The next generation of high-contrast imaging instruments

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HCIpp workshop, Jan 2020

Outline

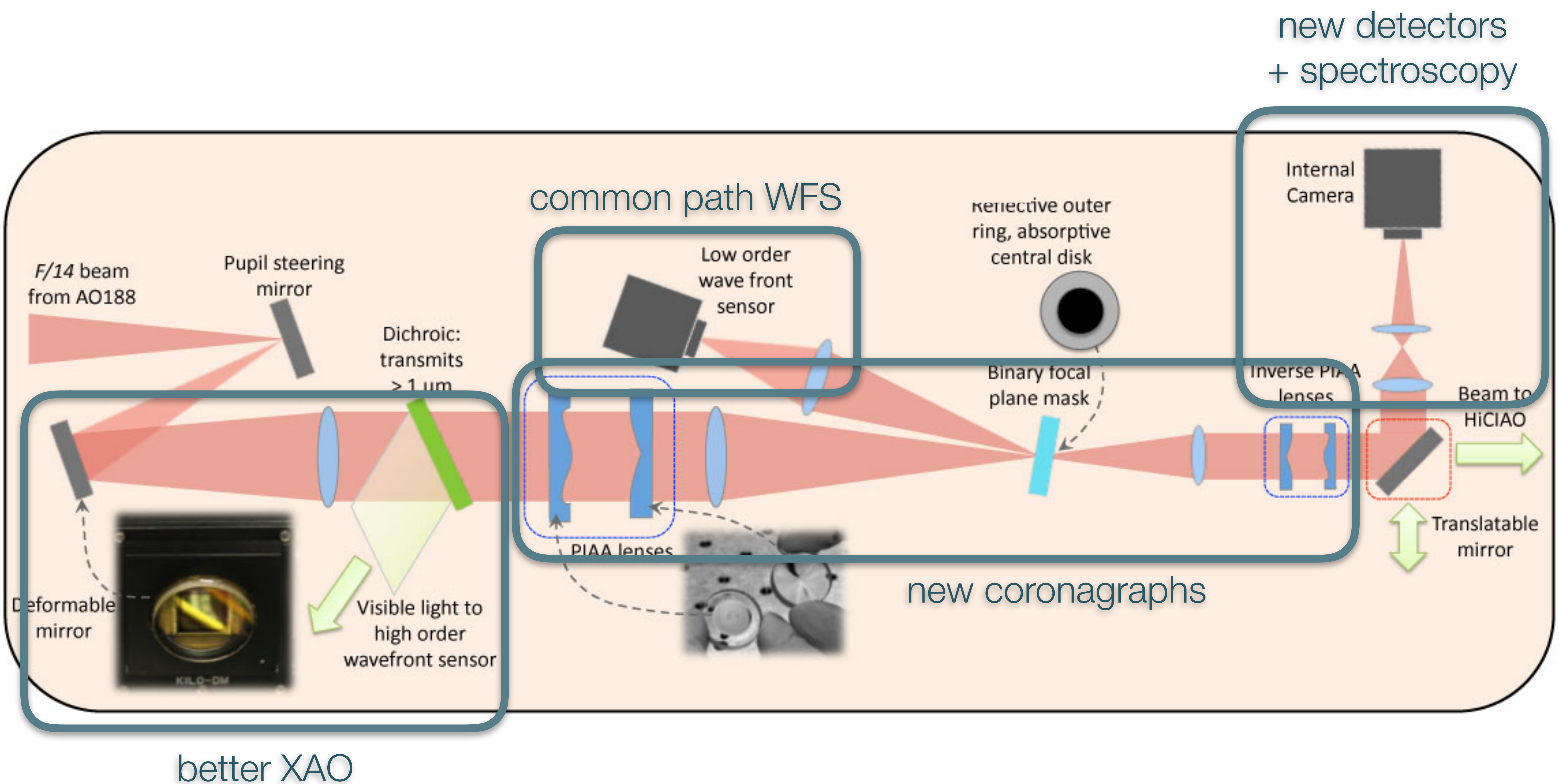
- Main trends in future HCI instrumentation
- Future instrumentation on 10-m class telescopes
- Future instrumentation on Extremely Large Telescopes

Main trends in HCI instrumentation

Smarter, better, faster, deeper

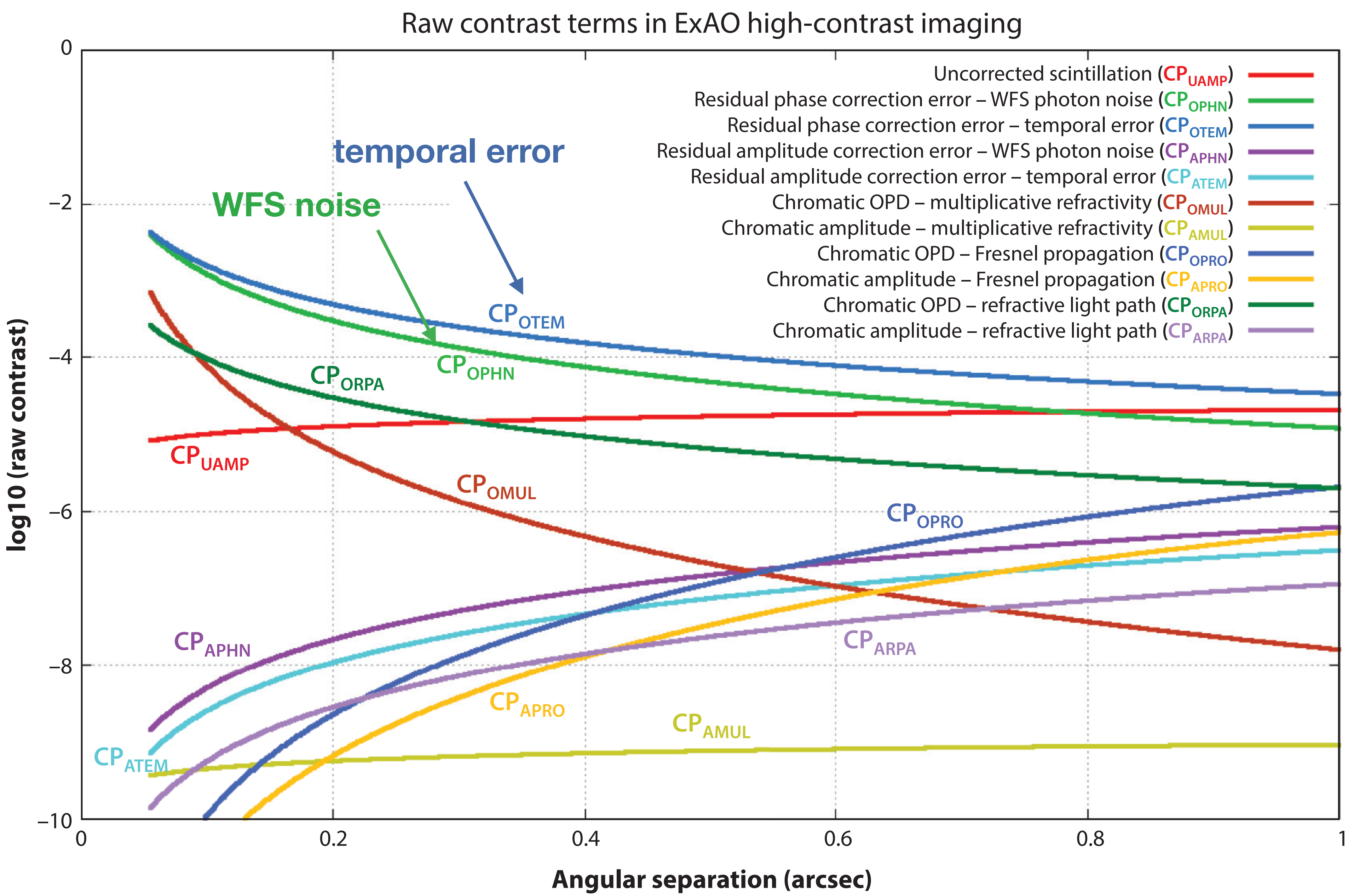
Overview of trends

(courtesy SCExAO team)



Extreme adaptive optics

Guyon 2018



8m telescope @ H band, WFS @ 0.8μm, 1 kHz

Extreme adaptive optics (cont'd)

- Pyramid WFS
  - better sensitivity —> fainter targets
  - better correction of low orders & pupil segmentation management
  - possible pairing with model-based reconstruction
- Faster extreme AO systems
  - enabled by new hardware: photon-counting detectors, GPU acceleration
  - reduced lag —> lower wind-driven halo

Extreme adaptive optics (cont'd)

- Predictive control / sensor fusion
  - optimally uses last measurements to predict aberrations at correction time
  - challenge: temporal relationships between past and future aberrations not known in advance and change continuously —> machine learning
- High-density DMs
  - woofer-tweeter configurations
- All these gains are not simply multiplicative, but strongly benefit each other
  - smaller residual WFE —> WFS more sensitive & linear, better calibrated —> improves predictive control efficiency

NCPA management

- NCPA identified as bottleneck in most HCI instruments

- Common-path WFS techniques

    - **Software** (mostly): speckle nulling, pairwise probing + Electric Field Conjugation, Linear Dark Field Control, Phase Sorting Interferometry, Kernel phase, etc.

    - **Hardware needed**: low-order WFS, Self-Coherent Camera, Zernike WFS, modal WFS, etc.

- Possible combination with post-processing

    - Coherent Differential Imaging —> joint estimation of speckle field and companion, using information from common-path WFS technique

    - Ideally also combined with (real-time) access to telemetry

New coronagraphs

- Vortex coronagraphs and Apodizing Phase Plates now mainstream
- Next step: fully optimized coronagraphs
  - need properly defined metrics (including null depth & throughput)
  - combination of pupil-plane and focal-plane elements
  - new promising concepts (e.g., Phase-Apodized-Pupil Lyot Coronagraph —> combines phase apodizer, focal-plane amplitude mask, and Lyot stop)
- Need to address segmented pupil
  - some coronagraphs more immune than others
  - DM may help to some level

Spectral resolution

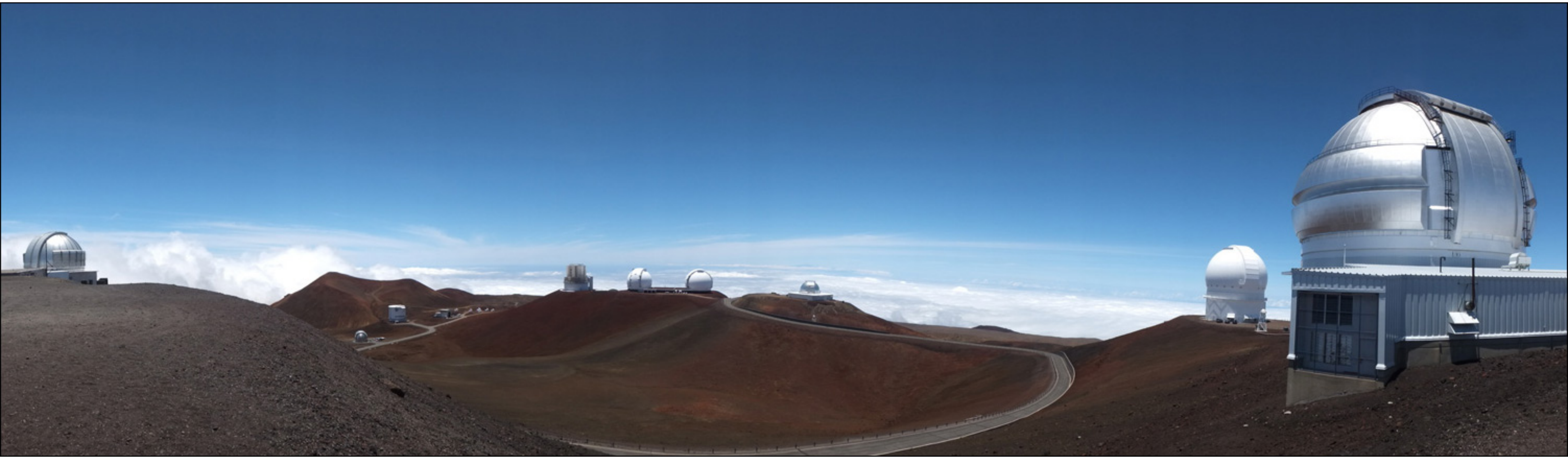
- Low-resolution IFS already mainstream
  - higher resolutions will become more and more standard
- Medium & high spectral resolution
  - enables the use of spectral features for detection (and characterization)
  - new concepts for HCI-specific IFS: fiber feeds, multiplexed Bragg gratings, etc. + associated operating modes (e.g., fiber dark hole)
- New signal extraction techniques
  - need to go beyond simple cross-correlation

Detectors

- Low noise / photon-counting detectors at all wavelengths
  - EMCCD — ideal for high sensitivity, high-speed wavefront sensing, but can also be used for visible HCI
  - IR-APD — can be used for AO, common-path WFS, and science
- Microwave Kinetic Inductance Detectors (MKIDs)
  - photon energy discrimination —> built-in low-res spectrograph
  - high-speed photon counting —> stochastic speckle discrimination
- Geosnap
  - pushing MCT technologies to mid-IR wavelengths

Image processing

- Combination with FP-WFS / spectral resolution
  - coherent differential imaging still in its infancy
  - still a long way to go to make optimal use of all the available information
- Machine learning for post-processing
  - shows promise for « simple » tasks
  - could become game-changing for optimal exploitation of huge datasets (high-speed, spectrally dispersed data + telemetry + etc)
- Future: real-time PSF estimation, using all sensors + ML to relate WFS telemetry to focal plane images using training sets



Future instrumentation on 10-m class telescopes

Surveys & technology platforms

Upgrades & new instruments: overview

- Upgrades
  - SCExAO
    (in constant upgrade)
  - MagAO-X
  - KPIC
  - SPHERE+
  - GPI 2.0
- New instruments
  - SHARK
  - ERIS
- Mid-IR: a first generation
- Other perspectives

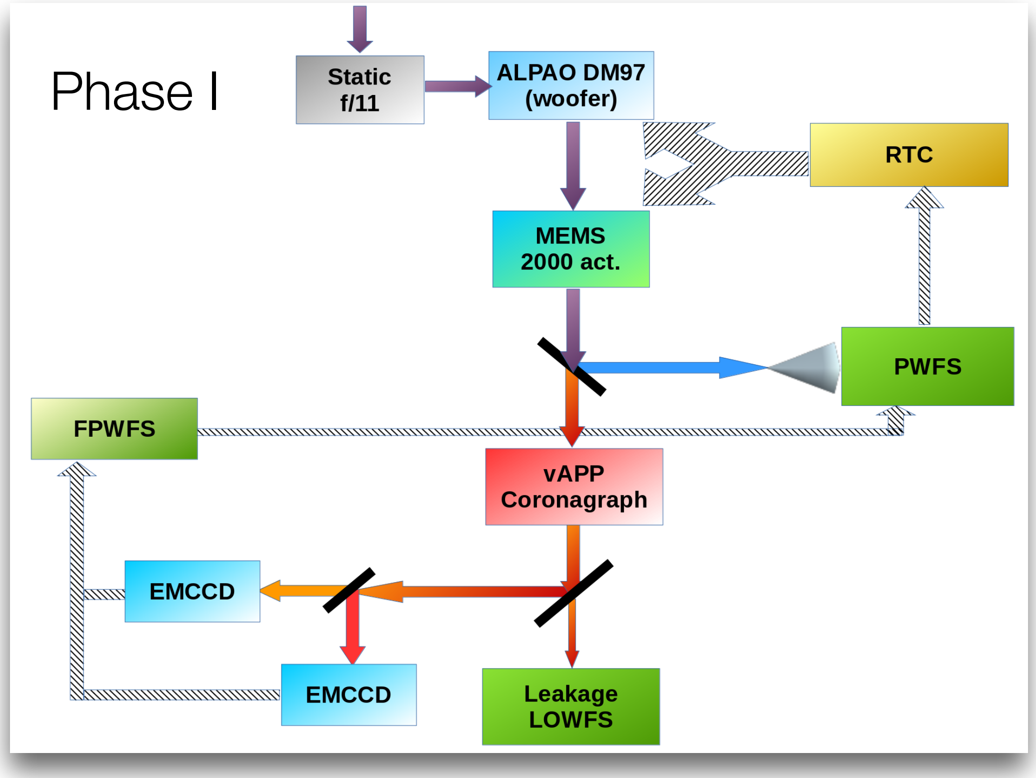
SCExAO: latest news

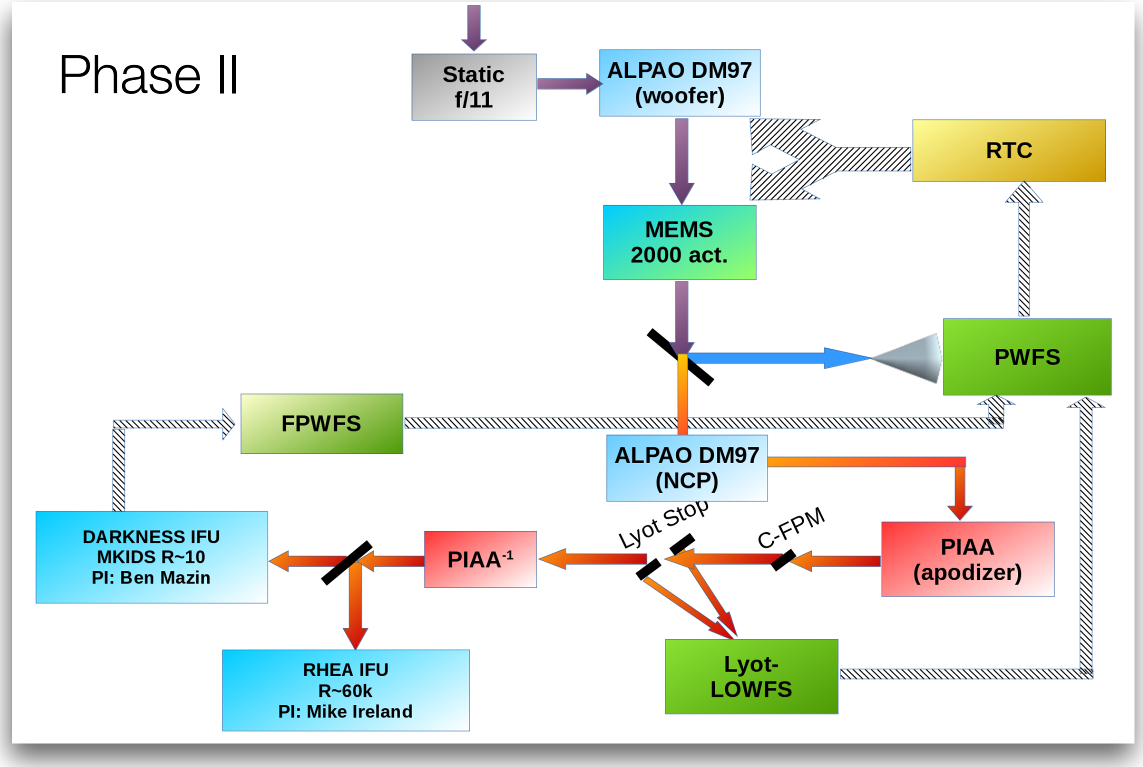
- First HCI instrument with IR PyWFS + IR APD detector
- Current / pending upgrades
  - Predictive control tested: significant gain, but far from theoretical predictions
  - Spectral resolution: single-mode fiber coupling with dedicated high-resolution IFS (RHEA) and with IRD Doppler spectrograph
  - MEC: MKID Exoplanet Camera (20k pixels, 0.8 - 1.4 µm, 1 µsec resolution)
- Future upgrades —> platform for TMT-PSI development
  - AO188: new RTC, new DM, near-IR PyWFS

MagAO-X: just got first light!

Males et al. 2018

- New AO system @ Magellan
  - Woofer-tweeter configuration (Alpao DM97 + BMC 2k)
  - Visible PyWFS + EMCCD
  - Predictive control at 3.6 kHz
- Common path WFS
  - LDFC / modal WFS
  - Real-Time Frazin Algorithm (EFC + servo-lag as probe)
- Science cameras: VisAO & Clio + upgrades to RHEA IFS & DARKNESS (MKIDs IFS)
- Coronagraphs
  - Phase I: VisAO + vAPP coronagraph —> Hα science!
  - Phase II: PIAACMC with Lyot-LOWFS + dedicated DM

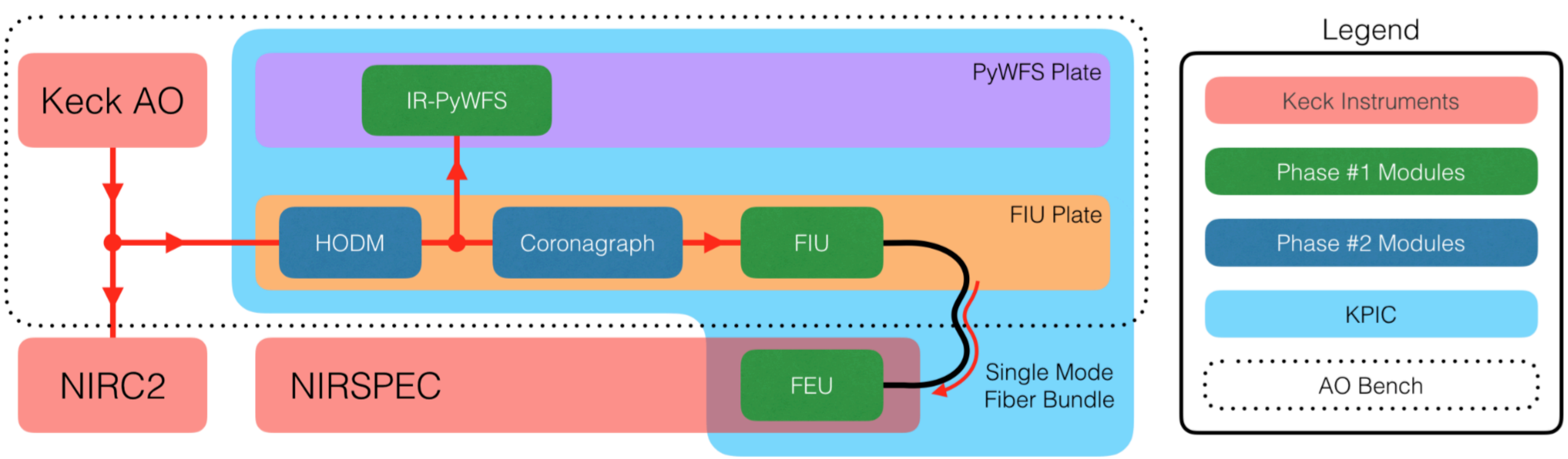




KPIC: concept & status

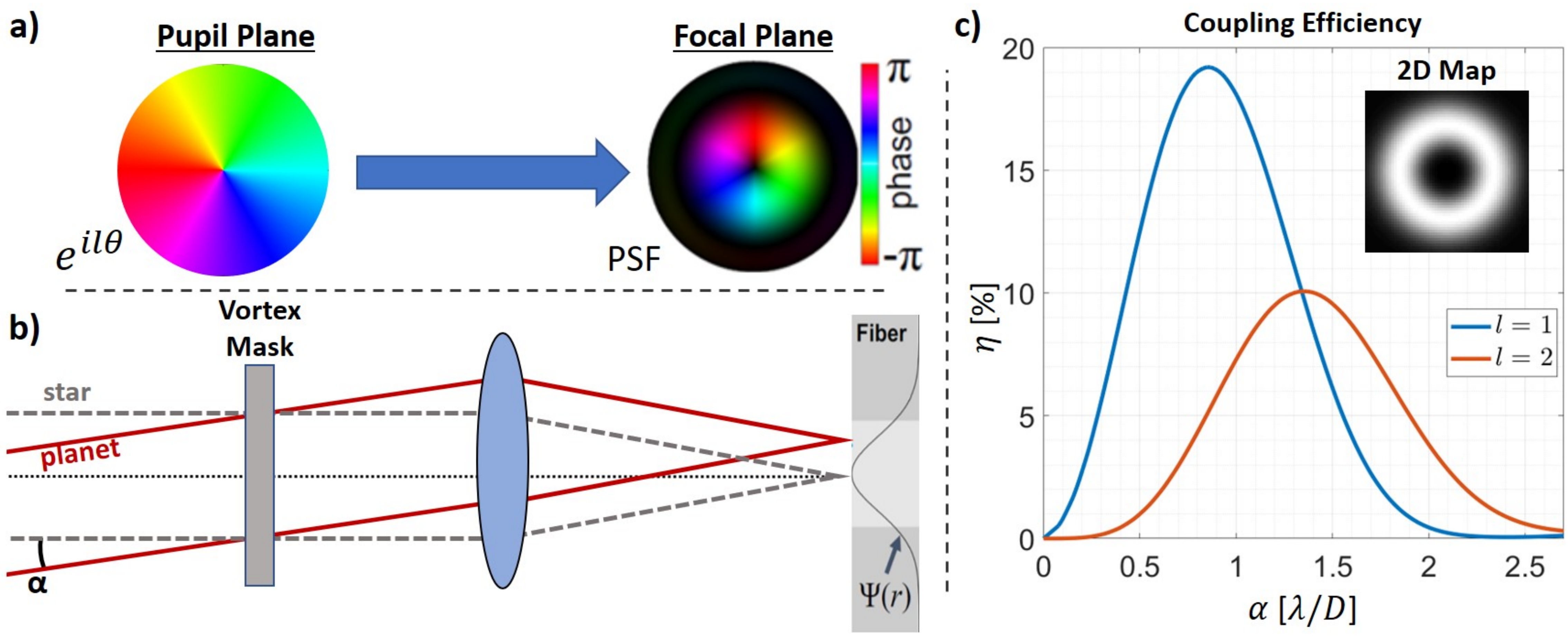
Mawet et al. 2018

- New XAO downstream Keck AO
  - IR PyWFS + IR-APD detector + 1k Boston DM
- Fiber feed to NIRSPEC
- New coronagraphs
  - new (optimized) vortex in NIRC2, also paired with IR PyWFS
  - K-band vortex fiber nuller



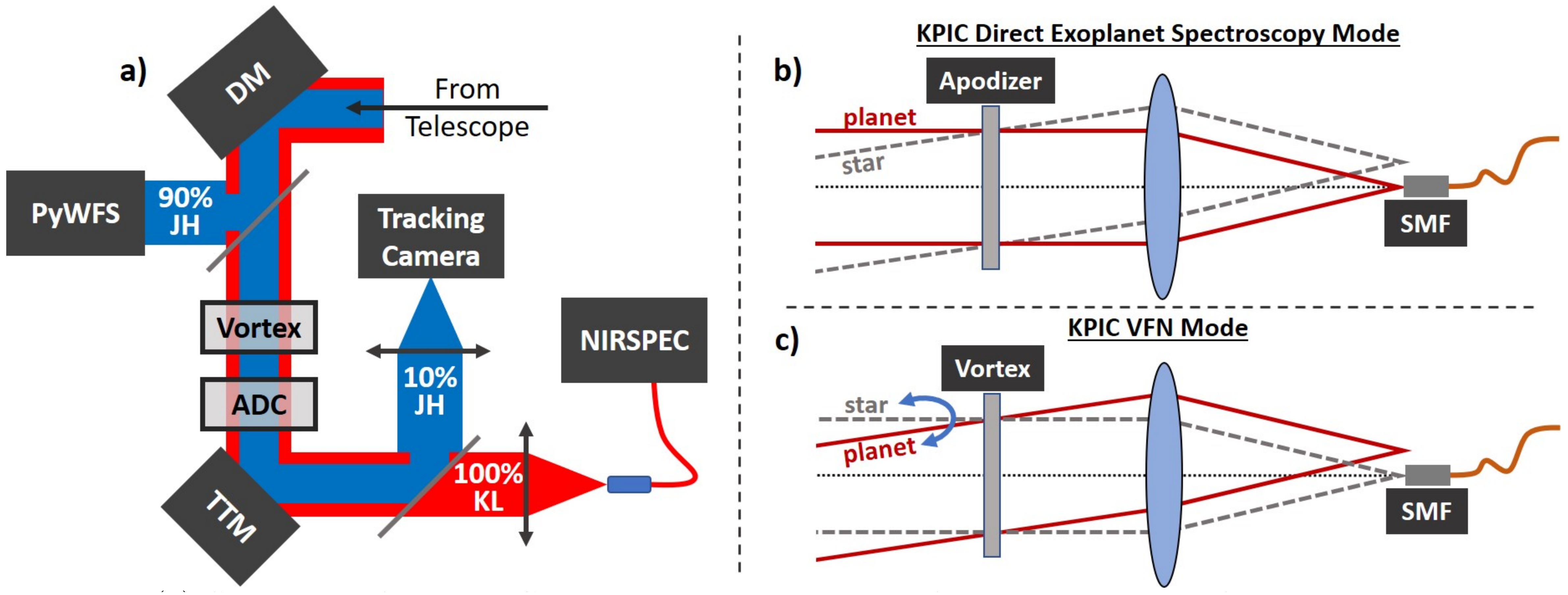
Vortex fiber nuller: concept

Etcheverri et al.2019



The VFN implementation in KPIC

Etcheverri et al.2019

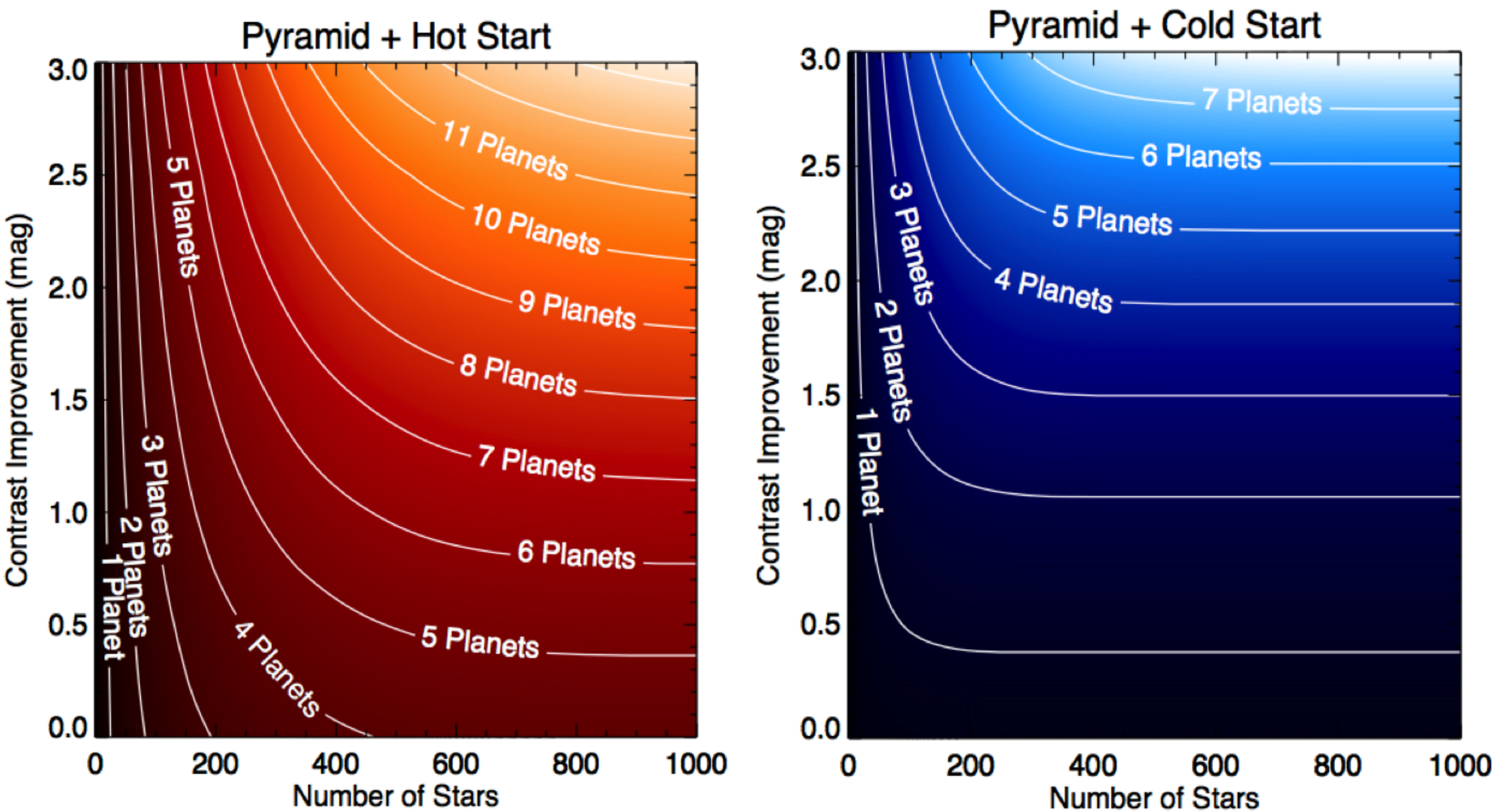


SPHERE+ and GPI 2.0: science goals

- Improve contrast by factor ~4 to reach lower masses and/or cold-start population
- Reduce IWA to reach closer to snow line, and bridge HCI with RV and Gaia planet populations
- Enhance the magnitude limit to access planetary populations in star-forming regions
- Perform better atmospheric characterization with higher spectral resolution

Expected yield

Chilcote et al. 2018



(if improvement just on contrast but not IWA —> marginal gain)

GPI 2.0 upgrade

- Upgrade concepts
  - pyramid WFS with EMCCD —> reach I ~ 13 mag
  - new MEMS DM with no defective actuator
  - high-performance RTC: operations at 2 kHz + predictive control
  - new APLC designs for higher throughput and smaller IWA
  - fast focal-plane WFS (possibly self-coherent camera)
  - fiber-feed module to send light to high-res spectrograph
  - new prism for broadband YJHK operation
  - better operability for queue mode scheduling
- Timeline: GPI decommissioned, upgrade ~18 months
—> should be @ Mauna Kea in 2022

SPHERE+ upgrade

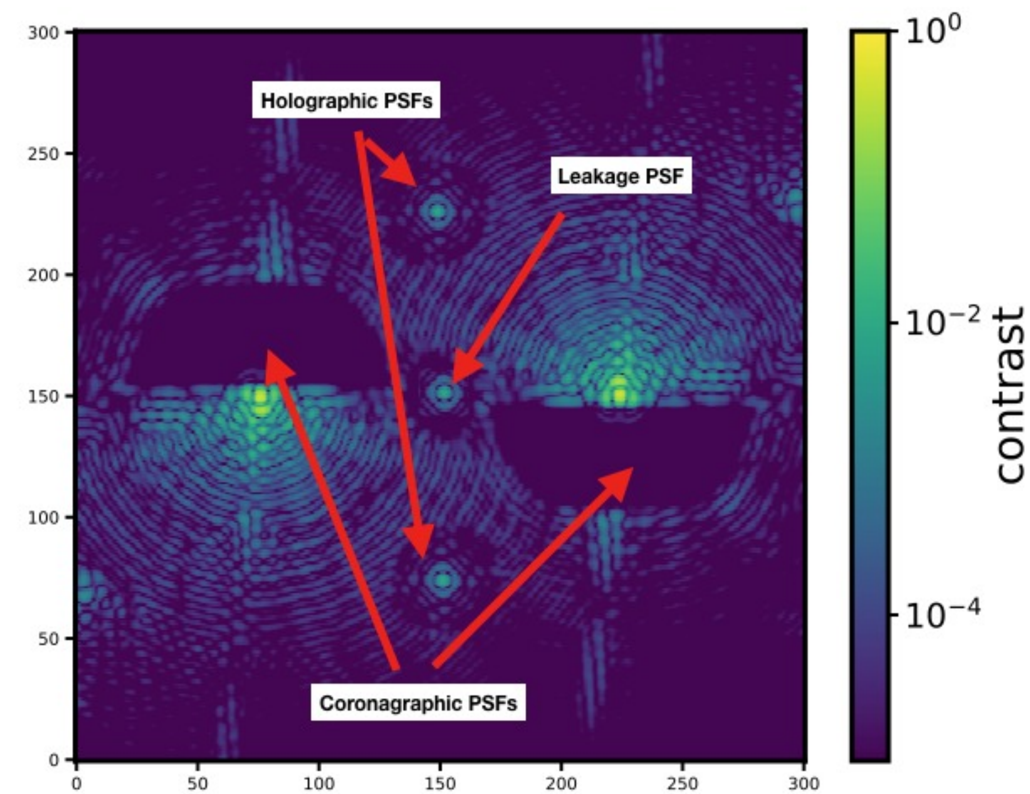
- Upgrade concepts
  - new AO module (SAXO2): PyWFS & faster RTC. To be used as second stage, in addition to current SAXO module.
  - NCPA management: Zernike wavefront sensor (ZELDA) and/or EFC with pair-wise probing
  - coronagraphy: new APLC designs for smaller IWA, and possibly phase-apodized pupil Lyot coronagraph (PAPLC)
  - spectral resolution: medium resolution with new IFS concept, high resolution by coupling to CRIRES+ (HiRISE project)
  - polarimetry: new derotator coating, replacement of IRDIS beamsplitter
  - fast visible camera (in addition to ZIMPOL)
- Timeline: project could start late 2020, with 4-yr development plan

LBT/SHARK

- Two channels: VIS & NIR (one on each side of binocular mount)
- Taking advantage of PyWFS + SOUL upgrade of LBT AO
- SHARK-VIS (2020)
  - expect 10^{-6} with fast frame rate camera from 400nm to 1000nm (no coronagraph)
  - upgrade: high-contrast spectroscopy (R=100,000) with IFS + SCAR coronagraph
- SHARK-NIR (2020-2021)
  - coronagraphic imaging at Y, J, H bands:
    Gaussian Lyot, shaped pupil, apodized Lyot, FQPM
  - long-slit spectroscopy at R~100 and 700
  - dedicated low-order DM to correct for NCPA + dedicated tip-tilt sensor

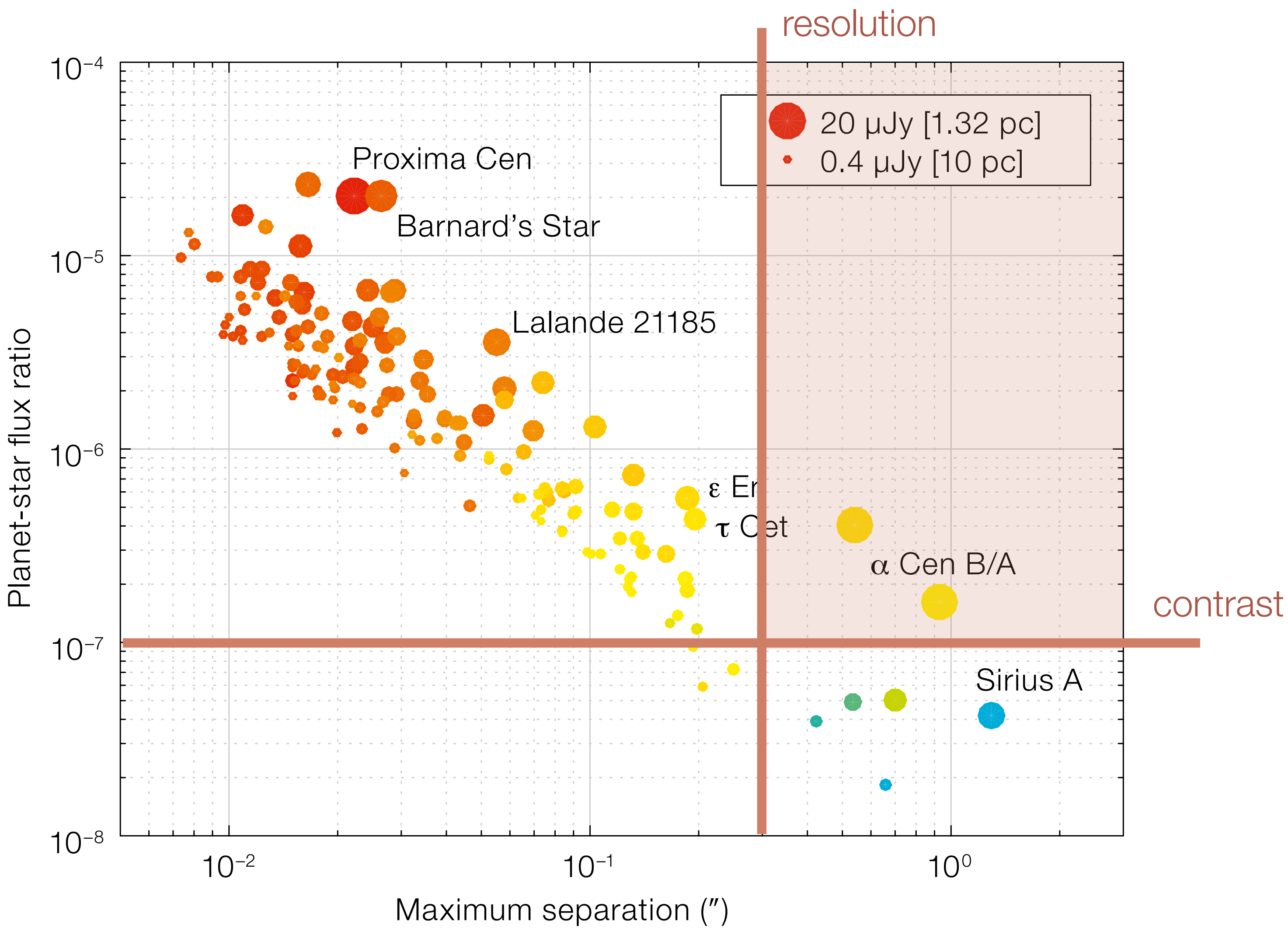
VLT/ERIS

- NIX: imaging + coronagraphy from K to M band
  - APP and classical vortex coronagraphs
  - focal-plane WFS with PSI & QACITS
- SPIFFIER: IFU spectroscopy from J to K band
  - based on a SINFONI upgrade, but not coupled with HCI capabilities
- First light expected in 2021



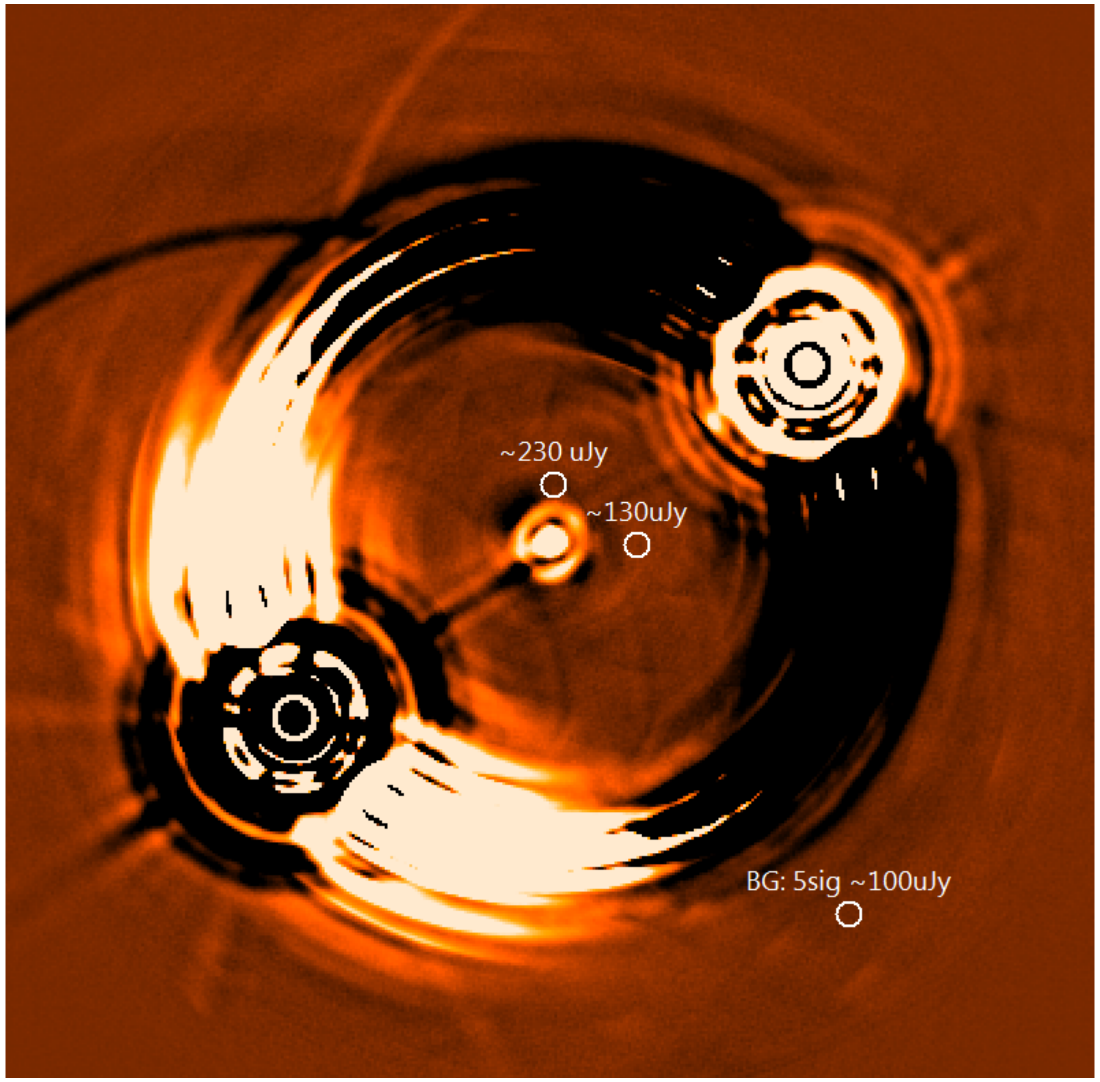
Mid-IR efforts

- Three projects aiming to bring HCI to mid-IR
  - VLT/NEAR
  - Gemini/TIKI
  - Magellan/MIRAC
- Goal: alpha Cen A/B
  - 100h sufficient to get down to 2 $R_\oplus$ in background-limited conditions



The VLT/NEAR campaign

- Almost 80 h of useful data
  - 20+ nights of ADI observations
  - alpha Cen A/B chopped in and out of vortex phase mask
- Data package available for download
  - original data: 7 Tb
  - after chop cycle (0.6 sec) averaging and subtraction: about 300k frames (360Gb)!
  - down-sampled to 1 min per frame for easy sharing (4600 frames)



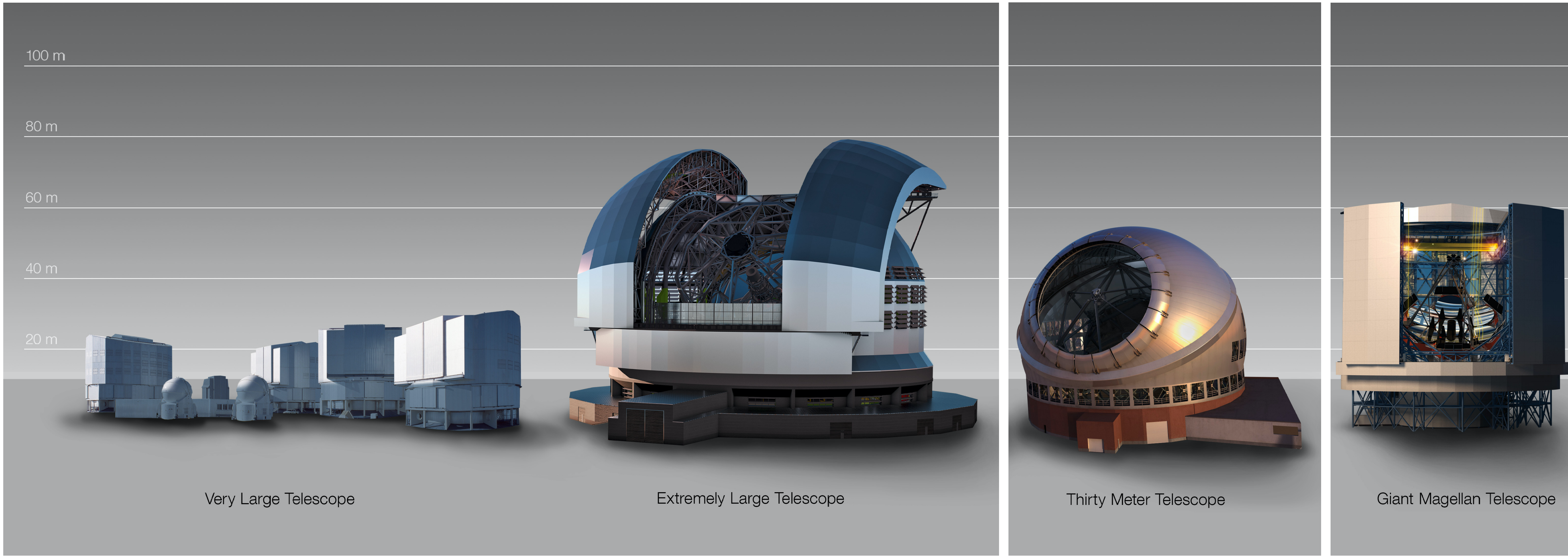
goal sensitivity: 80 μJy in 100 h

—Flash ad: Hi-5—

- Stellar interferometry recently entered the direct imaging game
  - ExoGRAVITY program on-going, and perspectives for GRAVITY upgrades
- VLTI/Hi-5: new project starting
  - 3-5 μm nulling interferometer, with contrast 10^{-4} (goal 10^{-5})
  - 4 mas inner working angle (= 0.04 AU at 10 pc!)
  - medium spectral resolution
- Main scientific goals
  - search for planets within snow line for stars in young moving groups
  - witness planet formation around snow line in nearby star forming regions
  - characterize some known RV planets (warm Jupiter targets)
  - characterize exozodiacal disks

Interferometry also used on single pupils

- NRM modes now proposed on several instruments
- Example: SCExAO
  - FIRST: sampling, rearranging, and combining the pupil with fibers
  - VAMPIRES: sparse aperture masking + high-speed speckle imaging in the visible range, combined with polarimetry. IWA = 10 mas!
  - GLINT: near-IR nulling interferometry based on sub-pupils



Future instrumentation on ELTs

Towards rocky planets

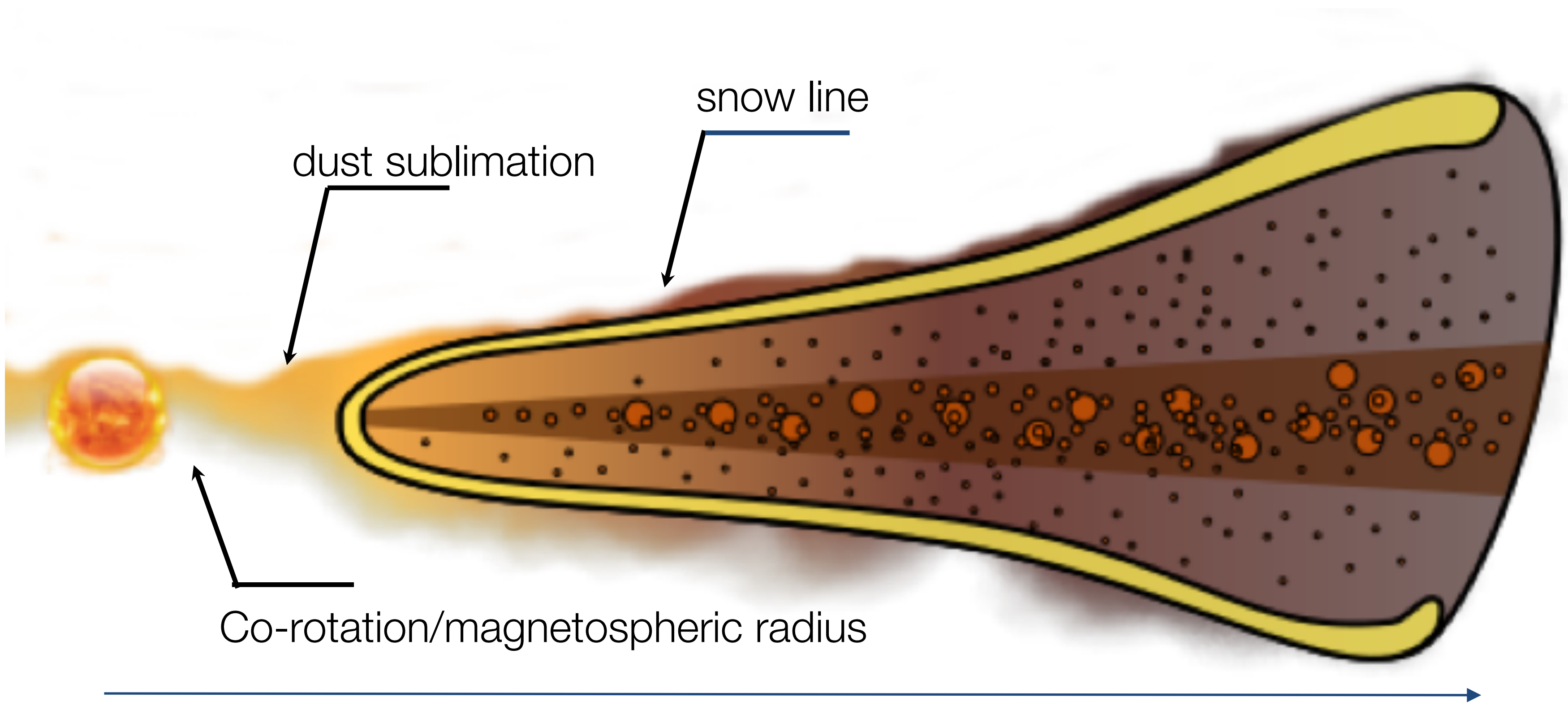
Overview (bold = partly/fully dedicated to HCI)

- European ELT
  - 1st generation: MICADO, HARMONI, **METIS**
  - 2nd generation: **PCS**
- TMT
  - 1st generation: IRIS, MODHIS
  - 2nd generation: **PSI**, MICHI
- GMT
  - 1st generation: GMTIFS
  - 2nd generation: **GMagAO-X**

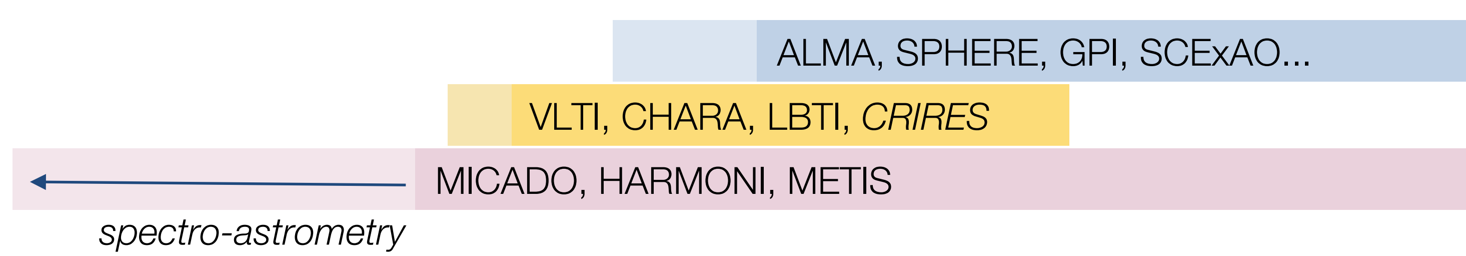
Key science drivers

(courtesy G. Chauvin)

- Initial conditions for planet formation



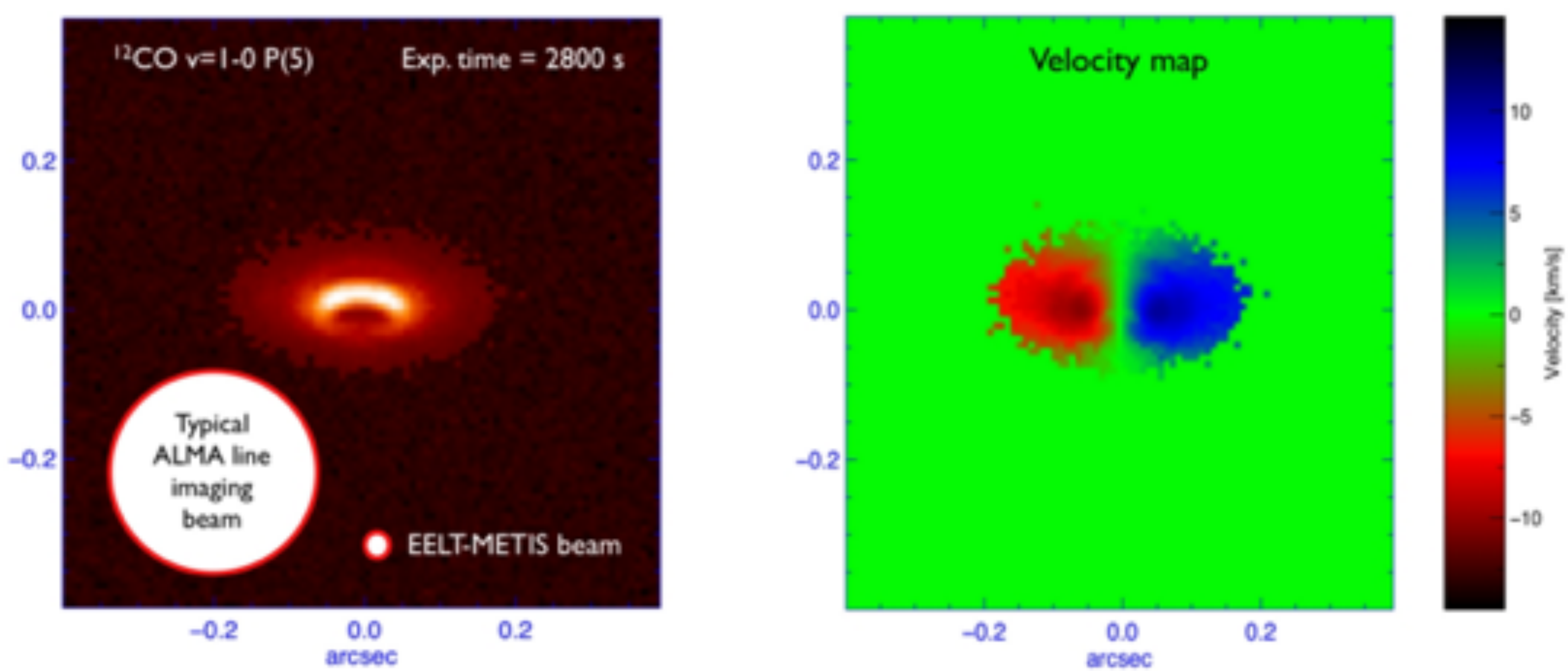
Distance	[au]	0.1	1.0	10.0	100.0
Temperature [K]		1000	300	100	30
Time		2 weeks	1 yrs	30 yrs	1000 yrs



Key science drivers

(courtesy G. Chauvin)

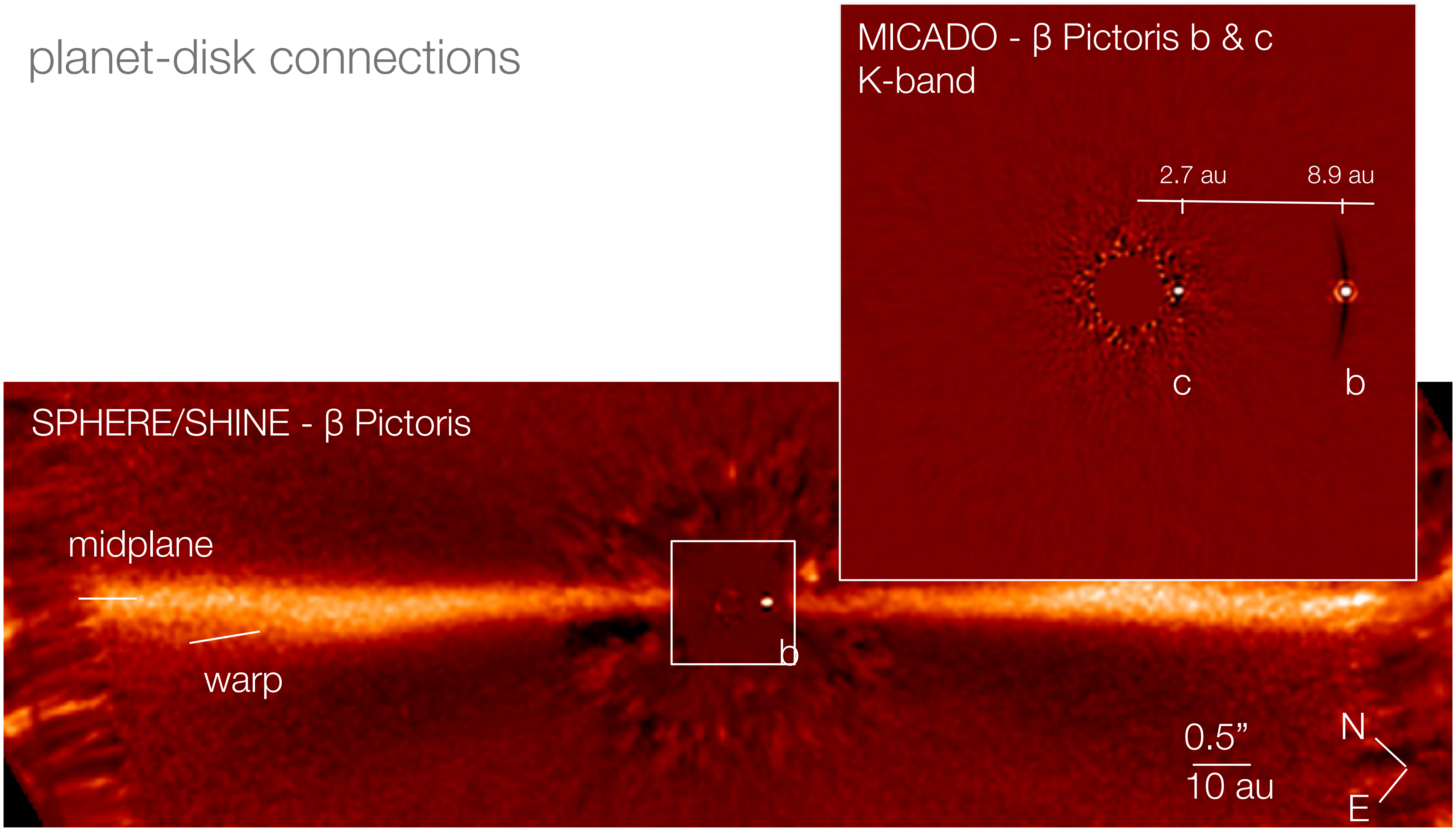
- Initial conditions for planet formation
  - Dust structure & properties in planet-forming regions (spirals, rings, gaps, shadows, etc)
  - Gas properties, spatial distributions, & dynamics (mid-IR molecules)



Key science drivers

(courtesy G. Chauvin)

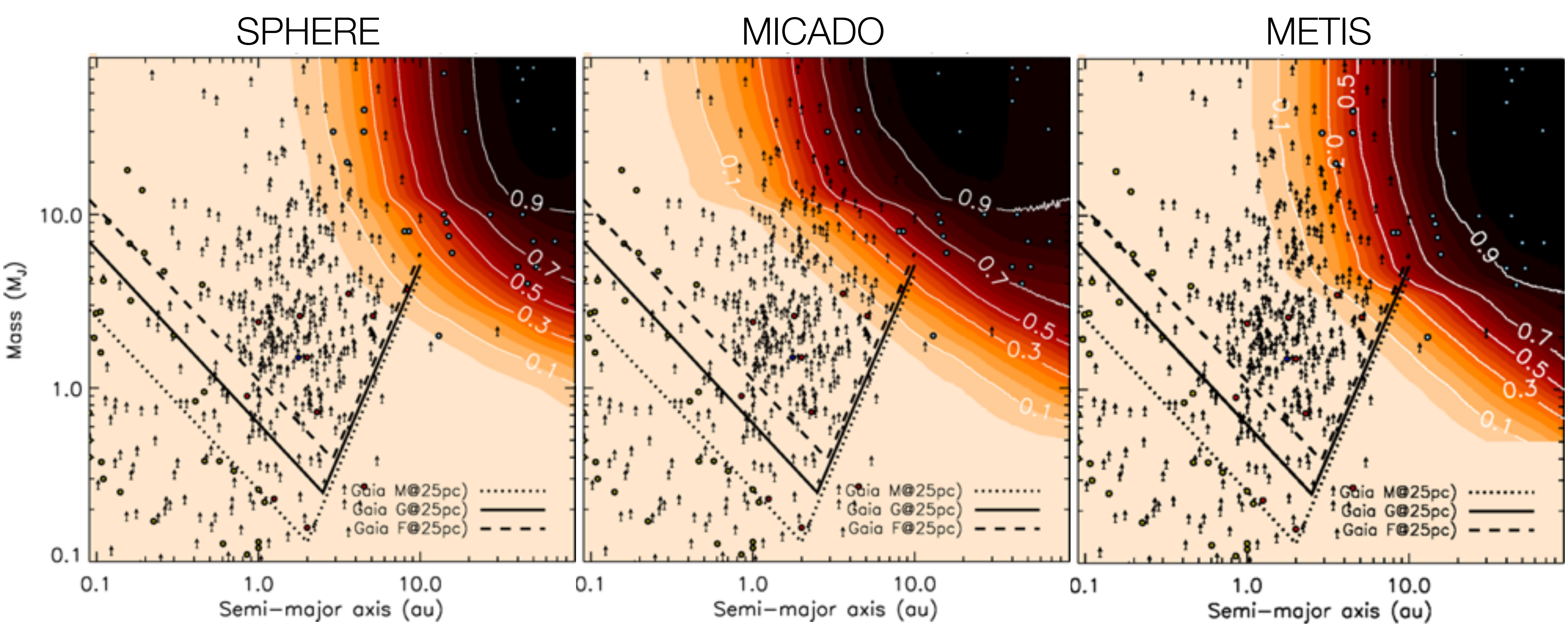
- Architecture of planetary systems
  - planet-disk connections



Key science drivers

(courtesy G. Chauvin)

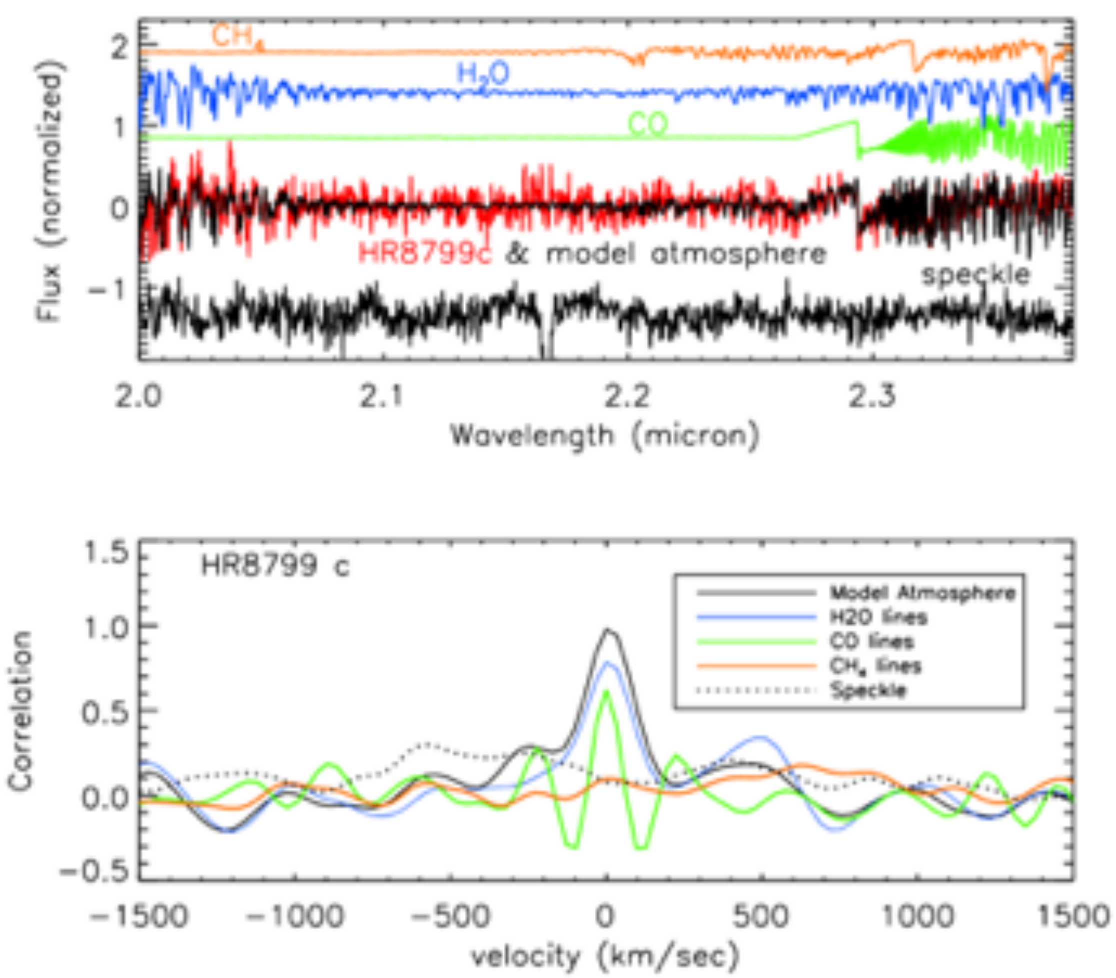
- Architecture of planetary systems
  - global content of giant planet population (although big survey unlikely)



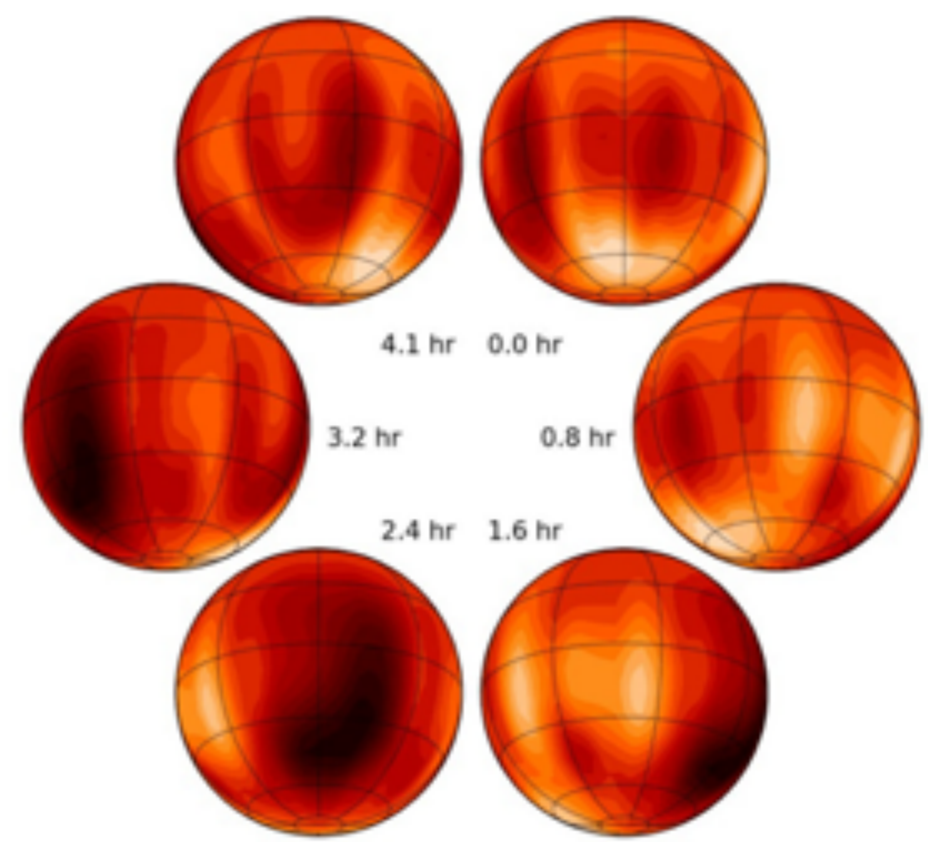
Key science drivers

(courtesy G. Chauvin)

- Physics of exoplanets
  - medium- to high-spectral resolution: cloud formation & evolution, molecular abundances, C/O ratio, T/P profile, Doppler imaging, etc



Keck/OSIRIS (R_λ = 4000) observation of HR8799 c
CO & H2O detection; Konopacky et al. (2013)

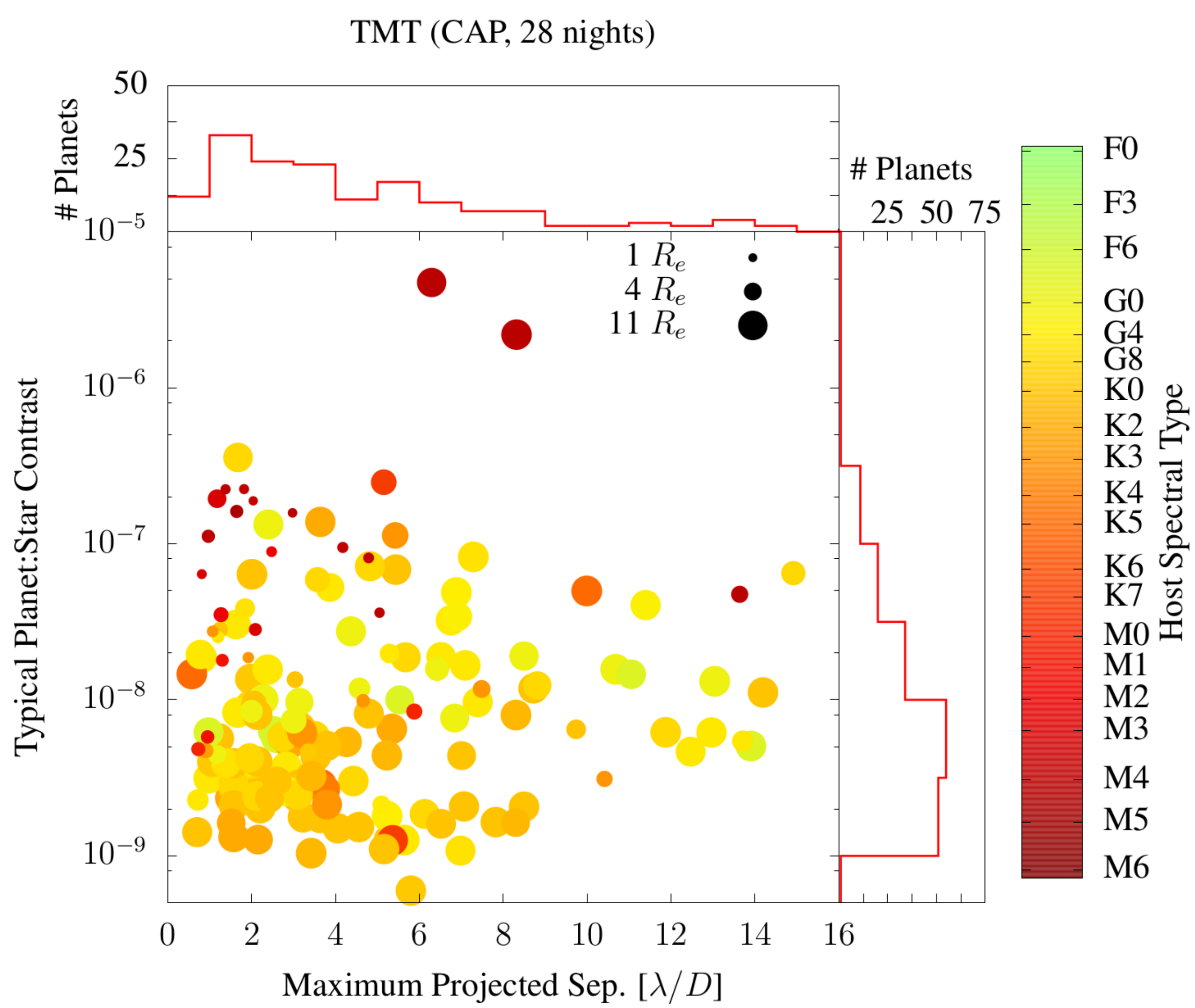


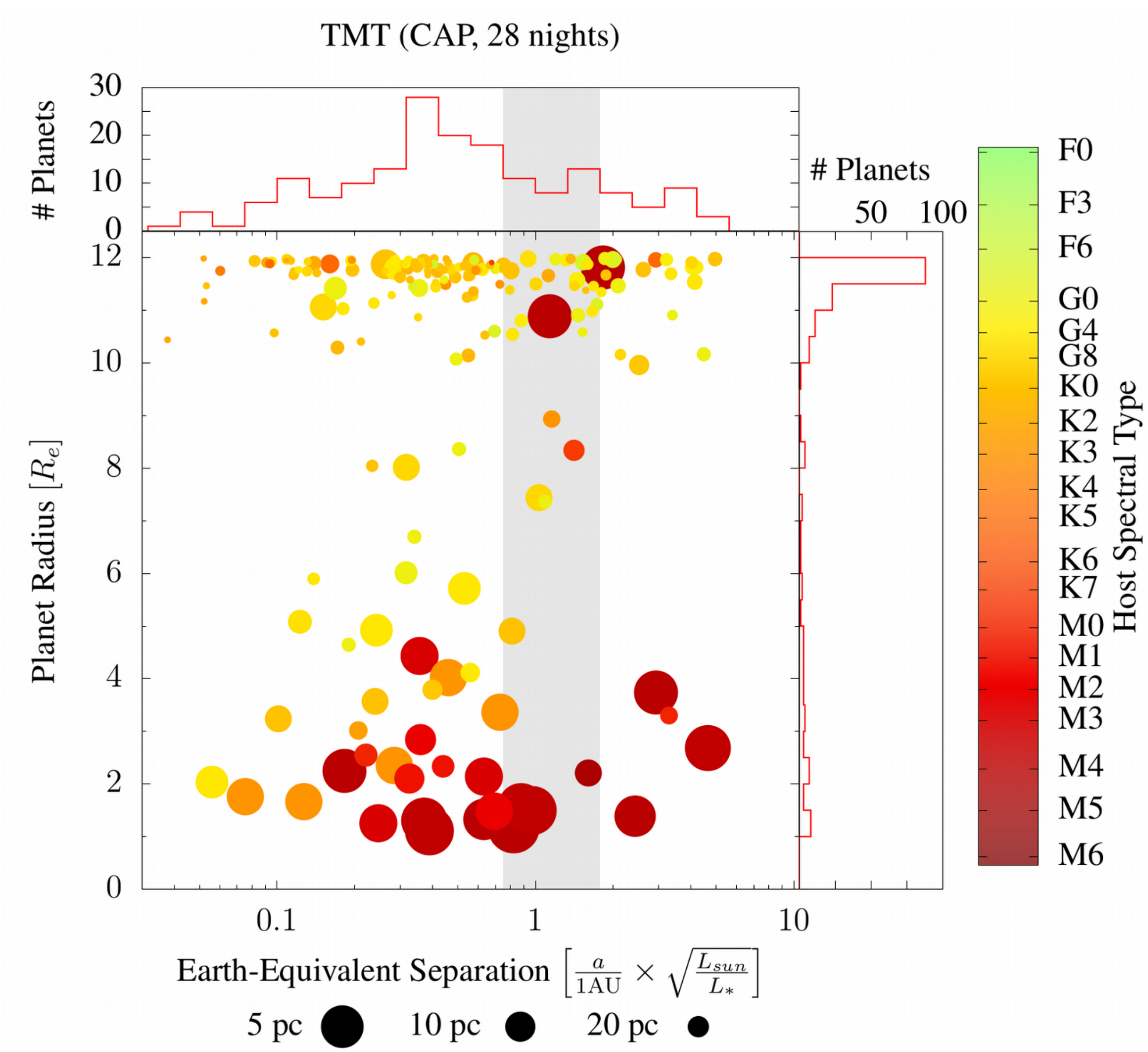
Luhman 16 B, 2 pc, Rotation 4.9hrs, CRIRES
spectroscopic variability (Crossfield et al. 14)

Key science drivers

(courtesy J. Males)

- Physics of exoplanets
  - RV planet follow-up (potential of visible instrument illustrated here)

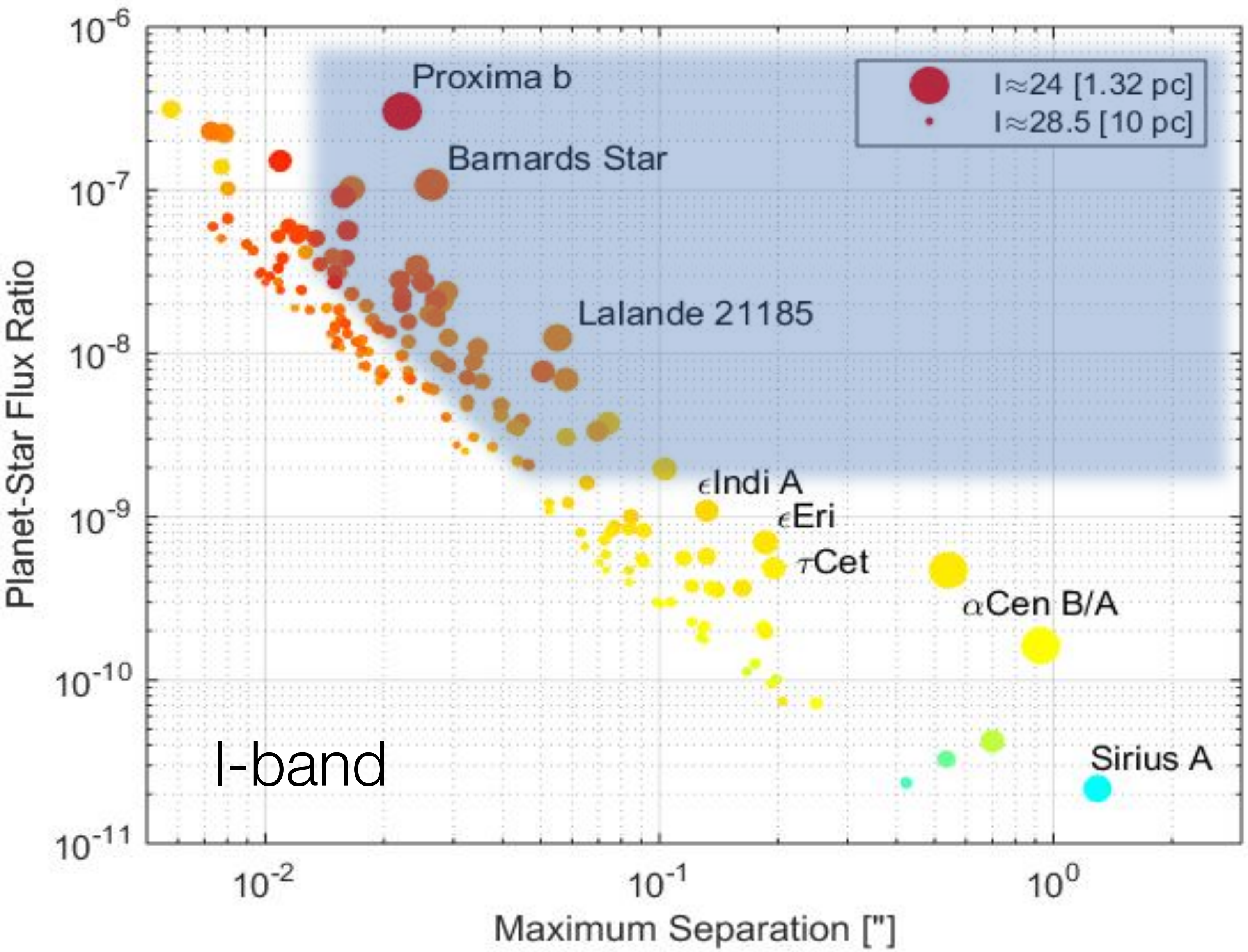


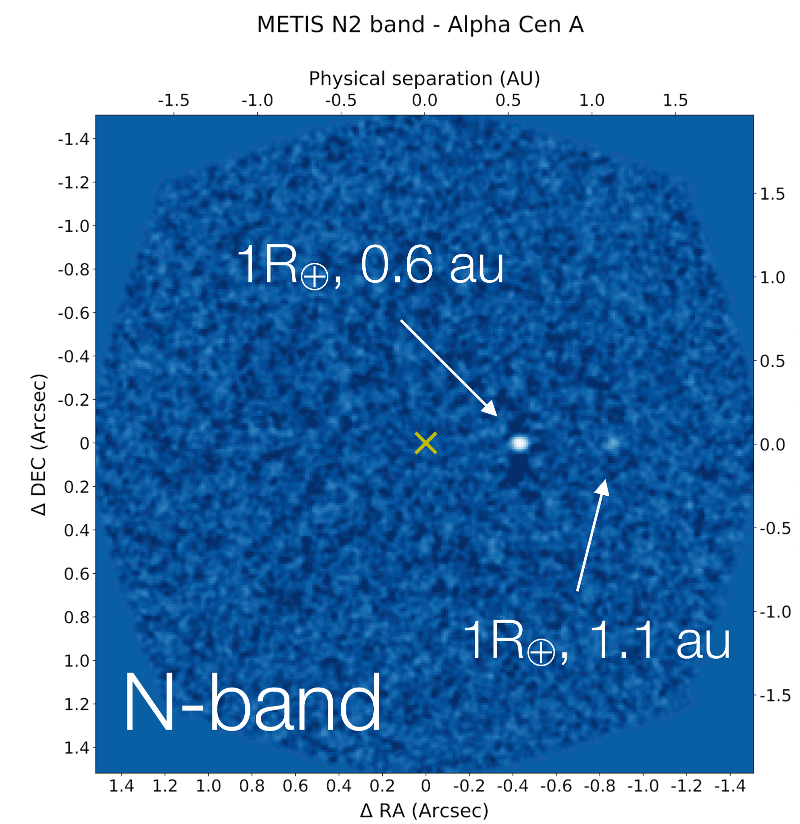


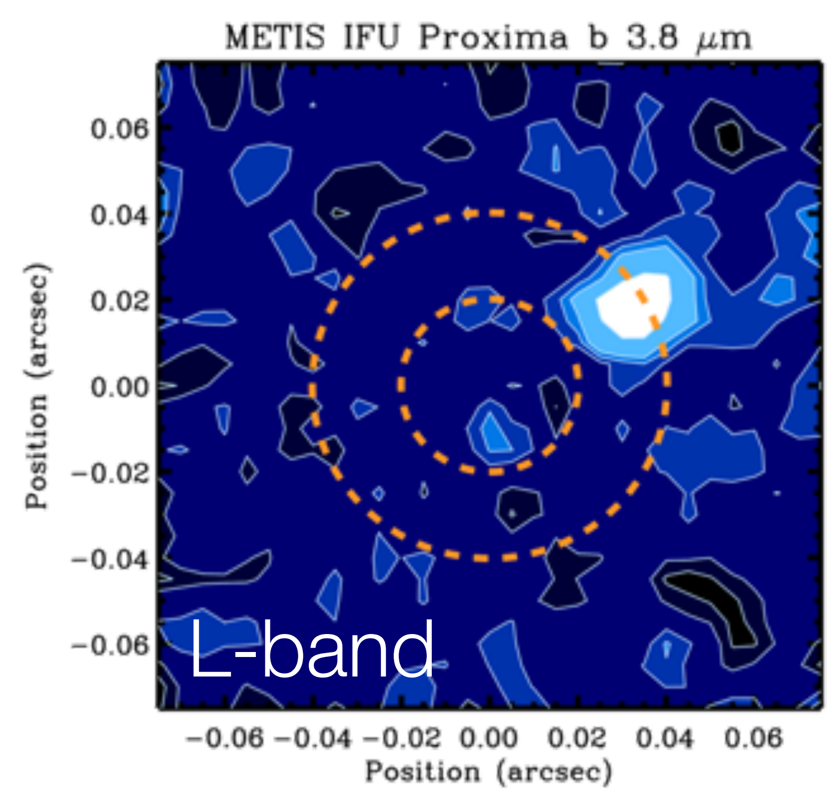
Key science drivers

(courtesy M. Kasper, I. Snellen)

- Physics of exoplanets
  - towards Earth-like planets





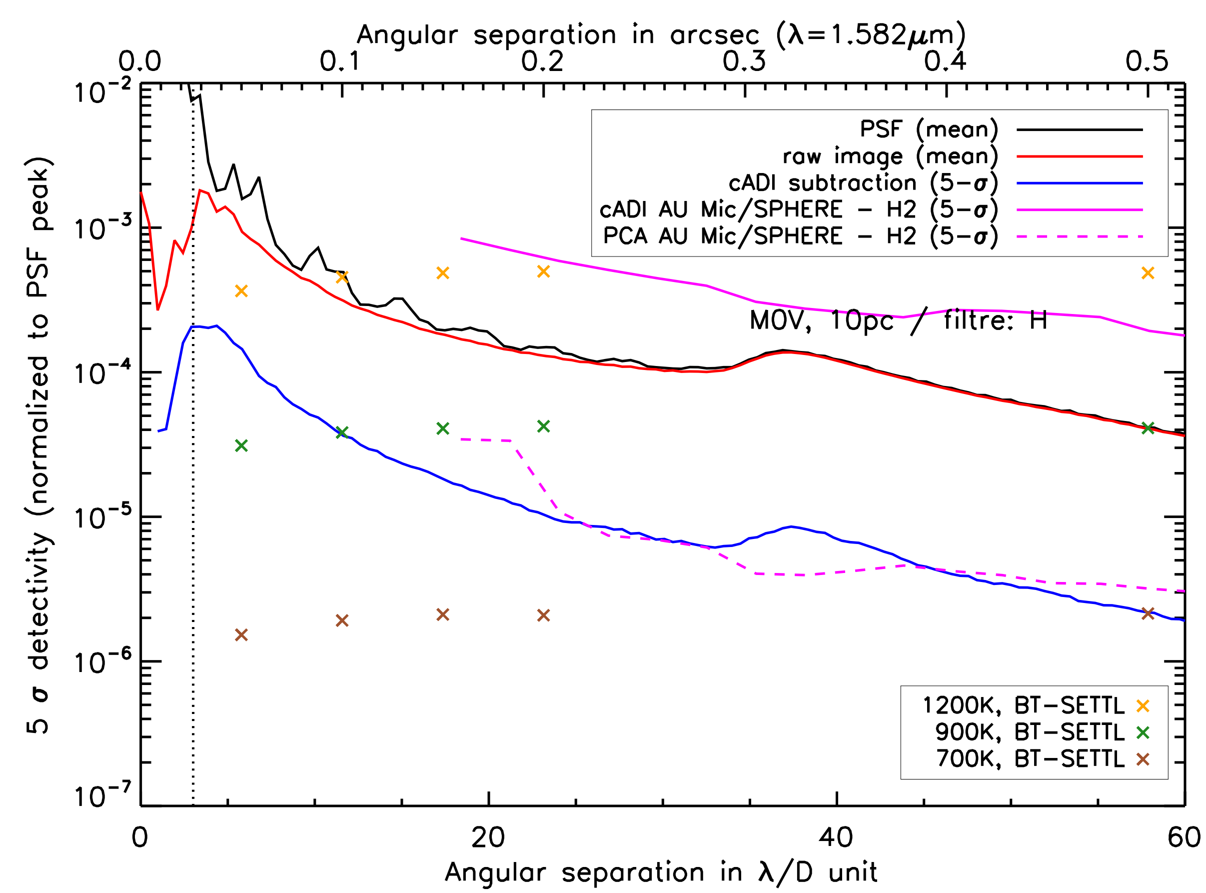


1st generation ELT/TMT/GMT instruments

ELT/MICADO

Perrot et al. 2018

- Not optimized for high contrast (although good SCAO)
  - no upstream apodization possible —> two classical Lyot, one vortex
  - ADC downstream focal-plane —> reduced performance
  - aperture masking and vAPP also included in baseline
- Expected performance similar to SPHERE at H, with access to smaller IWA
  - some gain expected at K band thanks to lower background

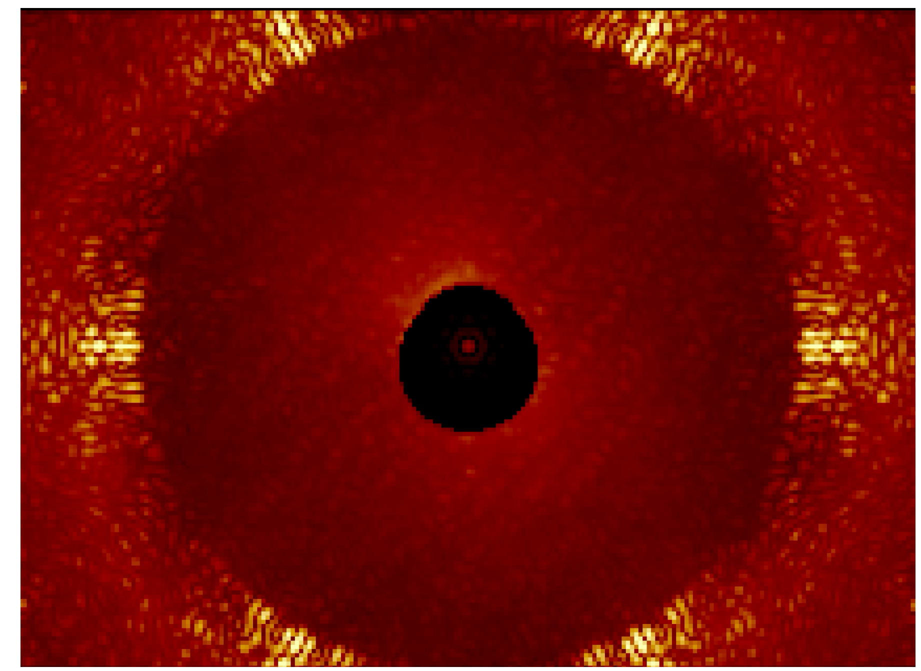


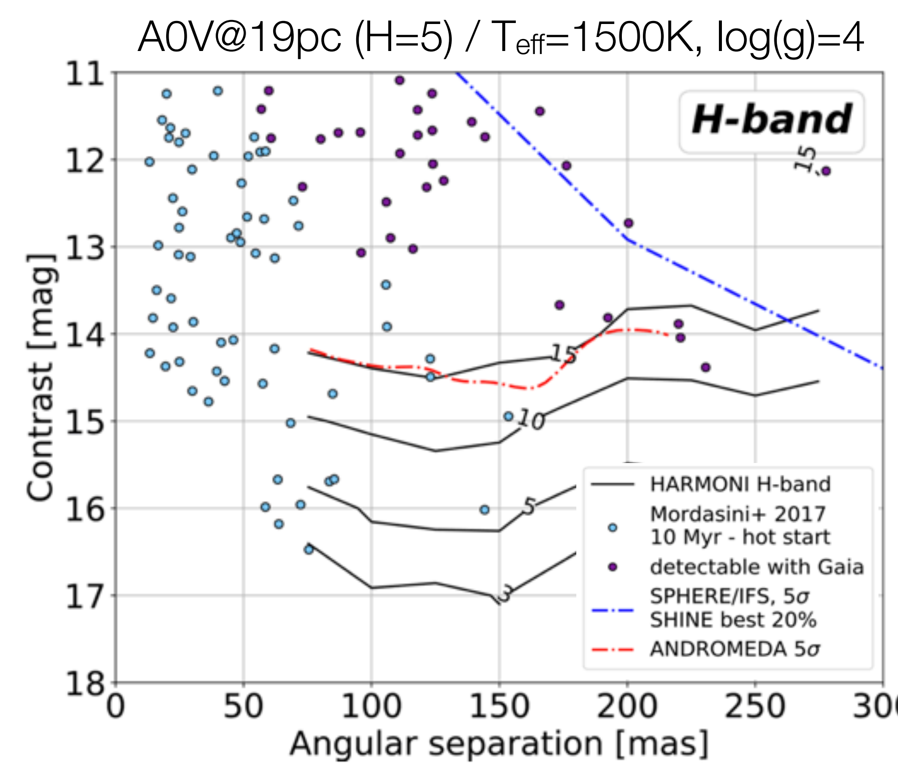
ELT/HARMONI

(courtesy A. Carlotti)

- SCAO/LTAO-fed IFS covering V to K
  - Spectral resolutions from 3,000 to 20,000
- Dedicated HCI module operating at H-K bands
  - two shaped-pupil apodizers (+ associated semi-opaque focal plane masks in cryostat)
  - 10^{-6} dark holes, 50-130 and 75-300 mas
  - NCPA measured in real-time with ZELDA
  - dedicated, fixed ADC
- Rely on molecular mapping to predict detection limits (R=17,000)

400 mas



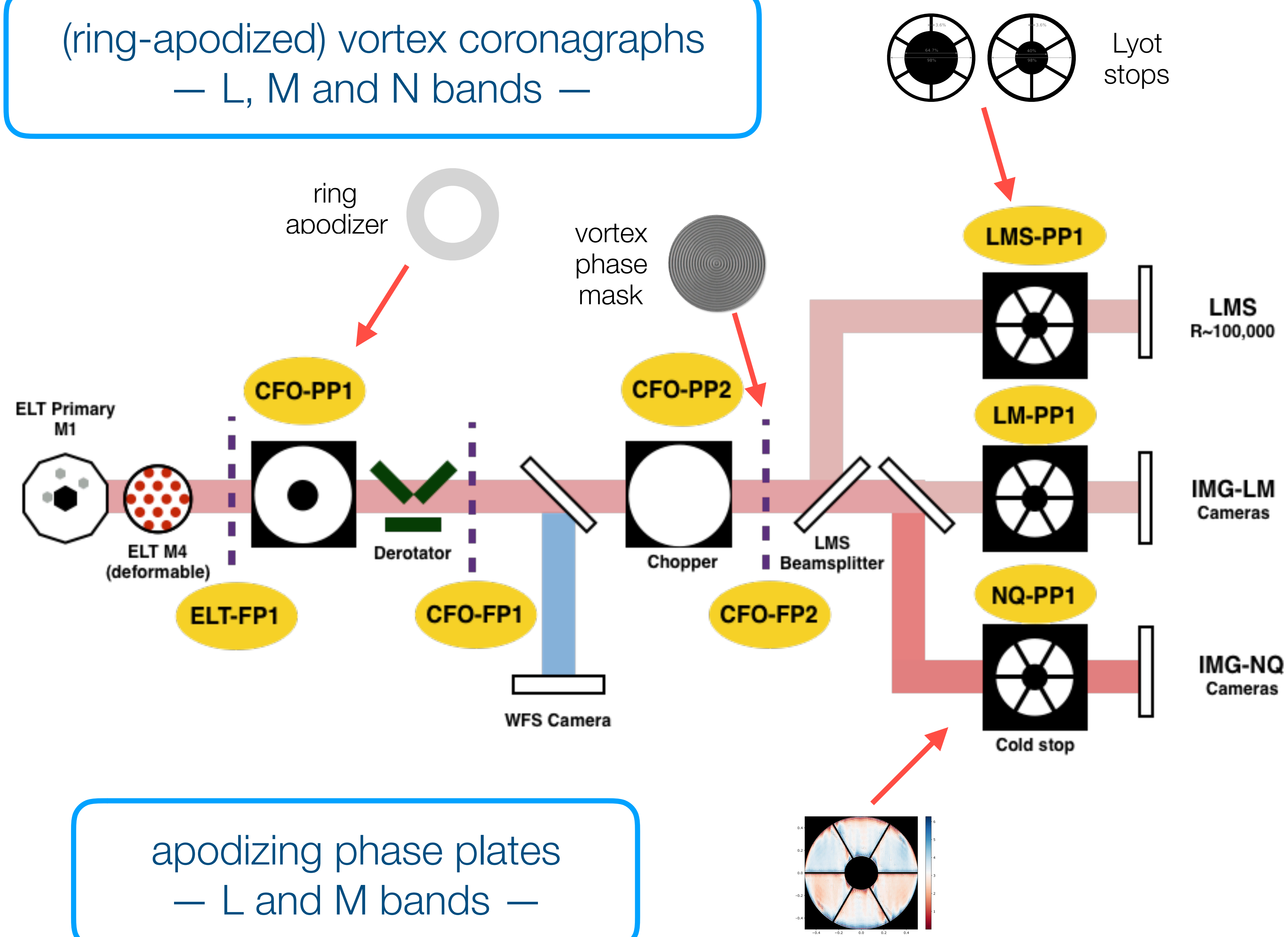


ELT/METIS

- Near-IR PyWFS provides high Strehl in thermal IR
  - > 80% at L band, > 95% at N band —> close to XAO conditions
- Apodized vortex coronagraph & vAPP (+ possibly classical Lyot)
  - High-contrast imaging at L, M, N bands
  - High-contrast IFU spectroscopy at L, M bands
- NCPA management
  - NCPA minimized by design: derotator in common path, SCAO pick-off close to VPM, etc.
  - QACITS for vortex pointing control
  - PSI for low-order aberrations (access to SCAO telemetry in real time)
- Pupil stabilization in common path

ELT/METIS block diagram

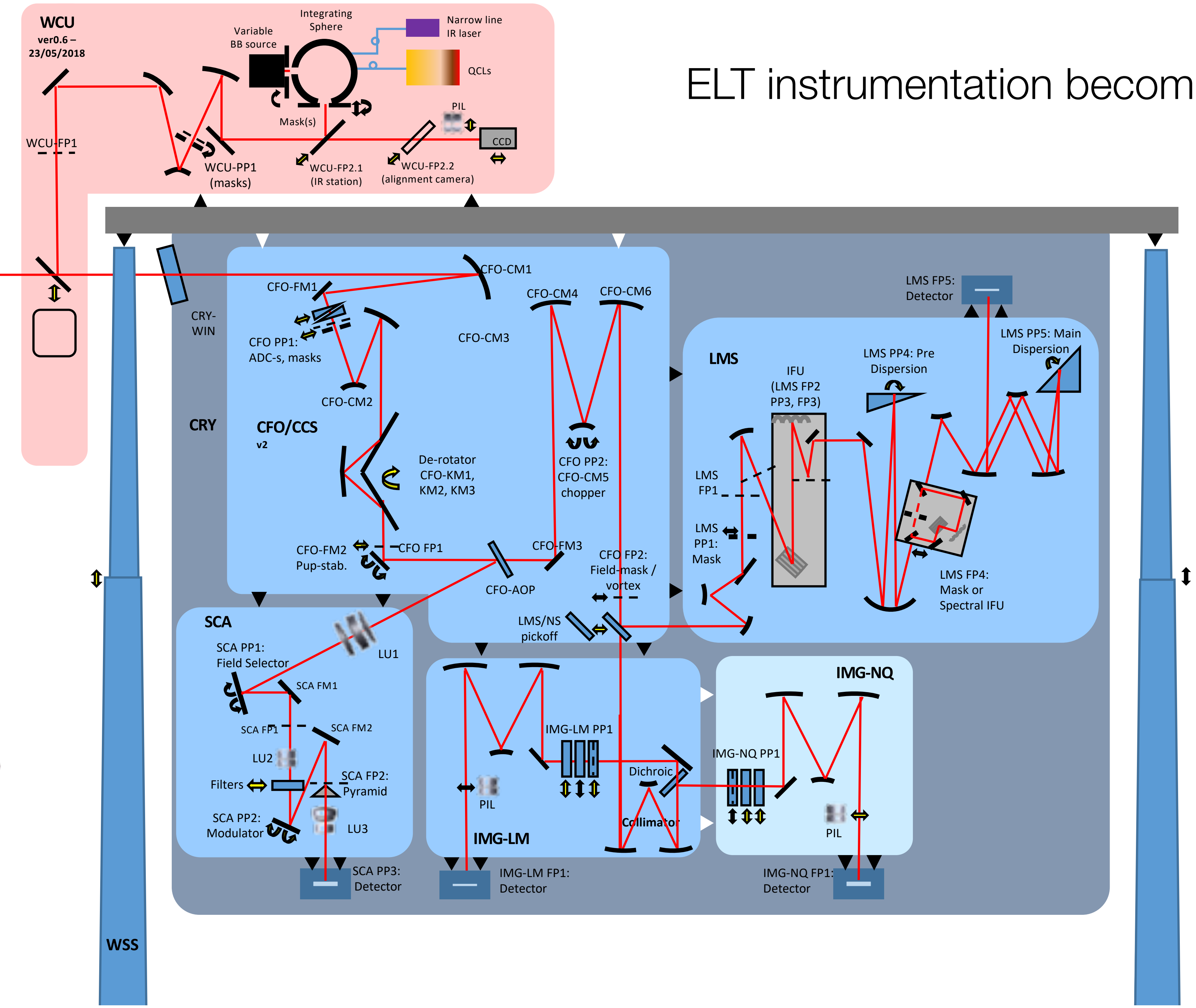
(ring-apodized) vortex coronagraphs
— L, M and N bands —



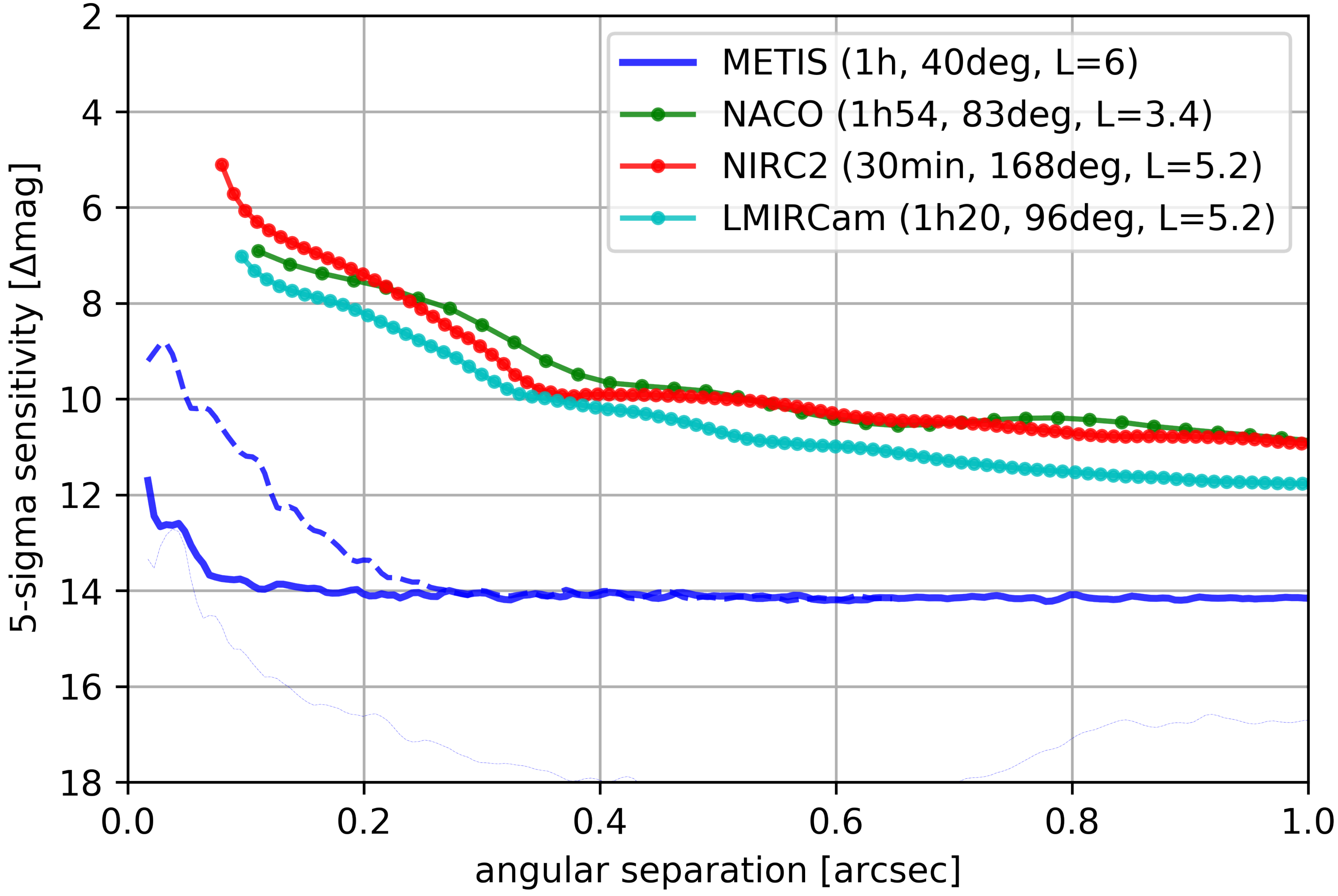
apodizing phase plates
— L and M bands —

ELT/METIS: a complex instrument

ELT instrumentation becoming huge (100M€ projects)



ELT/METIS expected performance



TMT: IRIS and MODHIS

- IRIS: infrared imaging spectrograph
  - fed by NFIRAOS adaptive optics module
  - spectral resolution up to 8,000 on 0.5” × 0.5” FoV
  - no specific HCI mode, but can be used for wide-separation planets
- MODHIS: similar concept as for KPIC
  - use NFIRAOS to inject into (bundle of) single-mode fibers
  - send to dedicated high-res near-IR spectrograph (R=100,000)

GMTIFS

- 1st light instrument for GMT
- Single-object, adaptive-optics-corrected, near-infrared integral-field spectrograph
  - works behind GMT LTAO system
  - 1-2.5 μm wavelength
  - resolving power 5,000 to 10,000
  - FoV 0.53” x 0.27” for best sampling (6 mas/pix)
  - not focused on HCI —> mostly planets at large separations
- Also features an imager with 20” FoV

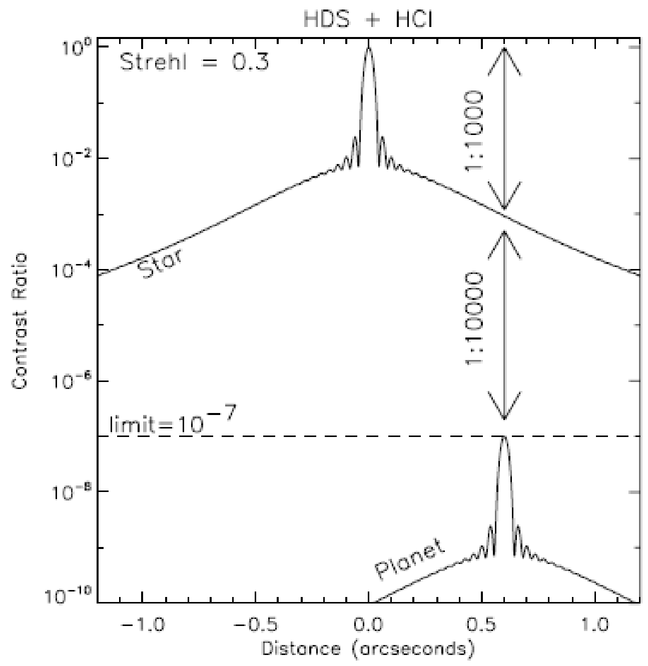
2nd generation ELT/TMT/GMT instruments

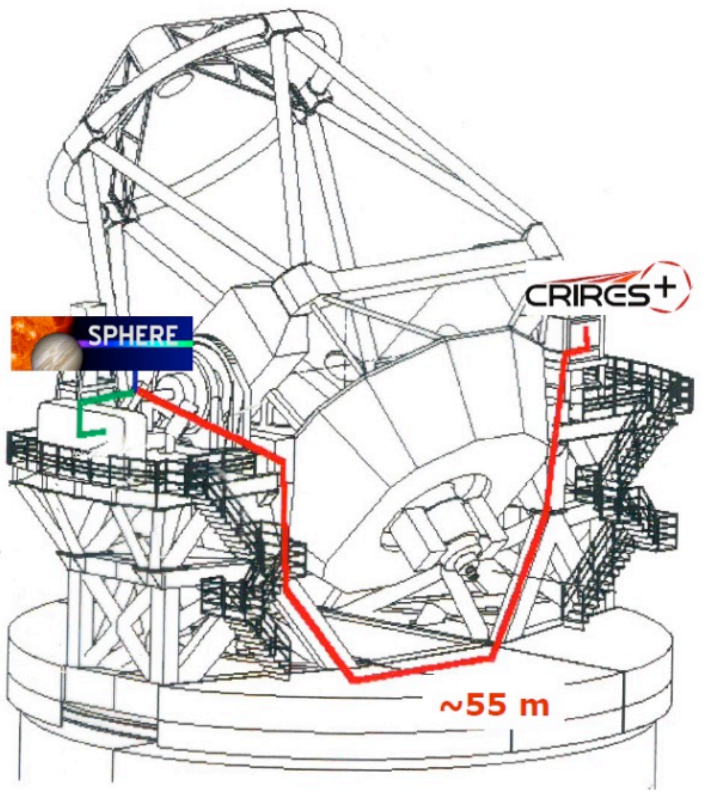
Challenges of super-high-contrast (visible/near-IR)

- Current AO systems at ~3 λ/D: ~10^{-3} raw contrast, ~10^{-4} detection limit
  - For habitable planets, we need ~1000x gain in raw contrast, and 10,000x gain in detection limit
- Current limits, and how to overcome them:
  - M stars too faint for ExAO WFS
    → more efficient wavefront sensing (e.g. unmodulated pyramid)
    → predictive control & sensor fusion between multiple sensors
  - Current systems are too slow → need low latency systems + predictive control
  - NCPA (incl. WF chromaticity) and slow speckles → focal plane wavefront control + sensor fusion
  - Lyot Coronagraph doesn't provide required suppression at 2 λ/D → advanced coronagraphs
- Planet image is still ~100x below starlight halo
  → high dispersion spectroscopy template matching
  → coherent differential imaging
  → use WF telemetry to subtract PSF

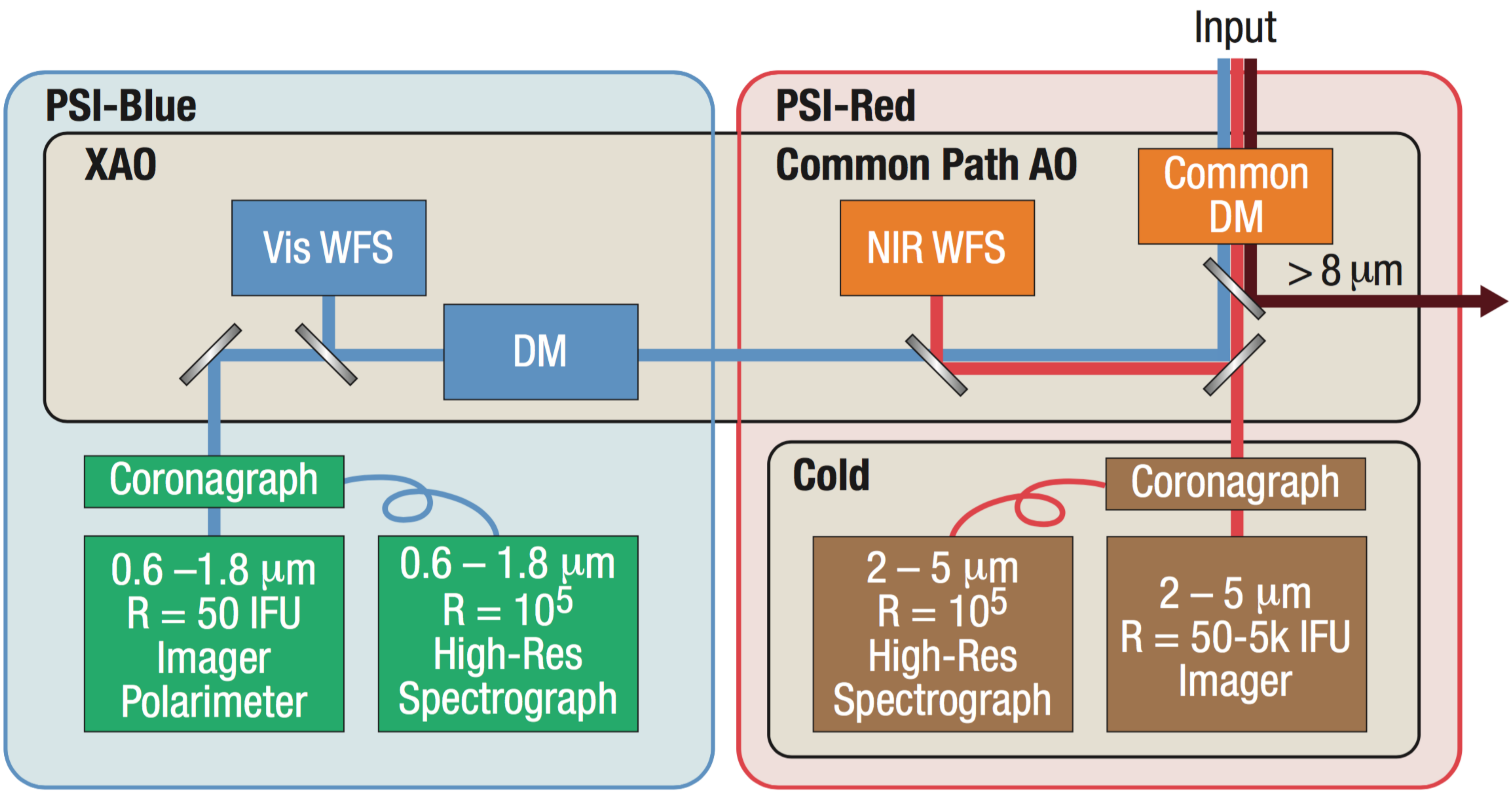
ELT/PCS (aka EPICS)

- Specifically targets Earth-like planets around M stars
  - 10^{-8} contrast at a few 10 mas on faint stars
  - goal: O_2 signature in Proxima b at 760nm and/or 1270nm
- Tools: focus on high-resolution spectroscopy and polarimetry
  - precursor instruments of fundamental importance
- On-going R&D
  - prototyping activities on the IFS (e.g., lenslet array vs image slicer)
  - fiber feed to high-res spectrograph: HiRISE demo
  - DM development
- Project expected to start ~2024





PSI (red and blue) & MICHI



MICHI: similar to METIS. Could be partly integrated with PSI (e.g., AO feed).

GMagAO-X

- Scaled copy of MagAO-X —> 21,000 actuators
  - combines seven Boston DMs of 3,000 actuators each, in parallel
  - also needs multiplexed EMCDDs to operate the visible PyWFS
- Concept of a ring-like IFU to be adjusted to expected angular separation of know RV planets
  - 16-sided reflective pyramid slicing the focal plane azimuthally, feeding sixteen 50μm core multi-mode fibers to feed the G-CLEF spectrograph
  - very high spectral resolution (R=218,000) from 650 to 950 nm

ELT instrumentation roadmap

(courtesy G. Chauvin)

Phasing

1st Generation   2nd Generation

Instruments - First Light	Description	AO	λ (μm)	Resolution	FoV	Add. Mode
MAORY/MICADO (PdR completed*) (2026-2028)	Spectro-imager	SCAO, MCAO	0.8 – 2.4	3000 - 18 000	53.0” 19.0” 6.0”	Astrometry 40μas Coronography Long-Slit Spectro
HARMONI (PdR completed) (2026-2028)	IFU Spectrograph	SCAO, LTAO	0.5 – 2.4	3500 7000 17 000	1.0” 10.0”	Coronography
METIS (PdR completed) (2026-2028)	IFU & Spectro-Imager	SCAO LTAO	3 – 20 3 - 5	5000 100 000	18” 0.4”×1.5”	Coronography Long-Slit Spectro
HIRES (Phase A completed) (2030+)	Optical and NIR High-Resolution Spectrograph	SCAO	0.37 – 0.71 0.84 – 2.50	200 000 120 000	0.82” 0.5”	Polarimetry IFU mode
MOSAIC (Phase A completed) (2030+)	Optical and NIR Wide/Narrow field Multi Object Spectrograph	- - MOAO	0.37 – 1.4 0.37 – 1.4 0.8 – 2.45	300- 2500 5000 – 30 000 4000 – 10 000	6.8” 420’ 2”	Multiplex ~ 400 Multiplex ~100 Multiplex ~10 Imaging?
EPICS (2030+)	Optical and NIR High Contrast IFU Spectrograph & imager	XAO	0.6 – 0.9 0.95 – 1.65	125 – 20 000 100 000?	2.0” 0.8“	Coronography Polarimetry

ELT on track for 2025 first light