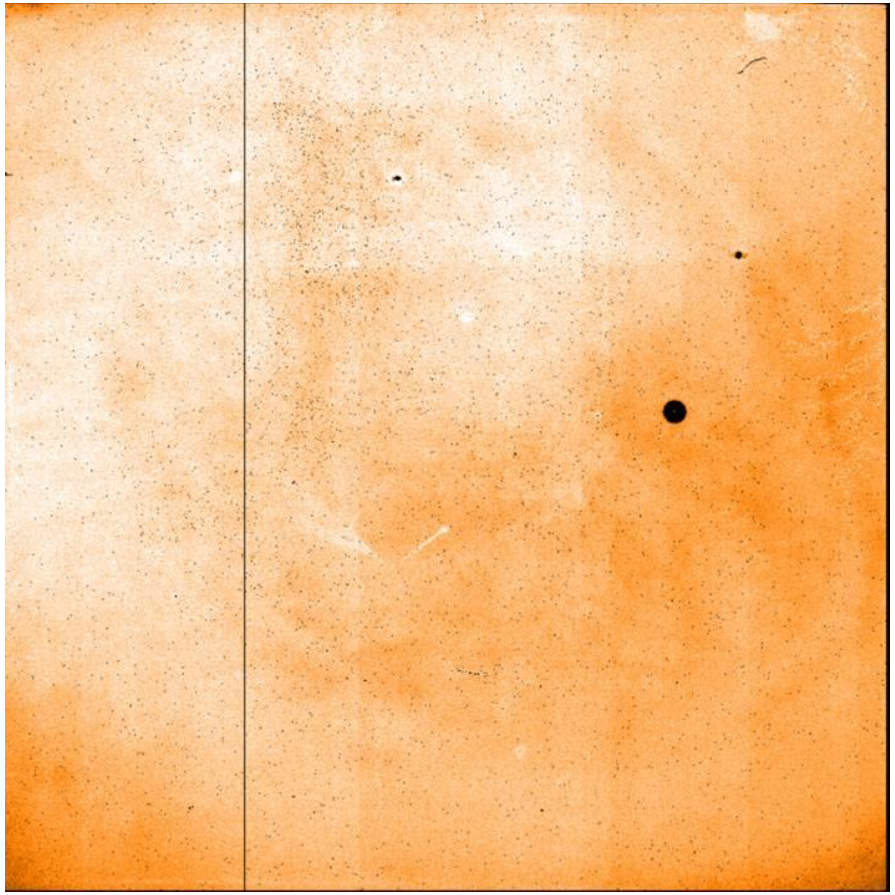
FIAT: a test facility for H4RG detectors testing



- FIAT designed to allow deployment of IR arrays for use in their final operating environment at their peak (optimized) performance; currently powered by NGC I in the future NGC II
- Automatic archiving of array characteristics in ESO archive

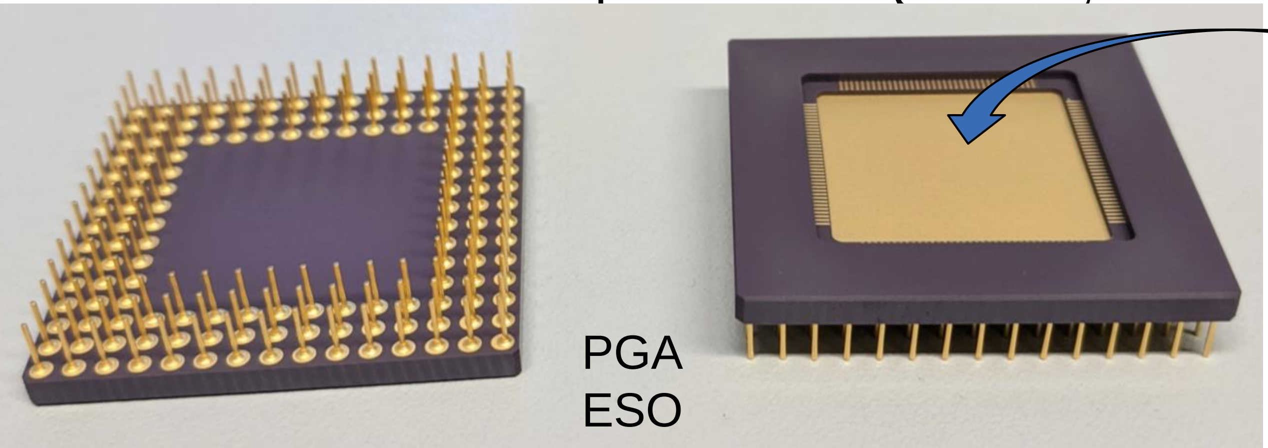




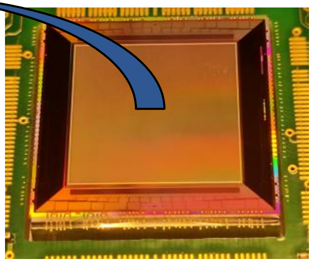


Large Saphira IR

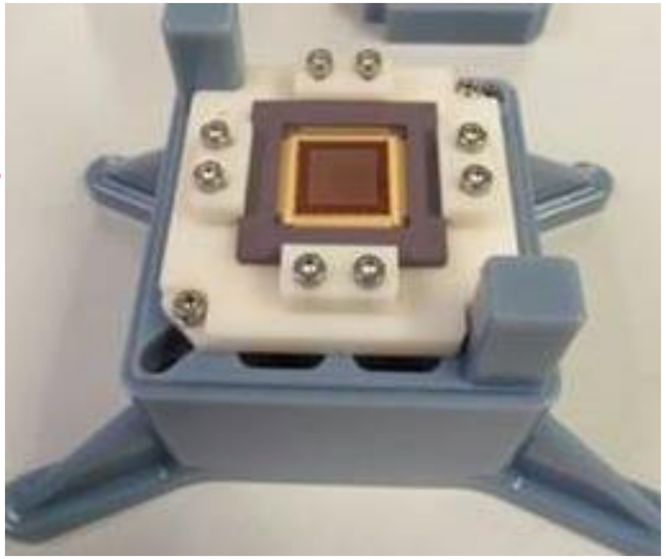
- Based upon very successful Saphira Detector used in GRAVITY (320x256 pixels)
- 512 x 512 eAPD, 2k fps, designed for fast (pyramid) AO as well as low-noise scientific read-out
- Possibility to be used in ELT- PCS, ELT PDS (TBC), step towards even larger eAPD arrays made in ESO member states
- Consortium ESO, MPE & NRC Canada (plus AIP Postdam in 2020); Contract with Leonardo UK well underway
- Package, detector mount & preamp designed at ESO
- Warm test of ROIC planned for Q1 2022, cold tests of APD Q2/Q3 2022



PGA
ESO



ME1120 ROIC
LEONARDO



* ROIC: Read Out Integrated Circuit

eAPD development?: from GRAVITY to the future?

- Large 512x512 SAPHIRA ROIC ME1120 for ESO complementary to 1Kx1K ROIC ME1070 for University of Hawaii IfA (NASA) and contract from ESA 2K
  - 1Kx1K ME1070: 16 outputs, low glow, long integration times, goal to compete with large format conventional HawaiiXRG arrays, low trap assisted tunneling
  - 512x512 ME1120: 64 outputs for high speed (8.7Mpix/s/output, DCS frame rate 1KHz), AB multiplexer for high speed, low glow, intermediate reference pixel subtraction for low noise, optimized for adaptive optics and pyramid WFS➔ ELT PCS
- Opportunity of the 1kx1k/2kx2k funded by NASA/UH & ESA to explore further this technology for science arrays?... Horizon Infratech 2022 to be submitted: VLTI WP in the frame of Asgard visitor instrument
  - NGC and cryostat on loan to ESA for current 2K testing.

New Generation of Controller (NGC II) launched in 2020

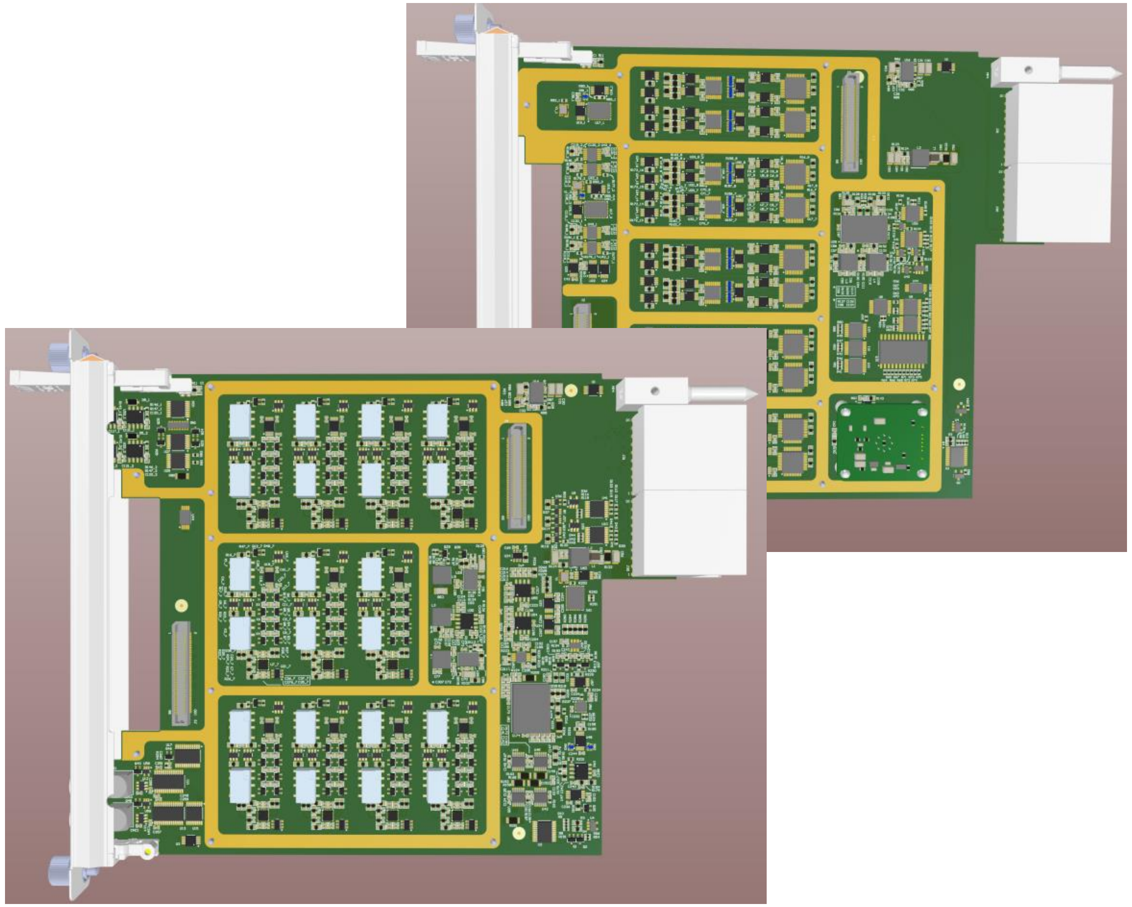
- Motivations:
  - Obsolescence of current New Generation of Controller I
  - technical limitations of NGC I not compliant with ELT and user's needs
- Develop a new ESO standard detector controller
  - For state-of-the-art detectors SAPHIRA, GeoSnap, H4RGs, CCDs (LBNL), Te2v CCDs
  - For ELT & new VLT instruments (starting with FORSup, CUBES, MAVIS..)
- Strategy:
  - Reduce the production time/cost: NGCII will be based on COTS for the back-end
  - The central development will be on the core part of a controller (front-end): clean, fast, stable clocks/biases, and video signal processing
- **Conceptual design well-advanced in 2021 and non-COTS prototypes for IR**
  - Our customers are eager to use NGC II and ELT-VLT delivery times are aggressive…
  - Collaboration with ANU for the liquid cooling NGC II design and prototyping

NGCII NON COTS Prototyping

- CMOS C20B20 RTM
  - 20x CMOS Clock & Bias
  - 10MHz, Adjustable High Level 2.0V to 5.5V
- CMOS AQ22 RTM
  - 22 Ch. Acquisition RTM
  - Fully Differential Signal Path
  - Switchable Gain

  ±2.048V or ±1.024V full scale input range

< ±2µV/K Drift
< 1µV$_{RMS}$ White Noise (10Hz to 1kHz)
< 0.5µV$_{RMS}$ Pink Noise (1mHz to 10Hz)



NGCII COTS

- ✓ 6-slot MTCA rack, expander hardware
- ✓ White Rabbit technology Devkit
- ✓ MMC Devkit

MicroTCA.4

Precision timing and analog signal extension for high energy physics. Consortium led by DESY.

EUROPEAN SPALLATION SOURCE

PICMG

Max Planck Institute for Plasma Physics

SLAC NATIONAL ACCELERATOR LABORATORY

CERN

DESY.

MTCA: Micro Telecommunications Computing Architecture

PICMG: PCI Industrial Computer Manufacturers Group

Commercial Components

- Shelf with Backplane
- FPGA Modules (with 10GbE)
- Power Supply
- ADC Modules

FPGA Modules (incl. 10GbE)

5/6 Slot Compact Shelf

600W PSU Module

ADC Module

Future needs for Astrocombs

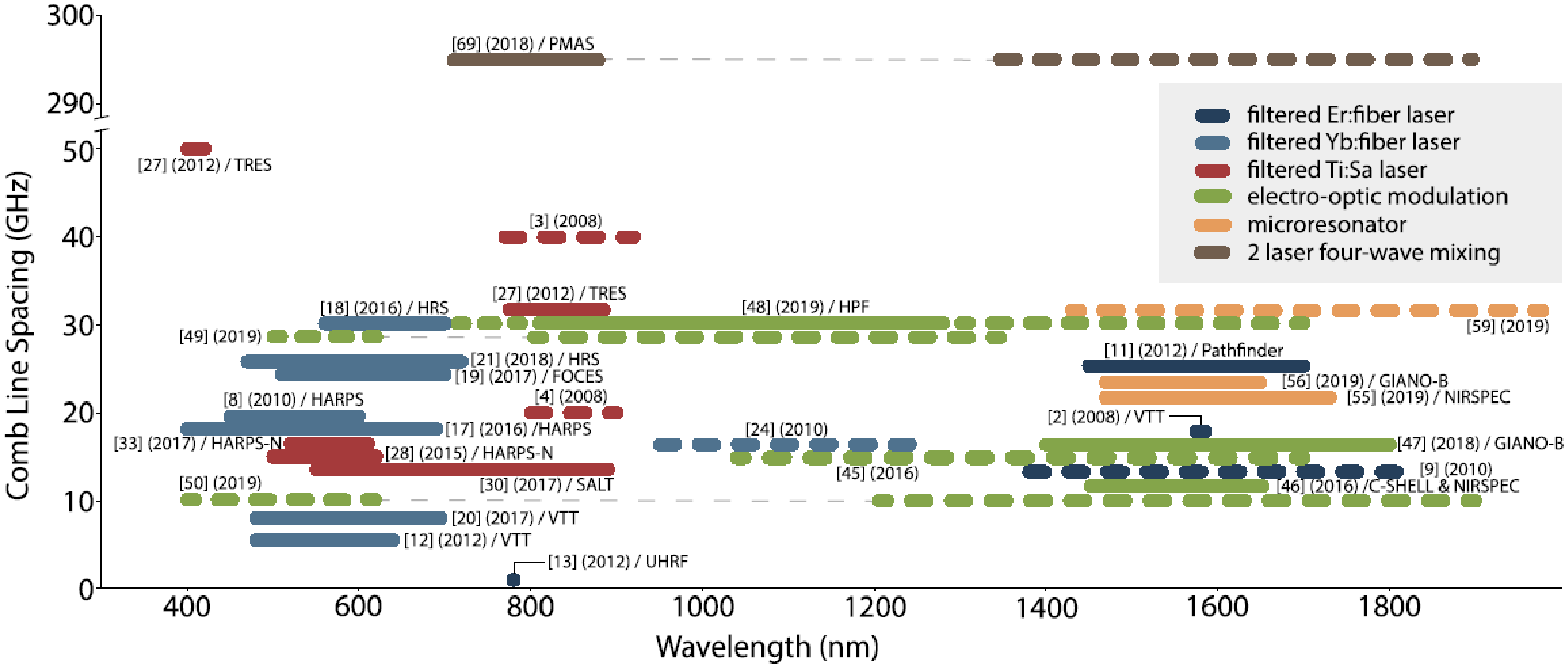
- Calibration systems based on Laser Frequency Comb (LFC) have been early identified as the ideal calibrators for high resolution spectrographs
- Typical science cases are Key for instrumenst like HARPS, ESPRESSO and ANDES@ELT (but also for CRIRES+, NIRPS, HR-MOS..):
- Unavailability of pure Th-A lamps makes the need for astrocombs even more urgent
- ESO has pioneered this technology with a 10+ year collaboration with MPQ (Haensch group) and contracts with MENLO System (Ger), to obtain turn-key astrocombs for HARPS and ESPRESSO
- Amazing, unique results obtained with HARPS

- Latest news: Horizon Infratec 2022 WP on astrocomb for HIRES/ANDES

Ultra stable calibration source: Laser Frequency Comb

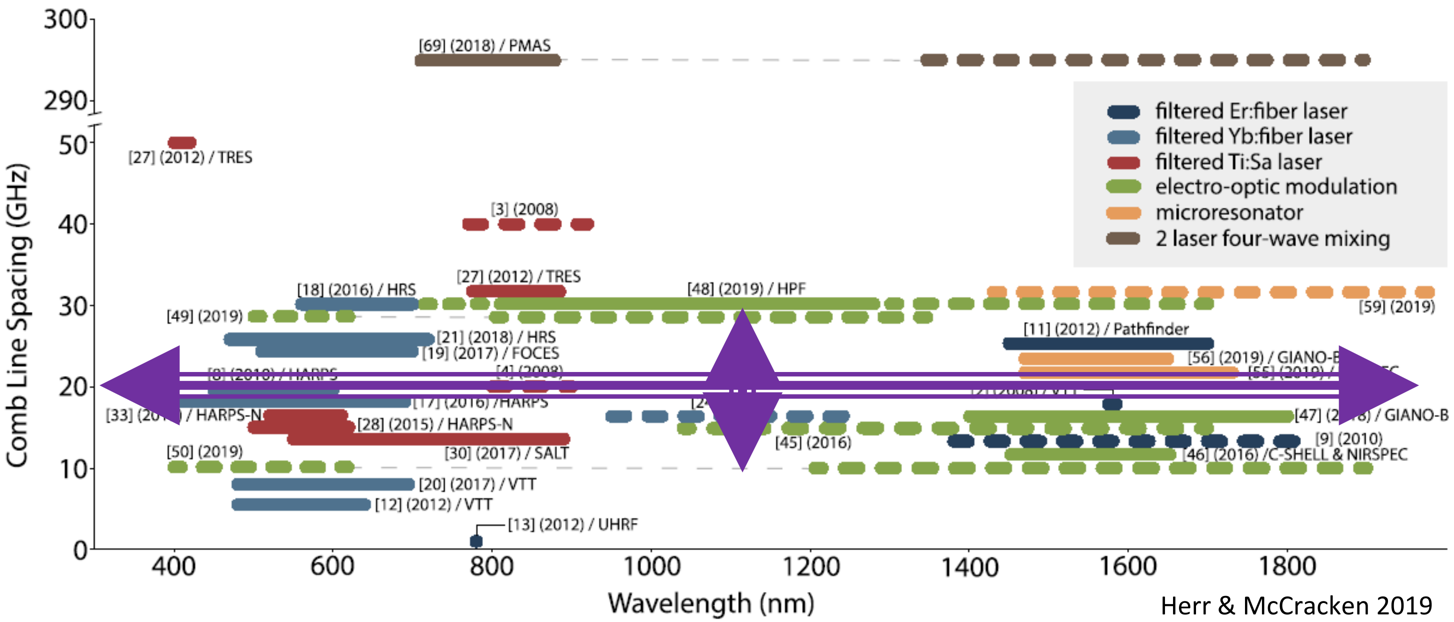
Current state of Laser Frequency Comb systems in astronomy for spectroscopy calibration:

- about 20 Astrocombs @ Observatories / 10 permanent / 2 @ ESO
- VIS (400-700nm) or NIR (1400-1800nm); Typical bandwidth 150 – 400nm



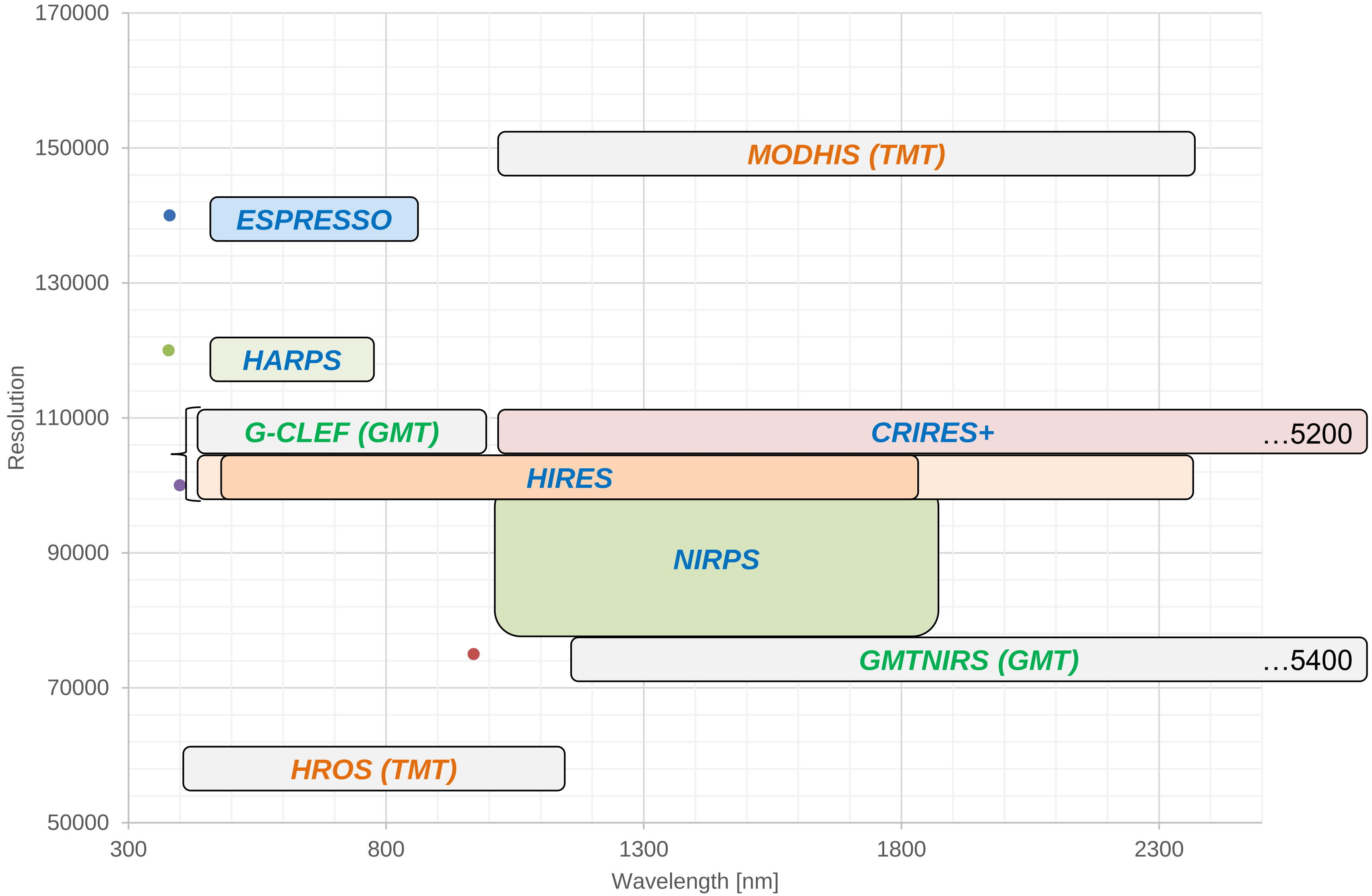
Ideal Future of LFC systems (based on need of existing and future instruments)

- Extend capabilities to UV (<380nm) to NIR (2400nm), maybe even MIR (5400nm)
- Tunable line spacing (allows to shift spectral lines on detector and to adapt to various spectral resolutions)
- extends wavelength coverage to UV (<380nm) without photo-degradation

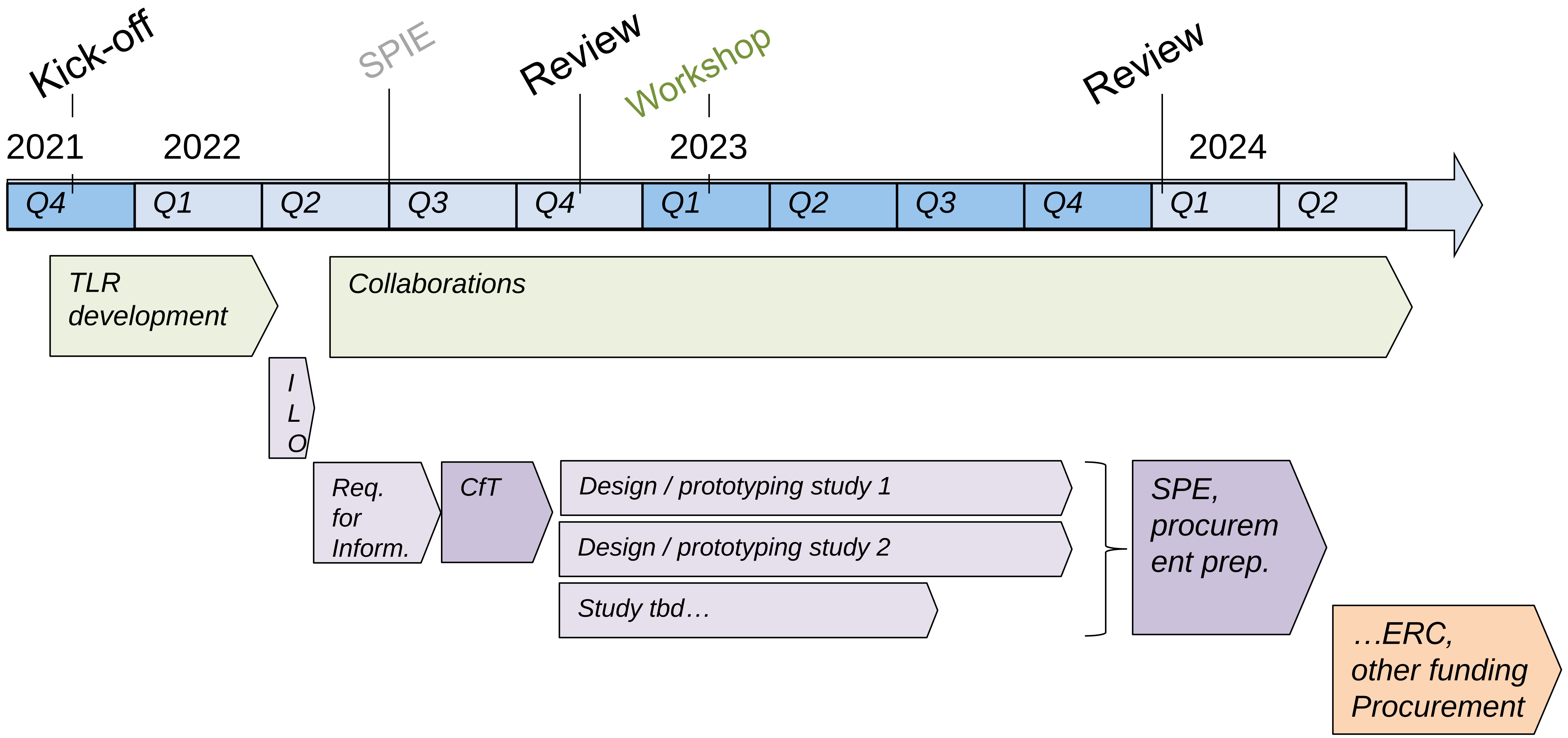


Herr & McCracken 2019

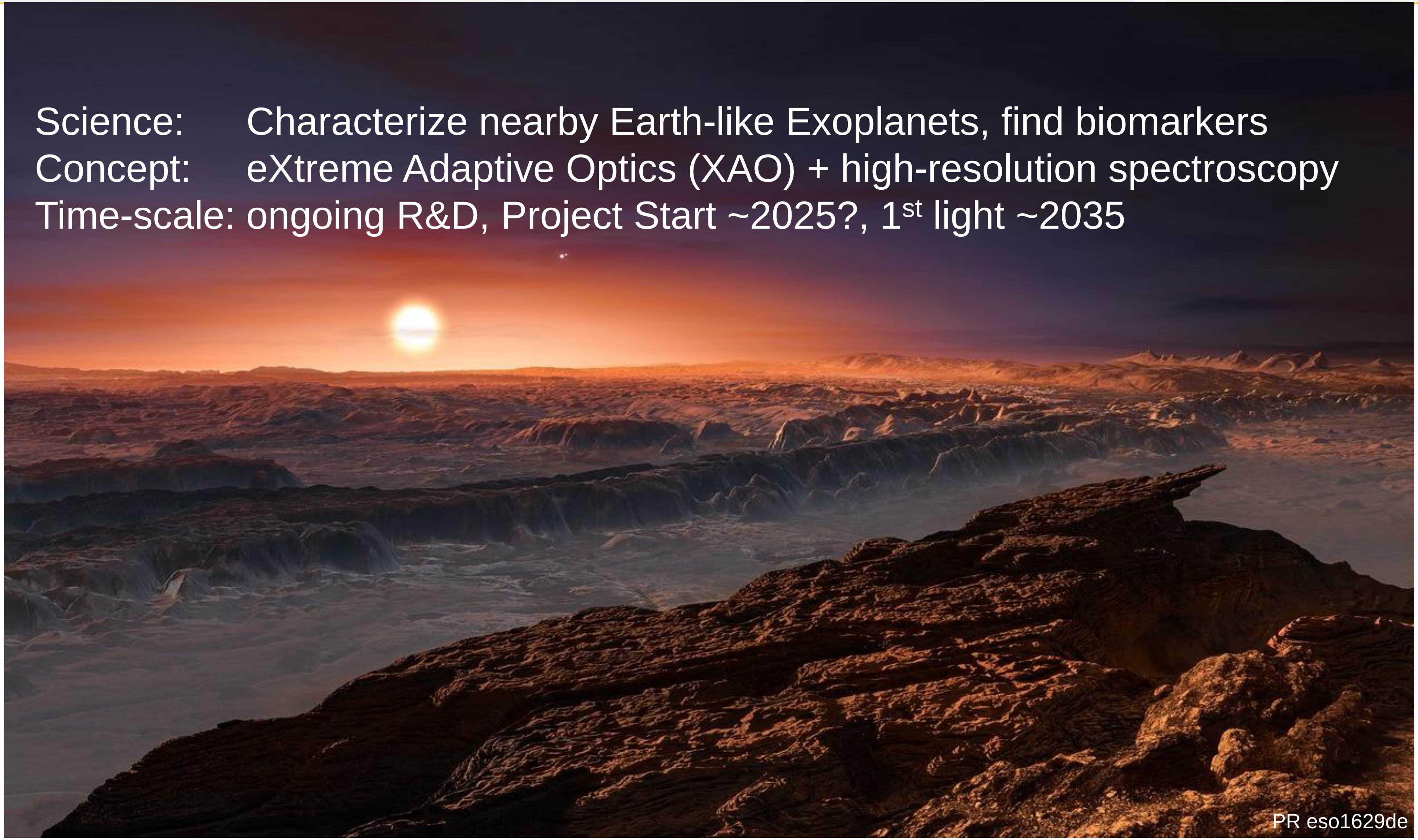
Potential customers



Astrocomb imeline

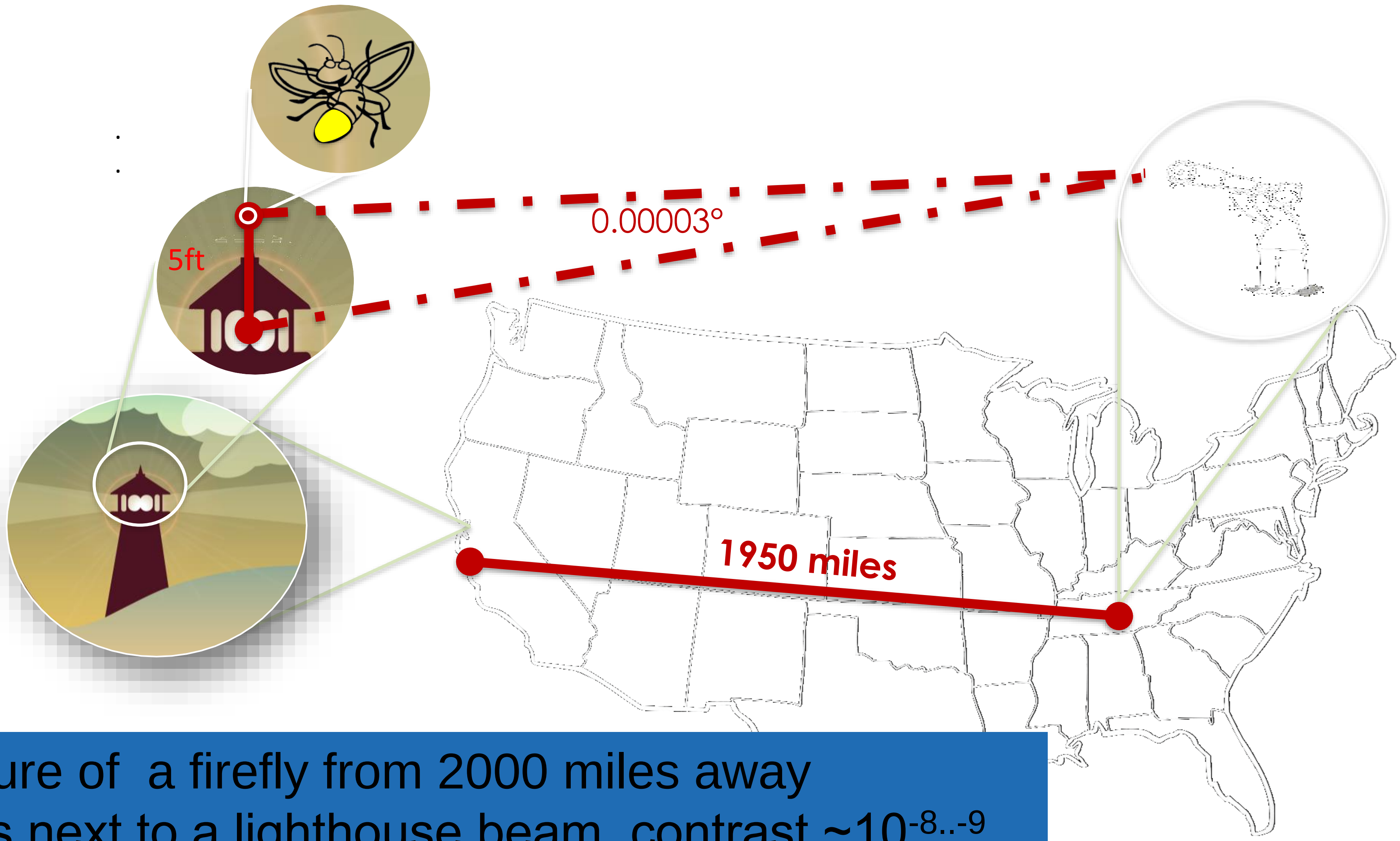


ELT – Planetary Camera and Spectrograph (PCS)



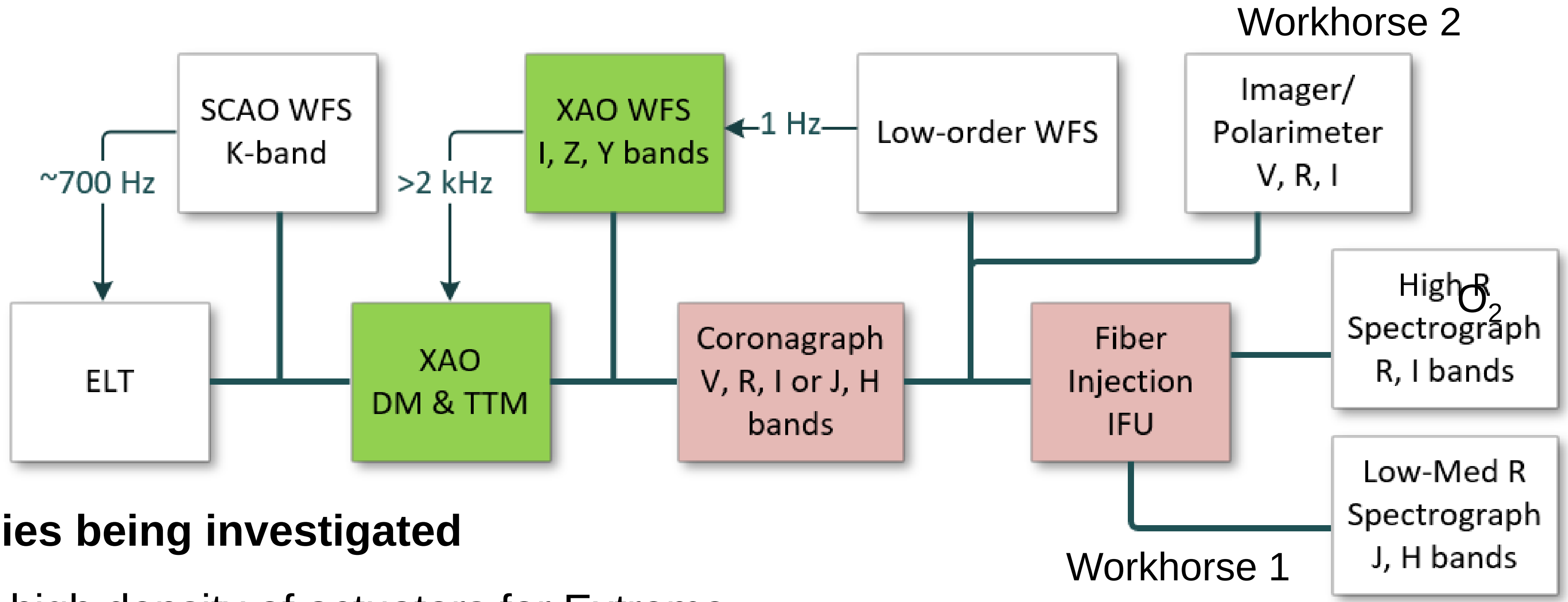
Science: Characterize nearby Earth-like Exoplanets, find biomarkers
Concept: eXtreme Adaptive Optics (XAO) + high-resolution spectroscopy
Time-scale: ongoing R&D, Project Start ~2025?, 1st light ~2035

Exoearths are VERY faint and difficult to observe



Take a picture of a firefly from 2000 miles away
…which sits next to a lighthouse beam, contrast ~$10^{-8..-9}$

Nearby Exo-earths with ELT PCS (>2030)



Technologies being investigated

- Deformable mirrors with high density of actuators for Extreme Adaptive Optics 128x128 actuators; 3kHz frequency
- Fiber injection in Integral Field spectrograph
- Real Time Computer with Machine learning algorithms
- Possibly curved near-IR detectors

Green: R&D (partially) underway

Red: Additional R&D proposed

PCS R&D current collaborations

- Institute Optique Paris (Fr): PhD Nelly Cerpa Urra on cascade AO (CAO)
- Lappeenranta University of Technology (Fi)
  - Reinforcement Learning
  - PhD Jalo Nousiainen at LUT, Fi, started 2019
- ETHZ (CH)
  - Meta Leaning, Image analysis with ML
  - PhD Markus Bonse started 2020
  - Contribute DM for lab setup (GHOST) on-loan to ESO
- Steward Observatory (US): Bench tests with MagAO-X (S. Haffert)
- *ANU/LESIA for implementation of COSMIC RTC*
- *SAXO+ potentially as part of PCS R&D (STC rec): **put PCS XAO concept on-sky***
- Major Horizon Infratech WP for PCS R&D to be submitted to the EC in April 2022

Conclusions

- The Technology Development programme is relativ… of funding and ESO FTEs at the time of the ELT constructi… re project at this point of time
- The scope tries to covers as much fut… ible via intensive collaborations with partners from … institutes (and possibly outside) which are motivated … echnologies and new methods (i.e PCS R&D)
- Tech Dev. is not ex… the whole development of a new technology but only to red… cal risk (up to TRLs 6 or so)

PLEASE FEEL FREE TO TALK TO ME IF YOU WISH
TO HELP US SETTING THE FUTURE
TECHNOLOGIES NEEDED FOR THE ELT/ VLT/ ALMA

SPARE SLIDES

Large CMOS development

- **Motivation: Guarantee long-term access to scientific-quality detectors in the visible wavelengths for astronomy**.
- CCDs are state-of-the-art visible detectors used in all ESO visible instruments.
  - CCD production is decreasing in favor of CMOS in public market. Only 1.5 suppliers worldwide are still producing large-format CCDs, and cost continuously increases.
  - Availability not guaranteed beyond ~1 decade, (ELT).
- CMOS detectors provide: New readout schemes / operation modes, lower prod. Cost / pixel. Some established design houses and larger variety of manufacturers.
  - However, commercial CMOS specifications do not (yet) reach our requirements, and investment and development will be required to get there.
- Join forces for instance very interesting ESA's ELFIS development program with Caeleste.
  - 10 years of development so far (multiple iterations)
  - several MEuro so far, more needed to get a production sensor
  - We could build on this development for our sensor in partnership with ESA at fractional cost?

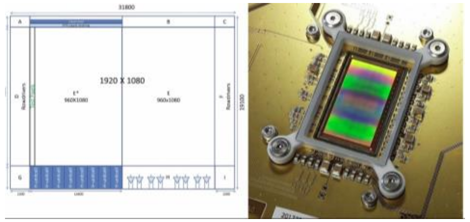


Fig 1:ELFIS building block and sensor

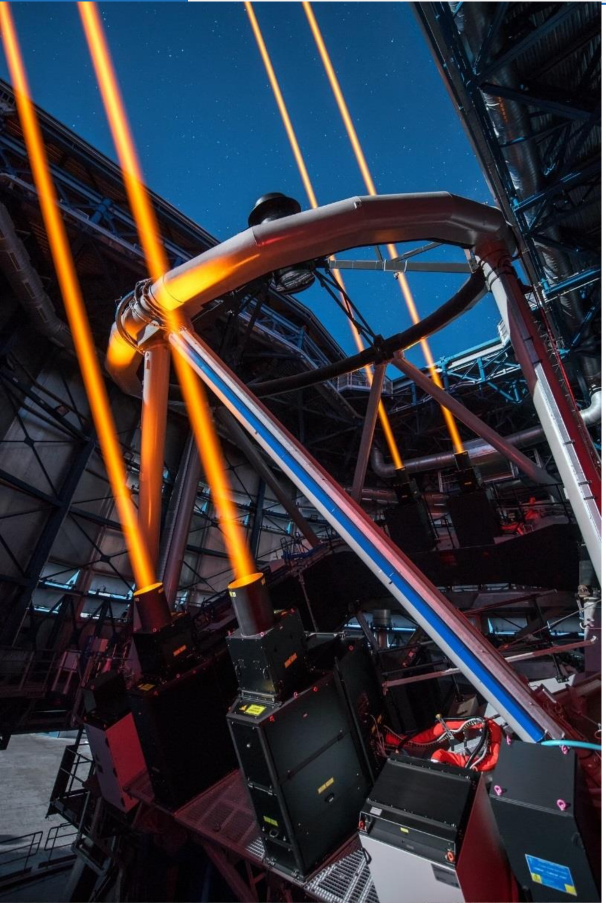
Needs for transmission gratings

Instrument	Ws	Wh	Type	Lines/mm	Angle of Incidence	Diff Order	Size	Size	Needed
CUBES	0.3	0.352	T	3107	36.07	1	170	220	1
	0.346	0.405	T	3600	35.82	1	170	220	1
BLUE MUSE	0.35	0.58	T or TG	1000	13.9	1	200	100	25
MAVIS	0.37	0.732	TG	750	12	1	40	40	1
	0.51	1.009	TG	550	12	1	40	40	1
	0.425	0.555	TG	1830	26.6	1	40	40	1
	0.63	0.887	TG	1000	22.24	1	40	40	1

Only one industrial supplier available for VPH gratings
An activity is included in the Horizon Infratech 2022 proposal led by INAF in close contact with ESO for CUBES

Instrument	Ws	Wh	Type	Lines/mm	Angle of Incidence	Diff Order	Size	Size	Needed
	0.83	1.05	T	664	21.4	1	164	160	4
	1.046	1.324	T	526	21.4	1	164	160	4
	1.435	1.815	T	384	21.4	1	164	160	4
	1.951	2.469	T	282	21.4	1	164	160	4
	0.827	0.903	T	1414	41.2	1	164	196	4
	1.538	1.678	T	760	41.2	1	164	196	4
	2.017	2.201	T	580	41.2	1	164	196	4
	2.199	2.4	T	532	41.2	1	164	196	4
FORSup	0.524	0.64	TG	484	17	1	105	112	1
	0.695	0.849	TG	480	18.23	1	105	112	1
	0.33	0.62	TG	660	6.08	1	105	104	1

Laser Guide Star development effort

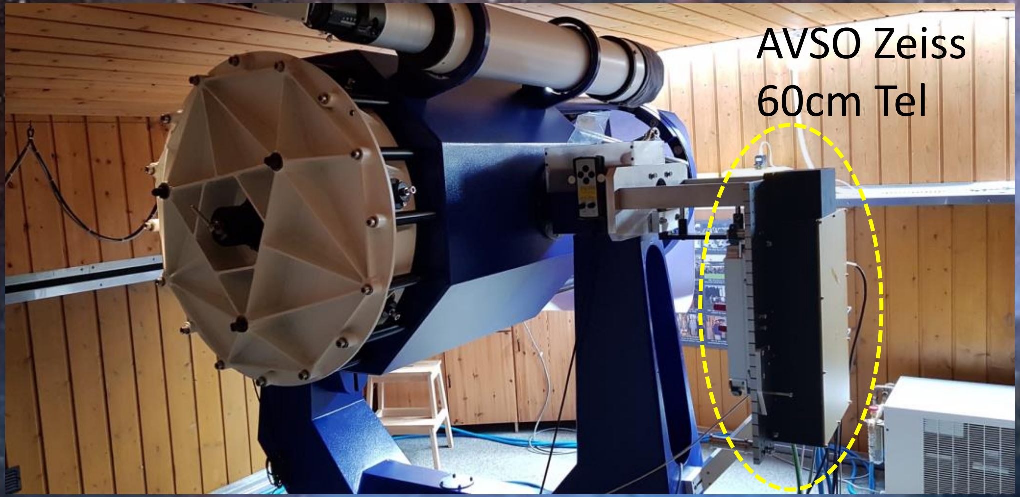


22W Sodium (589nm)
Laser @ VLT

- Laser Guide star concept essential for high sky coverage AO
- 22W Sodium (589nm) Laser standard product for observatories
- ESO-TOPTICA-MPB achieved 63W laser (world record) which are of great interest for satellite communication (collaboration with ESA) and for astronomy with high degrees of AO correction
- New AO concepts will be enabled by these high-power laser
- Full sky coverage AO…

63W Sodium (589nm)
Laser @ VLT

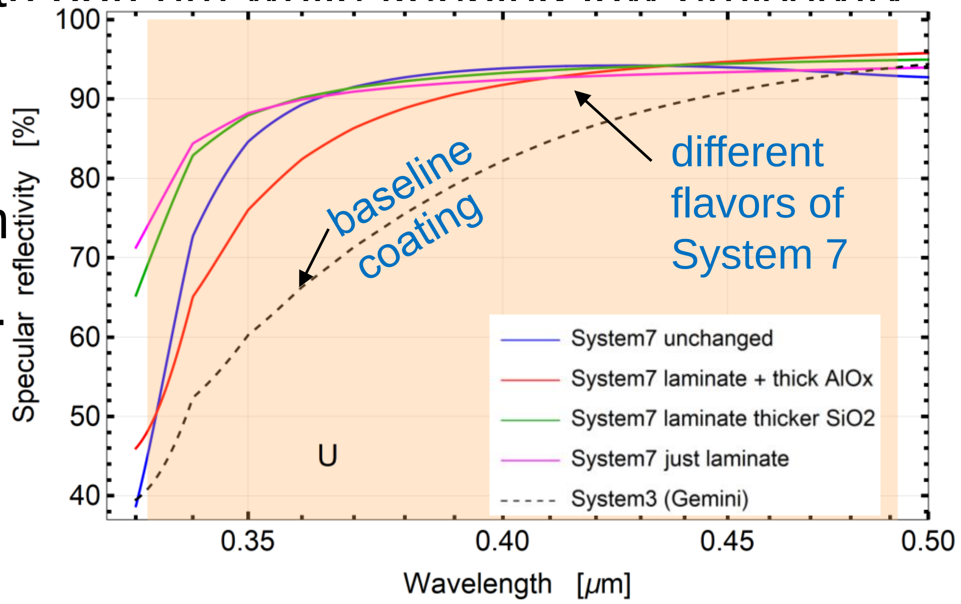
ESO Raman Fiber Lasers R&D (2017-2021) target: CaNaPy



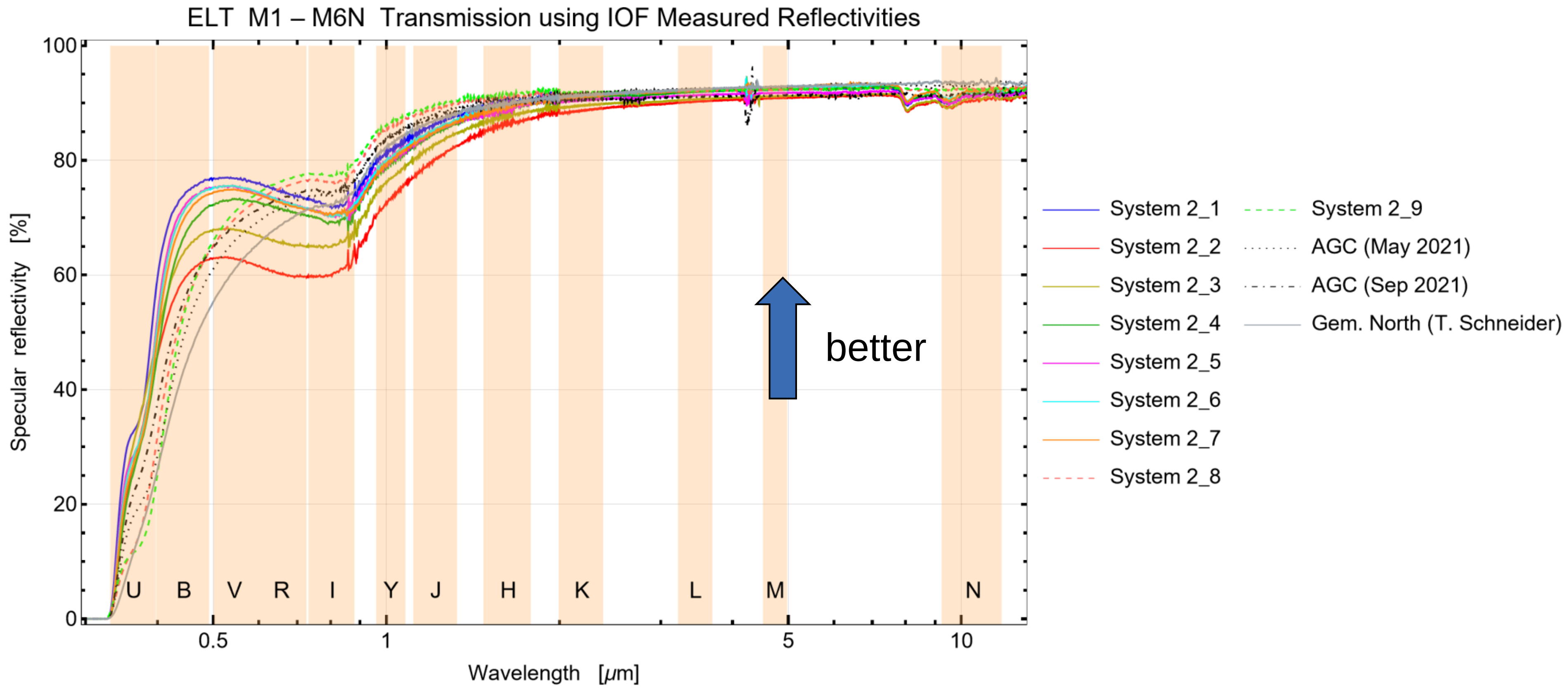
- Raman Fiber Amplifier + SHG 1178nm → 5 nm
- 100W RFA developed with MPBC
- , 3 papers, 1 PostDoc
- July 2021: 63W CW - Commissioned at AVSO
- Chirping developed with Toptica

Advanced reflective coatings dev. launched in 2020

- **Objective:** Development of advanced silver coatings for telescope mirrors with better UV reflectivity and high durability
- After CFT in late 2019, contract was signed with Fraunhofer IOF early 2020
- **Status:** (impacted by C-19)
  - Coating recipe definition and first testing phase
  - IOF deposited 9 different coatings on test substrates, all with layer(s) of AlOx
  - Numerical simulations show strong UV enhancement down to 330 nm while keeping low emissivity in the NIR
  - Some issues with emissivity peak near 10 µm (N-band)
  - One recipe may become interesting for HIRES (0.3 – 2.5 µm
  - Second coating phase shows promising recipes: next slides.



ELT Train Transmission



IOF's System 2_1 (possibly contains SiON or AlOx) yields ~15% more ELT throughput below 500 nm than the Gemini-style coatings. Conversely, there's some loss in the IR, although less.

HIgh REsolution Spectrograph: HIRES

- The high-resolution ELT instrument HIRES will allow astronomers to study astronomical objects that require highly sensitive observations. It will be used to search for signs of life in Earth-like exoplanets, find the first stars born in the Universe, test for possible variations of the fundamental constants of physics, and measure the acceleration of the Universe's expansion.
- The HIRES baseline design is that of a modular fibre-fed cross dispersed echelle spectrograph which has two ultra-stable spectral arms, visual and near-infrared, providing a simultaneous spectral range of 0.4 -1.8 μm at a spectral resolving power of R~100,000 for a single object. HIRES will also include an IFU mode fed by a single-conjugate adaptive optics (SCAO) module to correct for the blurring effect of turbulence in the atmosphere.