# EPICS, exoplanet imaging with the E-ELT

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JENAM 08, Vienna, 8 September 2008

# Outline

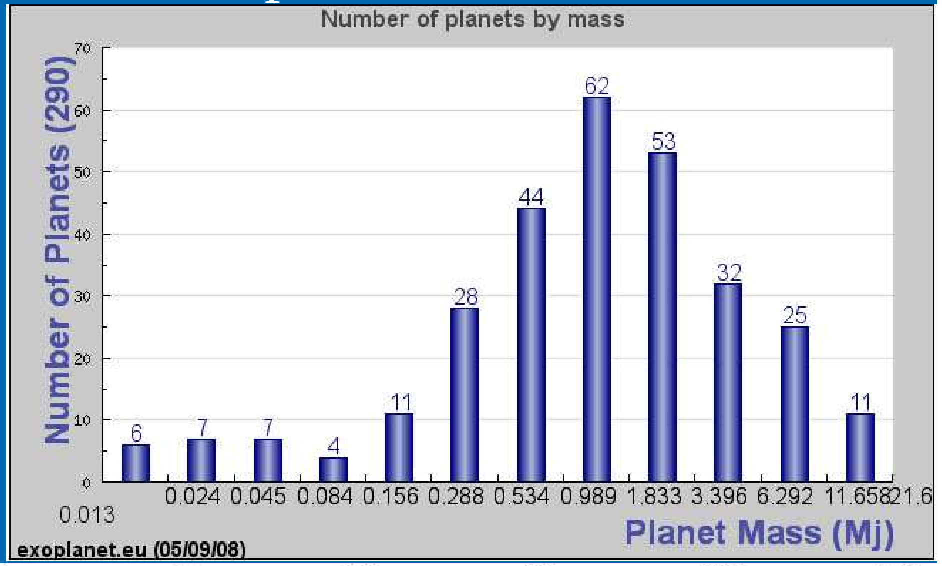
- Science goals
- Instrument concept (brief)
- Science Output prediction

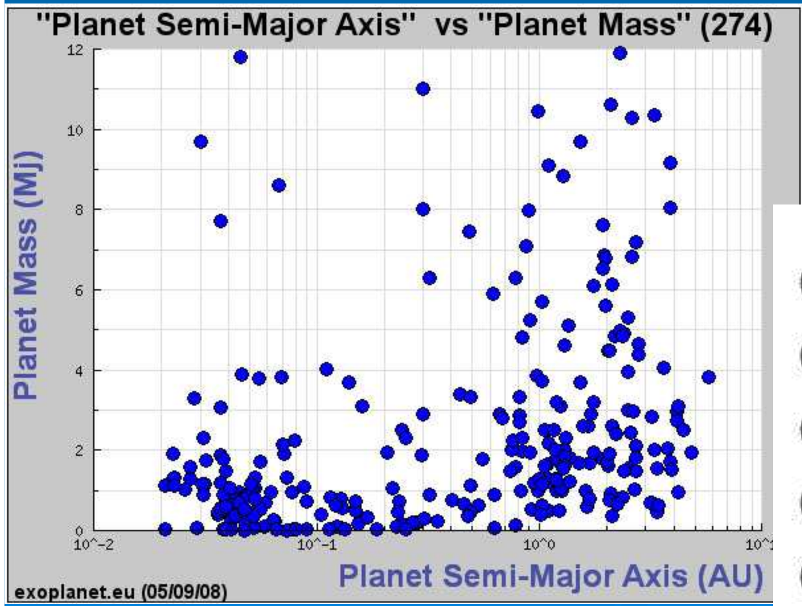
# EPICS phase-A study

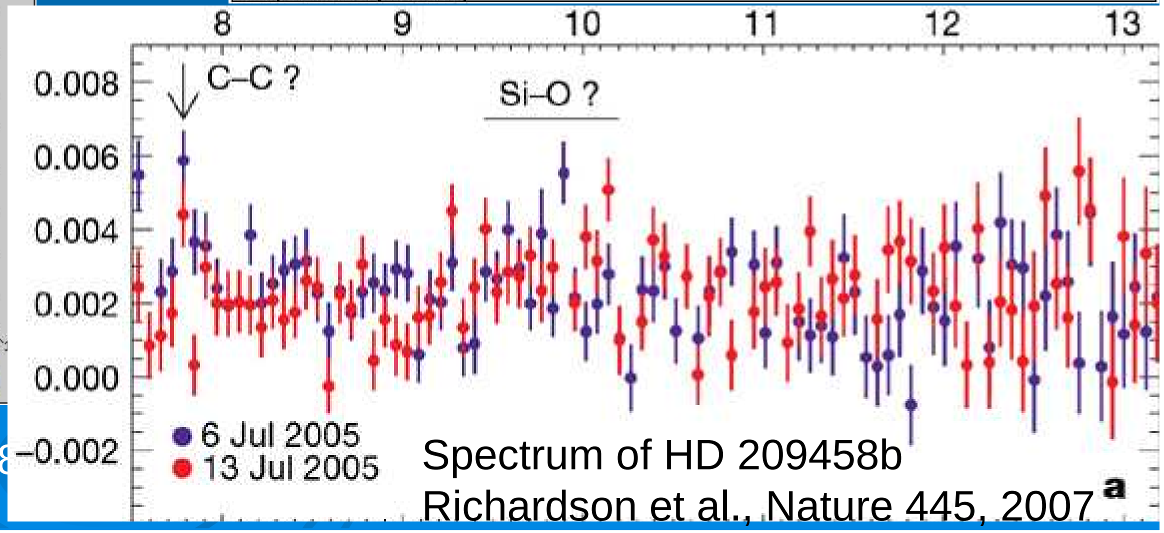
- E-ELT phase-B will conclude in 2010 with an instrumentation plan suitable to cover the highest priority scientific objectives (which include Exoplanets)
- EPICS phase-A (feasibility) study is one of these E-ELT instrument studies and has been kicked off in October 2007
- EPICS phase-A study goals: requirements to the E-ELT and the associated site, feasible instrument concept, scientific capabilities, cost, FTE effort, construction schedule
- EPICS phase-A is partially funded by ESO and the European Framework Programme 7 (FP7).

# Exoplanets 2008

- ~ 300 Exoplanets detected, >80% by radial velocities, mostly gas giants, a dozen Neptunes and a handful of Super-Earths
- Constraints on Mass function and orbit distribution
- Some spectral information from transiting planets




Spectrum of HD 209458b
Richardson et al., Nature 445, 2007

# (Some) open issues

- Planet formation (core accretion vs gravitational disk instability)
- Planet evolution (accretion shock vs spherical contraction, “hot start”)
- Orbit architecture (Where do planets form?, role of migration and scattering)
- Abundance of low-mass and rocky planets
- Giant planet atmospheres

# Object Class 1

**Young self-luminous planets**
in star forming regions or young associations

| Cluster | Lupus | Taurus-Auriga | Oph | Eta Cha | Cha | Upper Sco | Sco Cen | TW Hya |
|---|---|---|---|---|---|---|---|---|
| Age (Myr) | 1 | 2 | 2 | 4-7 | 1-10 | 1-10 | 1-25 | 10 |
| Distance (pc) | 150 | 140 | 125 | 100 | 140 | 145 | 130 | 60 |
| Separation Snow line G2V (arcsec) | 0.016 | 0.017 | 0.019 | 0.024 | 0.017 | 0.017 | 0.018 | 0.040 |
| I (G2V) | 9.9 | 9.7 | 9.5 | 9.0 | 9.7 | 9.8 | 9.6 | 7.9 |

**Requirements**:

Moderate contrast ~$10^{-6}$

High spatial resolution of ~30 mas (3 AU snow line for solar type star at 100 pc)

Host stars red and relatively faint: XAO constraint

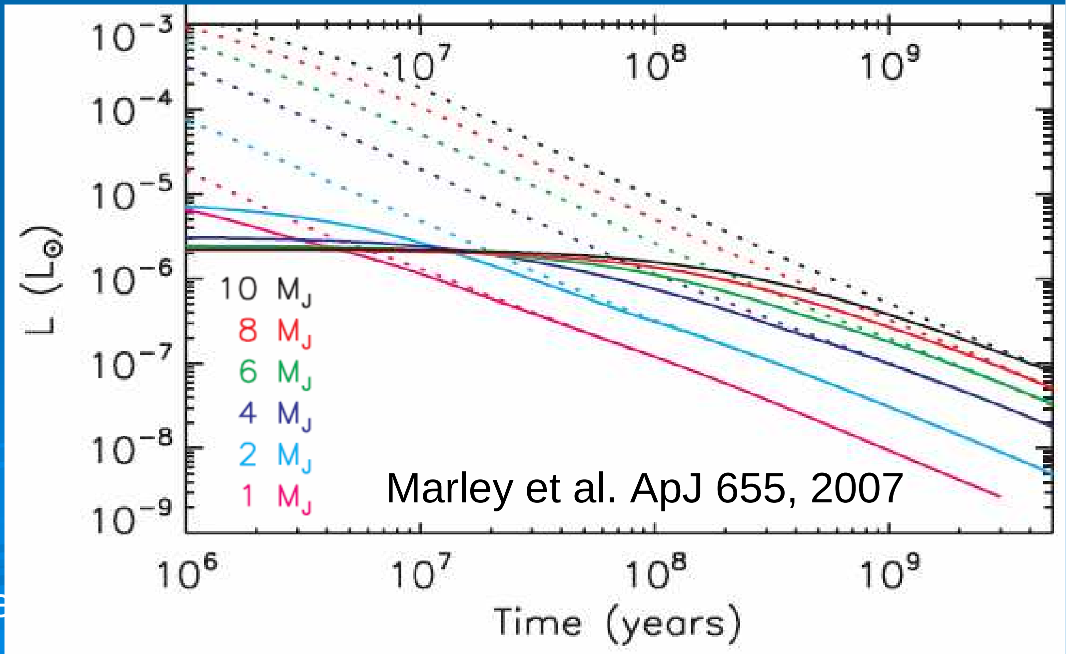
# Object Class 1 science

*Planet Formation*

**Gravitational instability** faster than **core accretion** ⇒ Frequency of planets at very young ages will help to differentiate formation models

**Spherically contraction** brighter than **simplified core accretion** ⇒ Brightness vs dynamical mass known from RV (e.g. with CODEX at the EELT) to differentiate.
RV challenging for young stars (cf. TW Hydrae), but ok to determine amplitude of known orbit

Young planets are subject to **migration**
⇒ Orbital evolution indicates migration efficiency



# Object Class 2

**Nearby (≤ 20 pc) Stars**
~500 stars from Paranal ± 30 deg, ~60-70% M-dwarfs

Detection of gas giants at orbital distances > ~5 AU and low-mass planets down to the Super-Earth domain.

**Requirements**
Small inner working angle:
e.g. Gl 581 d (~8$M_E$) with contrast $10^{-8}$ at 40 mas

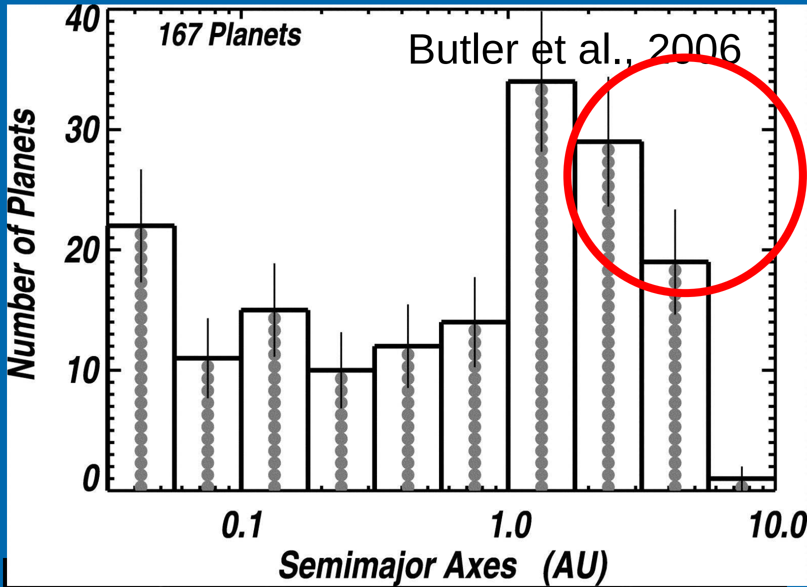
High contrasts:
Jupiter at 10pc: ~$10^{-9}$ at 500 mas

# Object Class 2 science

***Frequency and mass distribution of giant planets at old ages***

compare with star forming regions.

Orbit architecture (where do planets form?, role of migration and scattering)




***Abundance of low-mass and rocky planets***

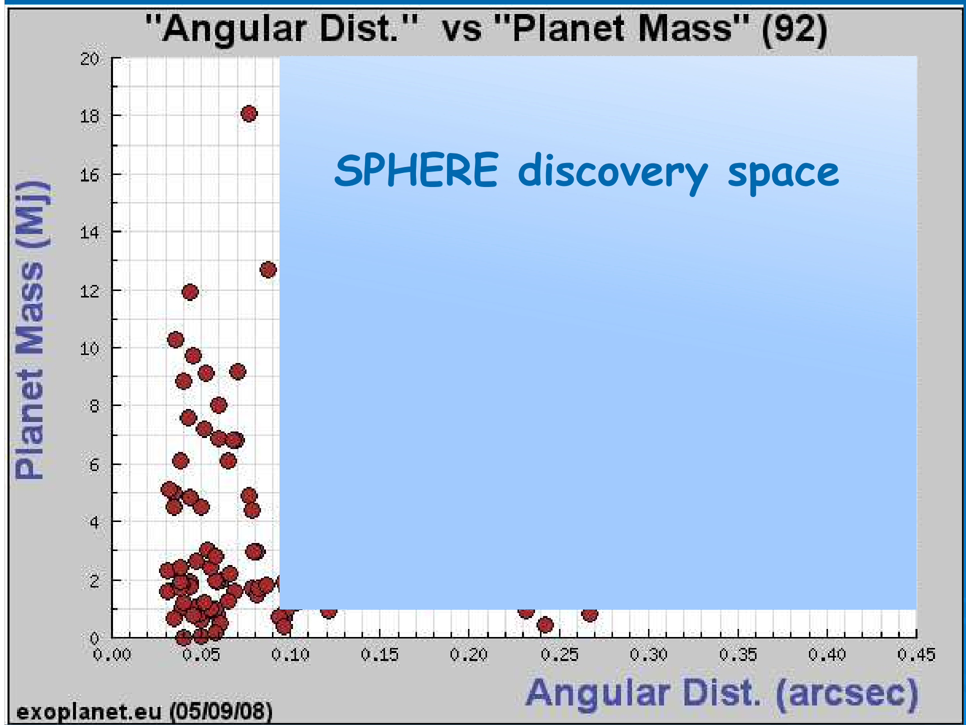
basic parameter for models of planet formation.

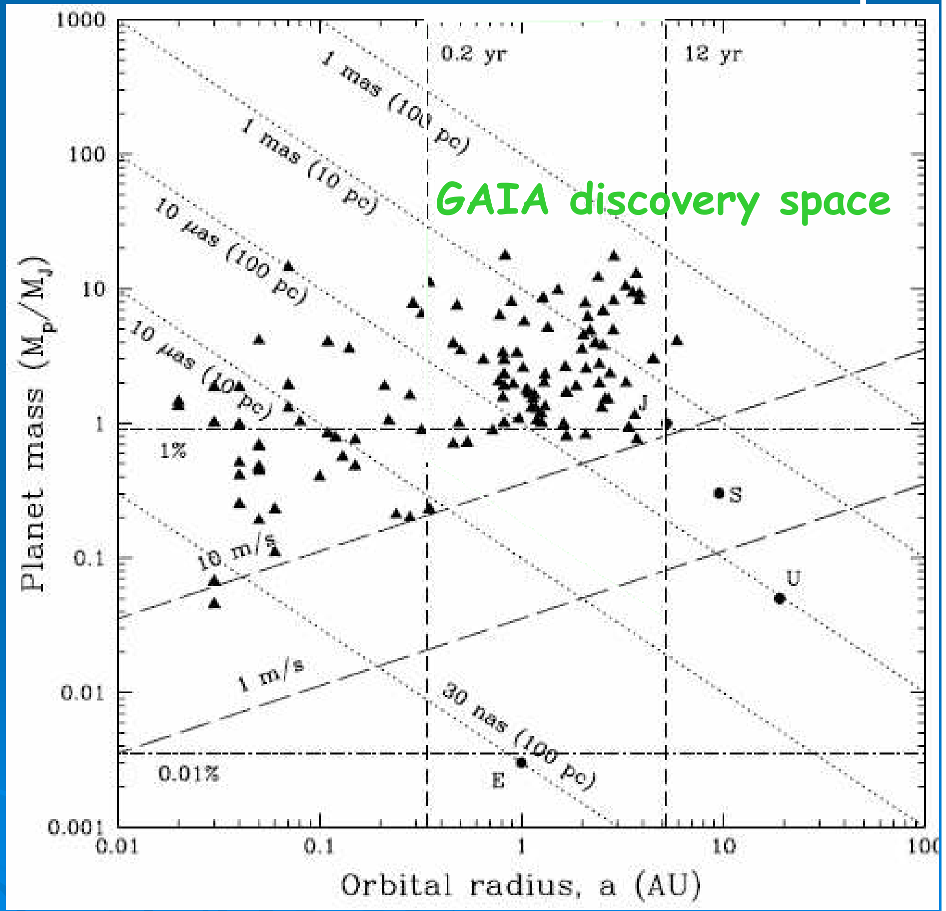
# Object Class 3

**Known Planets**
discovered by RV, direct imaging (SPHERE, GPI) or astrometric methods (GAIA, PRIMA)

From ESO/ESA WG report

**Requirements:** as object class 2
Spectroscopic mode needed



# Object Class 3 science

***Test planet evolution models***

Compare modeled spectrum to measurement for objects with known physical parameters (current issue in BD science)

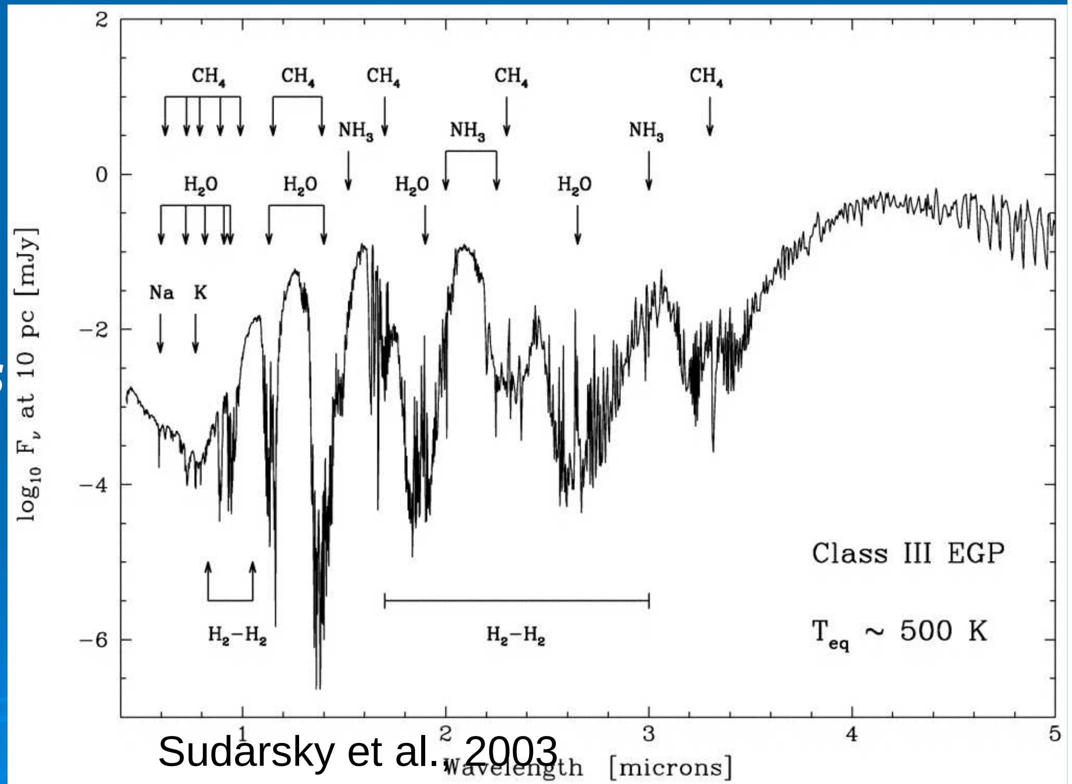
Dynamic masses from orbit

Age and metallicity constrained by star

***Understand planet atmospheres***

Chemical composition

Effects of clouds



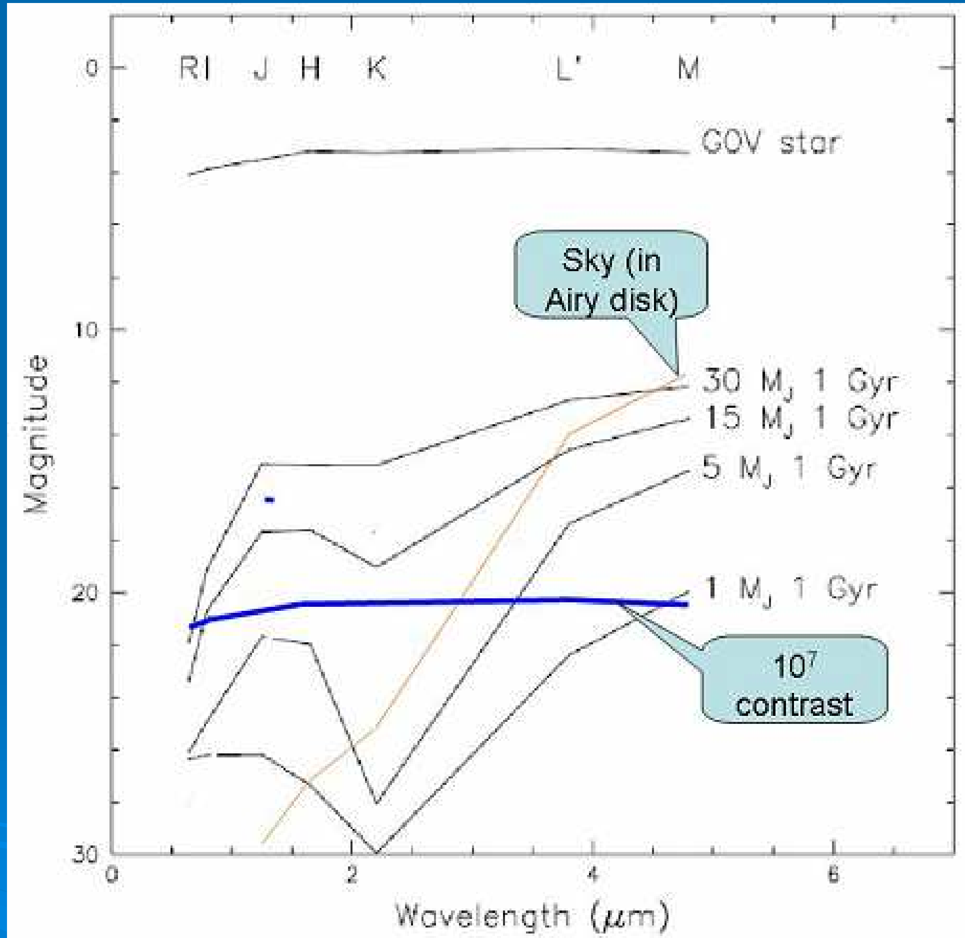

Sudarsky et al., 2003

# Concept

# Concept: MIR?

- Massive and young planets or planets in close orbits are warm and can efficiently be observed in the MIR (4-5 μm)
- Pb: ~4x lower spatial resolution and high sky background
- Object class 1: too low spatial resolution ✯
- Object class 3: too low spatial resolution or too low sensitivity ✯
- Object class 2 ok, but not at the requested >5 AU ☹

⇒ ***EPICS in NIR, complemented by METIS in MIR***



# Top Level Requirements

6. **a) Contrast requirements Y-H band** (10h telescope time, reference seeing conditions, 5σ detection):

| Brightness ratio at distance: [mas] | 30 | 100 | 300 | Limiting stellar Magnitude I band: |
|---|---|---|---|---|
| Science Case 1 | $10^{-6}$ | $10^{-6}$ | $10^{-6}$ | **9 (goal: 10)** |
| Science Case 2 | | **$2\ 10^{-9}$ (goal $10^{-9}$)** | **$10^{-9}$ (goal $4\ 10^{-10}$)** | 7 (goal: 8) |
| Science Case 3 | **$10^{-8}$** | **$10^{-9}$** | $10^{-8}$ | 7 (goal: 8) |
| Science Case 4 | $2\ 10^{-9}$ (goal $10^{-9}$) | $10^{-9}$ (goal $4\ 10^{-10}$) | $5\ 10^{-10}$ (goal $2\ 10^{-10}$) | 5 (goal: 6) |

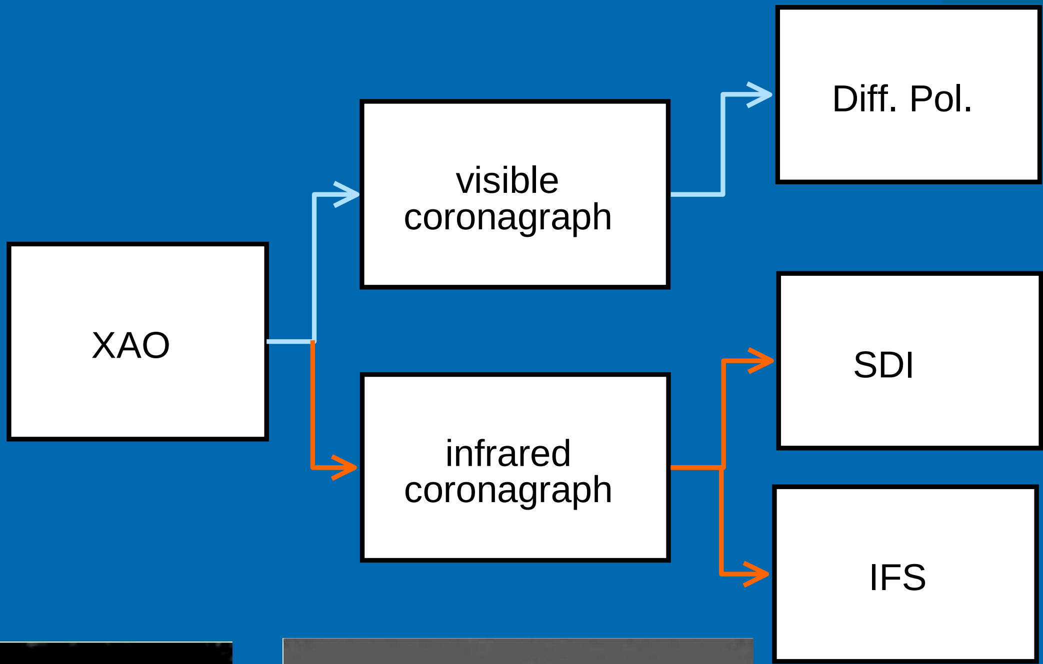
**b) Contrast requirements I band** (10h telescope time, reference seeing conditions, 5σ detection, for differential signal contrast ($I_1$(planet)-$I_2$(planet) )/($I_1$(star)+$I_2$(star) ) where $I_1$ and $I_2$ are fluxes in two spectral bands (on/off $CH_4$ absorption) or I(parallel) and I(perpendicular) for polarimetry]:

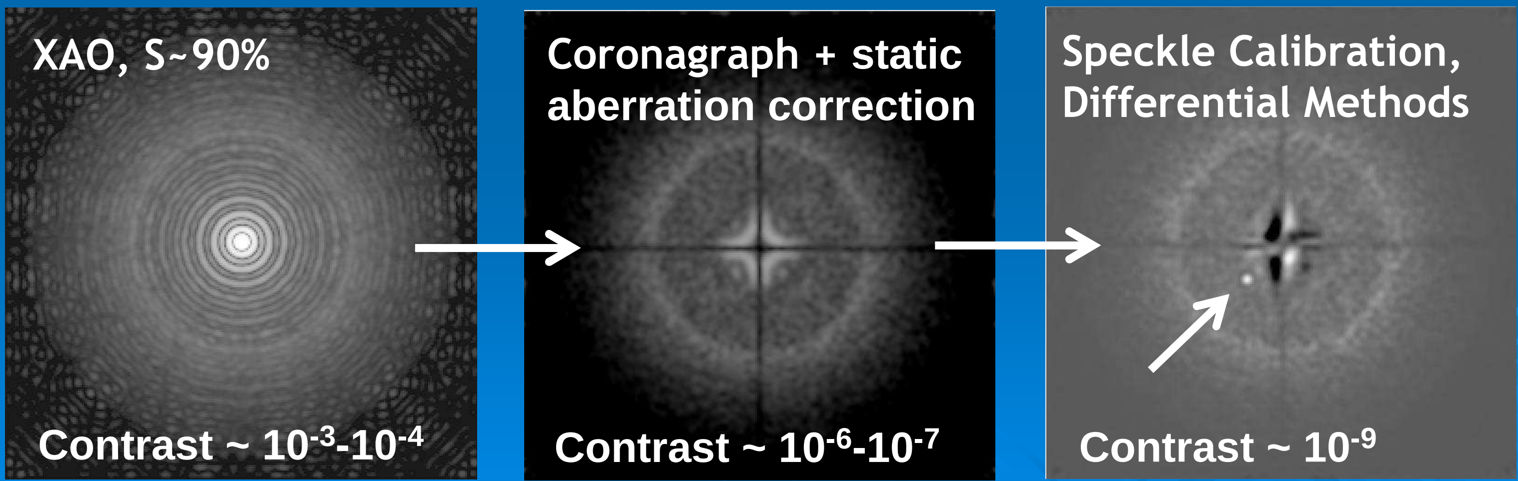
| Brightness ratio at distance: [mas] | 30 | 100 | 300 | Limiting stellar Magnitude I band: |
|---|---|---|---|---|
| Science Case 2 | | **$2\ 10^{-9}$ (goal $10^{-9}$)** | **$10^{-9}$ (goal $4\ 10^{-10}$)** | 7 (goal: 8) |
| Science Case 4 | $2\ 10^{-9}$ (goal $10^{-9}$) | $10^{-9}$ (goal $4\ 10^{-10}$) | $5\ 10^{-10}$ (goal $2\ 10^{-10}$) | 5 (goal: 6) |

# Concept: Achieve very high contrast

Highest contrast observations require multiple correction stages to correct for

1. Atmospheric turbulence
2. Diffraction Pattern
3. Quasi-static instrumental aberrations



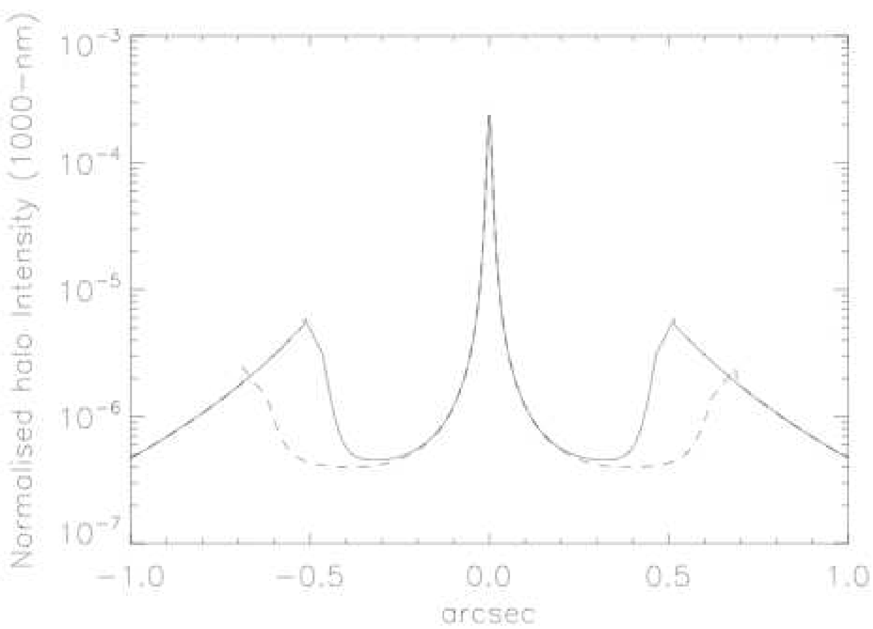
# XAO

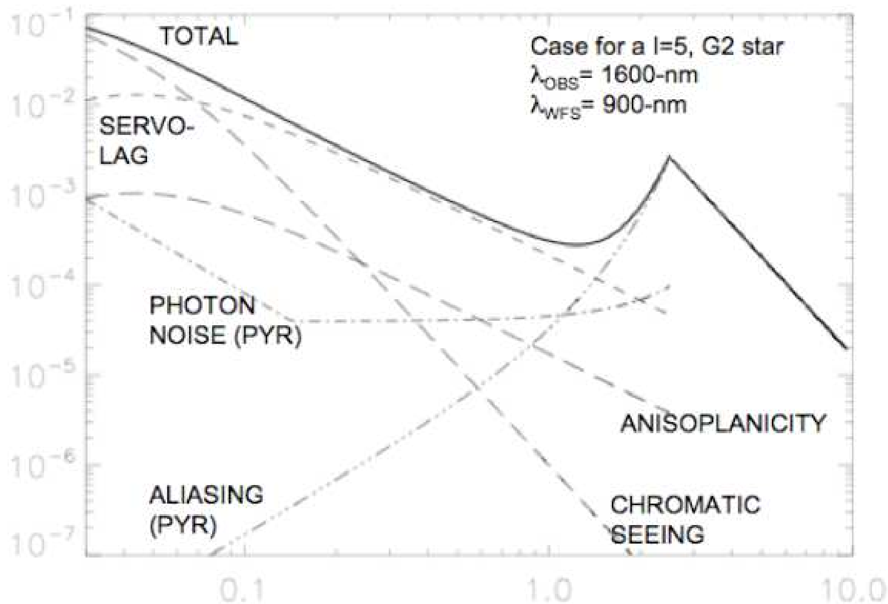
## Main parameters

- Pyramid wavefront sensor
- Sensing wavlength: 900 nm
- Framerate: 3 kHz
- Actuator spacing: 0.2-m -> 200x200
- M4 + Tweeter DM

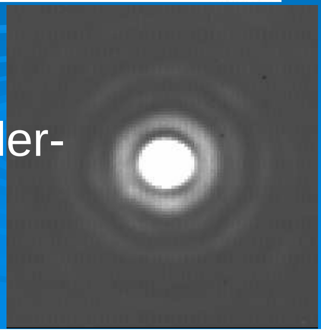
## Features

- Turbulent speckle halo $10^{-5}$-$10^{-6}$
- Servo-lag is dominant error
- Smaller actuator spacing ineffective



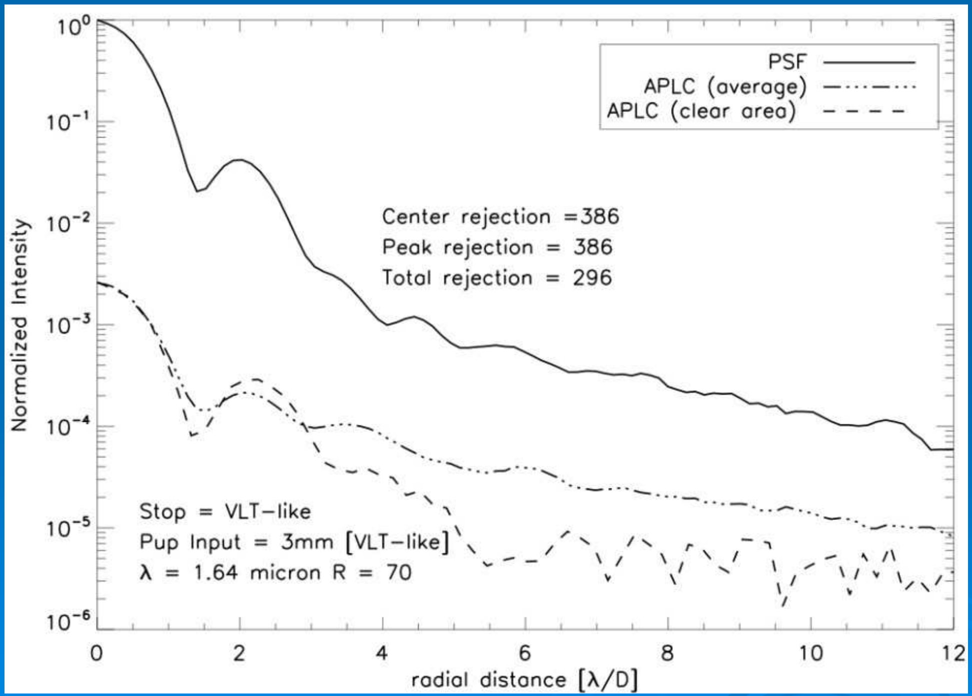



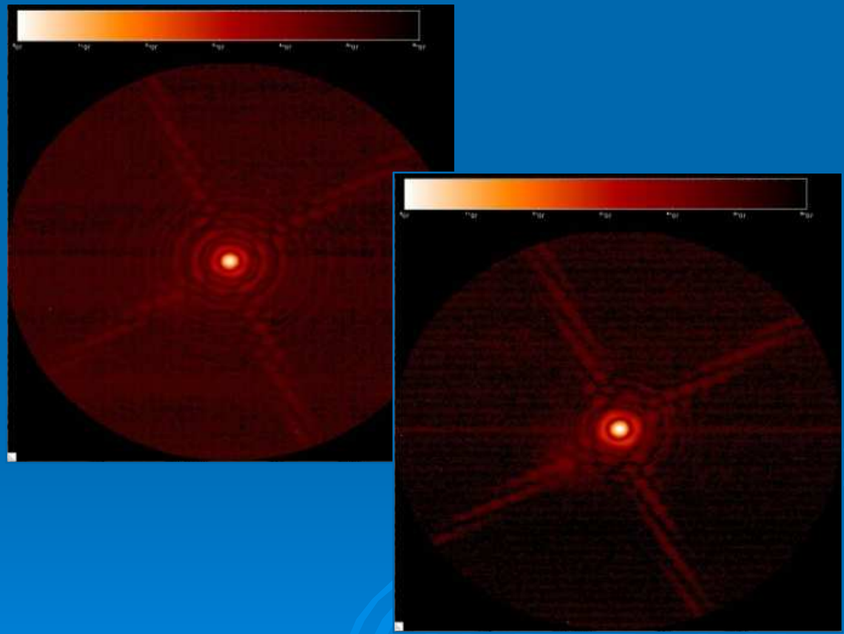

$S_H$ = 90%, 0.5" seeing, 8-m aperture (Esposito et al., Aller-Carpentier et al., SPIE08)



# Coronagraphy

- Diffraction residuals have similar effects as quasi-static aberrations
- Global study (Martinez et al. in prep) considering liability to real-life effects suggest APLC (possibly multi-stage) as baseline
- Complementary concepts (Dual-zone, multi-stage 4QPM) are **prototyped in the frame of FP7**. Initial results encouraging (MS-4QPM: $10^{-8}$ at 5λ/D for 20% bandwidth, Baudoz et al. SPIE 7015, 2008)



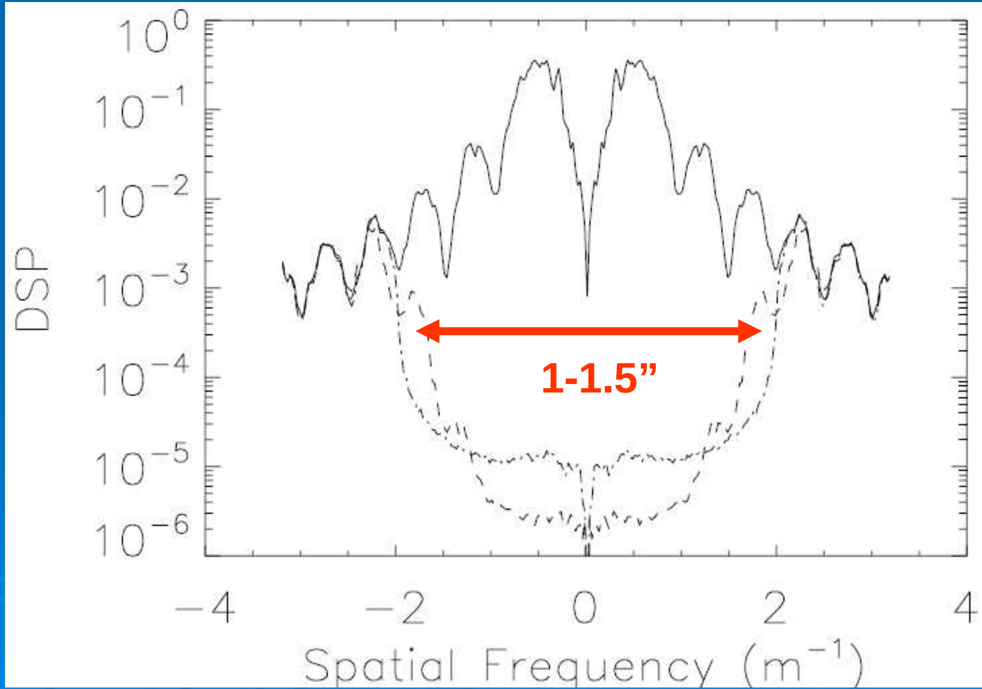
**See Martinez et al, SPIE 7015, 2008**
**APLC: $5x10^{-6}$ at ~5λ/D measured**

# Correction of quasi-static WFE

- Need to measure static aberrations at level of coronagraph with some nm rms at science wavelength
- Correction by XAO DM or dedicated DM. DM “cleans” its control area from speckles (rejection better than $10^{-4}$)

Standard WFE specs ok for most optics

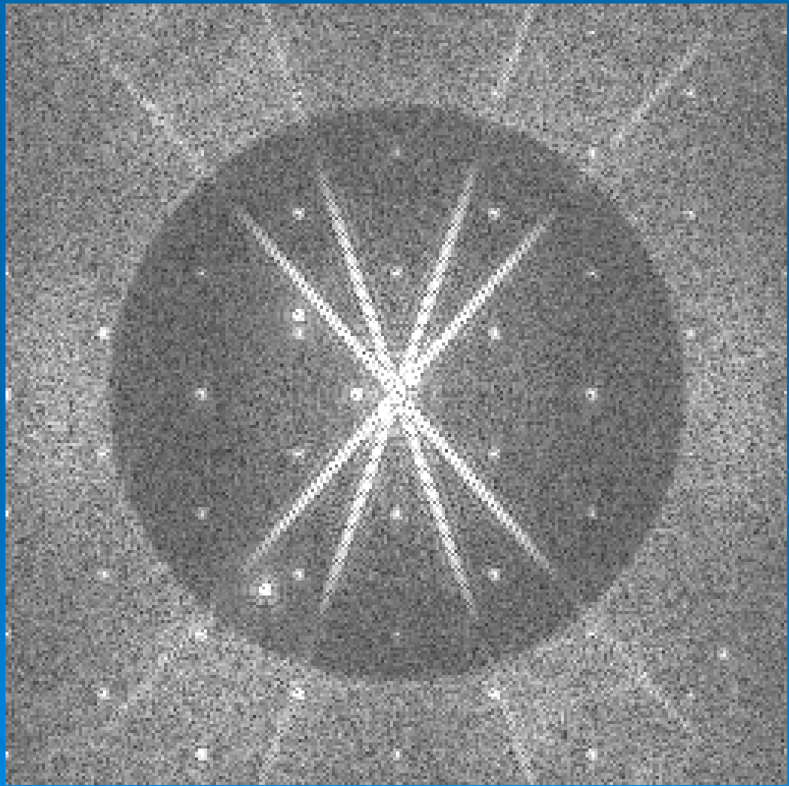
Measurement device to be demonstrated
⇒ FP7 funded exp.



# Data reduction, speckle calibration

Getting from systematic PSF residuals ($10^{-6}$-$10^{-7}$) to $10^{-8}$-$10^{-9}$

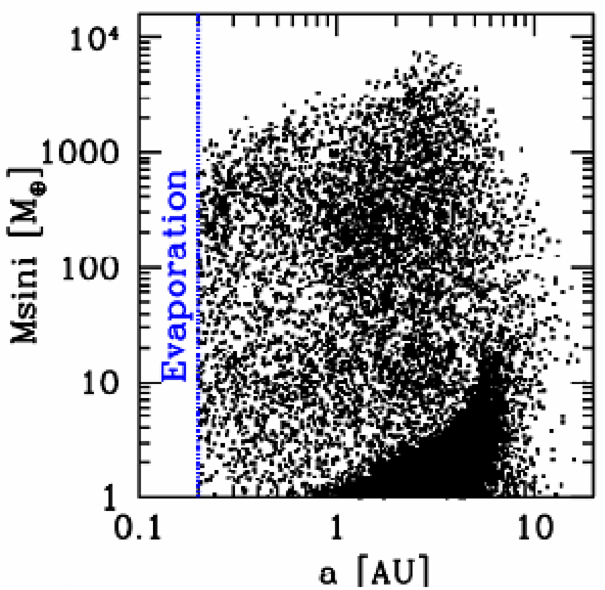
- **Spectral Devonvolution** (Sparks&Ford, Thatte et al.)
- Multi-band spectral or polarimetric **differential imaging** for smallest separation
- Angular Differential Imaging (**ADI**)
- Coherence based methods (speckles interfere with Airy Pattern, a planet does not)



# Detection rates, MC simulation

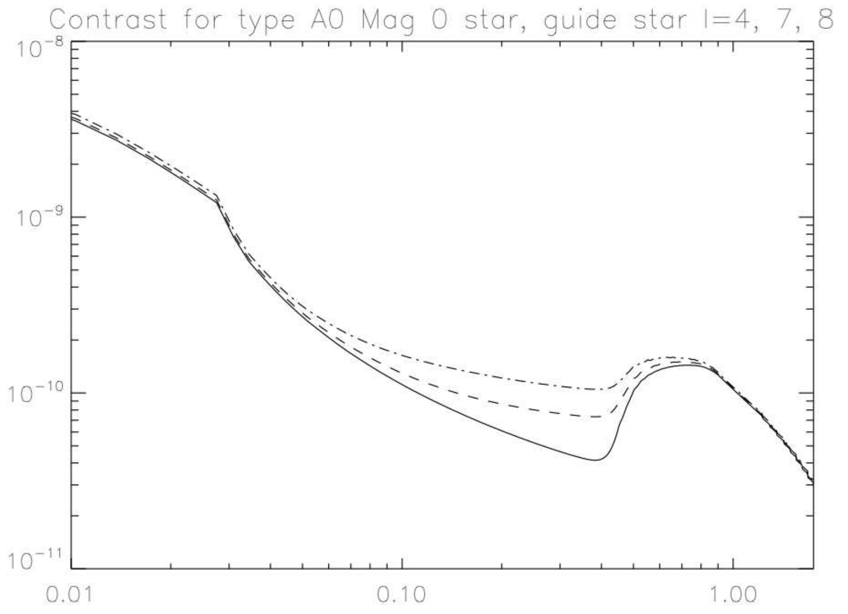
JENAM 08, Vienna, 8 September 2008

# Predicted Science Output




**MC simulations**

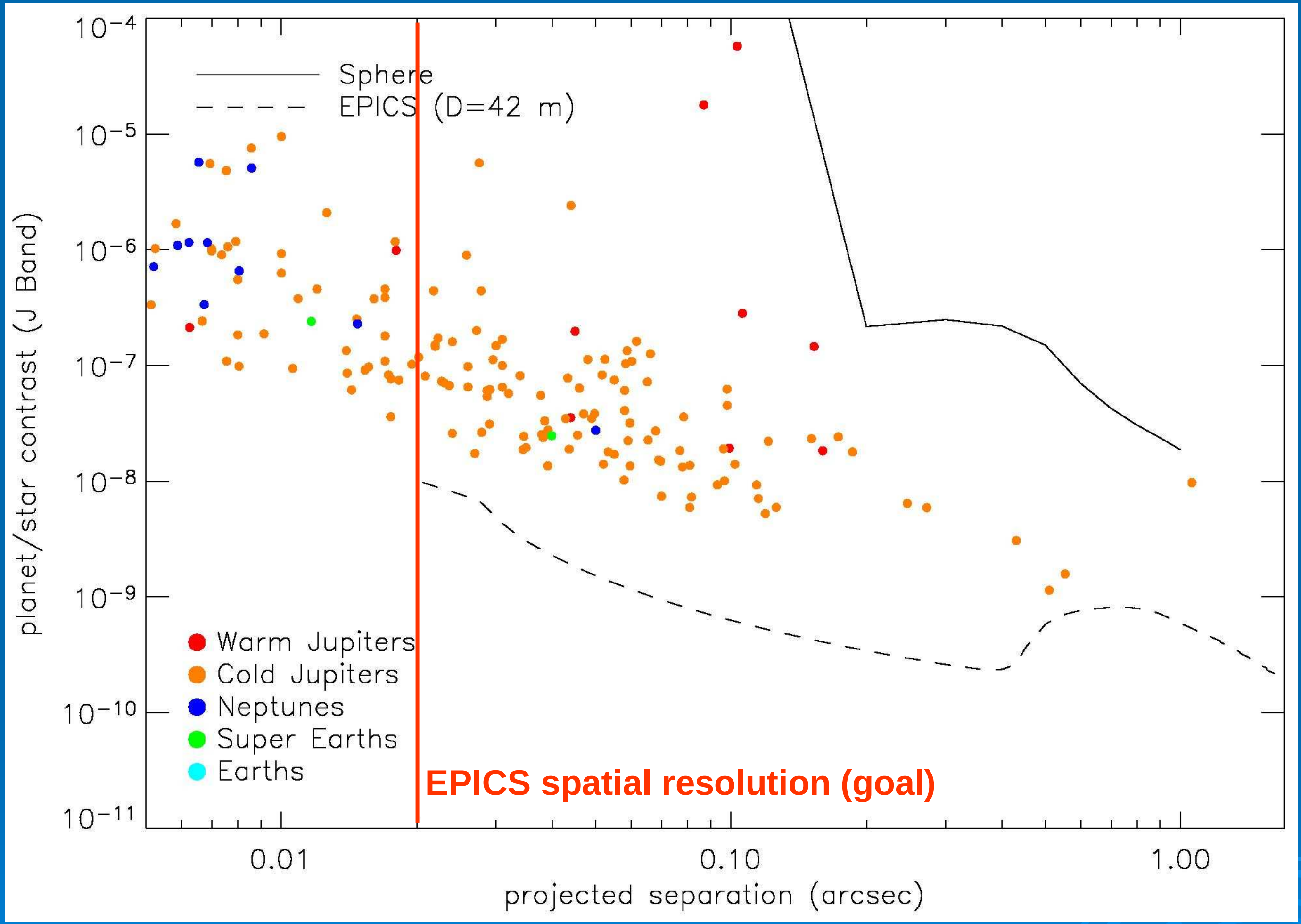
- planet population with orbit and mass distribution from e.g. Mordasini (2007)
- Model planet brightness (self-luminous, in reflection, albedo, orbital position,…)
- Match statistics with RV results




**Contrast model**

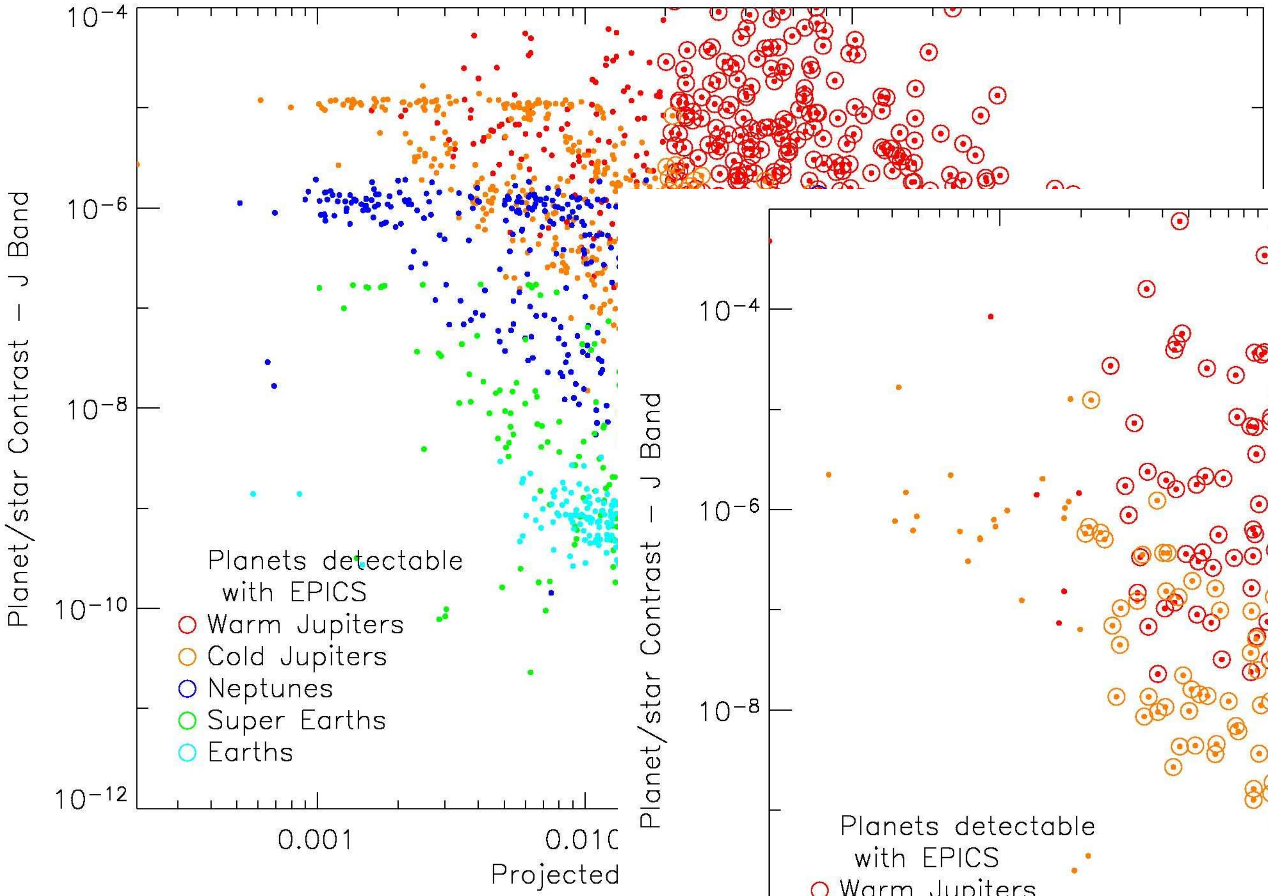
- Analytical AO model incl. realistic error budget
- Actual wavelength range and throughput estimate, 4h obs
- Data analysis considered
- Idealized Coro + statics corr.

# Objects, Class 3 (known planets)



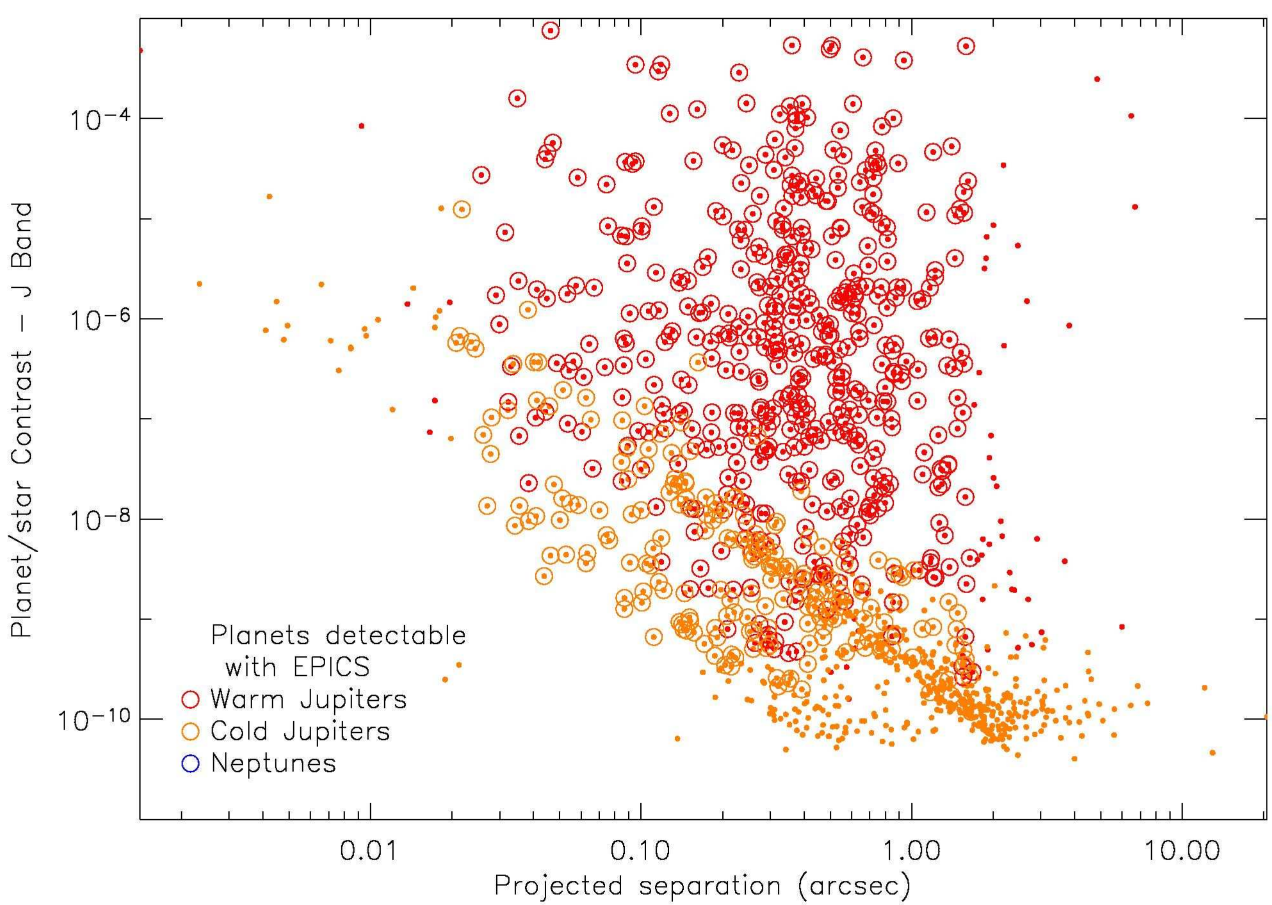

**About 100 currently known targets are readily observable with EPICS, and many more are expected to be discovered by e.g. GAIA or SPHERE**

# Detection rates, nearby+young stars




Mordasini et al. 2007

RV distribubtion, extrapolated to 40 AU




X

# Predicted detections with EPICS

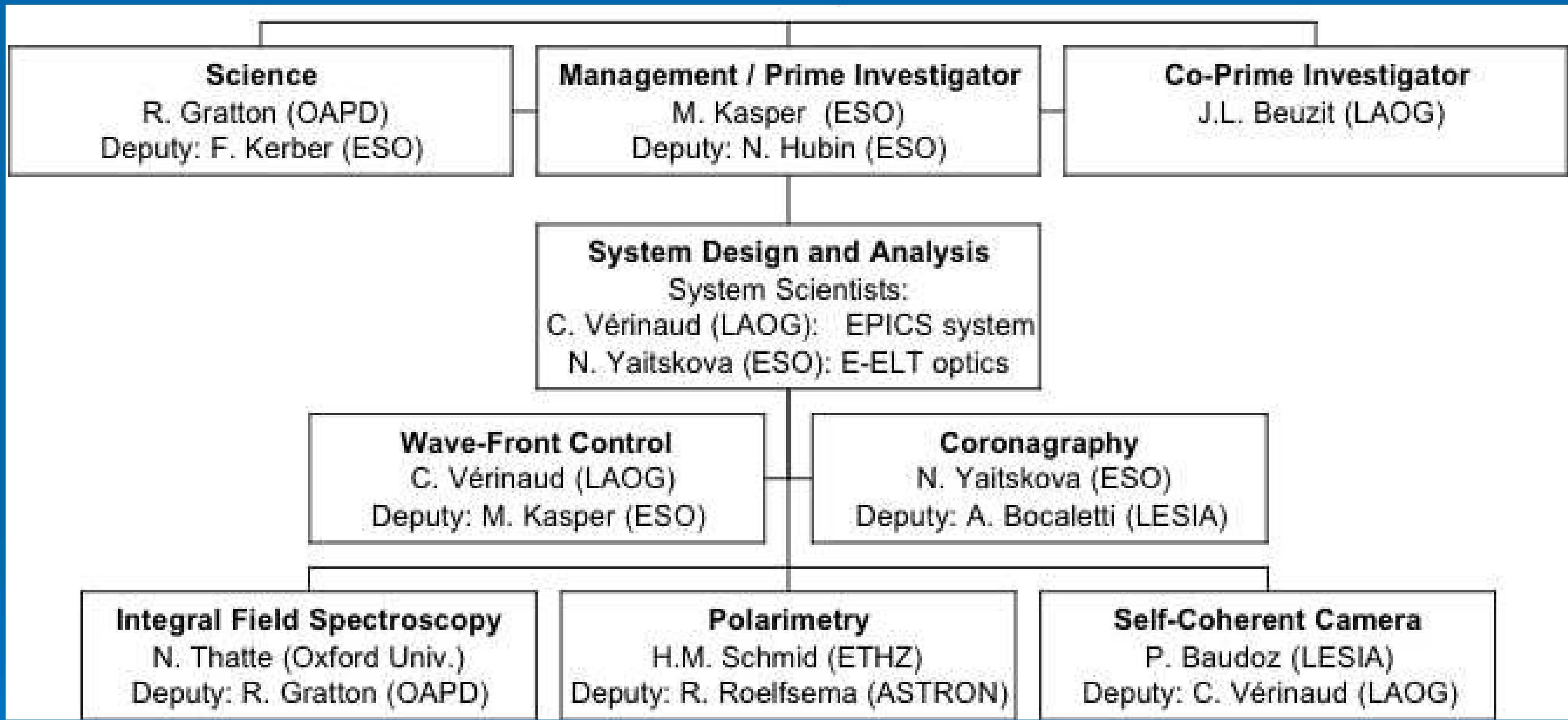
| Target class | # targets | Self-luminous planets | Giant planets | Neptunes | Rocky planets |
|---|---|---|---|---|---|
| 1. Young stars | 688 | >100 | >100 | Dozens | Very few |
| 2. Nearby stars | 512 | Dozens | >100 | ~100 | Dozens |
| 3. Stars w. planets | ~100 | Some | >100 | A Dozen | 2+ |

# Summary

- EPICS is the NIR E-ELT instrument for Exoplanet research using a “standard” high contrast imaging approach.
- Phase-A to study concept, demonstrate feasibility by prototyping, provide feedback to E-ELT and come up with a development plan
- Conclusion of Phase-A in 2010 with E-ELT phase B
- Potential to exploit the E-ELT capabilities in order to greatly advance and provide unique contribution to Exoplanet research

END

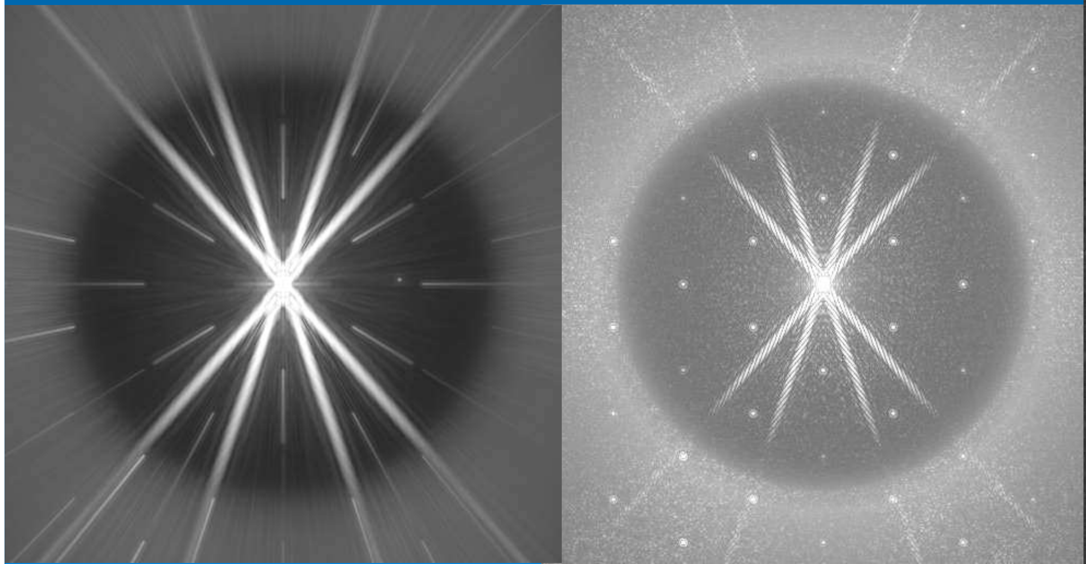
# EPICS organigram

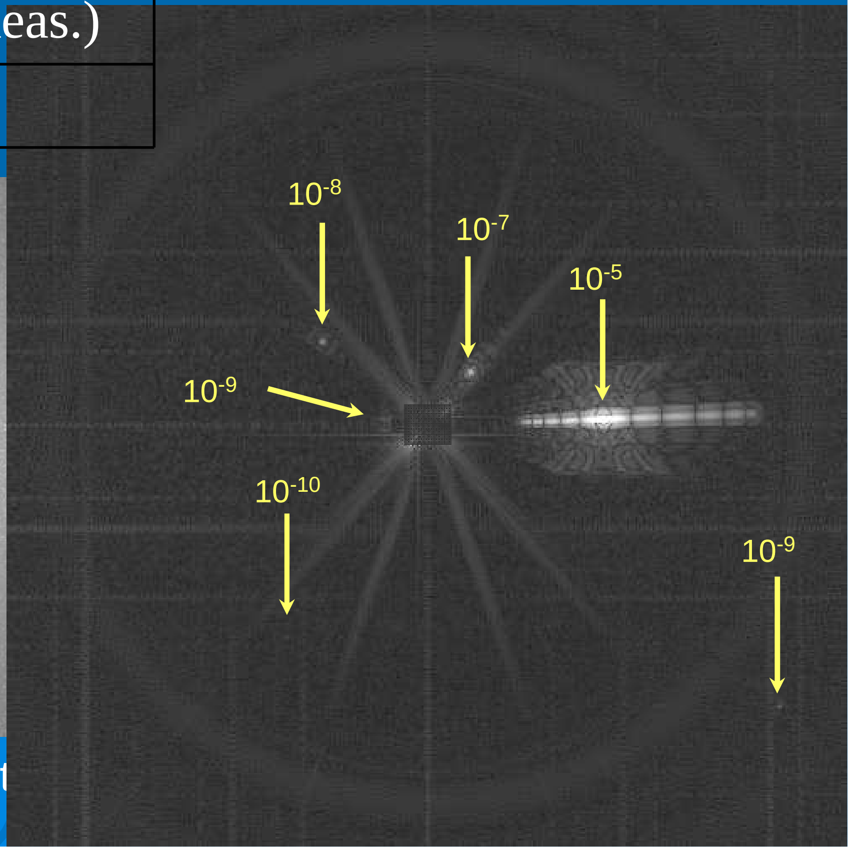


# SD test, no photon noise

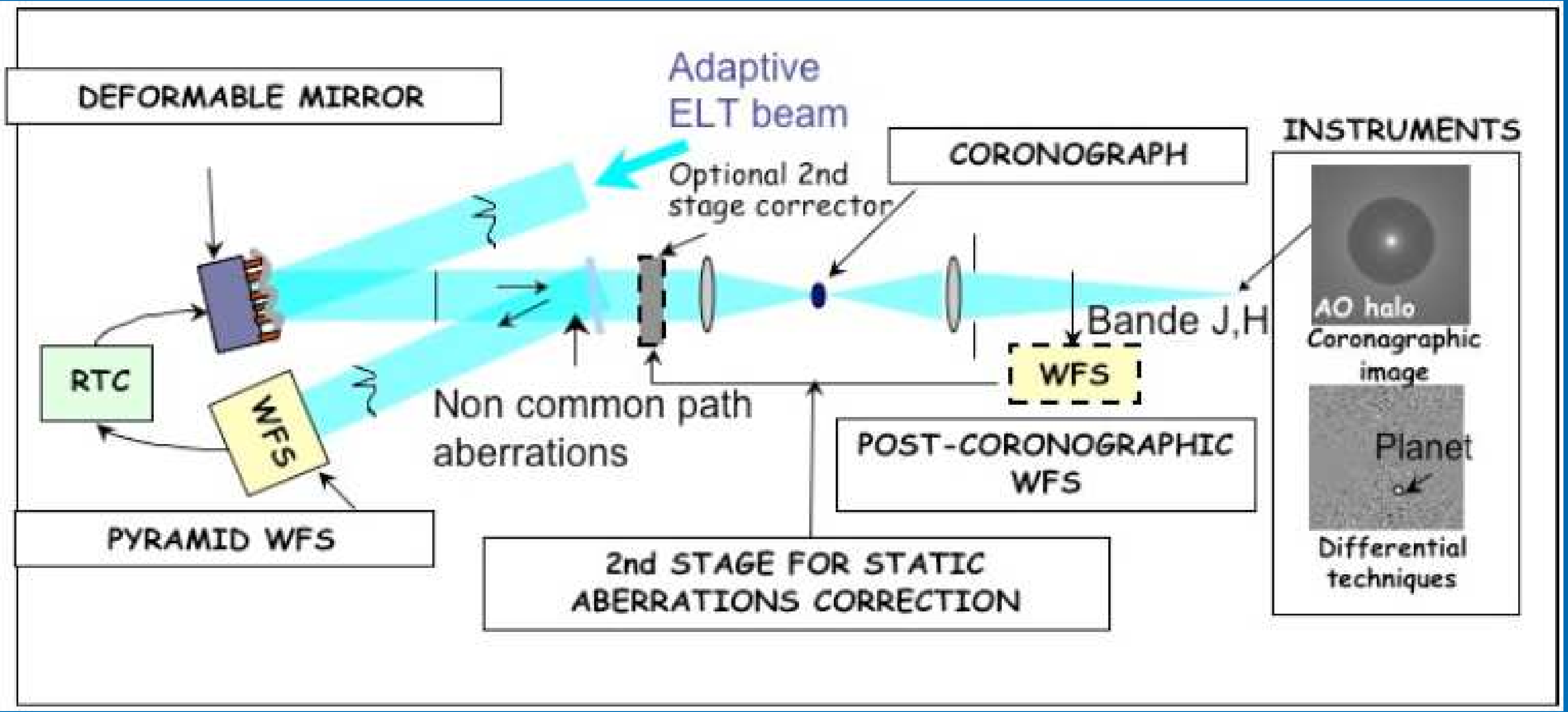
| Error source | Nominal values |
|---|---|
| Seg. Piston and tip-tilt | 90-nm rms |
| Seg. Mis-figure | 30-nm rms |
| EELT 5 mirrors HF | sqrt(5) *20 nm rms |
| XAO static in band | 5-nm rms ($f^0$, phase meas.) |
| Reflectivity dispersion | 1% rms |

PSF residuals reduced by >$10^3$





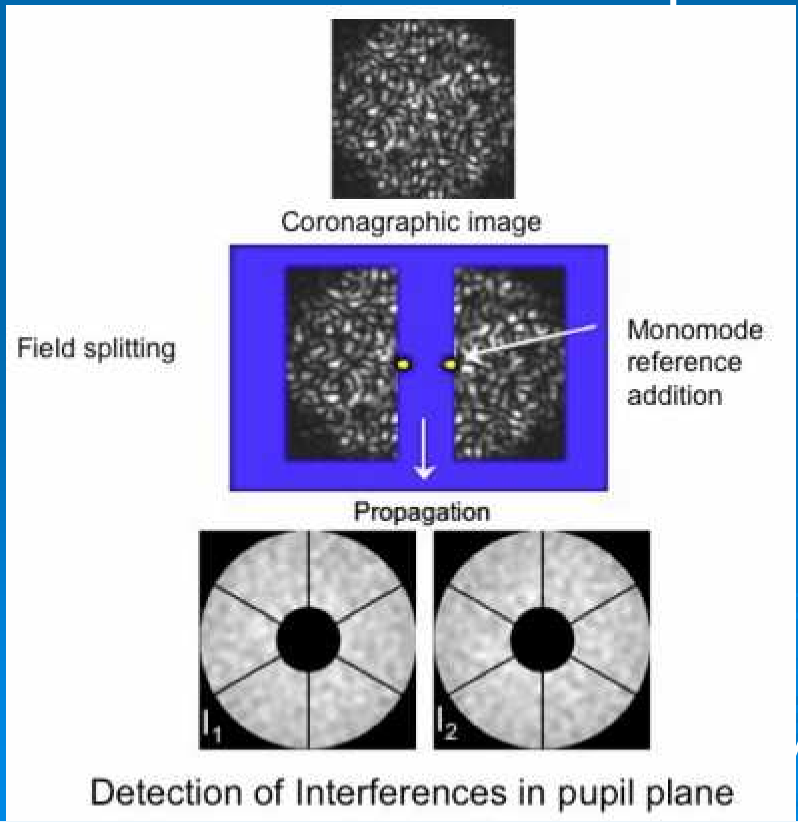
# EPICS concept



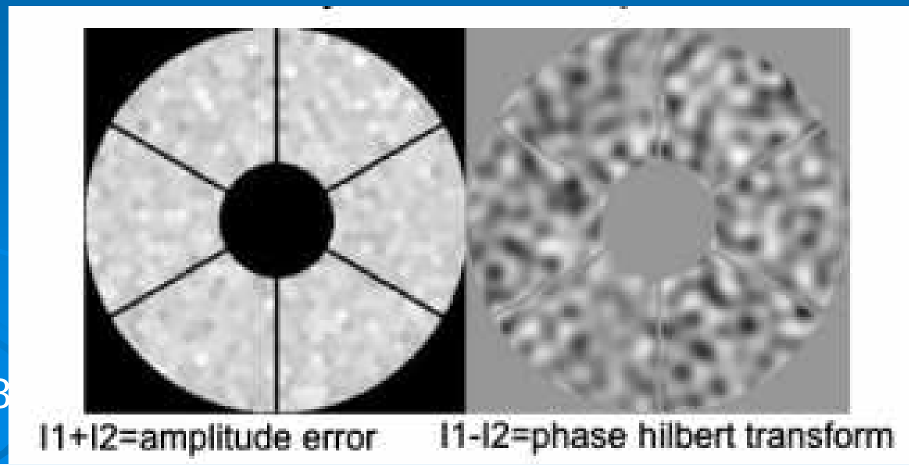

- “Traditional” concept
- Active control of quasi-static aberrations with FPWS

# Focal Plane Wavefront Sensor

- Measure quasi-static WFE at scientific wavelength
- Expected to measure WFE at a precision of some nm rms
- Correct with either WFS offsets or 2nd DM
- Residual 2nd order speckle level of $<10^{-6}$

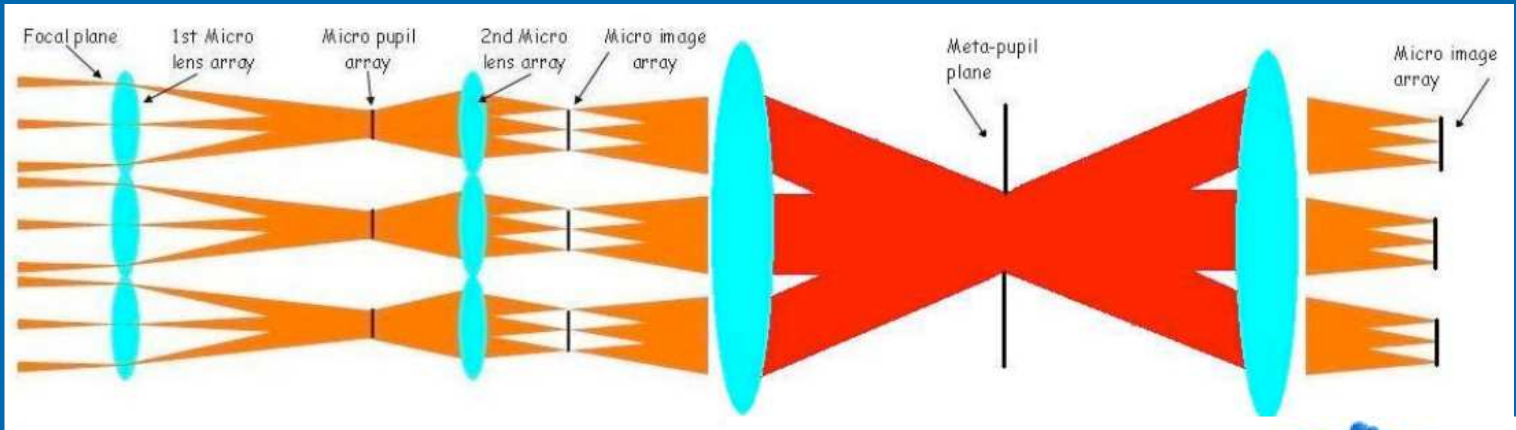



**Prototype at LAOG supported by FP7**
**See Verinaud et al. in about one hour**



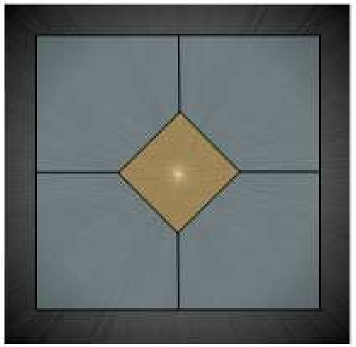
# Integral field spectrograph

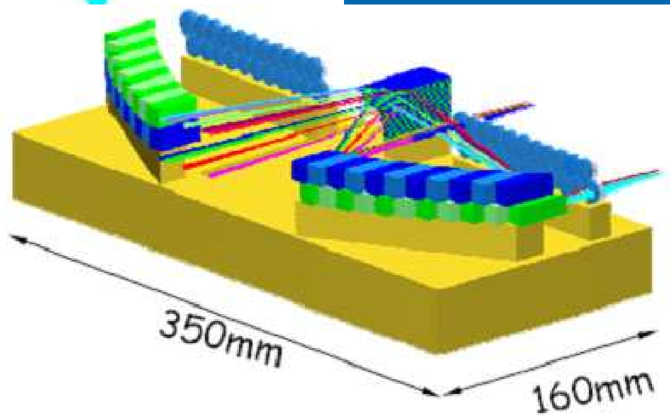
## Yes of course, but which type?




Analysis and experiments in the frame of FP7 to study lenslet and slicer based IFS aspects:

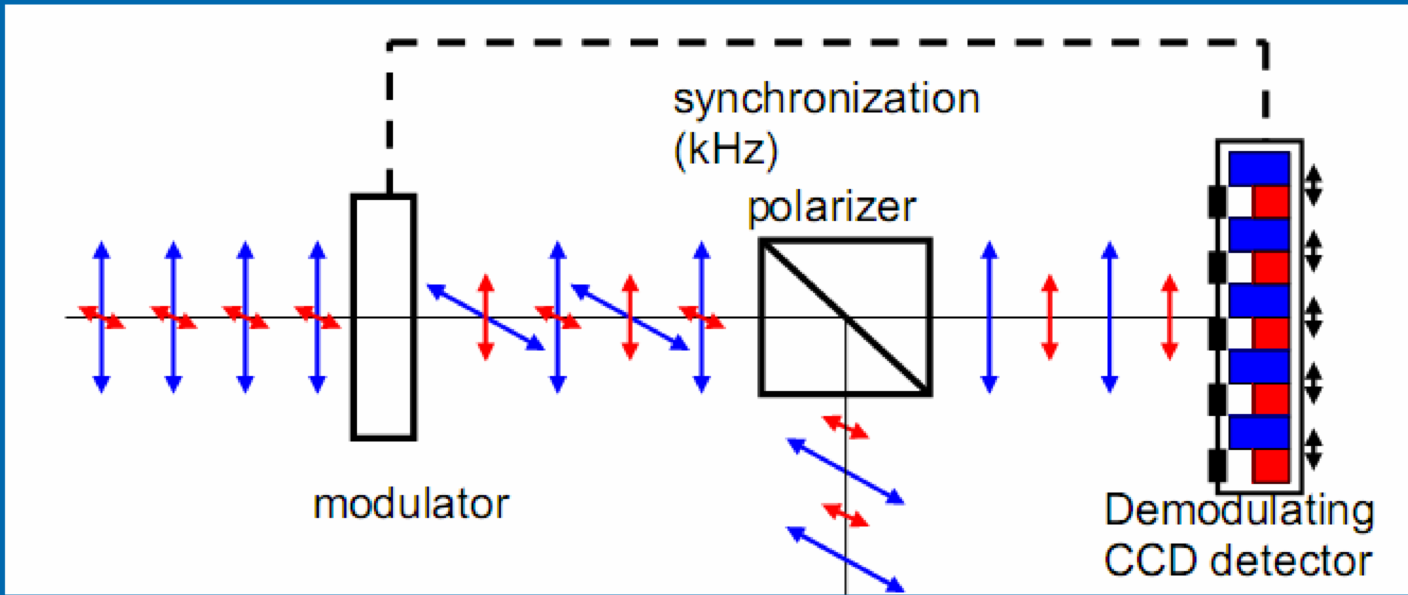
- Liability to IFS optics WFE
- Cross-talk
- Sampling and detector usage






EPICS concept may finally involve both types covering different FoV

# E-POL



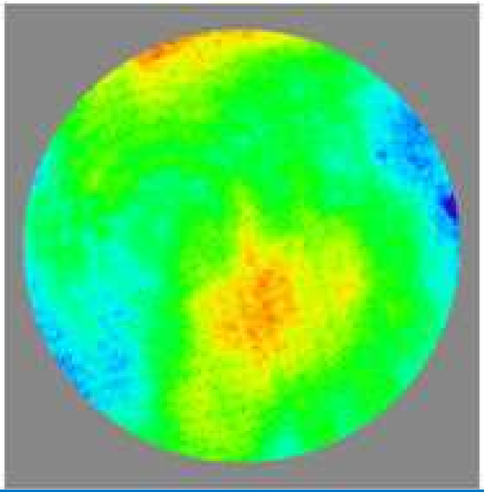

Convert polarization into intensity measure obtained on identical CCD pixels

- No flat field issues
- No chromatic effect
- differential aberration only from modulator and possibly birefringent components, calibrated to some extent by HWP and ADI
- Simultaneous detection with IFS tremendously reduces false-alarm probability

# Differential aberration requirements

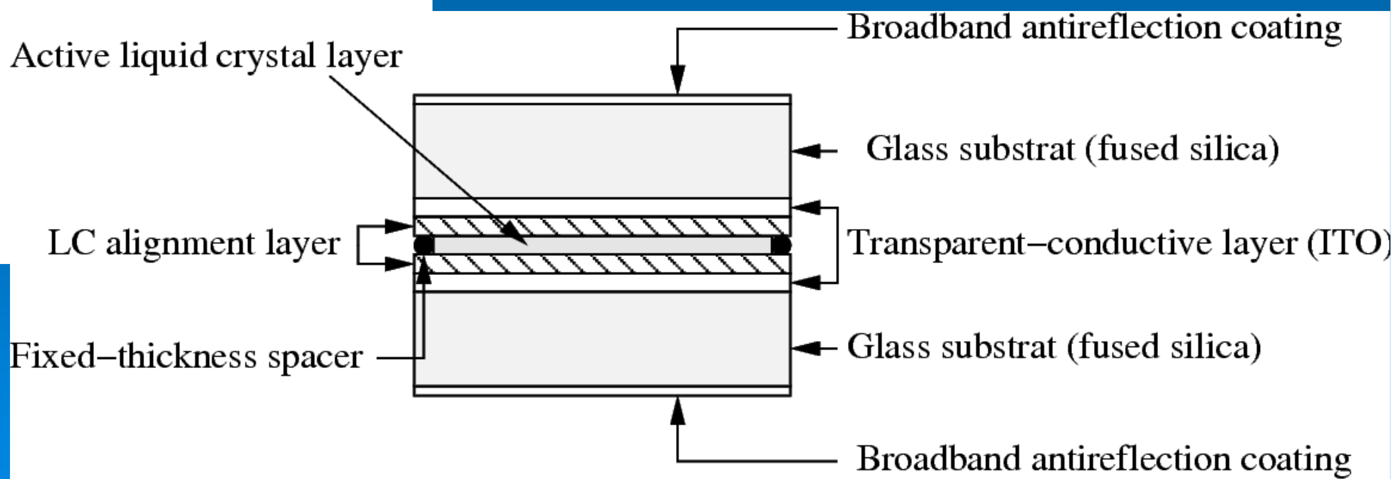
- A priori differential speckles are not compensated by DM and not calibrated by data reduction ⇒ stringent WFE requirements for optics
- Differential speckles connect to features of the residual coronagraphic PSF and are proportional to those in intensity
- The dominant such feature is usually the coronagraphic PSF core (typical level $10^{-3}$)

**⇒ sub nm differential WFE required to reach $10^{-9}$**



| OPD | microns |
|---|---|
| PV_Range | 0.0088 |
| RMS | 0.0011 |

Even better FLC modulator for prototyping and test on HOT in frame of FP7.



# Self Coherent Camera

## Further development supported by FP 7

see Baudoz et al, this conference

**Non-coherence between photons of the star and of the companion**