PCS – high-contrast imaging of Exoplanets with the E-ELT Roadmap

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&

EPICS consortium

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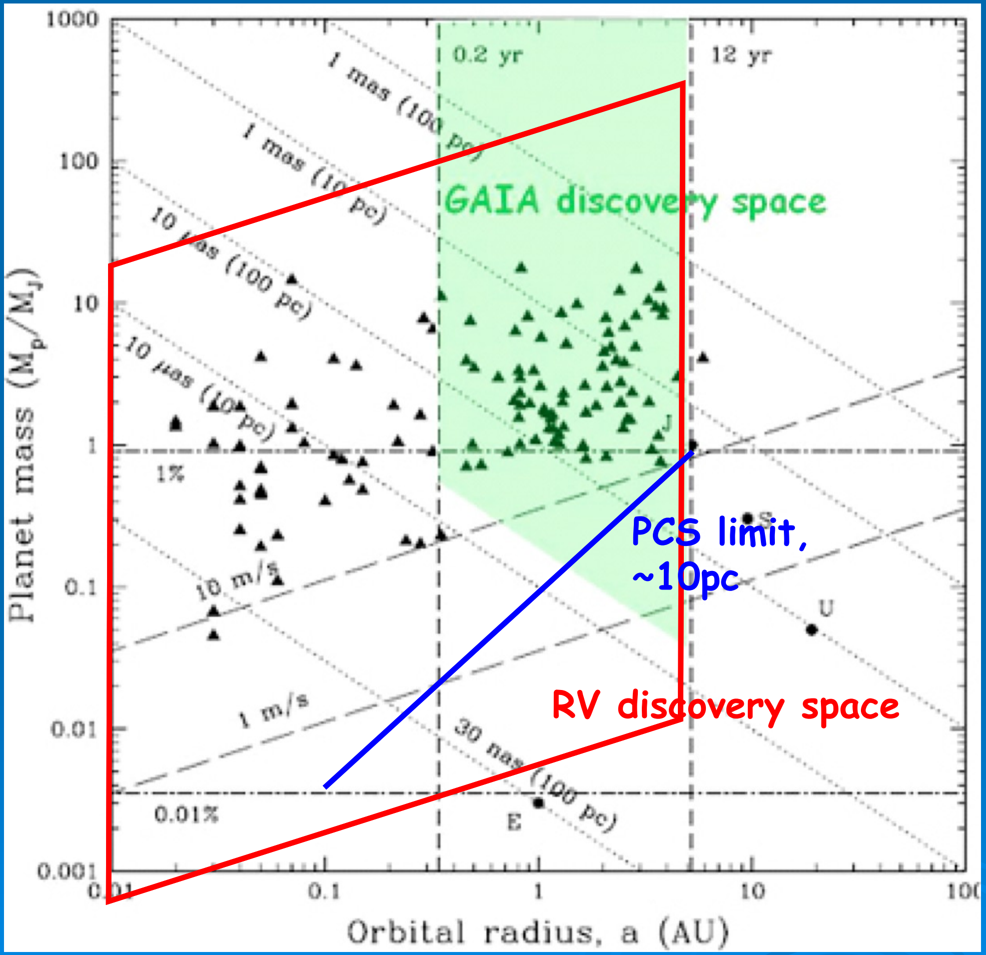
Outline

- Science, context and motivations
- HCI selected issues
  - XAO
  - Diffraction/WF control (coro, apodizer, speckle nulling)
  - Calibration after observation (IFS-SD, SCC)
- Timeframe for E-ELT high-contrast imaging

Scientific context in 2025+

GAIA: Know orbits all Giant Exoplanets out to 5 AU within 50 pc (V_{star} > 5)
RV: Know orbits (but not orientation on-sky) of most rocky planets in the solar neighborhood out to ~0.5-1 AU, even in HZ for M-stars



Perryman et al., 2005

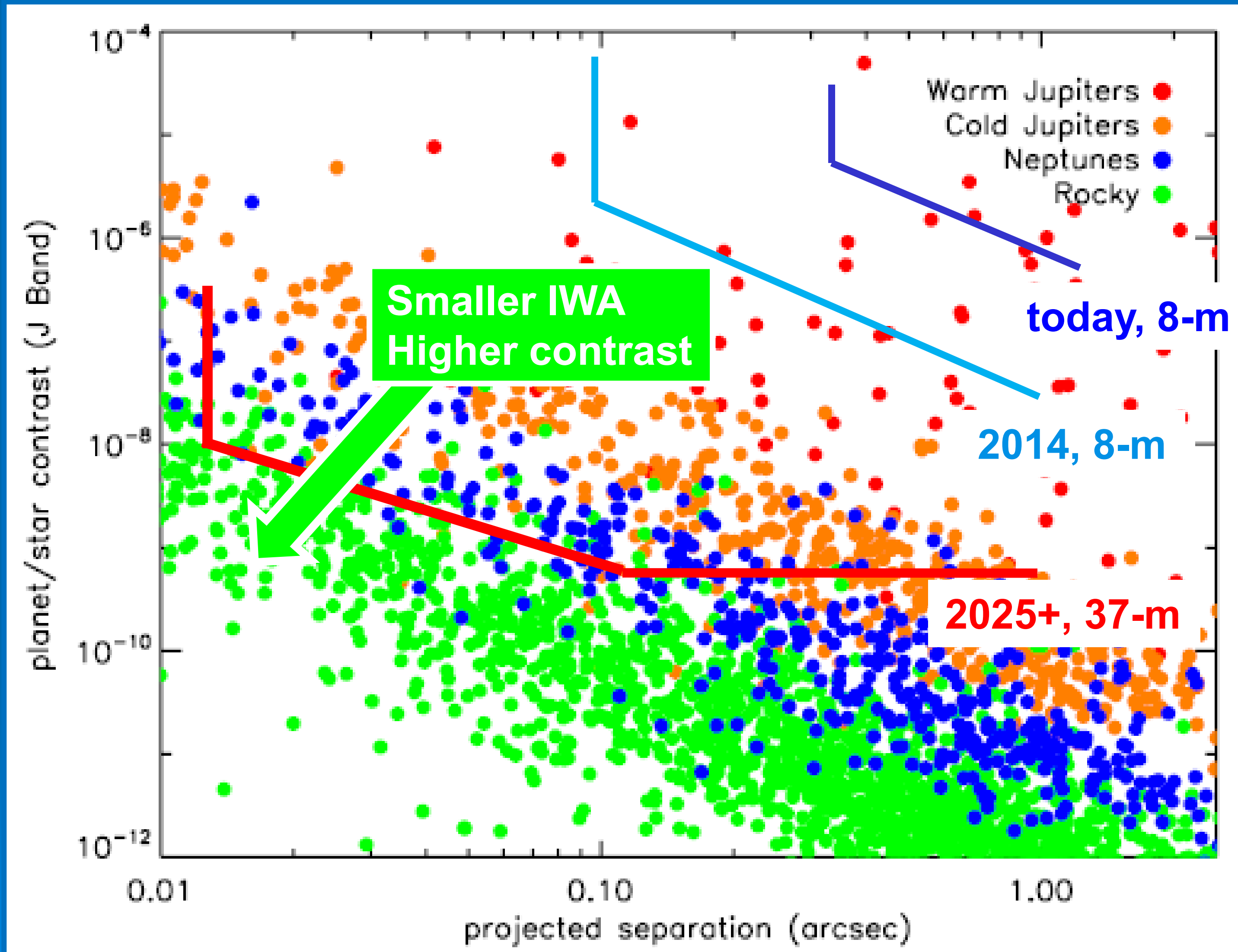
NIR Contrast, reflected light

Jupiter @ 5 AU is 10^{-9}
Earth @ 0.1 AU is 10^{-8} (HZ M-star)
≈ PCS photon noise limit for stars J~4-6 in some hrs observing time

Unique science objectives

1. Characterization of nearby irradiated planets – Rocky planets to Gas Giants
2. Survey of self-luminous Exoplanets (SFR, forming beyond snow-line)

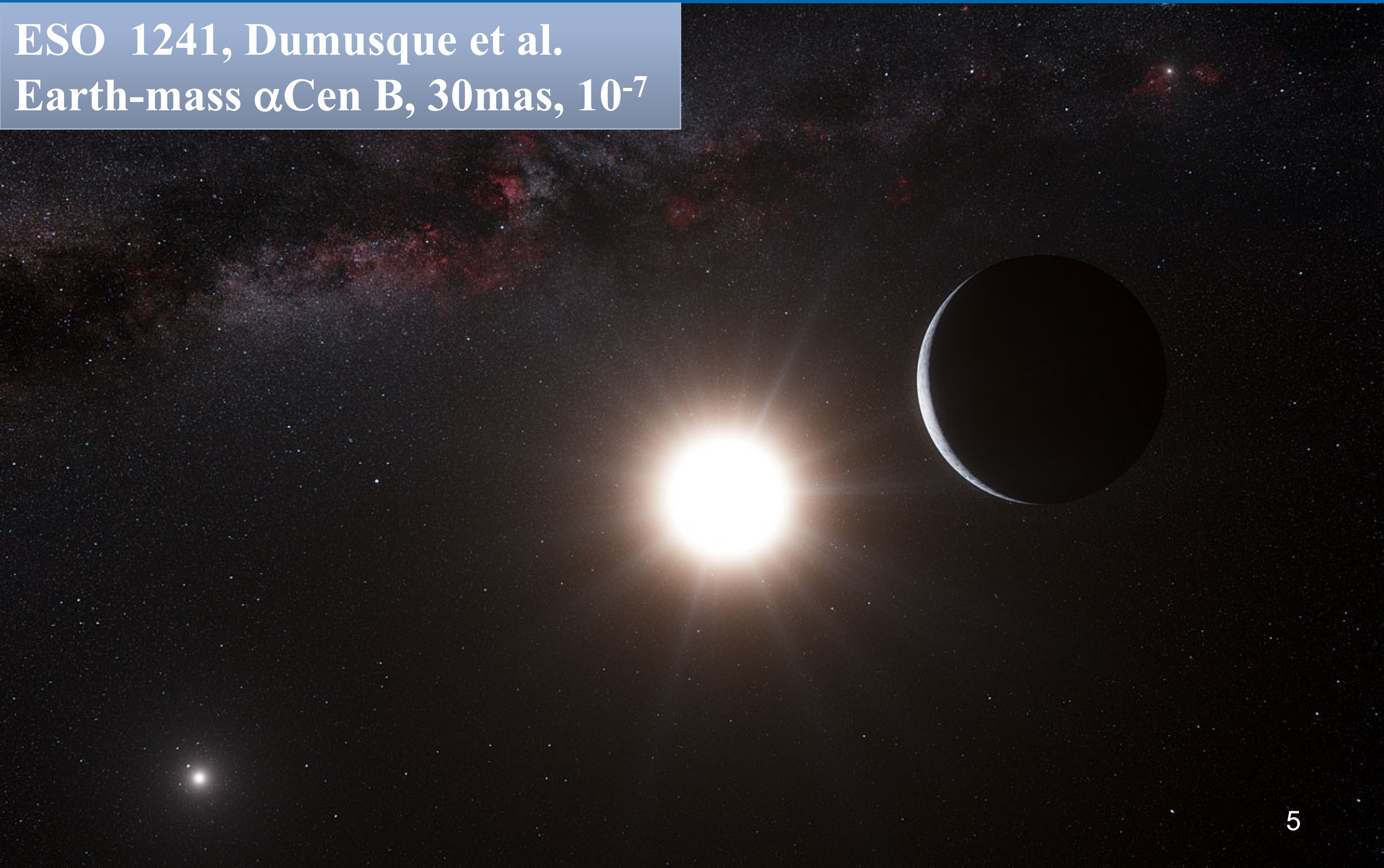
Contrast requirements



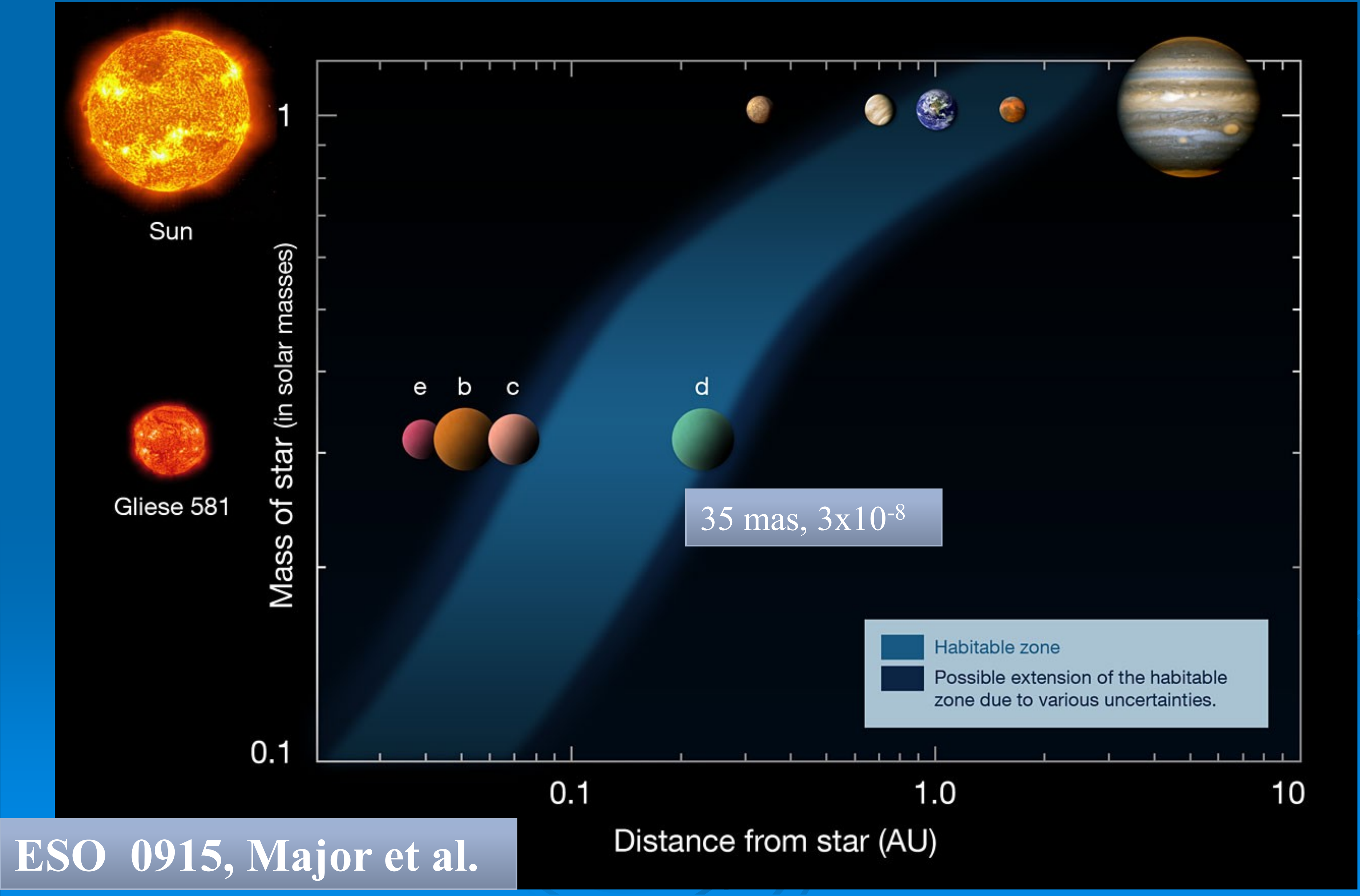
Bonavita et al. 2012

Science Goal 1:
Characterization of nearby planets

ESO 1241, Dumusque et al.
Earth-mass αCen B, 30mas, 10^{-7}



Science Goal 1: Characterization of nearby planets



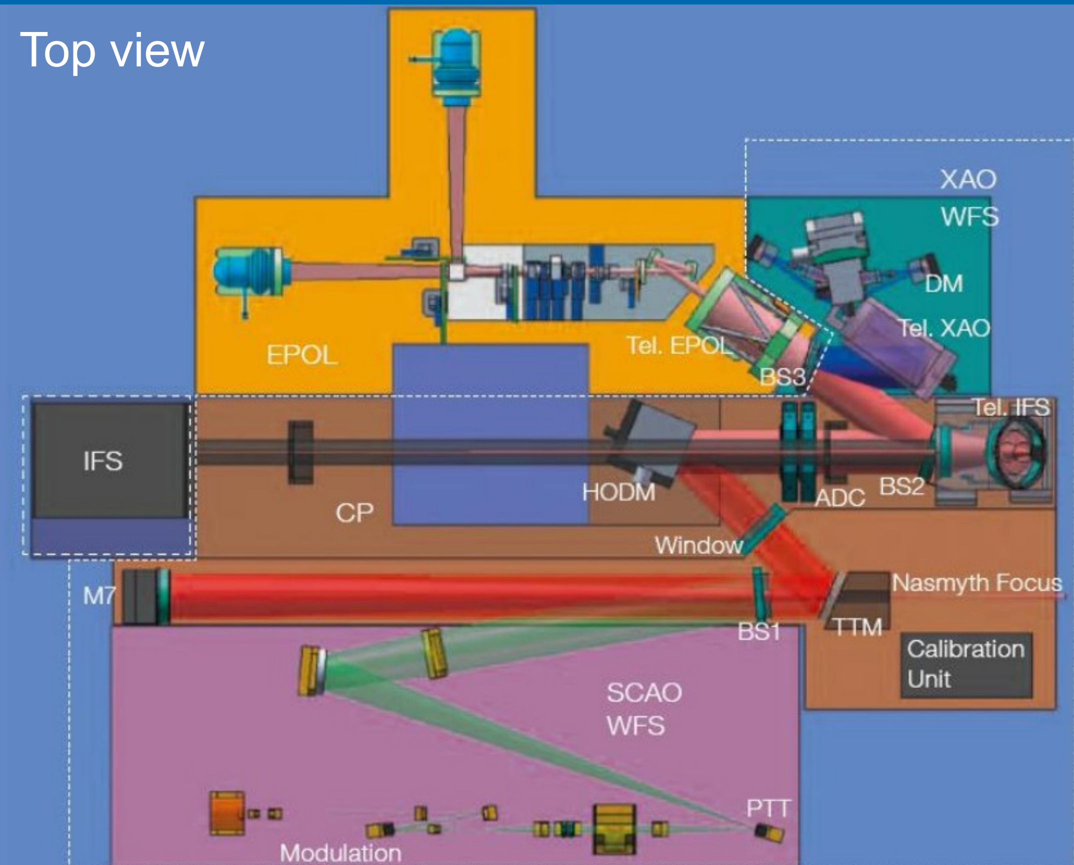
Top Level Requirements

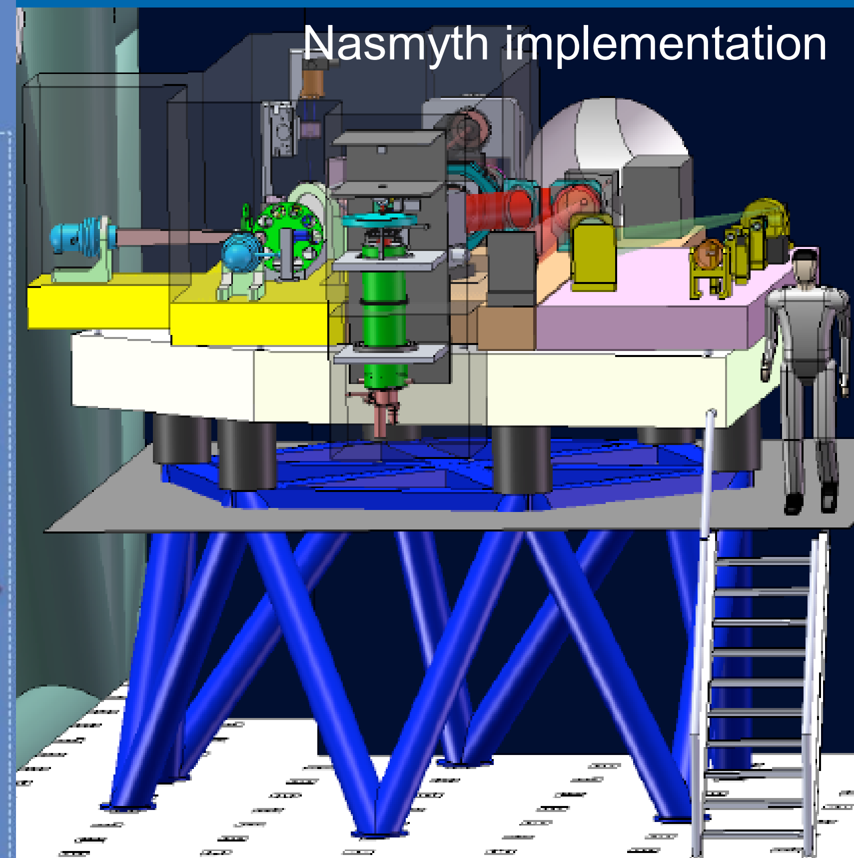
From science objectives & technical considerations

- TLR1: Wavelength range 600 nm to 1650 nm,
  Simultaneous coverage of each spectral band R, I, J, H
- TLR2: Observing modes
  Imaging (BB, NB), Spectroscopy (R~50 and R~500), Polarimetry
- TLR3: Field of view 1 arcsecond in diameter, Nyquist sampled
- TLR4: Contrast (5σ, $\Delta\lambda = 50$ nm, half plane)
  10^{-8} @ 15 mas (rocky planets, HZ of nearby M-stars) - NEW TLR!!
  10^{-9} @ 100 - 400 mas
  for stars with $J < 6$ and $I < 8$ in 10h telescope time.
  Polarized flux is 10x lower, same contrast for stars with $I < 3$

Spectral type	**Diameter @10pc**	**Imag @10pc**	**Jmag @10pc**	**Rel. abundance**	**# visible and I < 10 & d<20pc**
G	~1 mas	~4.2	~3.7	~5%	~40
K	~0.7 mas	~5.5	~4.9	~15%	~100
M	~0.3 mas	~9	~7.5	~80%	~200

EPICS concept to be revised for small IWA

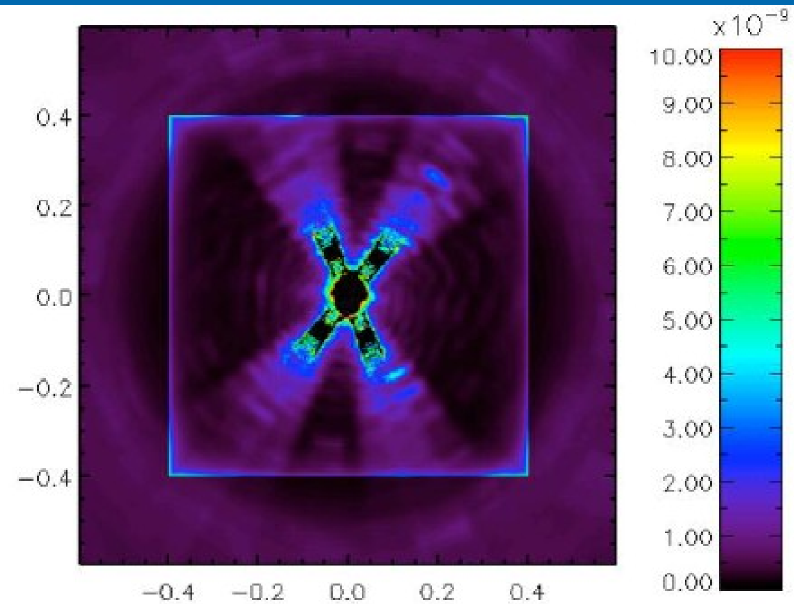


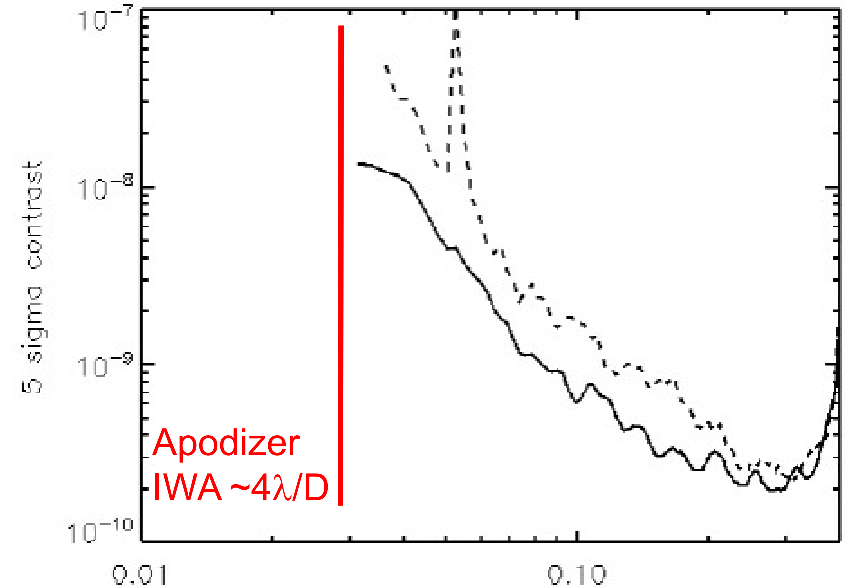


NIR imaging:	950-1650 nm, 0.8″ FoV, 2.33 mas/px
NIR IF spectroscopy:	R = 125, 1400, 20.000
Vis imaging:	600-900 nm, 2″ FoV, 1.5 mas/px
Vis polarimetry	

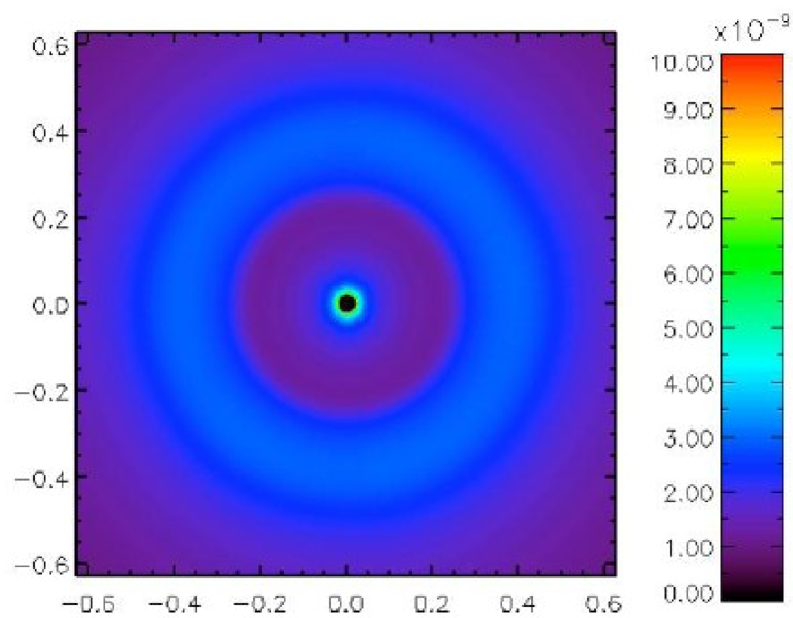
EPICS Analysis (E2E)

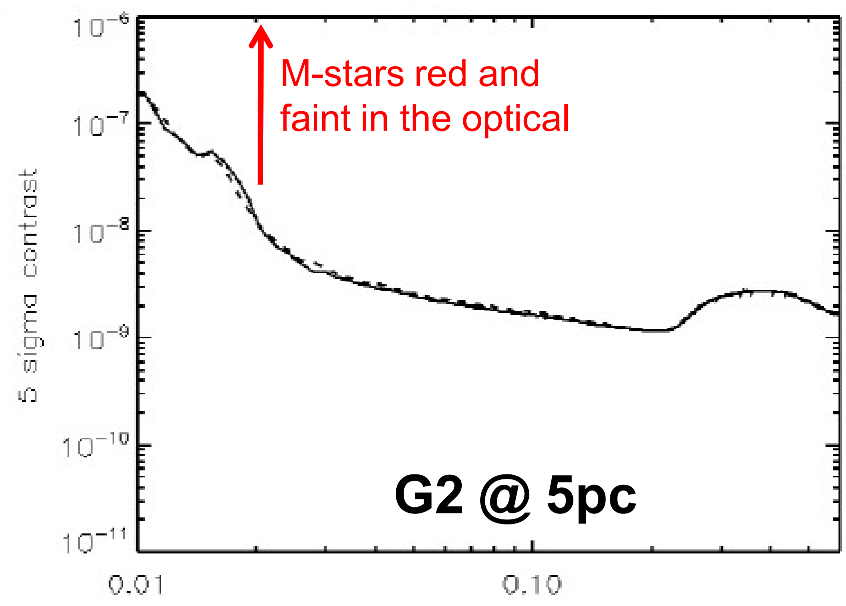
IFS





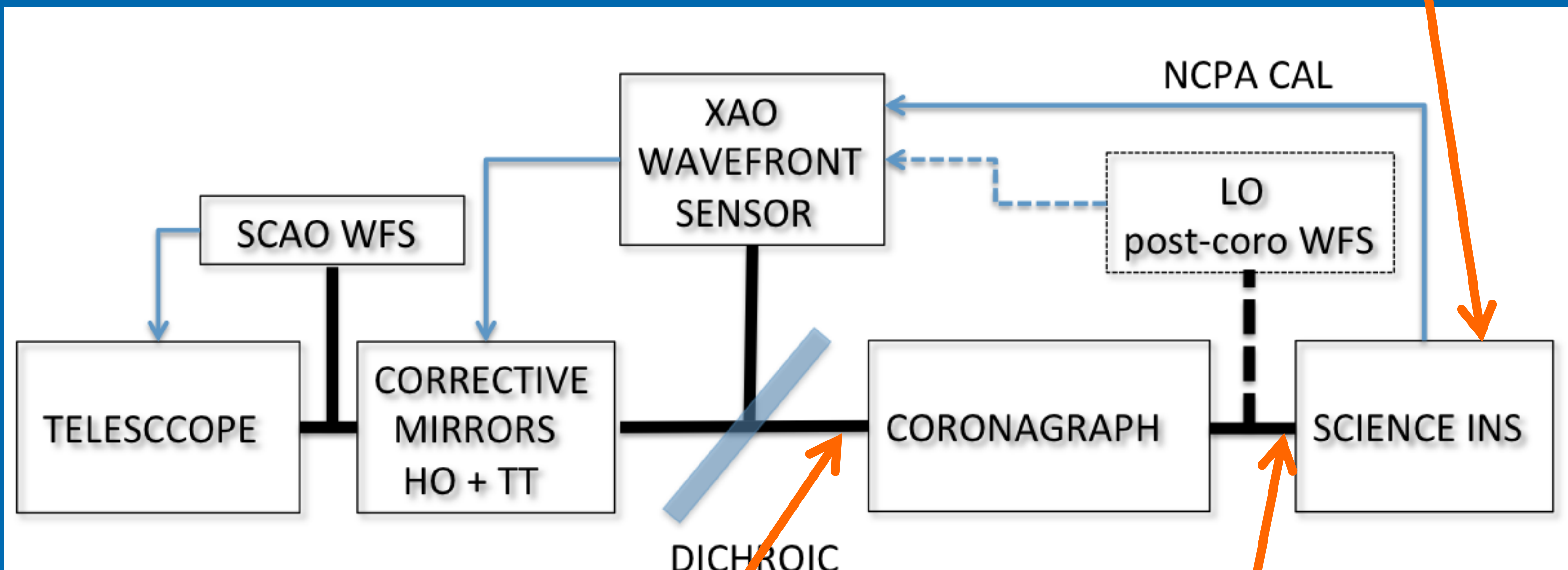
EPOL





PCS small IWA, 1st order requirements

QSS Calibration: 10%-1%
(CDI @ small IWA, SD/PDI/ADI)



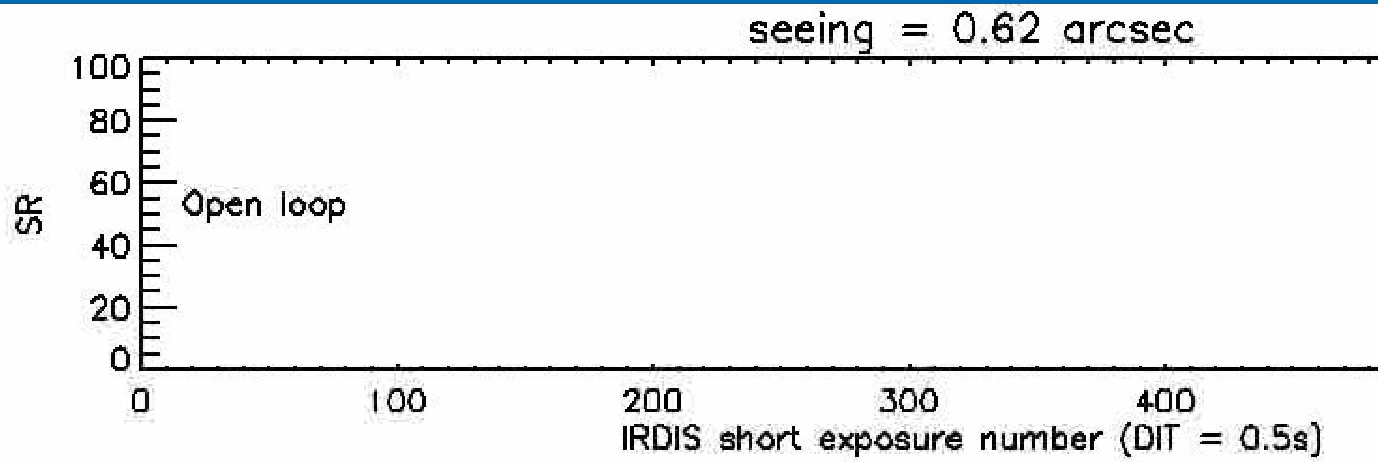
XAO Turbulence residual halo
~3x10^{-5} @ 15mas
~3x10^{-6} @ 100 mas

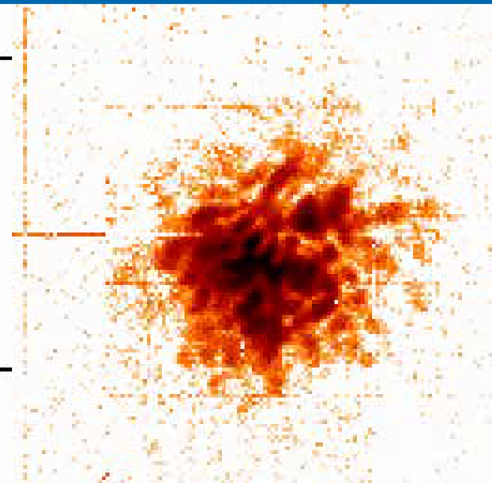
Pointing: 10^{-2}-10^{-3} λ/D

Coro leakage halo (Θ_{star} < ~0.05 λ/D): 10^{-5} (~XAO halo)
QSS (coro + WF control residuals): 10^{-7} - 10^{-8}

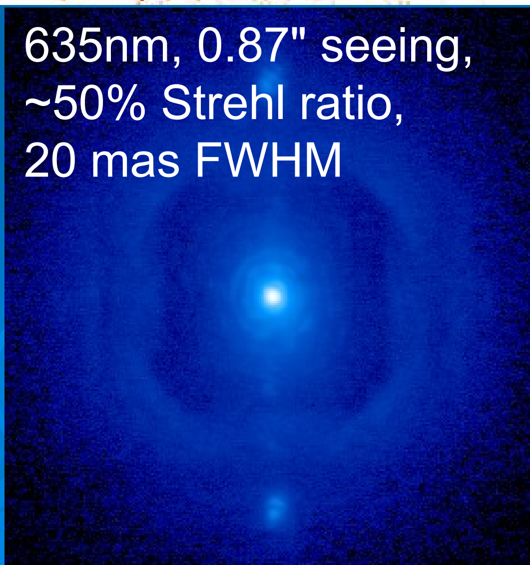
XAO maturity

- XAO PWS on sky: LBT, Magellan, Subaru (SCeXAO)
- SF-SHS for SPHERE and GPI





Credit C. Petit



Technology R&D needed for PCS:

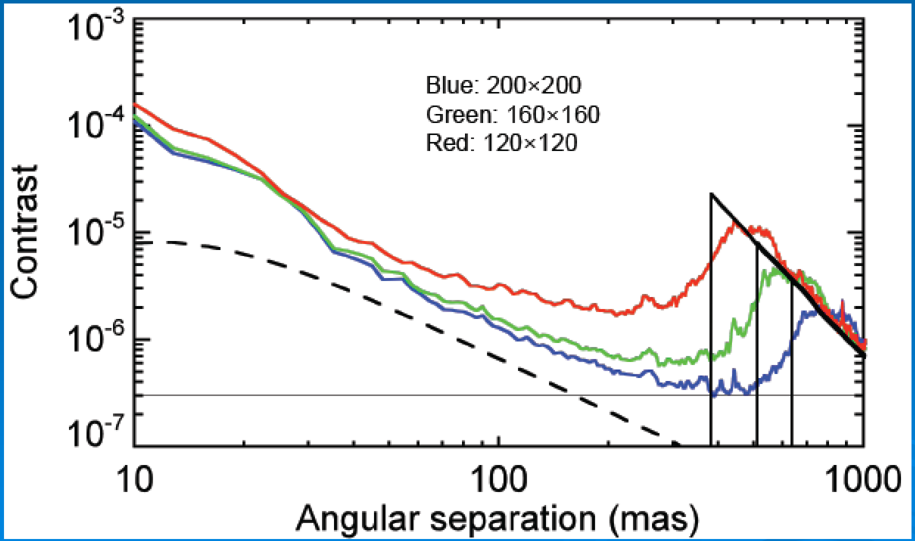
- Roof PWS simulations and laboratory tests
- DM concept and demonstrator

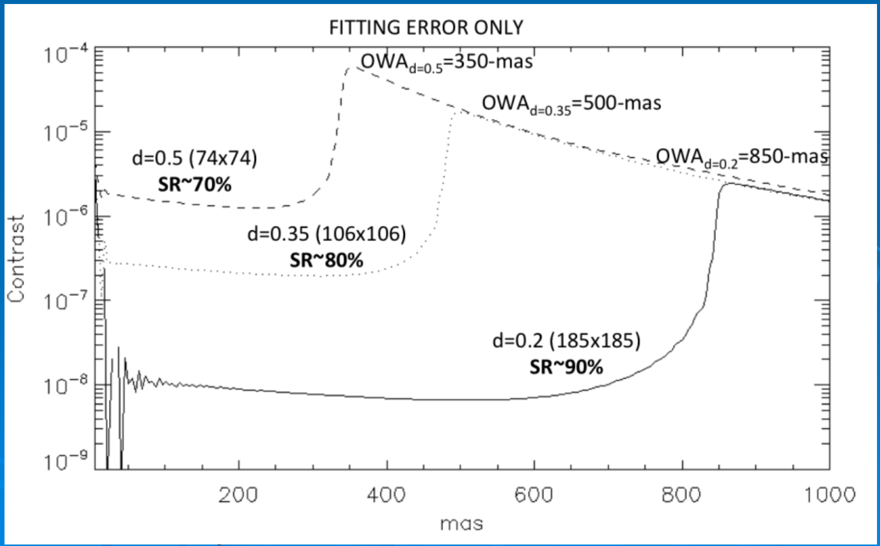
XAO dimensioning

EPICS phase-A: 200x200 actuators (SPHERE scaled to EELT)
Biggest potential for savings in cost and technological risk

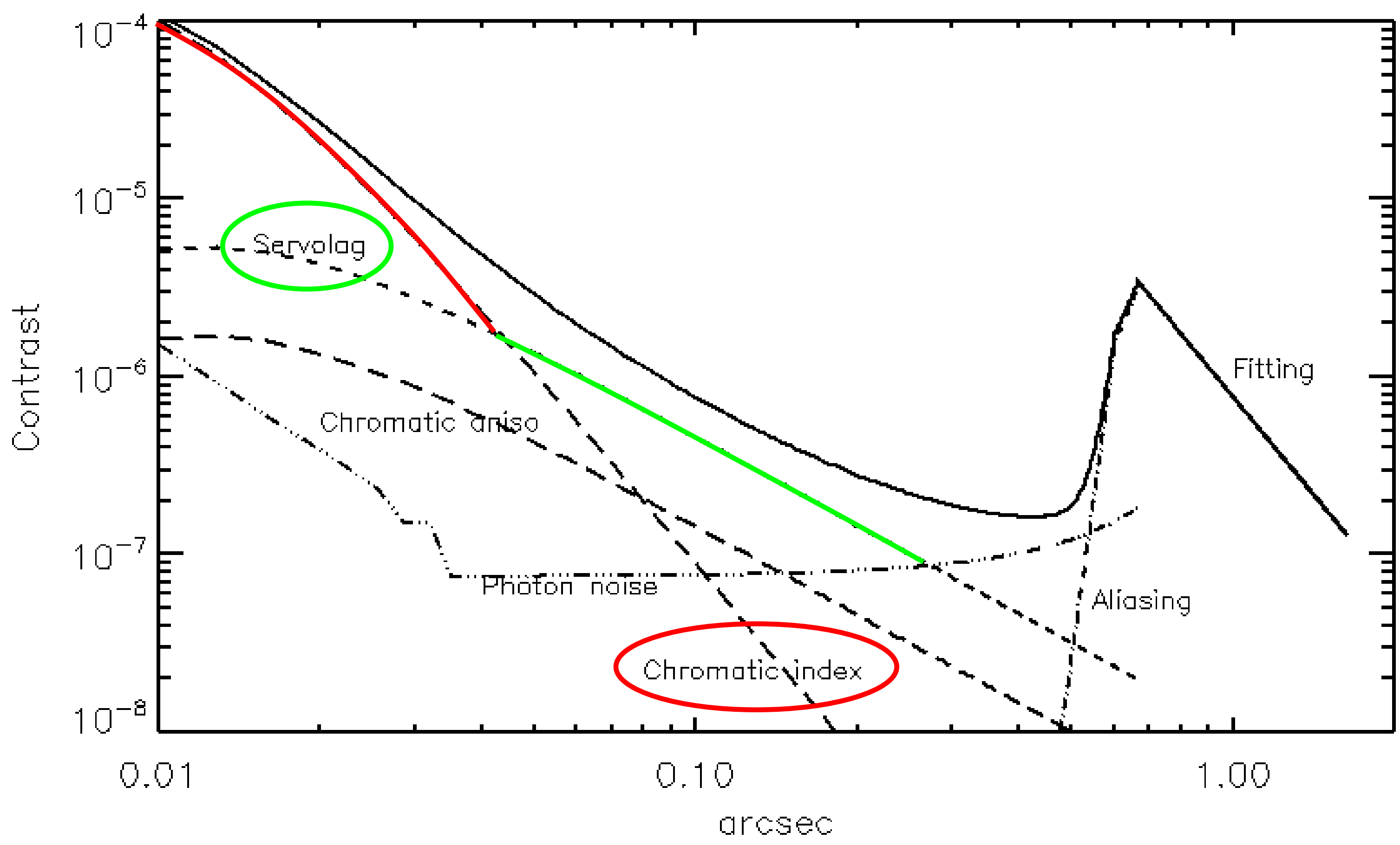
BUT more actuators provide
1.Higher Strehl ratio (stronger impact at shorter wavelength)
2.Larger outer working angle / correction radius
(400 mas OWA in J-band require ~125x125 actuators)

Important trade-off: technical feasibility risk vs science return



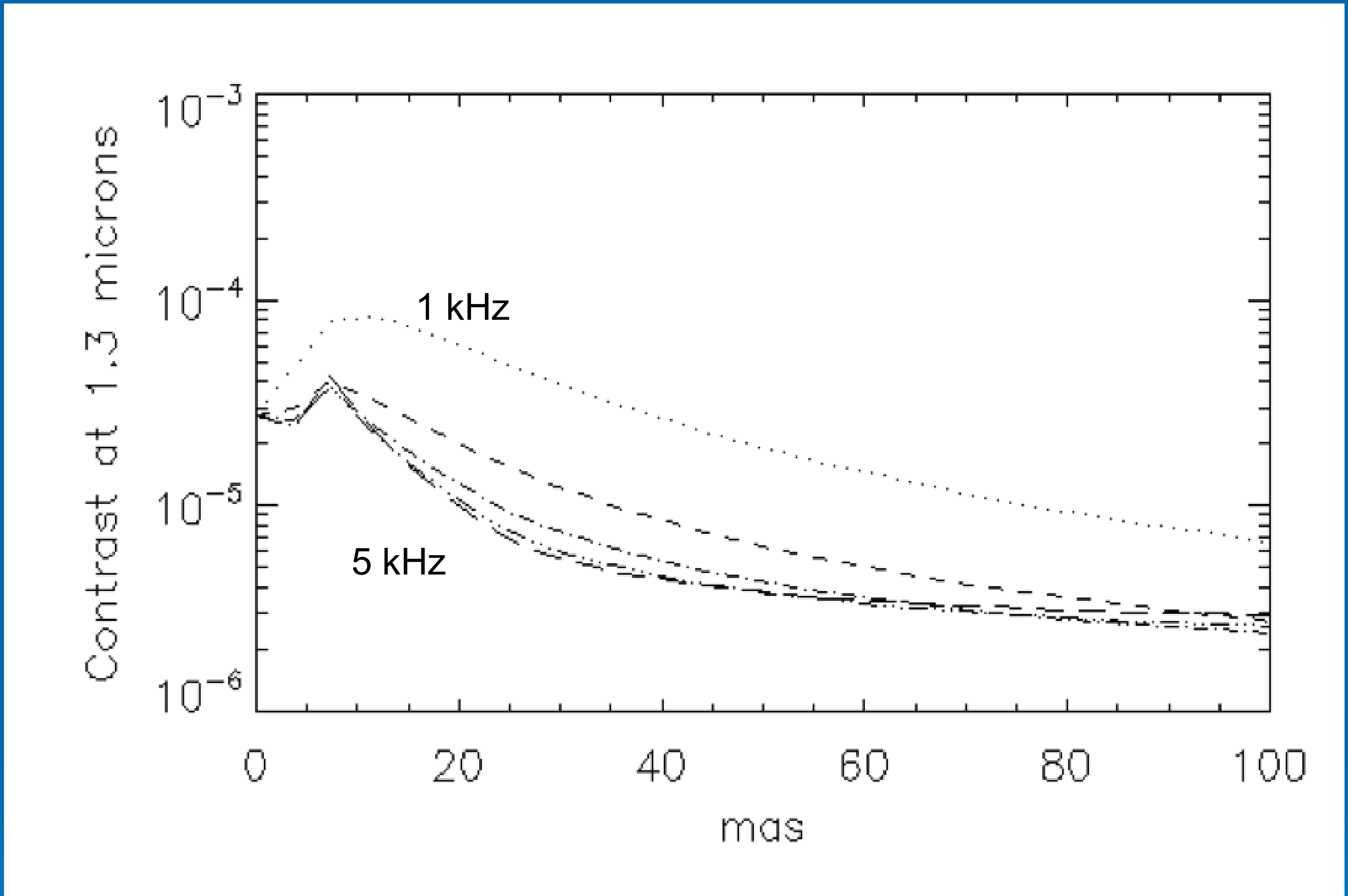


XAO error budget



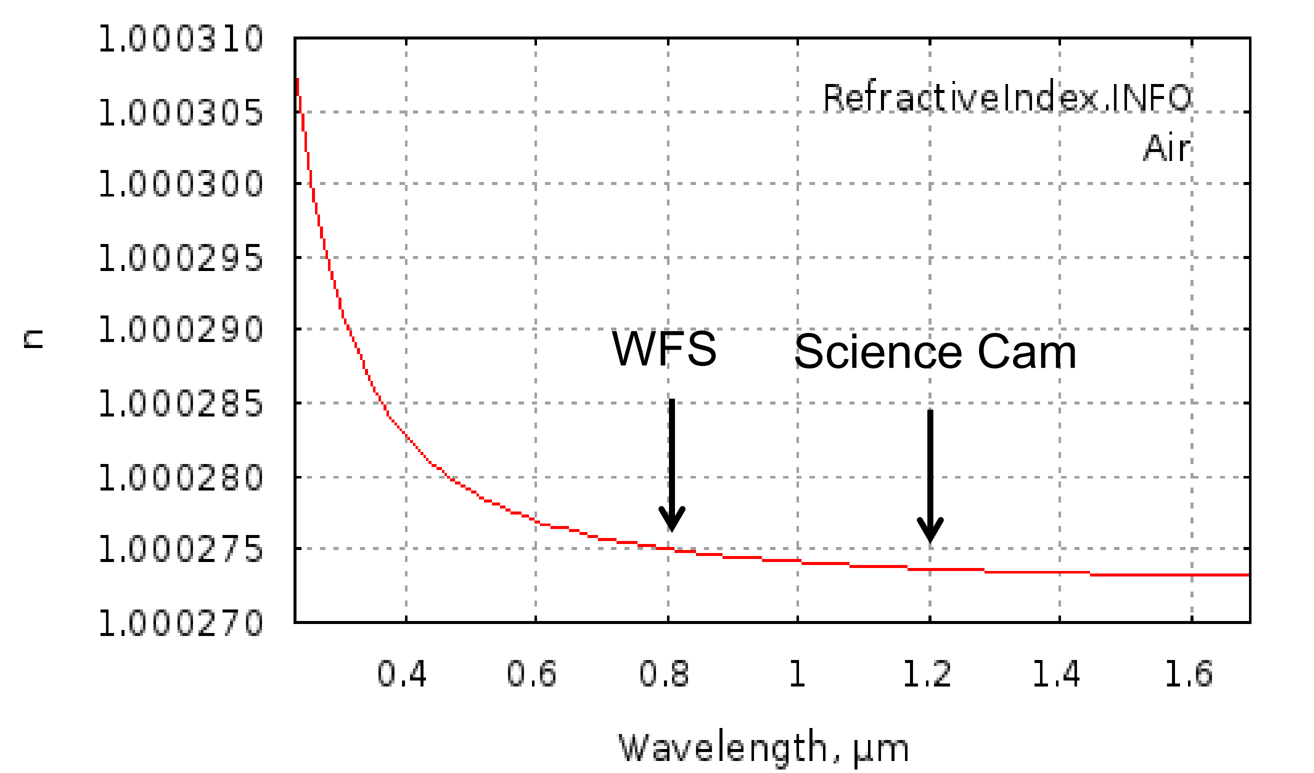
Residual halo with superb XAO (Roof PWS, 3kHz, I-band)

Temporal bandwidth error



R&D:
Develop concept (e.g. high framerate, low latency, advanced control)
Validation in laboratory and on-sky

Refractive index chromaticity



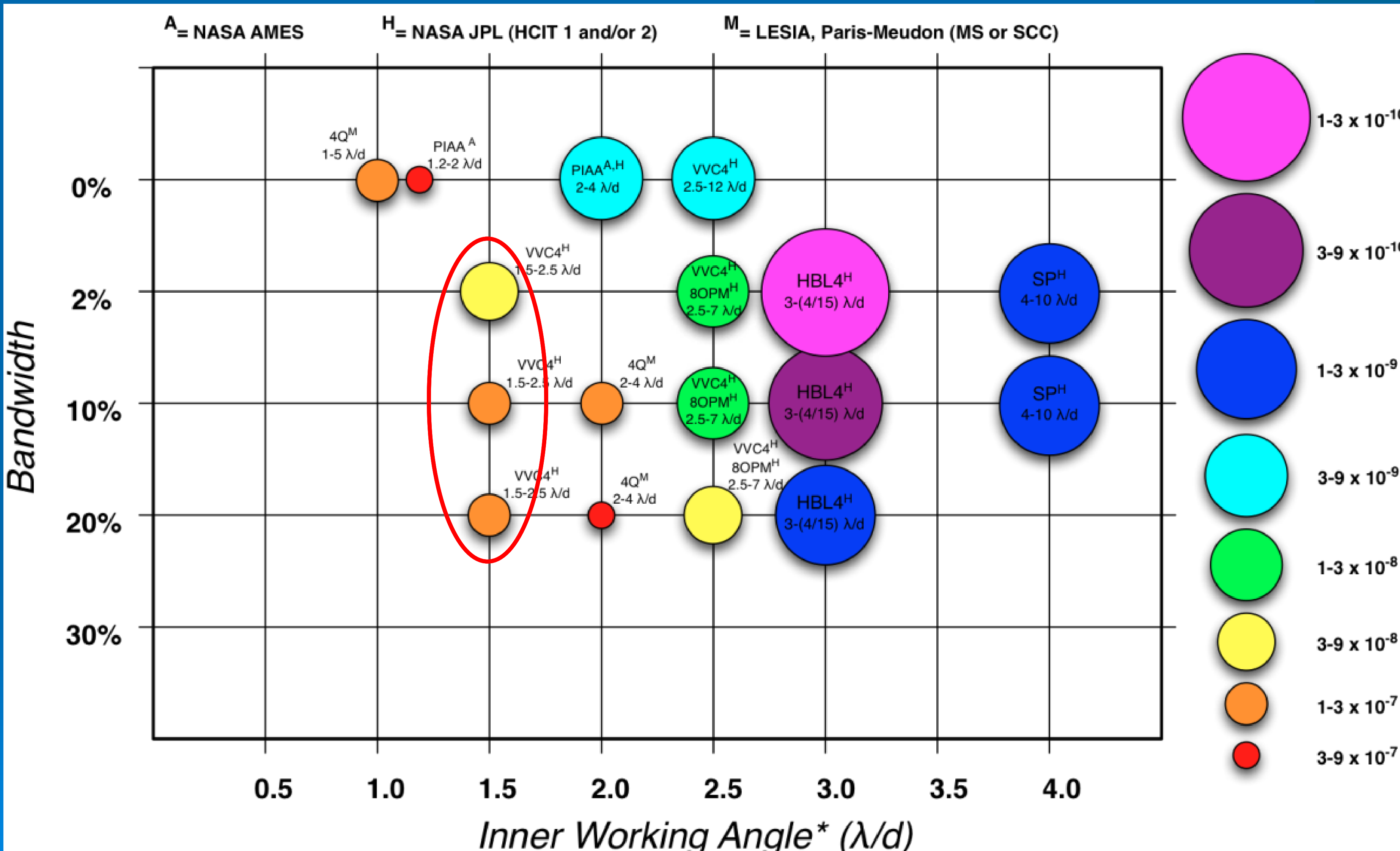
$$\epsilon(\lambda, \lambda_0) = \frac{\lambda_0}{\lambda} \frac{n_s(\lambda) - n_s(\lambda_0)}{n_s(\lambda_0) - 1},$$

Error is predictable and can be incorporated into AO control law.
R&D needed to develop this law, numerical and laboratory testing

Diffraction suppression concept

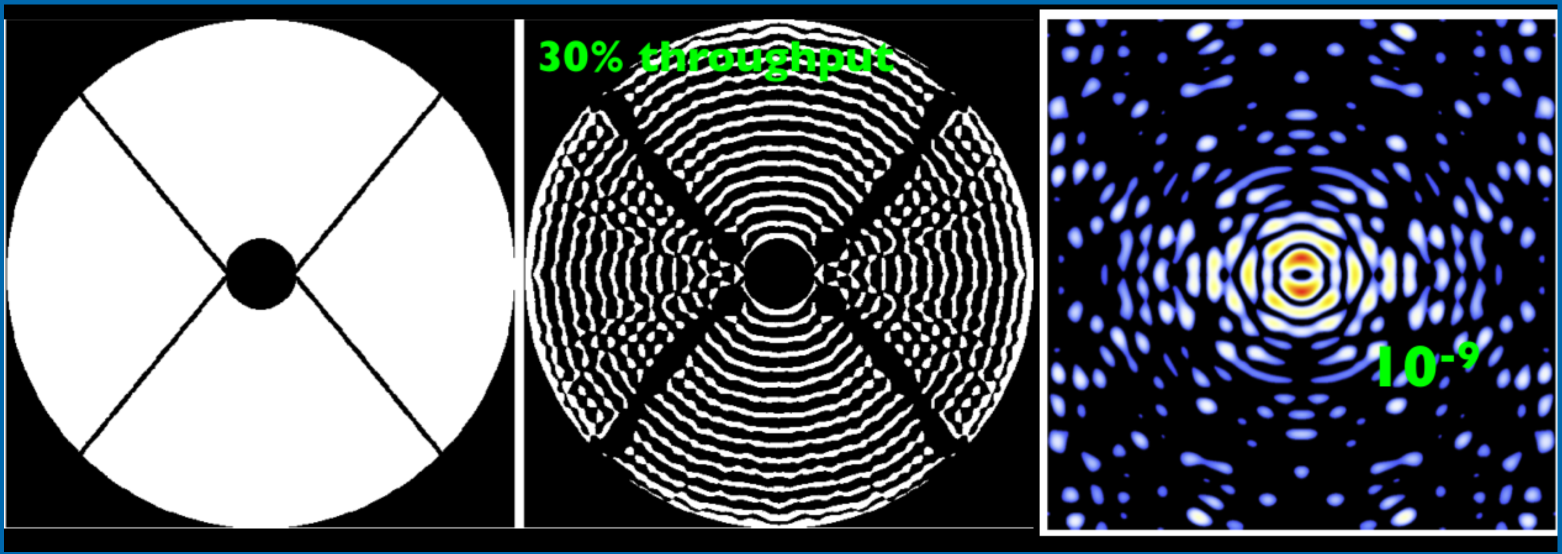
- Coronagraph for >15 mas (1.5-2 λ/D in NIR)
  - High-contrast over reduced spectral range
  - Characterization with IFS / NB imaging and EPOL polarimetry
- Apodization for >50 mas
  - High-contrast over large spectral range
  - Characterization with IFS / spectral deconvolution
- Requirements
  - Coronagraph source size leakage halo: ~10^{-5}
  - QS residuals (20% bandwidth, 0.5 mas source radius): 10^{-7} - 10^{-8}

Coronagraph technological maturity



Mawet et al. SPIE 2012

Concept 1: Apodized VVC4



Mawet & Carlotti

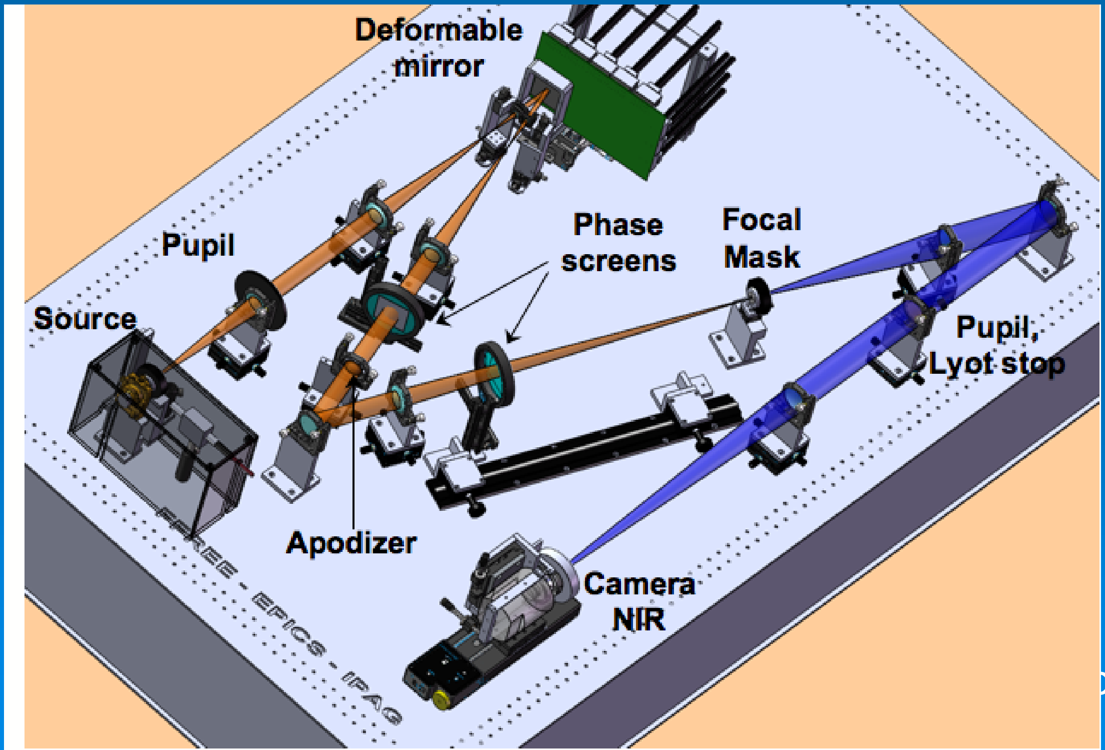
- Deals with aperture irregularities (central obscuration, spiders, gaps)
- Throughput up to ~50%, 1.5-2 λ/D, moderate pointing/source size sensitivity
- Possible to swap apodizer and coronagraph (IWA vs $\Delta\lambda$)

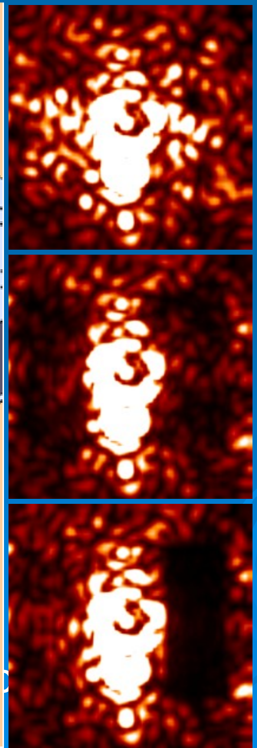
R&D:

- Numerical study assuming representative observing conditions
- Laboratory evaluation
- Concept and laboratory demonstration of 10^{-2} - 10^{-3} pointing

QSS correction and calibration

- Image plane electric field measured by e.g. Phase diversity, Speckle nulling, Self-coherent camera,…
- Correcting electric field (destructive interference) introduced by DM
- 10^{-8} at small IWA demonstrated in the lab (space conditions)
- R&D: Evaluate methods under ground-based conditions (XAO residual turbulence, E-ELT aperture, …) in the lab and on sky

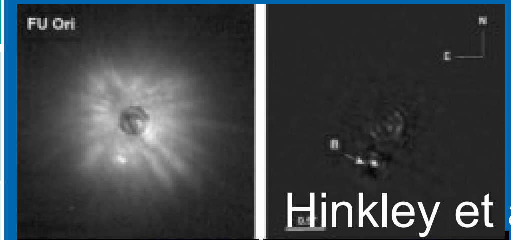




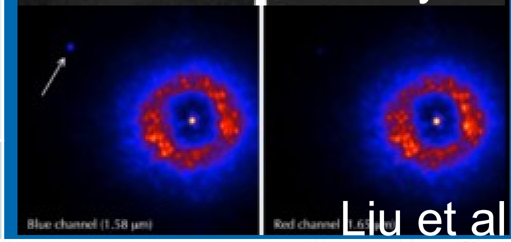
FFREE@IPAG
C. Verinaud et al., AO4ELT2, 2011

Postprocessing, differential methods

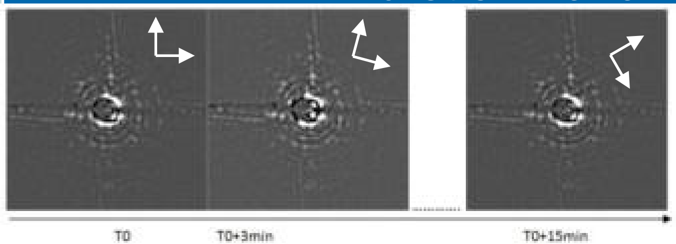
Method	IWA	Demo rejection on-sky
Spectral Deconvolution	~R*λ/D	~20 (Hinkley et al. 2011)
Spectral Differential Imaging (SDI)	1 λ/D	~10 (Biller et al. 2007)
Angular Differential Imaging (ADI)	A few λ/D	~30 (Marois et al. 2006)
Polarimetric Differential Imaging (PDI)	1 λ/D	~30 (Perrin et al. 2008)
Coherence Differential Imaging (CDI)	1 λ/D	~10 (Martinache et al. 2012)

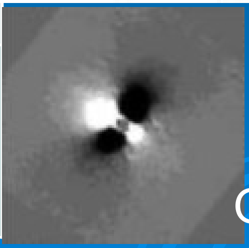


Hinkley et al. 2011



Liu et al. 2010





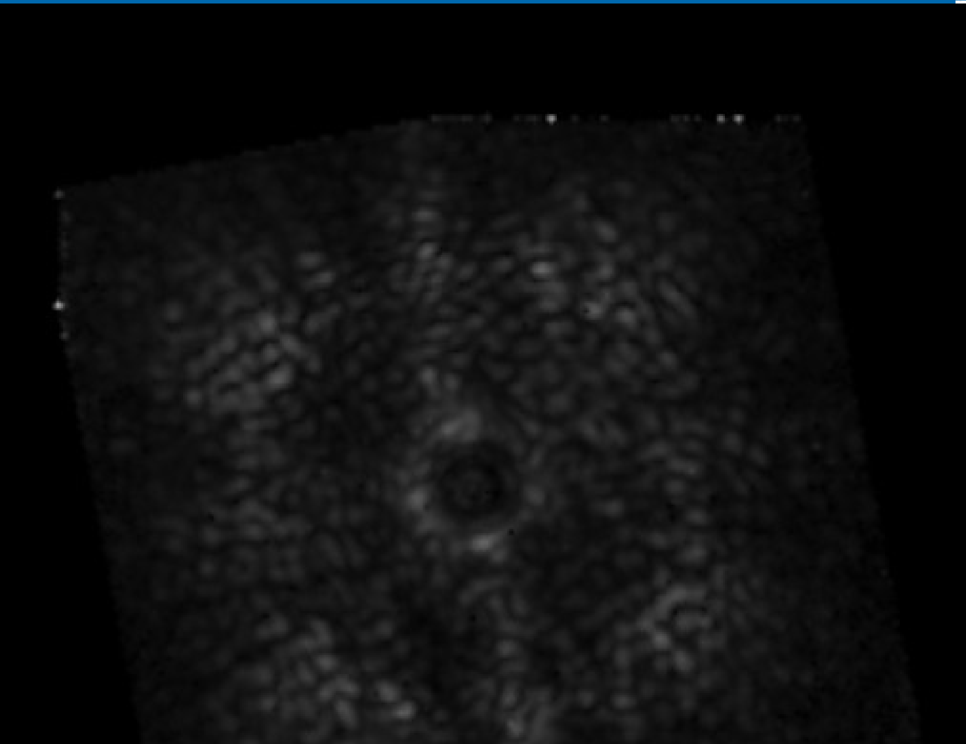
Quanz et al. 2011

R&D: Explore on-sky limits with SPHERE

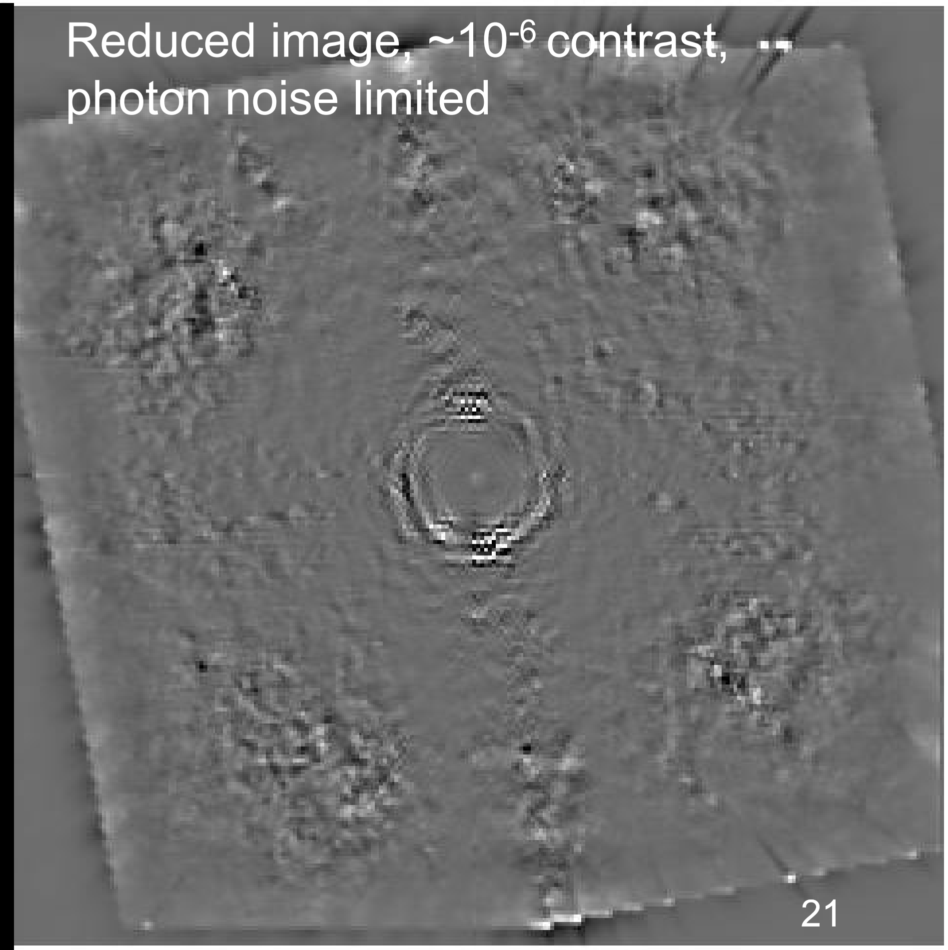
IFS, spectral deconvolution

Main characterization mode for PCS

R&D: IFS concept development and lab demo



SPHERE H-band data cube
APLC, no QSS compensation
Credit R. Gratton



PCS R&D activities at the national level

- Eridani (French ANR, Baudoz et al.) proposal submitted

  Targeted at some select aspects of the HCI problem. Strong synergies with

  WP 0 (HCI bench development)

  WP 7 (Apodized VVC)

  WP 8 (on-sky speckle calibration with SPHERE)

- EPOL-related NOVA proposal funded (Keller et al.)

  Coronagraphy + polarimetry using achromatic (vector) apodizing phase plates

  Enhance high-contrast data reduction algorithms to polarimetric observations.

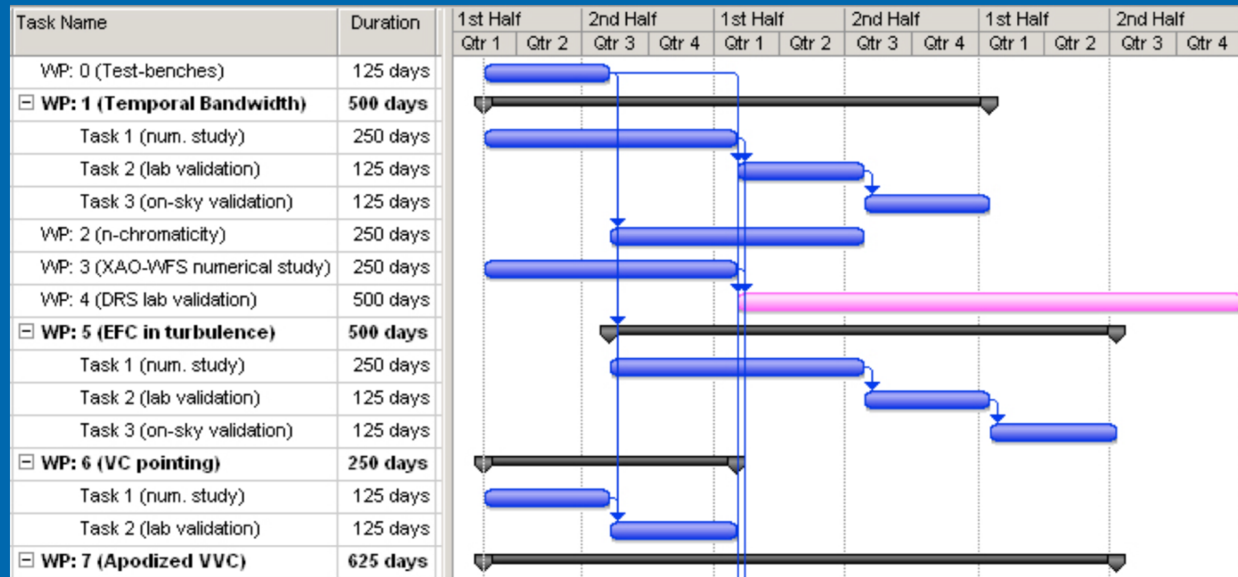
- IFS-related R&D funded at a low level by INAF T-REX (Gratton et al.) and internally at Oxford university (Tecza et al.)

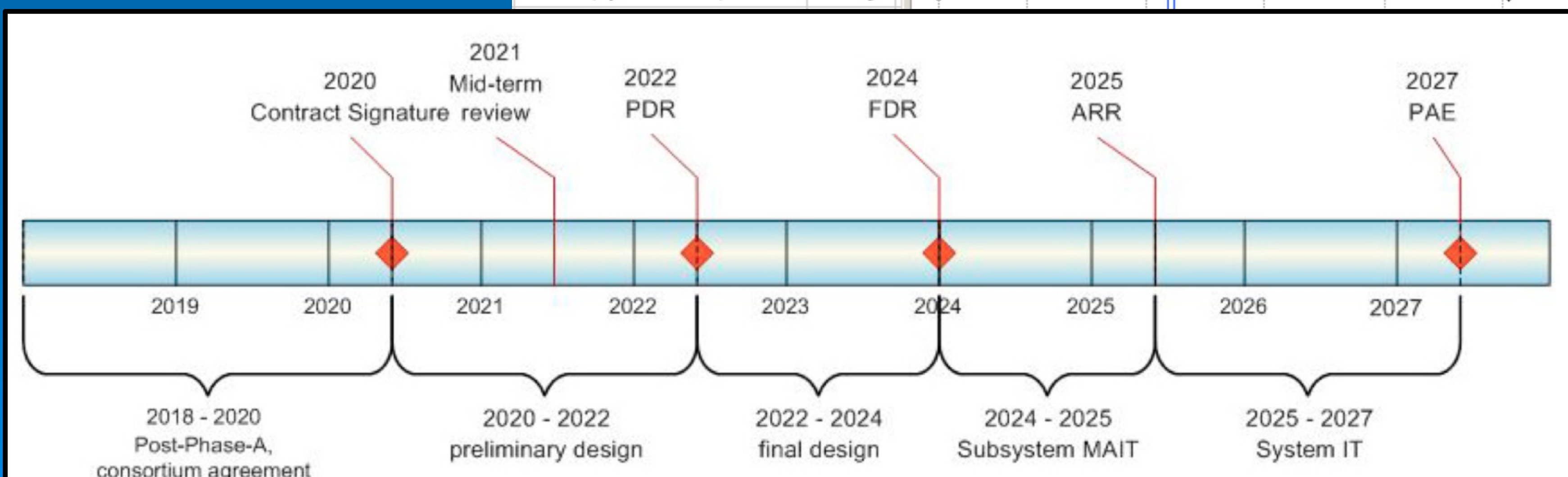
  Main focus on concept development (slicer or lenslet-based technology)

Schedule

Given by 2014:
SPHERE on-sky
E-ELT approval

2015: R&D start
2018/19: TRL demo,
Project start





Summary

1. PCS will be a versatile EELT instrument for
   a) characterization of Exoplanets down to Earth-mass
   b) the detection and study of forming planets
2. Concept technological choices are advanced
3. 3-5 years R&D programme
   - XAO (incl. DM! Consider risk mitigation)
   - Small IWA Coronagraphy/Wave-front control
4. 1st light >2027

Photon-noise limited sensitivity

XAO Halo: 3×10^{-5}, ExoPlanet: 10^{-8}

=> $N_{Halo} \approx 3000\, N_{EP}$

$SNR = N_{EP} / sqrt(3000\, N_{EP}) > 5$ (5 sigma criterion)

=> $N_{EP} > 3000 \cdot 5^2 = 75000$ photons (Min number of photons form EP)

E-ELT, 8 hrs, 50nm BW in J-Band, 10% transmission:

J_{EP} <~ 26, J_S <~ 6