Preparation to future long-term space missions for exoplanets high contrast direct characterization

based on a biased view towards high contrast imaging (HCI)

- “Optimal Exoplanet Imagers” workshop (Leiden, Feb 2023)
- Presentation to ESA Science and Tech directorate (May 30th)

and important complementarities and synergies with long baseline interferometry

SF2A 2023

D. Mouillet, I. Laginja, M. Ferrari

Take-away messages

High contrast exoplanet characterization is a major long-term goal

Programmatic way to reach the goal under discussion (missions, collaborations, instruments) including intermediate steps and complementarities

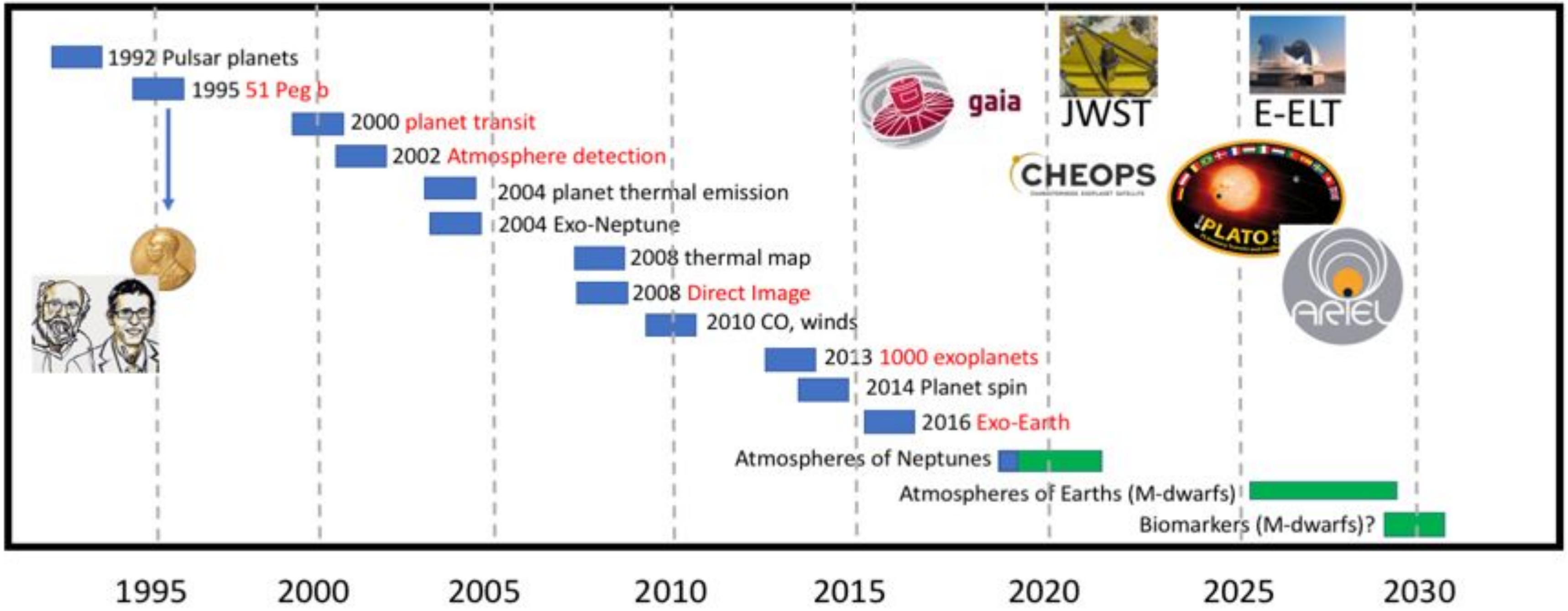
Technology maturation to be worked-on now

- to be ready for programmatic decisions in 2030
- to be organized coherently (as various scales)
- a wealth of expertise in Europe

Important synergies

- HCI / interfero ; ground-space
- Need for significant improvement of wavefront control
- High potential of the high contrast-driven dev for other applications

A Revolution in Exoplanet Research (European perspective)



Next steps

After the wealth of RV and transits for detection, statistics, and first characterization

Probing some diversity around bright stars and/or larger separation: ARIEL, PLATO

Characterization of low mass planet samples up to probing the conditions of life

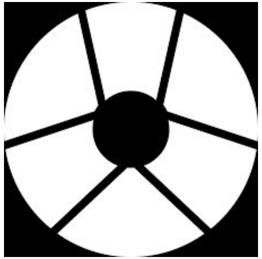
- on brightest, most favorable cases
- long deep exposures
- getting rid of the primary, fundamental limitation: stellar flux

High contrast

Programmatic context: next steps ?

NANCY GRACE ROMAN SPACE TELESCOPE

2-DM wavefront control for high contrast demonstration (on an unfriendly pupil)

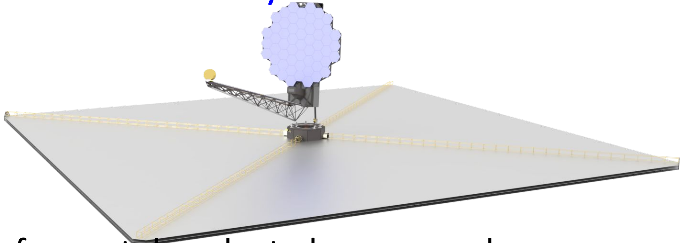


LIFE

Voyage2050, Quanz et al

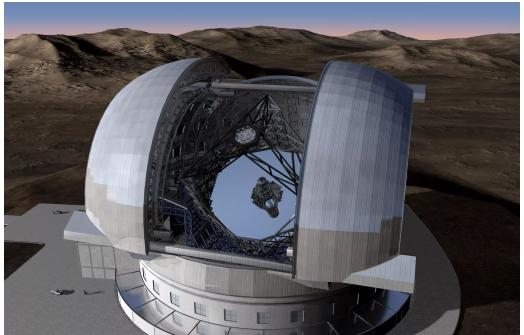
+ Life collaboration paper serie

HabWorlds Observatory

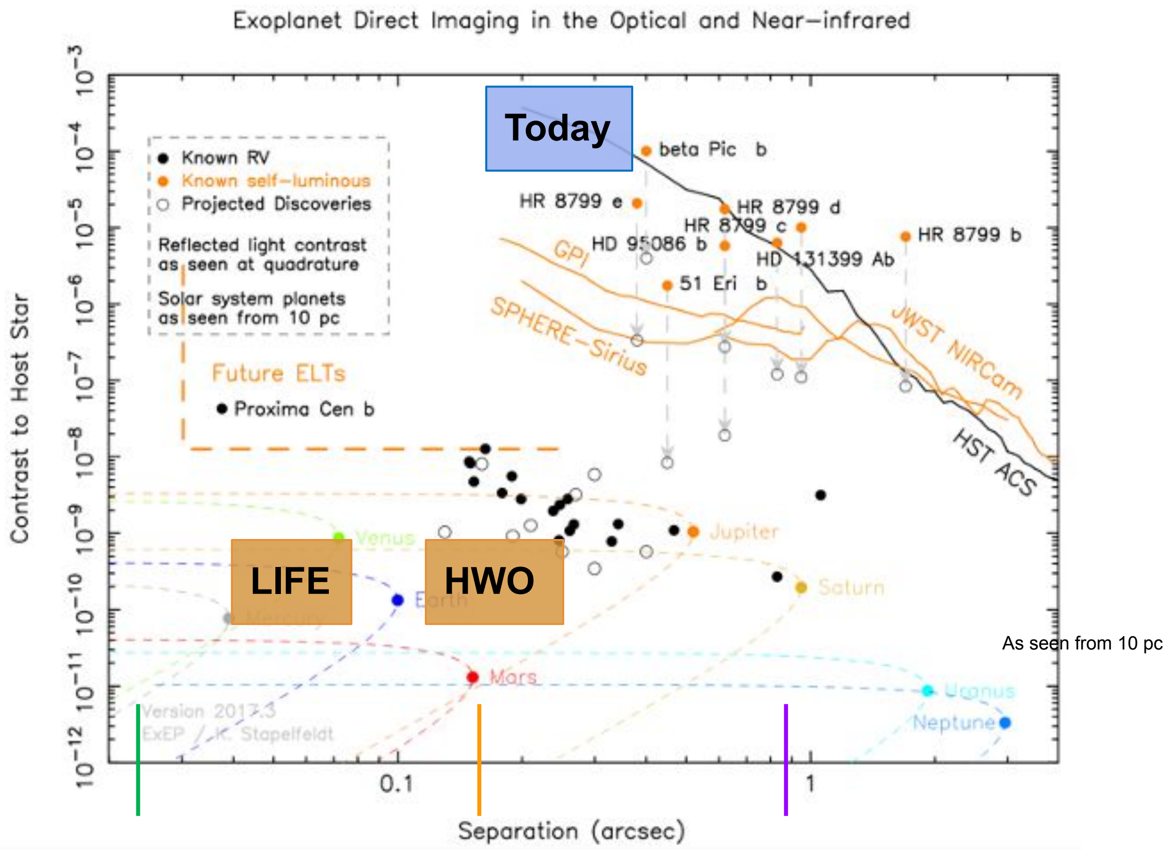


Mission for next decade, to be prepared now

While high contrast is an important part of **ELTs** on the ground



Global direct imaging roadmap



Mind the log scales !

Reflecting planets:

Contrast α $(R_P / sep)^2$

Self luminous:

Flux = $f(T, R_P)$ = f(age, mass)

	λ (µm)	D (m)	λ/D (mas)	3 λ/D (mas)
JWST MIRI	10	6,5	317	952
JWST NIRCAM	2,5	6,5	79	238
VLT NIR	1,6	8	41	124
ELT NIR	1,6	39	8	25
HWO	0,8	6,5	25	76
LIFE	10	100	21	62

Complementarity **UV-NIR** vs **MIR**

From Quanz presentation Voyage2050

Scientific complementarity:

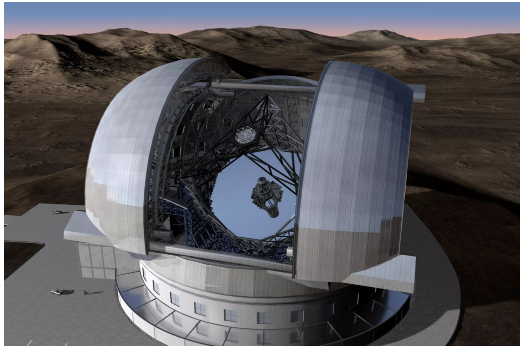
albedo, polarization, hazes/clouds, shortest separations ⟺ thermal probing, integrated atmosphere, different molecules

Commonalities and synergies:

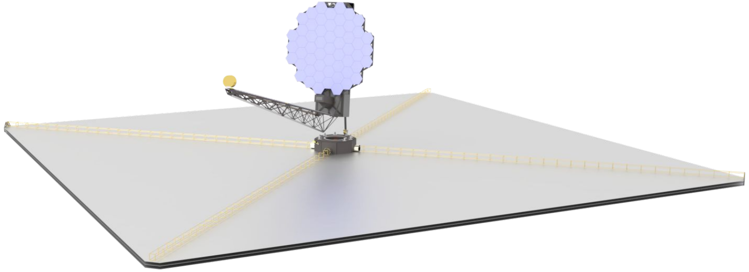
- common **community**
- **scientific preparation** (targets, spectra, interaction with disks, dynamics, …)
- **system analysis**: WFS&C, (auto-)calibration, nulling/coronagraphy error budgets and tolerancing, post-processing, novel stability and optical specs, integrated optics, detectors

Complementarity **HCI ground** vs **HCI space**

from ground



from space



Scientific complementarity:

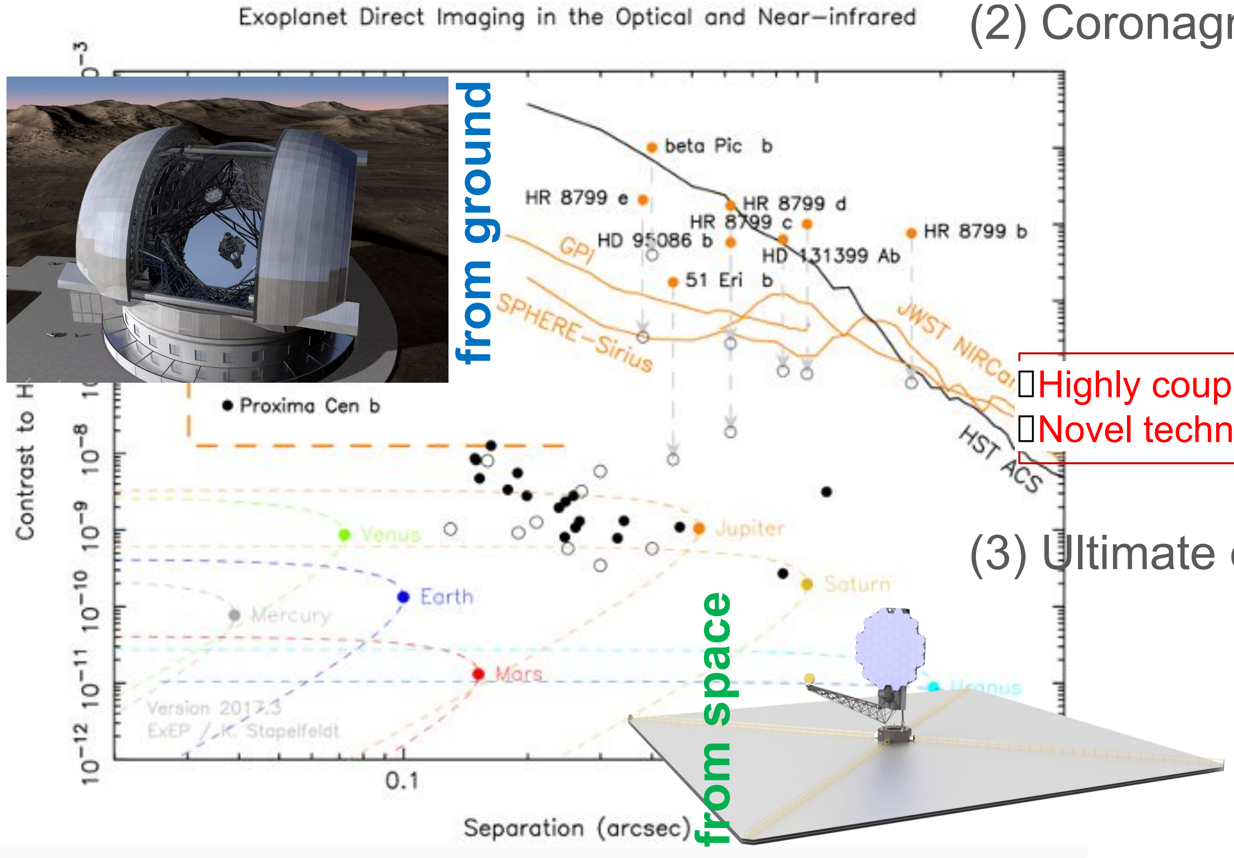
Better angular resolution → HZ around M-dwarves

Deeper contrast → HZ around solar-type stars
Broader bandwidth → finer spectral coverage and characterization

Commonalities and synergies:

- common **community**
- **scientific preparation** (targets, spectra, interaction with disks, dynamics, …)
- **system analysis**: WFS&C, (auto-)calibration, **extreme adaptive optics**, post-processing, novel stability and optical specs, integrated optics, detectors

Complementarity **HCI ground** vs **HCI space**



(2) Coronagraphy + differential techniques

Limited raw contrast (short perturbation timescales)

Great collecting area, and angular resolution

- Highly coupled system analysis
- Novel technological and demonstration challenges

(3) Ultimate on-board contrast

Pushing to extreme and stable contrast close to diffraction limit !

No atmospheric constraints (transmission, variabilty)

Missions, technology, roadmap

need to organize on long-term scales

Techno maturation and programmatic decisions have intrinsic distinct timescales

US HWO on-going plan de facto triggers/defines some milestones and sets some important opportunities/boundary conditions

Lots of synergies and potential positive resulting know-how and products for various applications

Lot of work ! in which Europe has an important role to play

Missions, technology, roadmap

need to organize on long-term scales

Programmatic aspects:

- ESA will issue its **"Long Term Plan"** in November this year
- Exoplanet characterization strongly present in Voyage2050 survey
  - characterization in the mid-infrared *(Senior Committee Report)*
  - possible European contribution to HWO for an instrument

Techno maturation activities

- HWO drives techno maturation by 2029 *(see below)*
- Possible contributions rely on demonstrated expertises
- Contacts desired at various levels *(ESA, national agencies, coll.)*

CNES prospective starting !

community invited to express interest by next September

ESA poll for emerging techno

WITSO workshop Nov 2023

Dedicated workshop on high contrast early 2024 ?

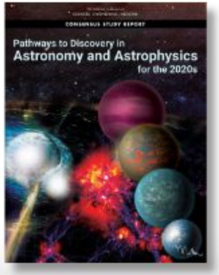
Astro2020 Primary Recommendation

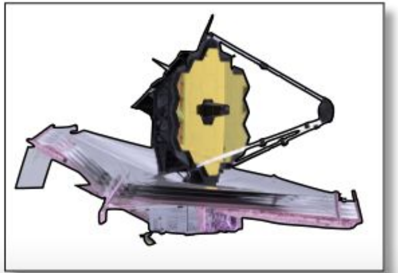
- Infrared / Optical / UV space telescope with ~ 6-m inscribed diameter to search for life on exoplanets and enable transformative astrophysics

The Habitable Worlds Observatory

- Primary technical requirements for coronagraphic survey are:
  - System-level stability at ~ picometer-level
  - Coronagraphic contrast ≥ 10^{10}

- Strategic guidance





The Habitable Worlds Observatory: *The Big Picture*

- **Build to schedule**: Mission Level 1 Requirement e.g Planetary missions
- **Evolve technology**: Build upon NASA investments i.e.
  - JWST segmented optical system, Roman coronagraph, & Sensors
- **Next Generation Rockets**: Leverage opportunities offered by large fairings to facilitate mass & volume trades
- **Planned Servicing**: Robotic servicing at L2
- **Robust Margins**: Design with large scientific and technical margins
- **Mature technologies first**: Reduce risk by fully maturing the technologies prior to development phase.

GOMAP

Great Observatory technology Maturation Program

Stage 1: HQ Preparation
Establish GOMAP plans and policies

Stage 2: Habitable Worlds Observatory Concept Maturation Study
Analyze architecture options; Mature enabling technologies;

with a Science Techno Architecture Review Team (**START**) including international ex-officio representatives

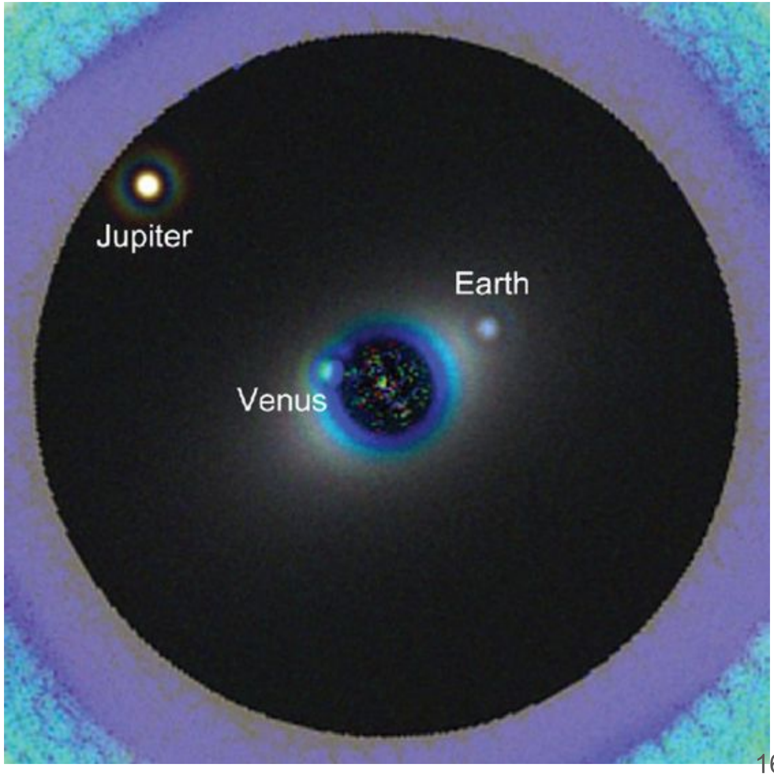
Stage 3: Evolved Pre-Phase A for Habitable Worlds Observatory
Establish mission architecture; Execute design trades; Mature technologies;
Maintain technical capabilities for Future Great Observatories (FGOs)

HCI in Europe

Europe has been involved **from the very beginning**

Dalcanton et al. 2015
N’Diaye et al. 2016

- series of first papers showing it is **indeed possible to deal with diffracted light** at level necessary for solar system twin
- this work was done by people working on ground and space HCI, from Europe and the US
- was still missing important steps like WFS&C and stability, but shows the **know-how to make it happen** is there

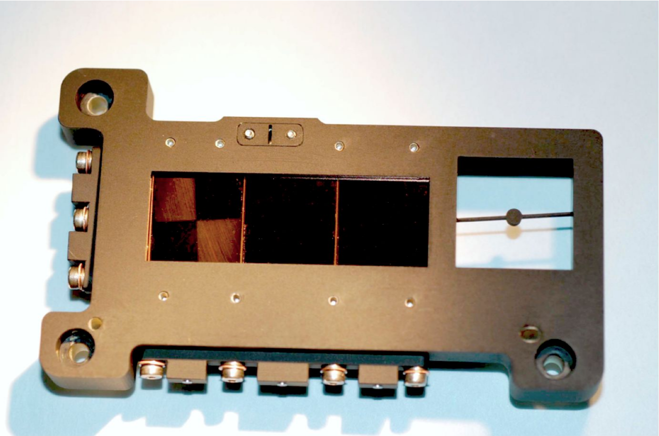


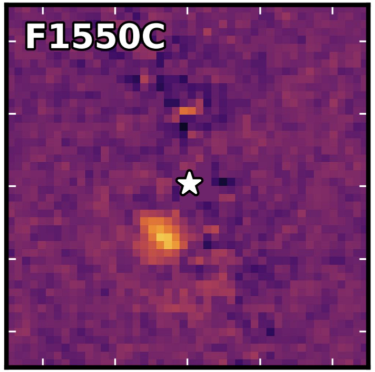
HCI community in Europe

- Europe has a high level of HCI research
- Very active exoplanet community in general (observations, modeling, spectral analysis, instrumentation)
- Examples of excellence in HCI instrumentation in Europe:
    - JWST coronagraphs
    - RST mirrors
    - coronagraph development
    - experimental research and lab demos
    - post-processing solutions

Institutions involved in
HCI instrumentation from space

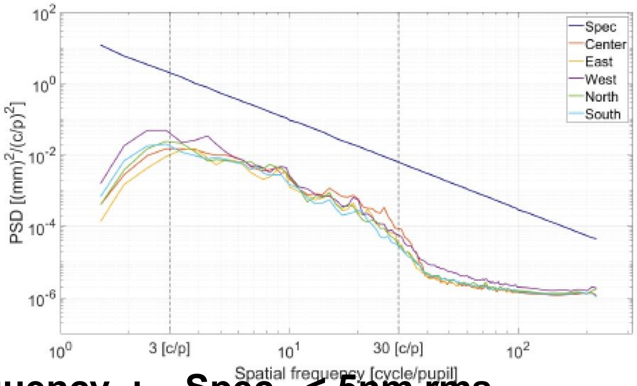
JWST coronagraphy





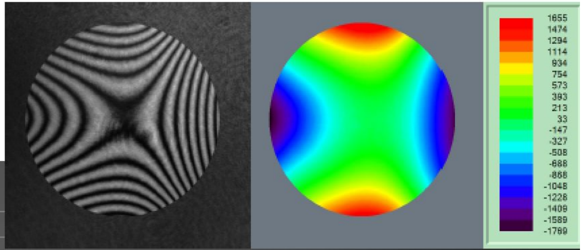
ROMAN CGI / Off-axis parabolas

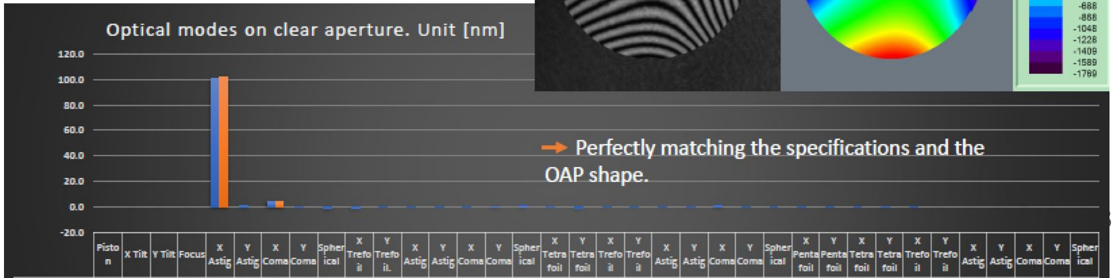
Mid-Frequency Spec. < 2nm rms



Low-Frequency : Spec. < 5nm rms

Zernike aberration RMS [nm]	Specifications	Results
Astig 3x	102	100.5
Coma 3x	3.9	4.1



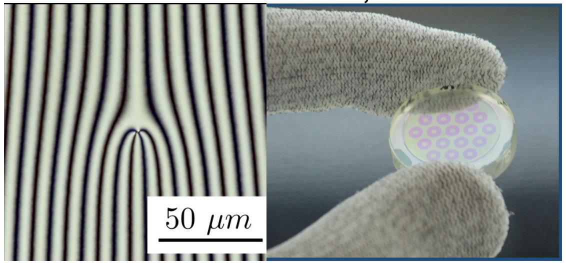


Coronagraph development

Technological development

Broadband liquid-crystal coronagraphs

Doelman et al. 2020,2021

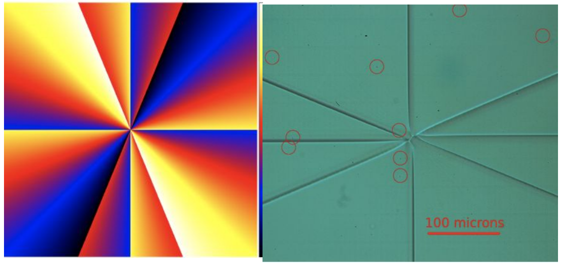


Active coronagraphs

Kühn et al. 2018

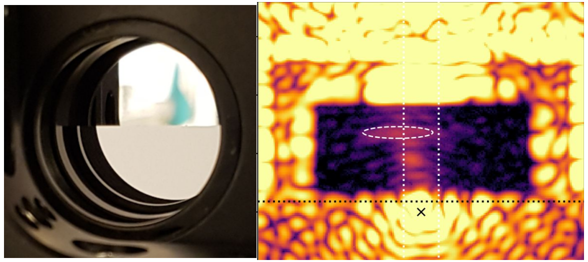
Wrapped vortex coronagraph

Galicher et al. 2020

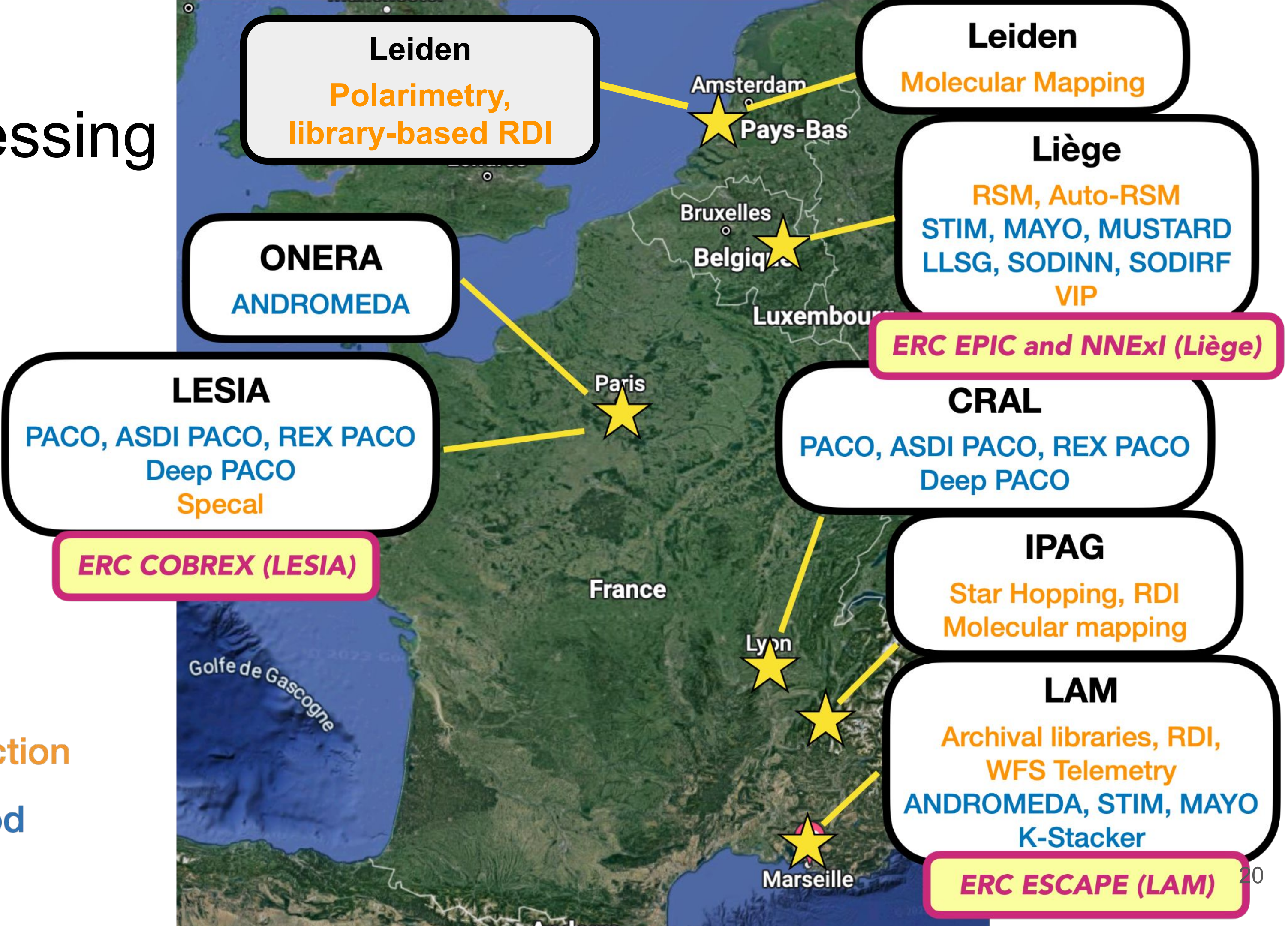


PAPLC

Por et al. 2020



Post-processing for HCI



Starlight subtraction

Detection method

HCI in Europe

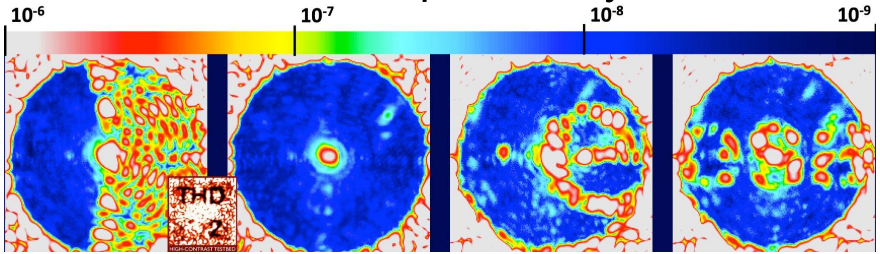
Many more activities in Europe!

Table lists summary in (now outdated) table from Snellen + Snik et al. 2020 Voyage 2050 white paper

Large space telescopes	• Euclid high precision optical telescope (Wachter and Markovic 2018; Wallner et al. 2017) • ESA deployable mirror development (Marchi et al. 2017)
Adaptive Optics	• SPHERE extreme AO system: (Fusco et al. 2006; Petit et al. 2014; Beuzit et al. 2019) • The très haute dynamique bench (THD; Galicher et al. 2014, Baudoz et al. 2018) • Using 2 DMs for phase/amplitude control (Mazoyer et al. 2017) • ESA active optics developments (Hallibert & Marchi 2016; Laslandes et al. 2017) • Deformable Mirror development (Charlton et al. 2014)
Coronagraphy	• 4QPM coronagraph for JWST (Boccaletti et al. 2004, Baudoz et al. 2006b) • APLC coronagraph (N'Diaye et al. 2015, 2016a) • Coronagraph optimization (Carlotti et al. 2014) • AGPM/Vortex coronagraphs (Forsberg and Karlsson 2013; Delacroix et al. 2013) • Advanced liquid crystal coronagraphs (Snik et al. 2012, Doelman et al. 2017; Por et al. 2018; Snik et al. 2018)
Wavefront / electric field sensing	• SCC (Baudoz et al. 2006a; Galicher et al. 2008) • ZELDA Zernike WFS (N'Diaye et al. 2013, 2016b, Vigan et al. 2019) • vector-Zernike WFS (Doelman et al. 2019) • Pyramid WFS (Ragazzoni et al. 2017) • Segmented space telescope phasing (JWST+LUVOIR; Leboulleux et al. 2018) • Speckle nulling (Martinache et al. 2014) • COFFEE phase diversity (Paul et al. 2014) • Holographic Modal WFS (Wilby et al. 2017), incl EFC (Por & Keller 2016) • Phase-Sorting Interferometry (Codona and Kenworthy 2013) • Asymmetric Pupil-WFS (Martinache et al. 2013) • vAPP fpWFS (Bos et al. 2019) • QACITS algorithm (Huby et al. 2015)
Spectroscopy	• High-contrast imaging + High-resolution spectroscopy: Snellen et al. (2014, 2015), Vigan et al. (2018) • SPHERE microlens-based IFS (Claudi et al. 2006) • Slicer IFS: SINFONI (Thatte et al. 1998), HARMONI (Thatte et al. 2014) • SCAR coronagraph + single-mode fiber spectrograph (Haffert et al. 2019; Por & Haffert 2019b)
Polarization techniques	• Polarization-based 4QPM and VVC coronagraph (Mawet et al. 2006) • Liquid-crystal coronagraphy + polarization filtering (Snik et al. 2014b) • SPHERE-ZIMPOL (Schmid et al. 2018) • Advanced polarimetric techniques: Snik & Keller 2013; Snik et al. (2014a)
Detectors	• MKID detector development for visible light: Baselmans et al. (2017), Bueno et al. (2018)
Astrophotonics	• Photonic reformatting - NAIR (Harris et al. 2018) • 3D printed microlenses on single mode fibre IFUs (Dietrich et al. 2017; Haffert et al. 2019c)
System design	• SPICES HCI space telescope concept (Boccaletti et al. 2012)
Data-reduction techniques	• Spectral Differential Imaging (Claudi et al. 2008, Vigan et al. 2010) • Principal Component Analysis (Amara & Quanz, 2012) • ANDROMEDA (Cantalloube et al. 2015) • ALICE (Choquet et al. 2014)

Experimental research and laboratory demos for HCI

- theory → modeling → lab demos
- requires full loops with sensing & control, knowledge of optical model → **crucial for transition to real instruments** and definition of flight hardware
- HCI instrumentation research requires very well calibrated **optical testbeds**



THD2 testbed / Paris

- space-based applications
- ground-based applications
- been around for 10+ years

SPEED testbed / Nice

- segmented telescope emulator
- coronagraphs
- ground-based applications

CIDRE testbed / Grenoble

- ground-based application
- alternative coronagraphs, wavefront shaping

MiTHIC testbed / Marseille

- recently: spectroscopy for HCI (ground)

Future strategy

We need a **pro-active engagement** with HCI

Further community building:

- Coordination between ESA and academic community for early participation in maturation studies
- Continuous discussion with the agency
- Have a dedicated contact point for HCI?

→ Involvement on science side

Prepare for technology roadmap:

- Identify possible areas for optics and tech development

→ Involvement on technology side

Start a European development program for technology validation

1. Coronagraphic systems
2. Wavefront sensing and control
3. Integral field spectrograph + spectroscopic data analysis
4. Polarimetry (science and technology)
5. Data analysis algorithms
6. Precision optics and detectors
7. Photonic technology

Wishes from HCI community:

- clear and visible long-term interest, coordinating on-going forces
- intermediate milestones for critical technology maturation (driven by HCI, useful for other applications)
- a strong position for upcoming opportunities, coordination with international community

Take-away messages

ESA long term plan in November

High contrast exoplanet characterization is a major long-term goal

Programmatic way to reach the goal under discussion (missions, collaborations, instruments) including intermediate steps and complementarities

Technology maturation to be worked-on now

to be ready for programmatic decisions in 2030

to be organized coherently (as various scales)

a wealth of expertise in Europe

CNES prospective starting !

community invited to express interest by next September

ESA poll for emerging techno

- WITSO workshop Nov 2023
- Dedicated workshop on high contrast early 2024 ?

Important synergies

HCI / interfero ; ground-space

Need for significant improvement of wavefront control

Important potential of the high contrast driver for other applications