ELT PCS
Planetary Camera and Spectrograph

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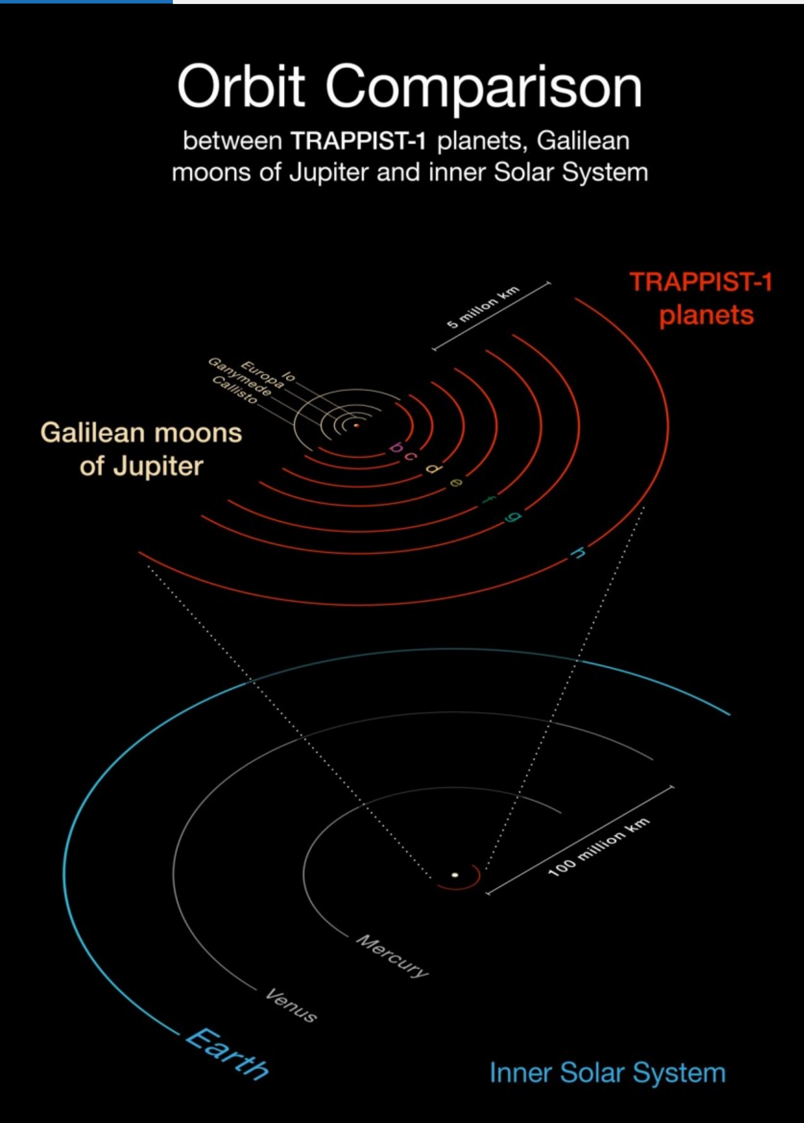
Trappist 1 (May 2016 / Feb 2017)



PRs eso1615, eso1706
Gillon et al., Nature 533/542, 2016/17

- 7 ~Earth-size planets
- Orbital periods: 1.5 - 20 days
- Three planets (e,f,g) in Habitable zone of Trappist-1 (M8-star)
- 40 Lightyears from us
- Transit method

Proxima b (Aug 2016)

PR eso1629de
Anglada-Escudé et al., Nature 536, 2016

- Terrestrial planet in Habitable zone of Proxima Cen (M6 star)
- 4.2 Lightyears from us
- M sini: 1.27 Earth masses
- Orbital period: 11.2 days
- Radial velocity method

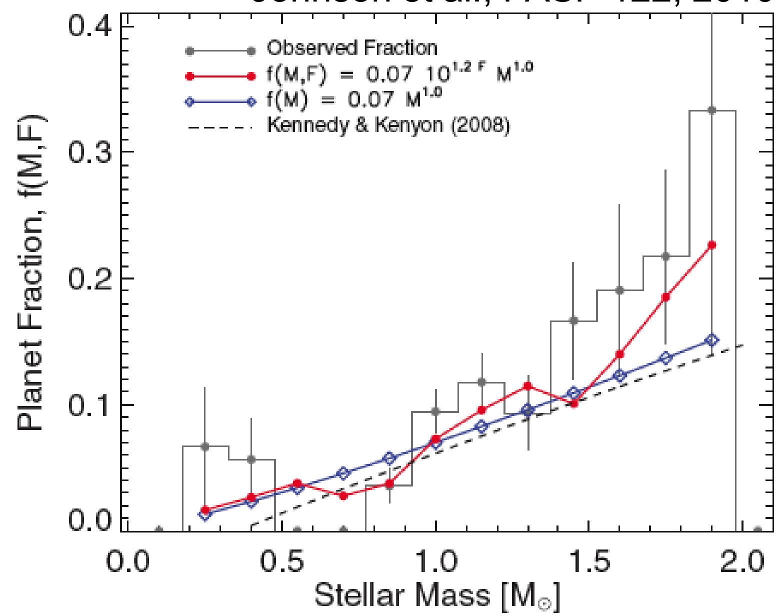
Ross 128 b (Nov 2017)

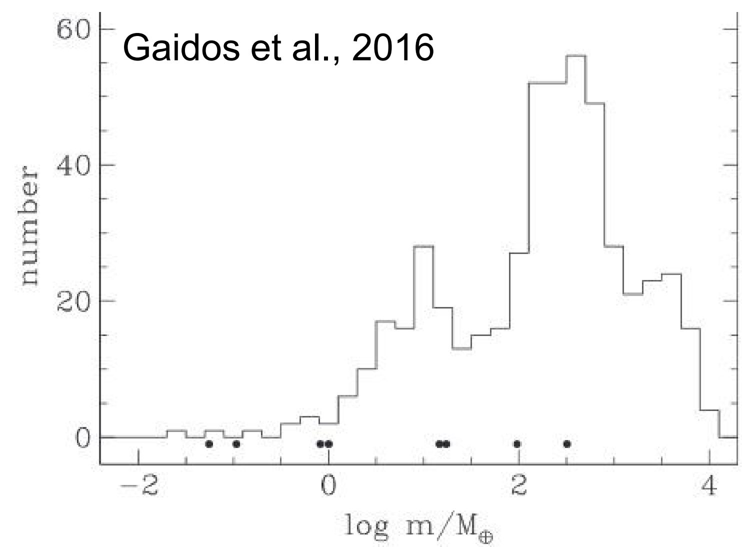
- Weakly active M4 star
- 11 lightyears
- M sini = 1.35 $M_\oplus$ Planet in Habitable zone (insolation 1.38)
- Orbital period: 10 days
- discovered by RV method

Planet abundances (RV, Kepler)

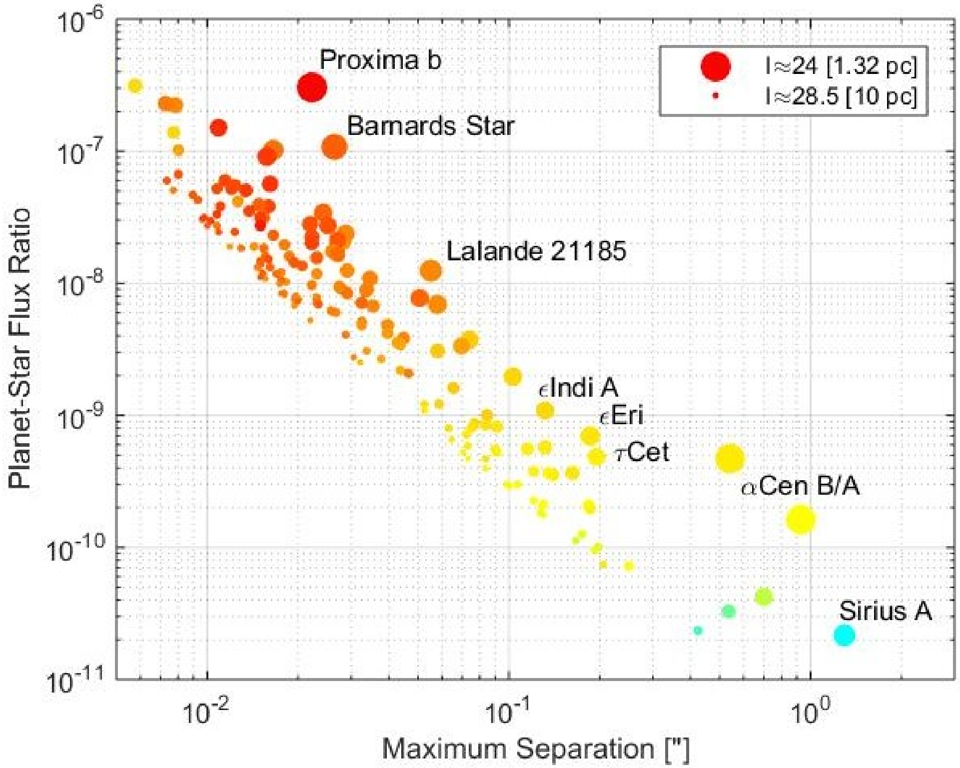
- Gas giants
  - $p \propto M_\star$
    (3% for M-stars, 14% for A-stars)
  - Strong influence of metallicity
  - $M_p \propto M_\star$
- Ice giants and terrestrial planets
  - ~2 planets / M-star (~0.3 in HZ)
  - ~1 planet / G-star (~0.2 in HZ)
- There are at least as many planets as stars in the Milky Way, > 10^{11}

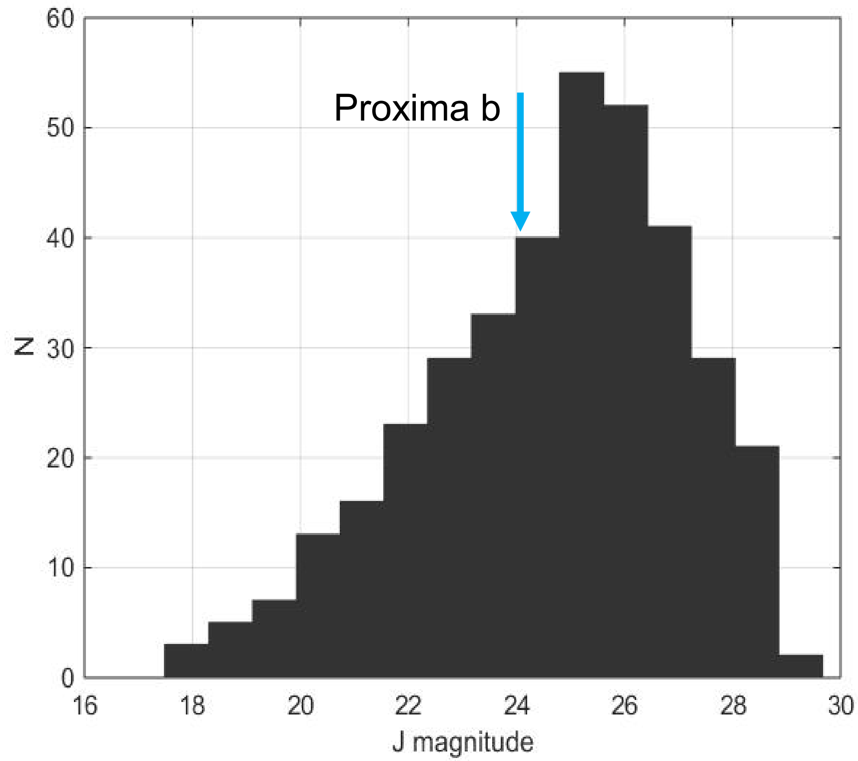
Johnson et al., PASP 122, 2010





Observational requirements





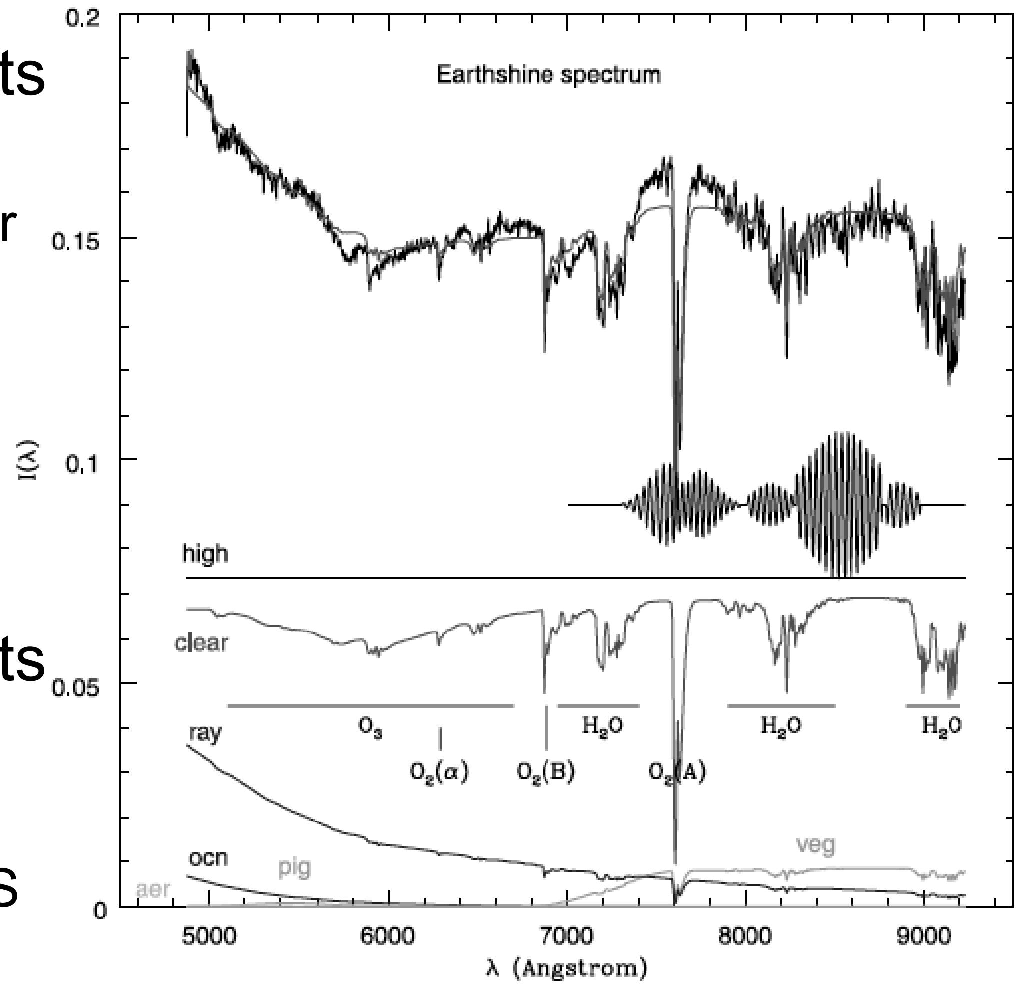
Terrestrial Planets more abundant around M-stars

Most of our neighbors are M-stars (80%)

- high contrast and small IWA ($\lesssim 10^{-8}$ at few tens of mas)
- good sensitivity (I,J $\gtrsim$ 26)

Observational requirements

- potentially habitable planets
  - In HZ, i.e. temperature and surface pressure suitable for liquid water
  - Radial velocity, transits
- habitable planets
  - Presence of liquid water
- (probably) inhabited planets
  - Presence of biomarkers (O_2, O_3, CH_4)
  - Imaging spectroscopy - PCS



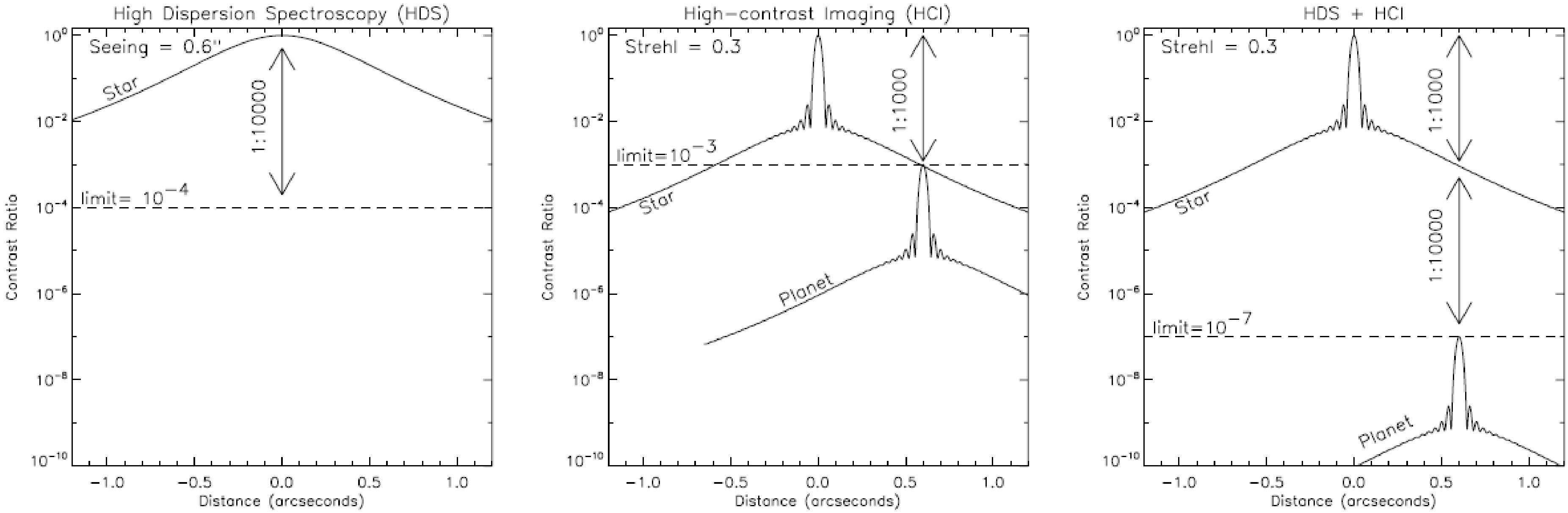
Woolf et al. 2002

PCS, TL Science and TLR

- Characterize Exoplanets from Jupiter down to Earth masses through imaging and spectroscopy
- Search for biomarkers in spectra of potentially habitable planets around nearby late-type stars

- Wavelength range: 600 to 1650 nm (goal 2300 nm)
- Observing modes: Imaging, Spectroscopy (R~50 and R~100.000), Polarimetry
- Contrast $< 3 \times 10^{-8}$ @ 15 mas, $< 10^{-9}$ @ 100 mas
- Sensitivity $I, J > 26\ \mathrm{mag/hr}$

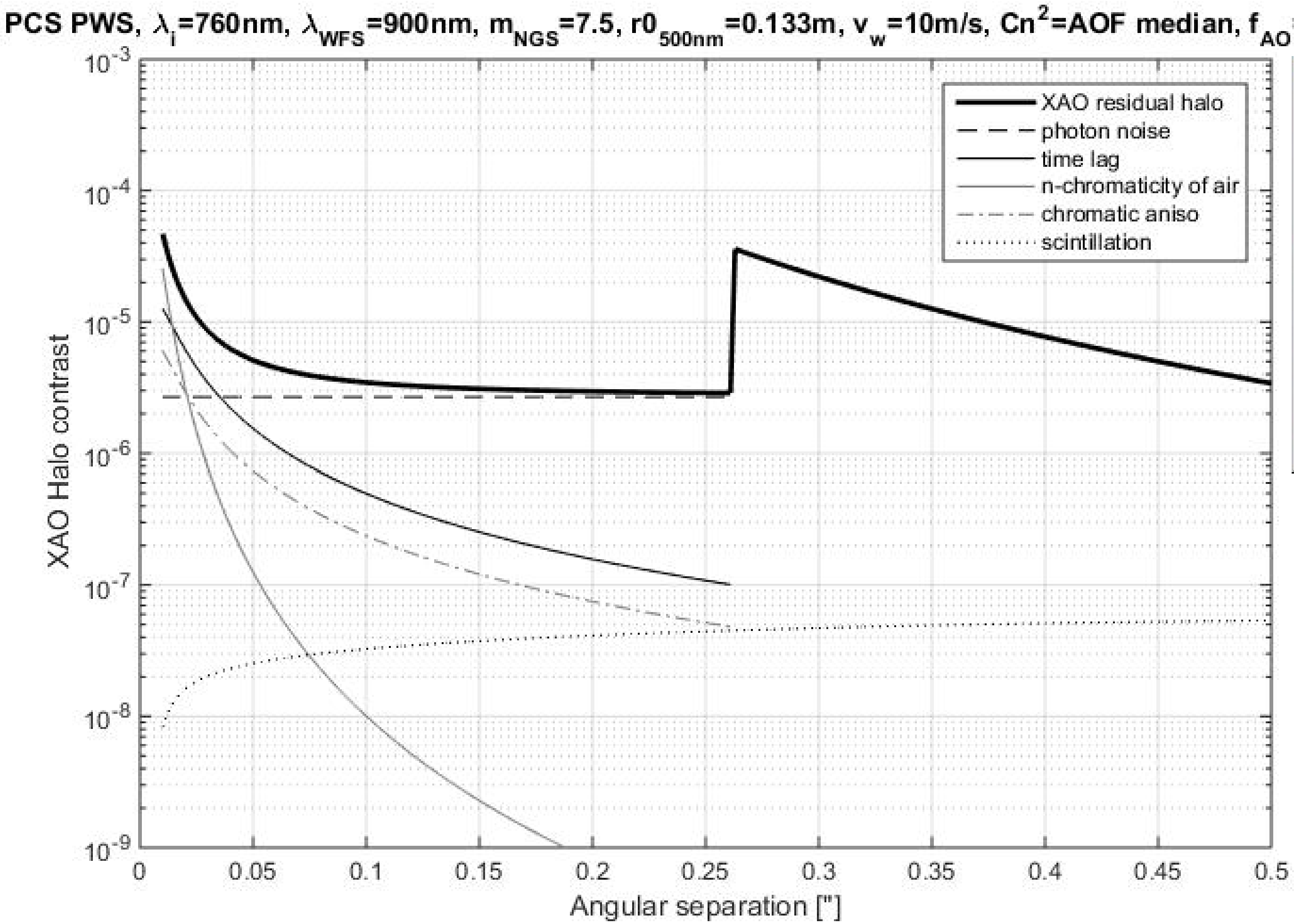
Basic Concept: HCI/HDS

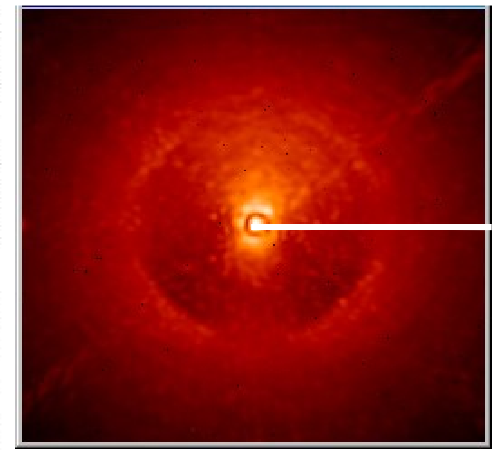


Snellen et al. 2015

- 10^{-4} HDS gain already demonstrated
- TLR $< 10^{-9}$ @ 100 mas: $< 10^{-5}$ raw PSF contrast at 10 λ/D already demonstrated (SPHERE, GPI, MagAO etc.)
- TLR $< 3 \times 10^{-8}$ @ 15 mas: $< 3 \times 10^{-4}$ at 2.5-4 λ/D remains to be demonstrated

XAO raw contrast: O_2 @ 760nm





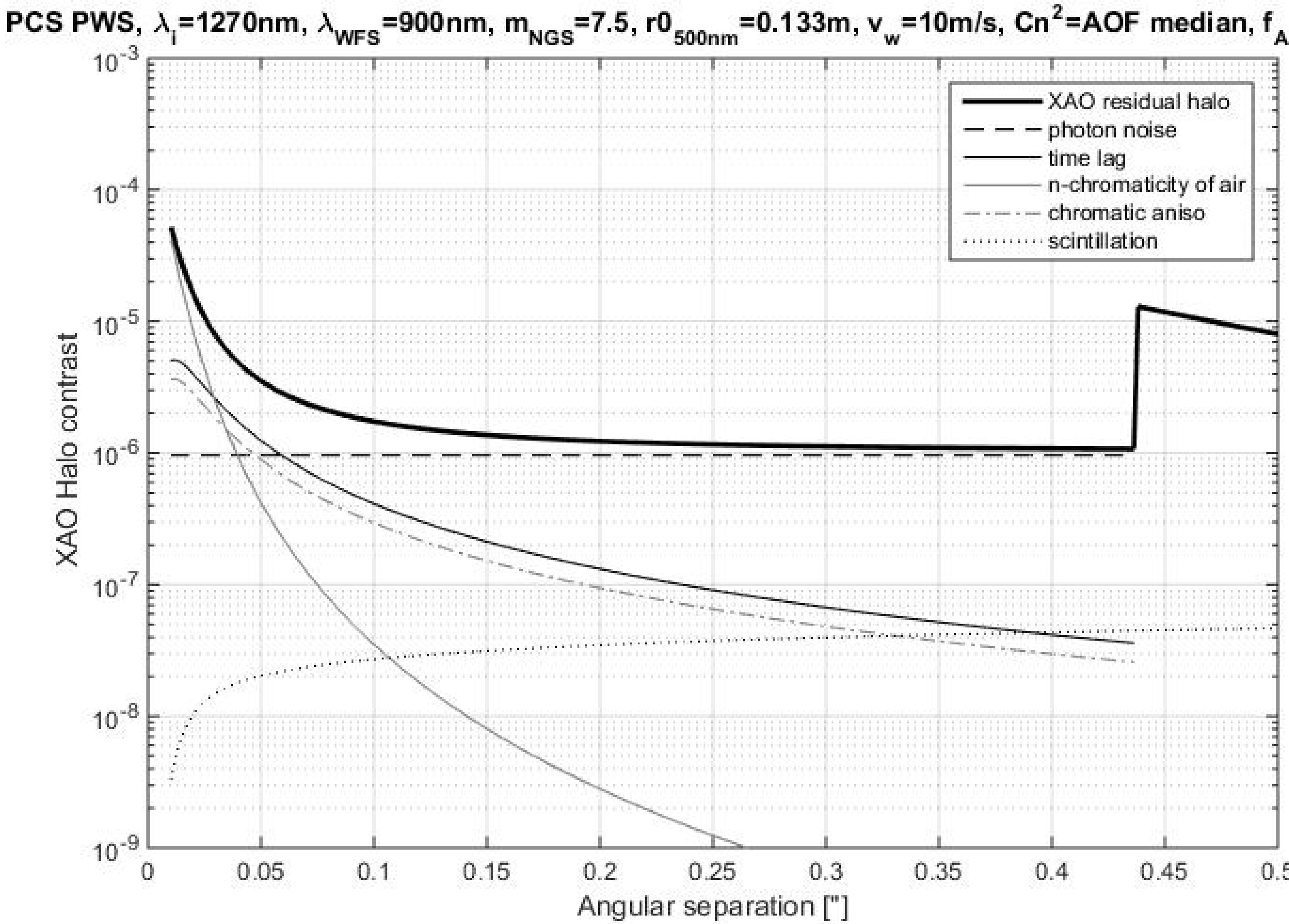
Time lag & chromatic aniso $\propto \theta^{-5/3}$

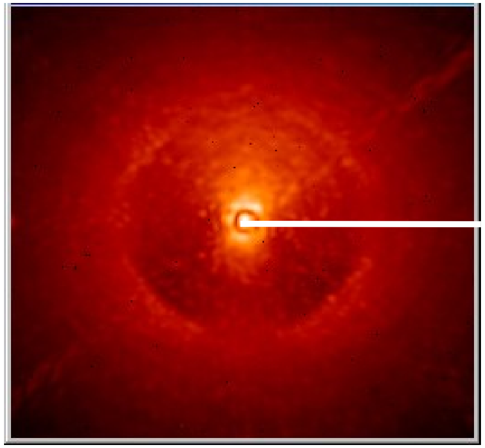
n-chromaticity $\propto \theta^{-11/3}$

Noise propag. $\propto const.$

SR ~50%, Raw PSF contrast at 15-50 mas $\sim 10^{-5}$

XAO raw contrast: O_2 @ 1270nm





1270nm vs 760nm

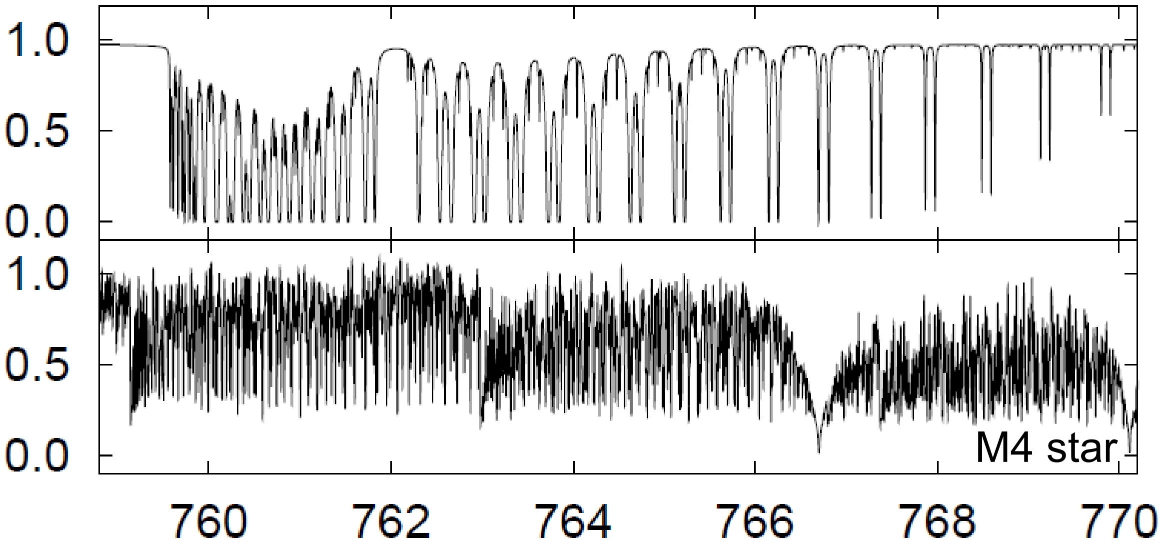
Contrast quite achromatic at small IWA

Better contrast at larger sep.

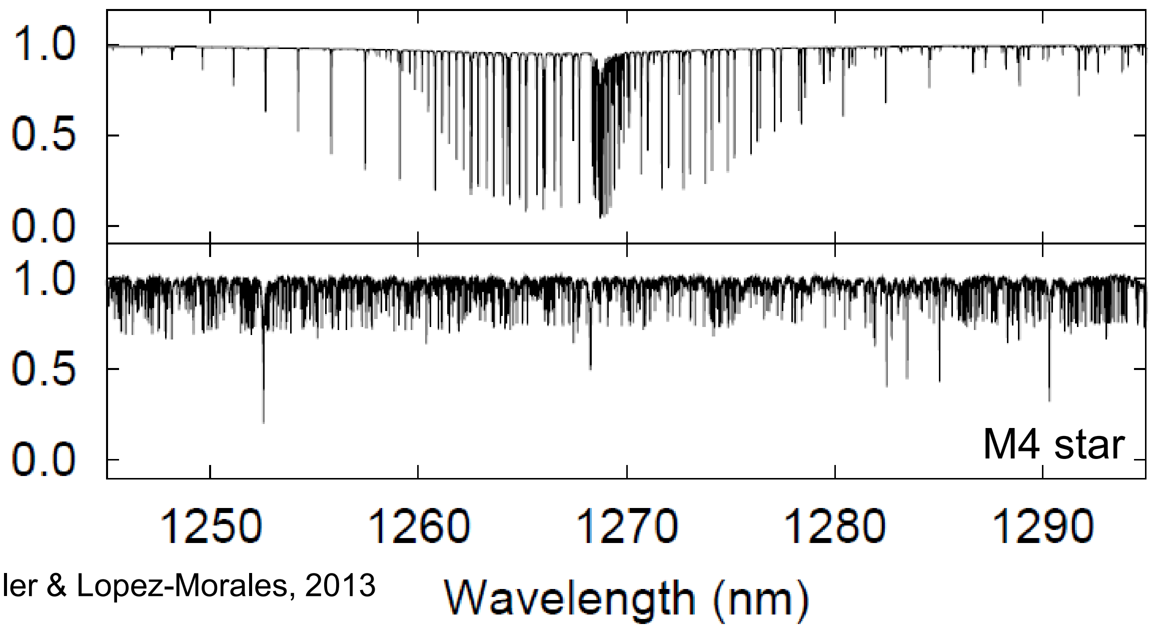
SR ~80%, Raw PSF contrast at 15-50 mas $\sim 10^{-5}$

Higher Strehl ratio

Oxygen bands at 760nm and 1270nm



- $\Delta\lambda \sim 10\ nm$
- $T \sim 0.5$



- $\Delta\lambda \sim 20\ nm$
- $T \sim 0.8$

Rodler & Lopez-Morales, 2013

PCS O_2 detection, rough estimate

Proxima Cen: 1.3 pc, I = 7.4, J = 5.4
Proxima b: 0.05 AU (HZ) = 37 mas, contrast I, J $\sim 1 \times 10^{-7}$
Instrument: T=10%, K-factor 3×10^{-5}, BW O_{760nm}: 10nm, BW O_{1270nm}: 20nm

<u>760 nm (Strehl-ratio 50%)</u>

$$n_{p,*} \sim 3.3 \times 10^7 \frac{\gamma}{(ELT\ s)},\ n_{halo} \sim 990 \frac{\gamma}{(ELT\ s)},\ n_{p,b} \sim 3.3 \times (1-0.5) = 1.7 \frac{\gamma}{(ELT\ s)}$$

$$SNR = {}^{1.7}/_{\sqrt{990}} = 0.054/s$$

$$\boldsymbol{t_{5\sigma} \sim 2.4\ \mathrm{hr}}$$

<u>1270 nm (Strehl-ratio 80%)</u>

$$n_{p,*} \sim 2.5 \times 10^8 \frac{\gamma}{(ELT\ s)},\ n_{halo} \sim 7500 \frac{\gamma}{(ELT\ s)},\ n_{p,b} \sim 25 \times (1-0.8) = 5 \frac{\gamma}{(ELT\ s)}$$

$$SNR = {}^{5}/_{\sqrt{7500}} = 0.0577/s$$

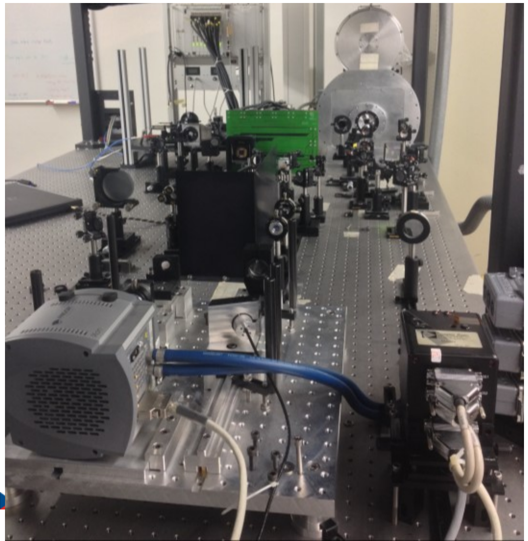
$$\boldsymbol{t_{5\sigma} \sim 2.1\ \mathrm{hr}}$$

$t_{5\sigma} \propto K$-factor

(Snellen et al. 2015) Proxima Super-Earth, 600-900 nm, ELT, $K = 3 \times 10^{-4}$: $t_{10\sigma} \sim 10$ hr, $\boldsymbol{t_{5\sigma,ELT} \sim 2.5\ \mathrm{hr}}$
(Lovis et al. 2016) Proxima b, O_2, VLT, $K = 2 \times 10^{-4}$: $t_{3.6\sigma} \sim 480$ hr, $\boldsymbol{t_{5\sigma,ELT} \sim 39\ \mathrm{hr}}$
(Wang et al. 2017) Proxima b, O_2, TMT, $K = 5 \times 10^{-6}$: $t_{10\sigma} \sim 100\ hr$, $\boldsymbol{t_{5\sigma,ELT} \sim 15\ \mathrm{hr}}$

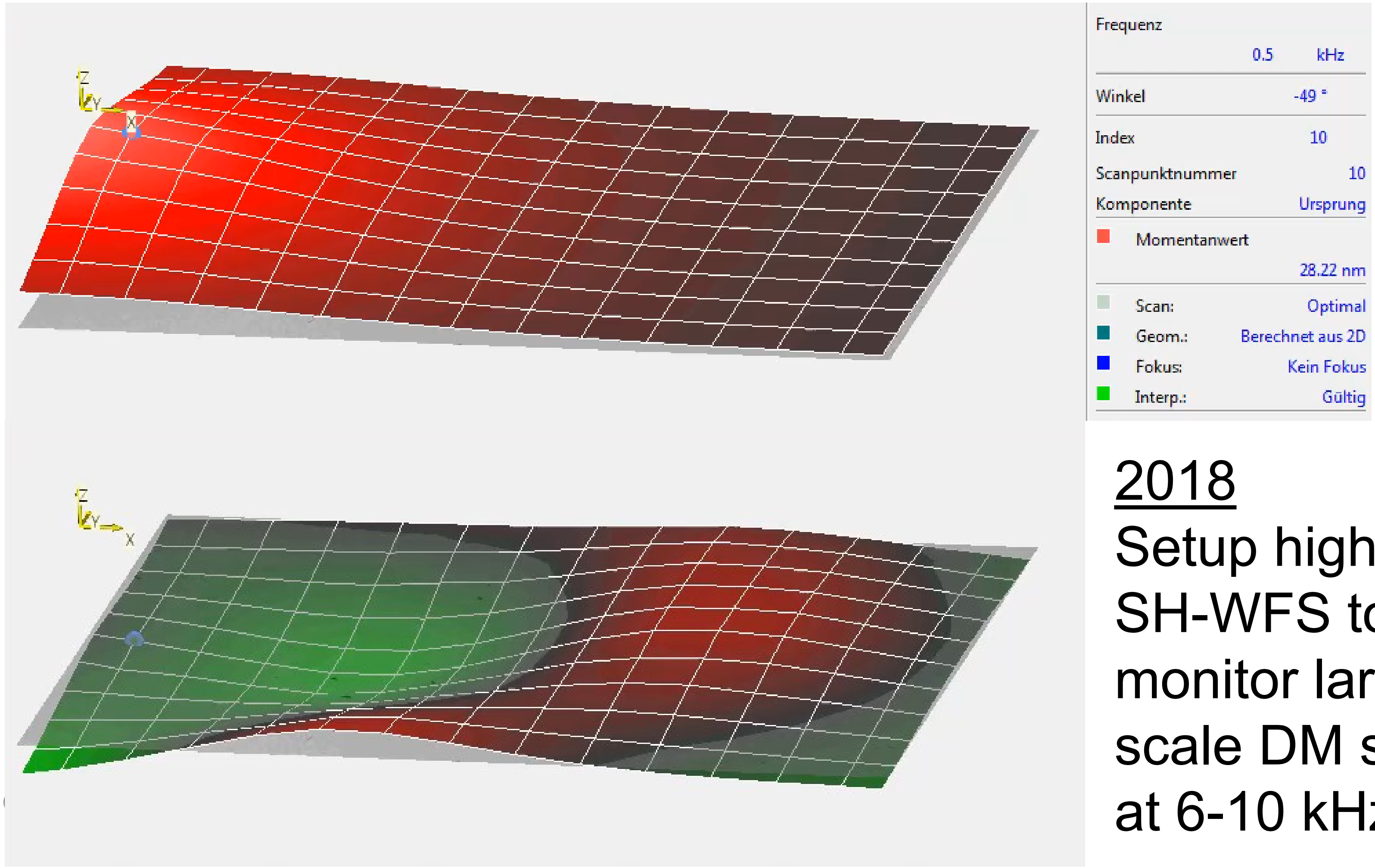
XAO related PCS R&D at ESO

- XAO simulations
  - Comprehensive end-2-end simulation to validate concept, system dimensioning, performance estimate
  - Define strategy to minimize temporal and n-chromaticity errors
  - PhD thesis, Nelly Cerpa Urra, collaboration with. Kulcsar (IOP, Paris)
  - Postdoc, Engineering fellow, Prashant Pathak
- XAO validation on high-order testbench (HOT)
  - turbulence simulation, woofer (ALPAO) / tweeter (BMM kilo-DM) DM combination, modulated PWS WFS, coronagraph, infrared test camera (ITC)
  - HOT up and running
- XAO DM R&D
  - Number of actuators: 11000 (goal 20.000)
  - Pitch (on M1): 0.32-m (goal 0.24-m)
  - Stroke and position resolution: ±1.5 µm, ≤ 0.1nm
  - Small (50nm) stroke settling time: ≤ 150µs



XAO DM development

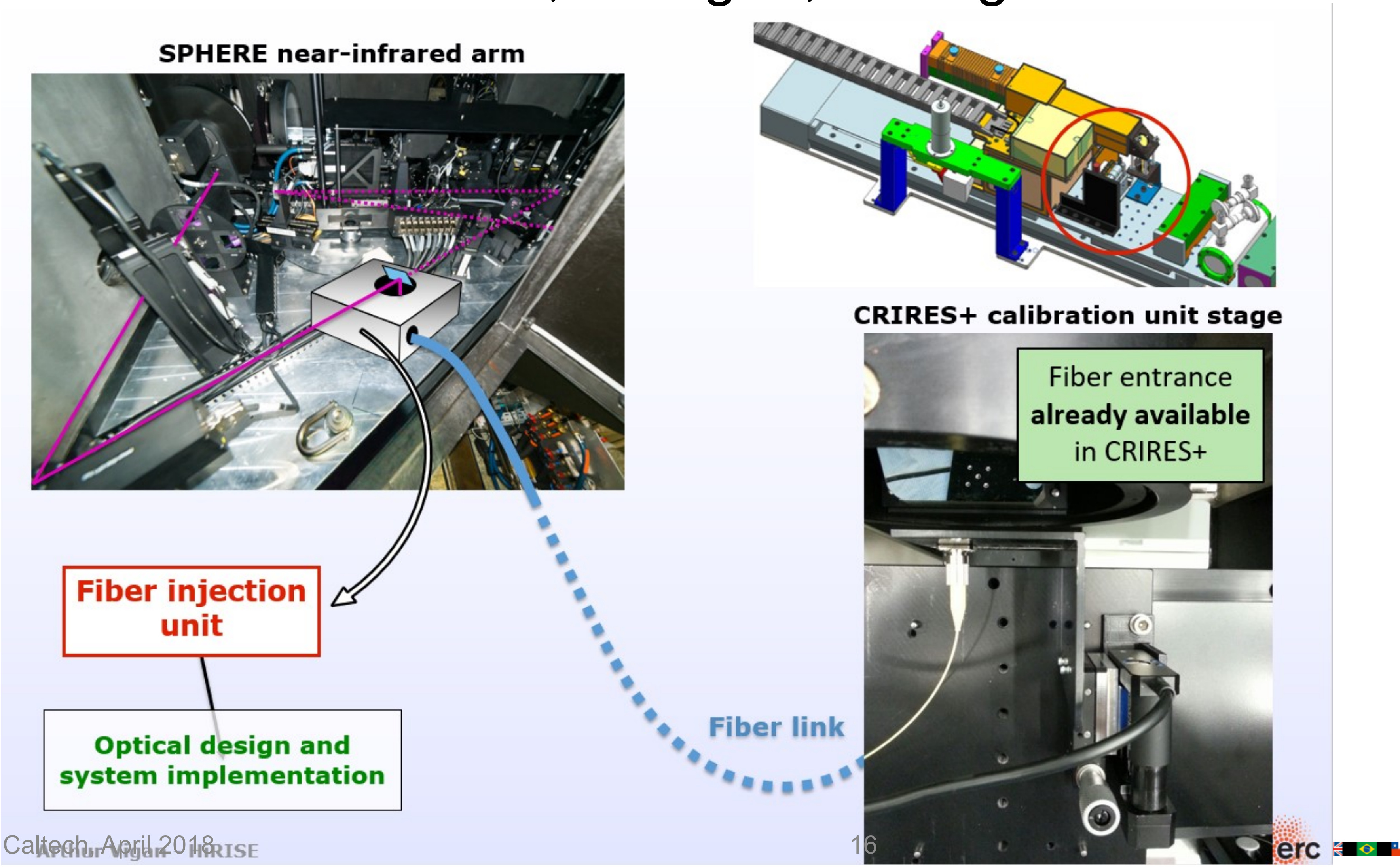
- Study prototype with very high time resolution



<u>2018</u>
Setup high-speed SH-WFS to monitor large scale DM surface at 6-10 kHz

Community activities, HiRISE

- SPHERE/CIRES+, A. Vigan, ERC grant



Community activities, RISTRETTO

- HCI/HDS for Proxima b, led by C. Lovis (Geneva)
- XAO (K-factor ~ 3000-5000)
  - SPHERE upgrade (ongoing study led by the SPHERE consortium)
  - AOF + 2nd stage
  - Ongoing study for fast RTC running at ~4 kHz: led by Processor Architecture Lab at EPFL (Lausanne)
- Highres Spectrograph (optical)
  - RISTRETTO, led by the Geneva Observatory (using ESPRESSO quite difficult choice in practice)
  - Single-mode Complex Amplitude Refinement (SCAR) coro, J. Kühn (ETH Zurich) and E. Por / S. Haffert (Leiden)

Summary and timeline

- PCS aims at M-star planets in HZ and biomarkers
- Instrument concept combines HCI and HRS
- XAO performance at small IWA is critical
- Dedicated R&D underway at ESO and community

- ESO wishes to do PCS, but resources are (still) short
- Project start ~2022 unless external funding appears (possibly even from outside member countries)