SPHERE / ZIMPOL
POLARIMETRIC CONCEPT AND CALIBRATION

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cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
Polarisation as a tool to study the Solar System and beyond
Action MP1104

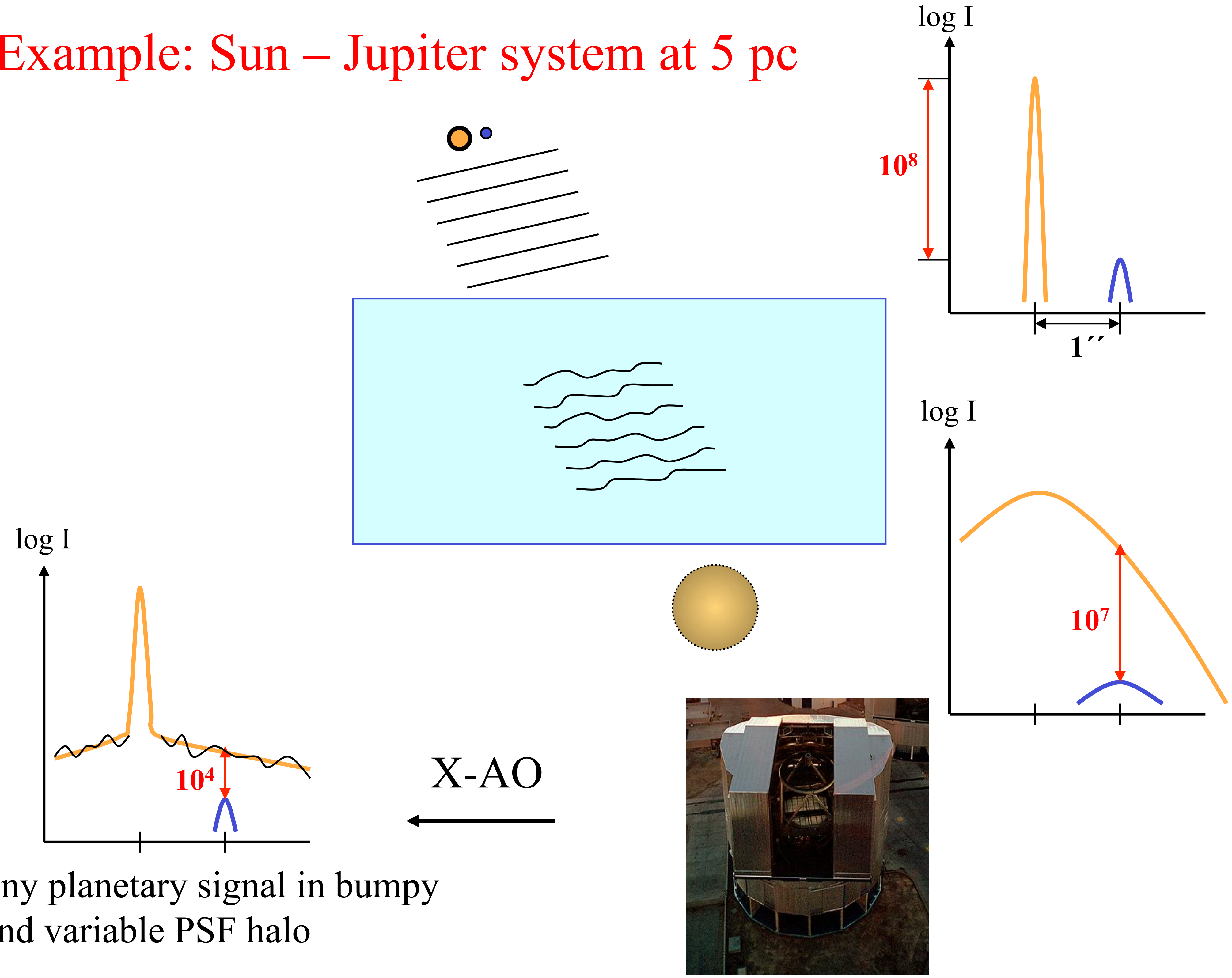
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Outline

1. High-contrast differential imaging
2. The SPHERE project
3. ZIMPOL
3. ZIMPOL/SPHERE CPI
4. Polarimetric calibration
5. Conclusions

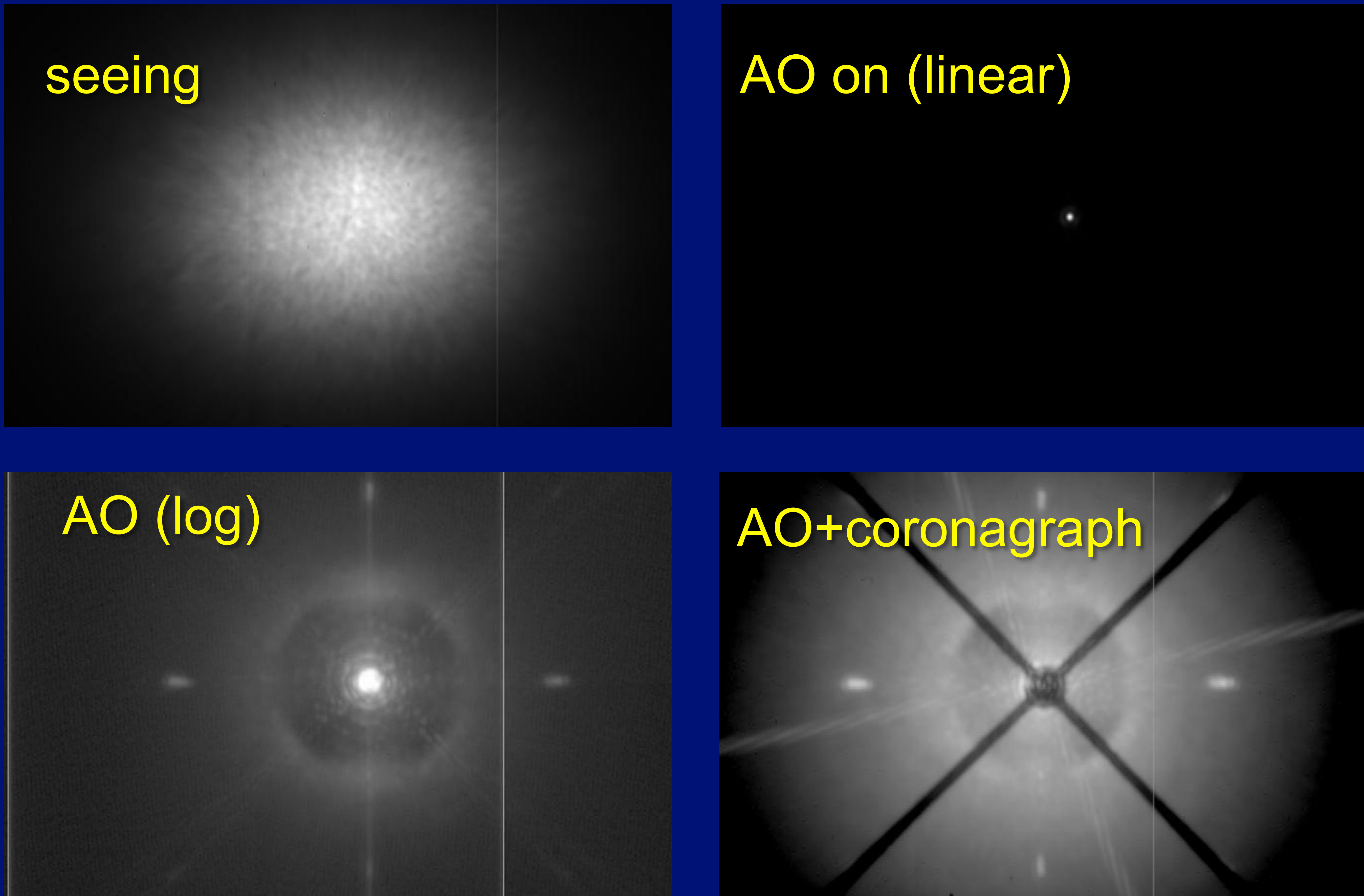
Adaptive optics

Example: Sun – Jupiter system at 5 pc



tiny planetary signal in bumpy and variable PSF halo

SPHERE PSF



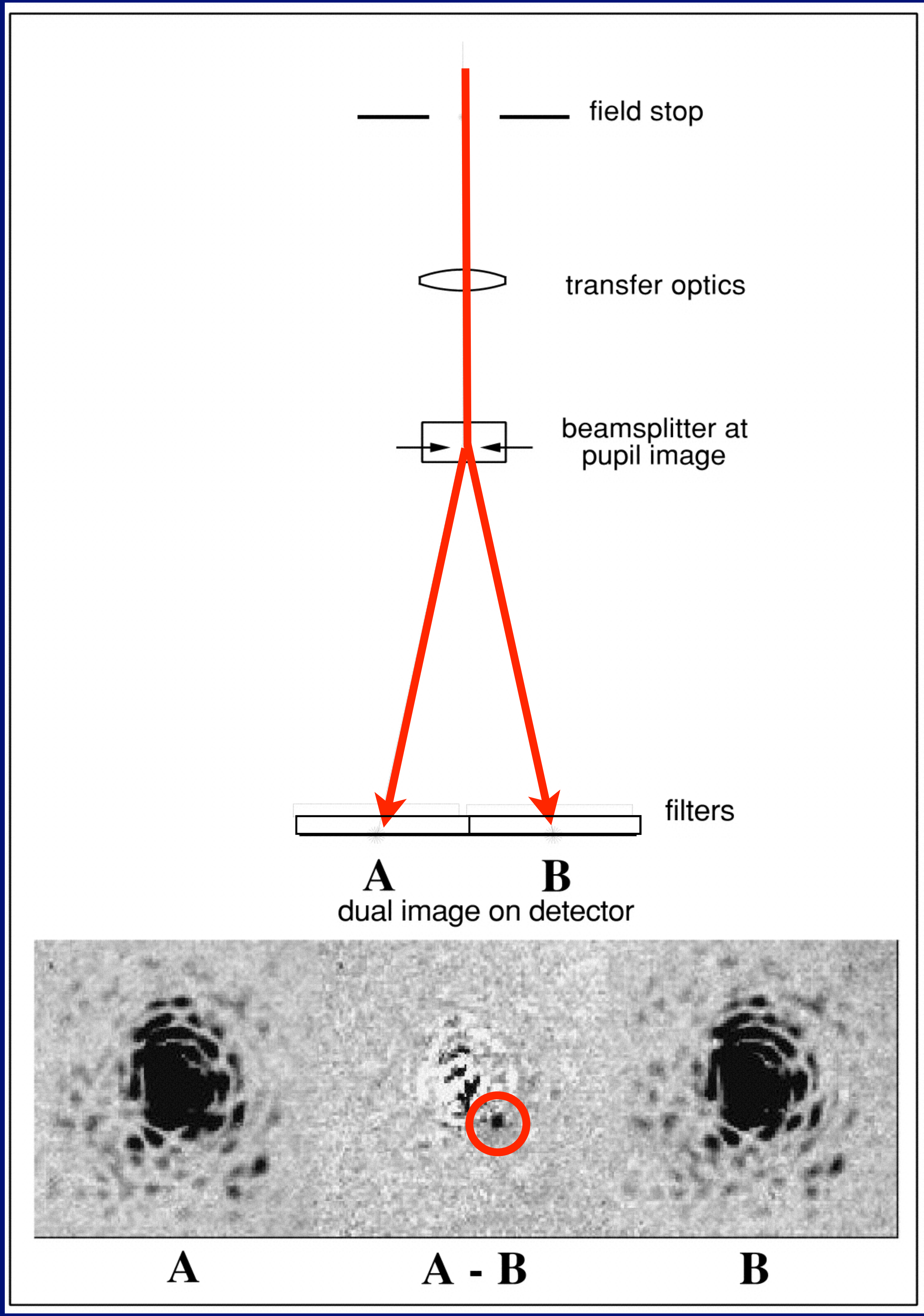
Differential imaging

Speckle noise can be removed with differential imaging

⟹ angular differential imaging (ADI)

⟹ spectral differential imaging (SDI)

⟹ polarimetric differential imaging (PDI)



From Racine et al. 1999

The SPHERE project

Spectro-Polarimetric High-contrast Exoplanet REsearch

Large european consortium

ESO 2nd generation VLT-instrument

Delivery to Paranal in late 2013 / first call for proposals in Sept. 2014

0.5 - 2.3 µm

high-contrast extreme-AO system

different coronagraphs

state of the art imagers, spectrographs, polarimeters

→ One of the most sensitive ground-based instruments for high-contrast imaging of extra-solar planets and circumstellar material around bright stars.

Polarimetry with SPHERE

ZIMPOL (Zurich Imaging Polarimeter)

- 3.5 x 3.5 arcsec FoV (detector) / 15 mas resolution at 600 nm
- 520-900 nm
- filters (two arms): broad R, I, ... ; narrow CH_4, KI, ...; line Hα, OI, ...
- Polarimetric sensitivity 10^{-5}

SPHERE

- extreme AO, (9^{mag} star), Strehl ~50% for 600-900 nm
- coronagraphy (Lyot coronagraphs, 4QPM)
- IRDIS: polarimetry in the 950 - 2300 nm range

→
- polarization contrast limit 10^{-8} for bright stars
- detect planets around nearby stars d < 5 pc
- characterize scattered light from circumstellar disks

SPHERE in Grenoble

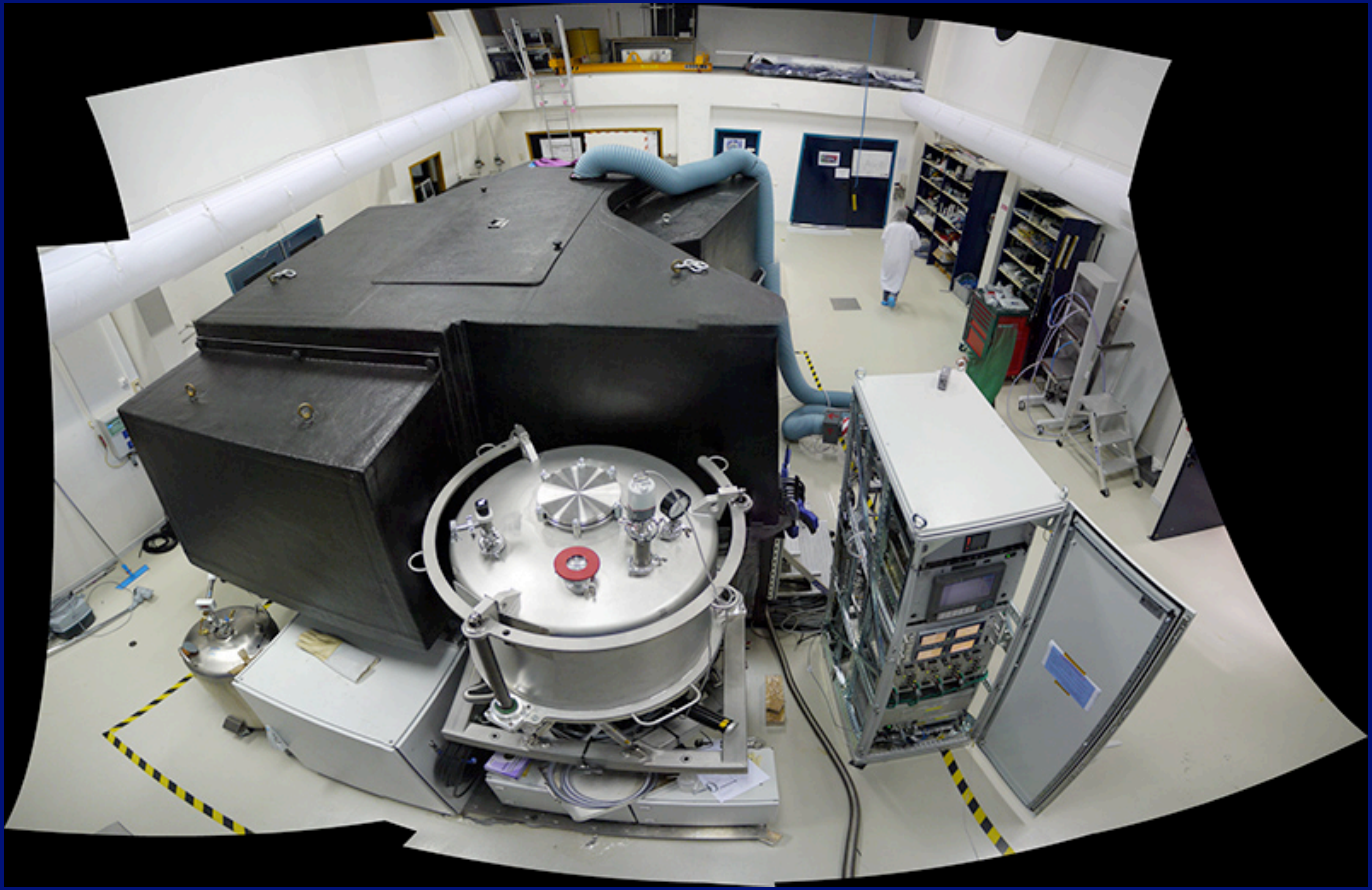
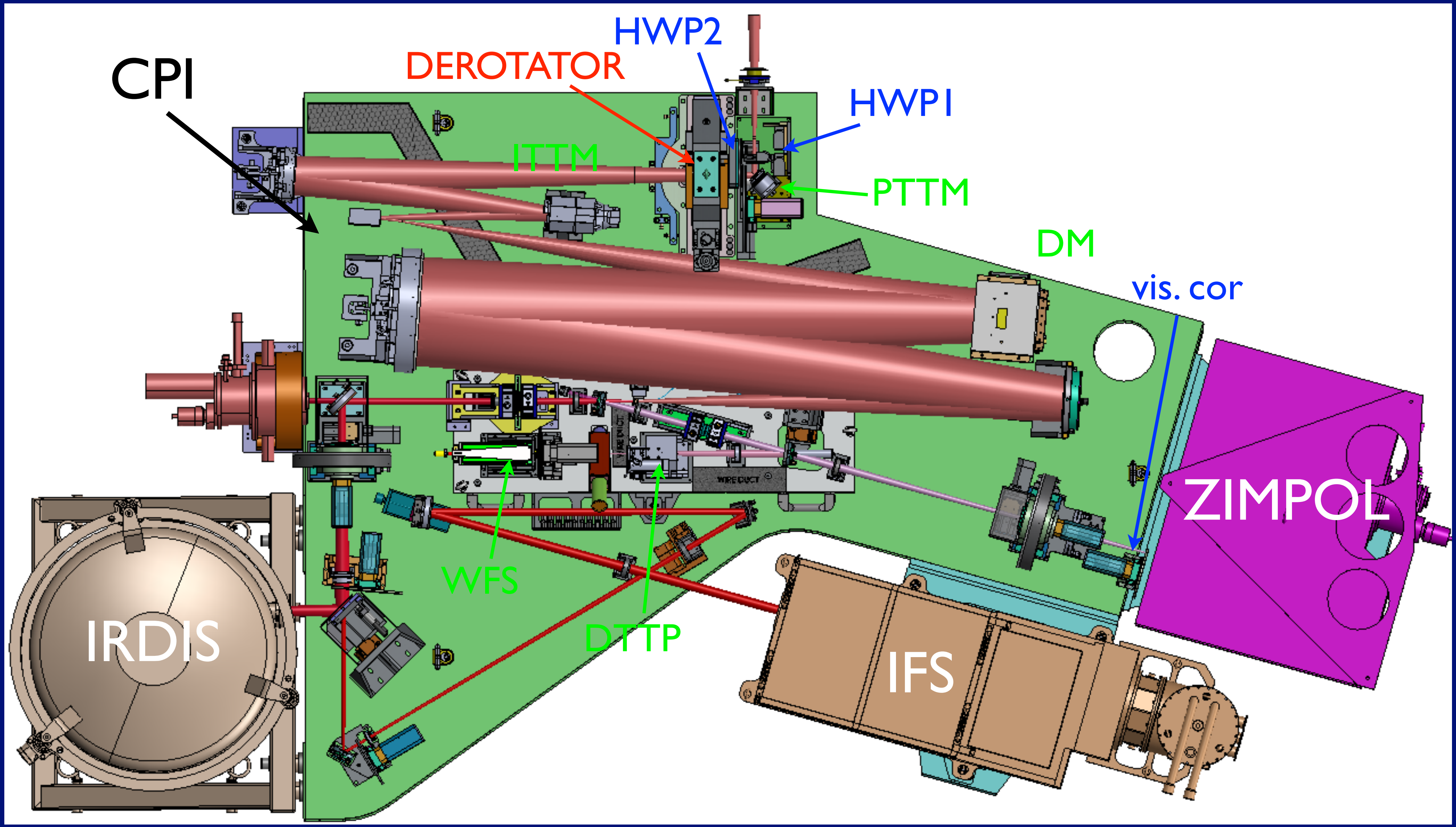


Photo courtesy J.-F. Sauvage and J.-L. Beuzit

Integration at Paranal

Nasmyth platform UT3

SPHERE instrument overview

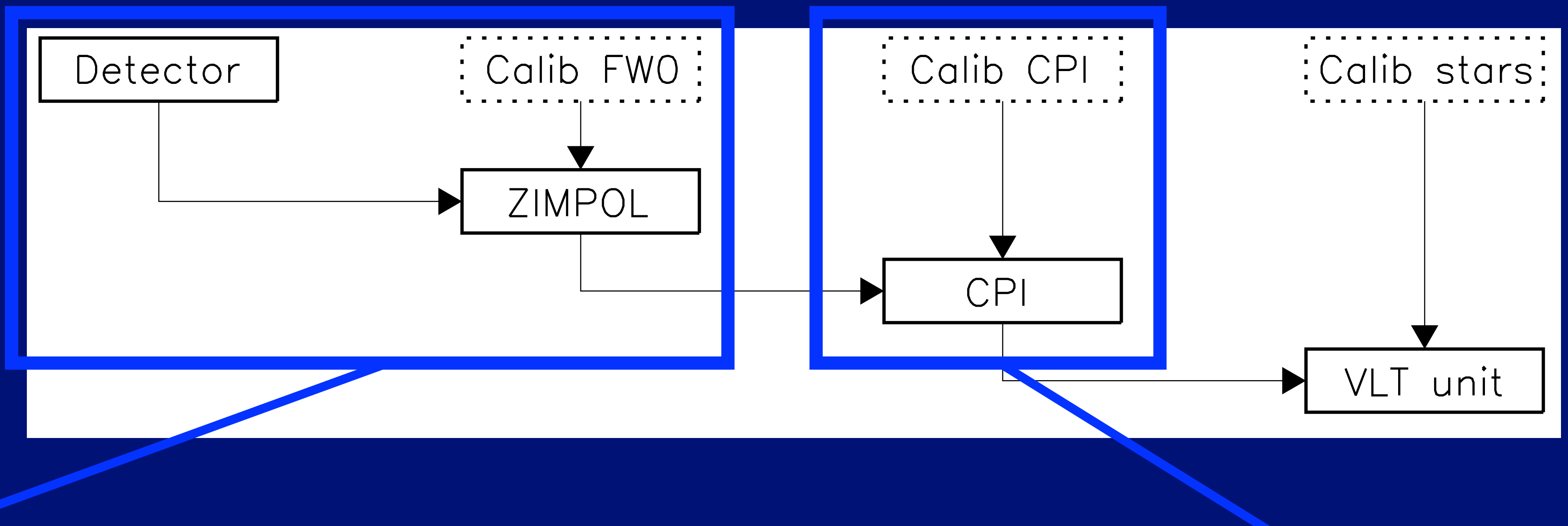


IRDIS Infra-Red Dualbeam Integral field spectrograph (950 - 2320 nm)

IFS Integral Field Spectrograph (950 - 1650 nm)

ZIMPOL Zurich IMaging POLarimeter (520 - 900 nm)

Step-by-step calibration



ZIMPOL calibration

Two-phase demodulation

Charge traps

Modulation/demodulation efficiency

- Synchronization effects
- Static charge and light leakage
- Wavelength dependence of HWPs
- Wavelength dependence of FLC modulator package

CPI calibration

Telescope polarization

Derotator cross-talks

Compensation of Derotator polarization

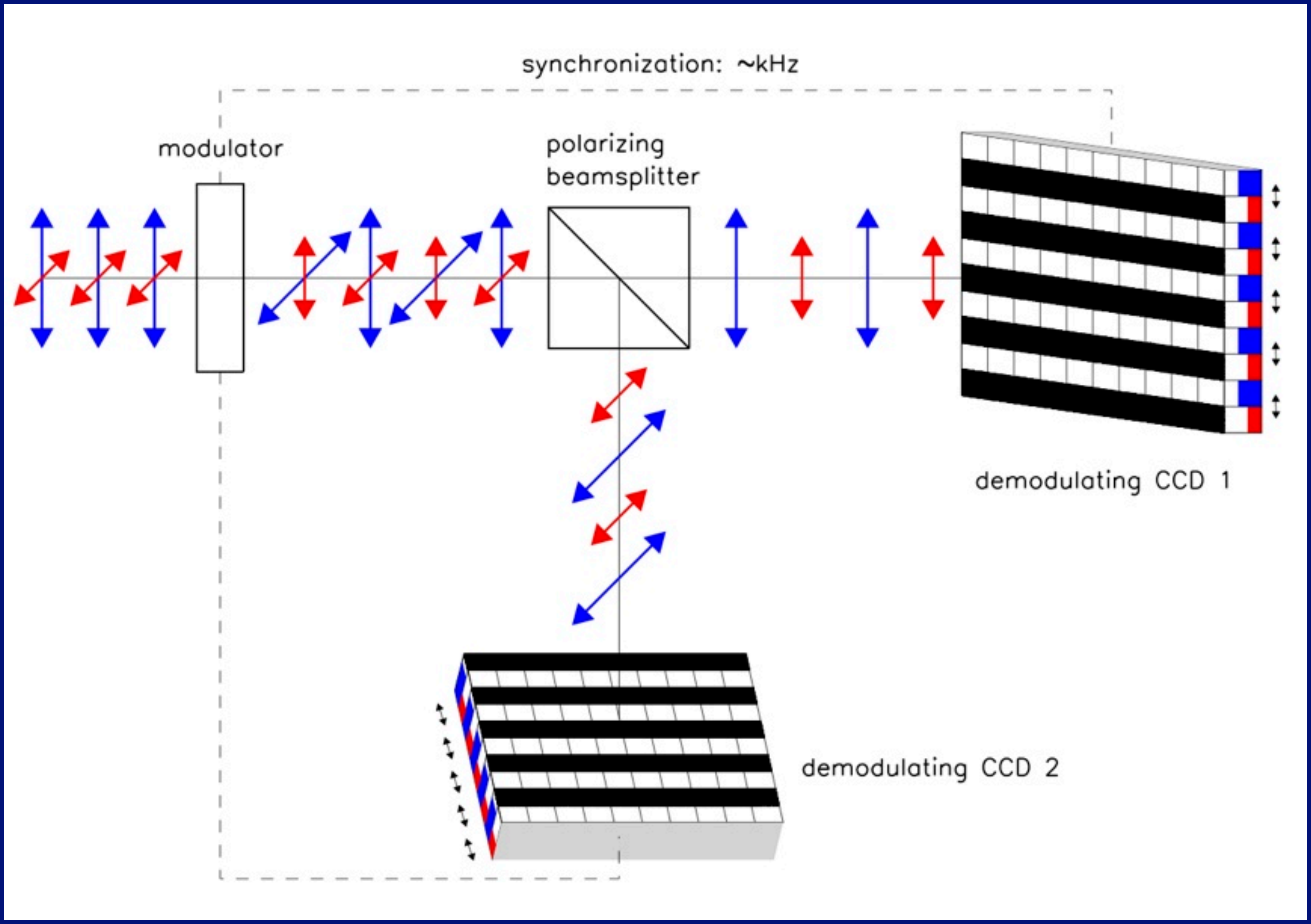
HWP2 polarization switch

(polarimetric beam shift effect)

The ZIMPOL principle

Fast polarization modulation-demodulation using charge-shifting on a masked CCD detector

(Povel 1990 et al., Povel 1995)



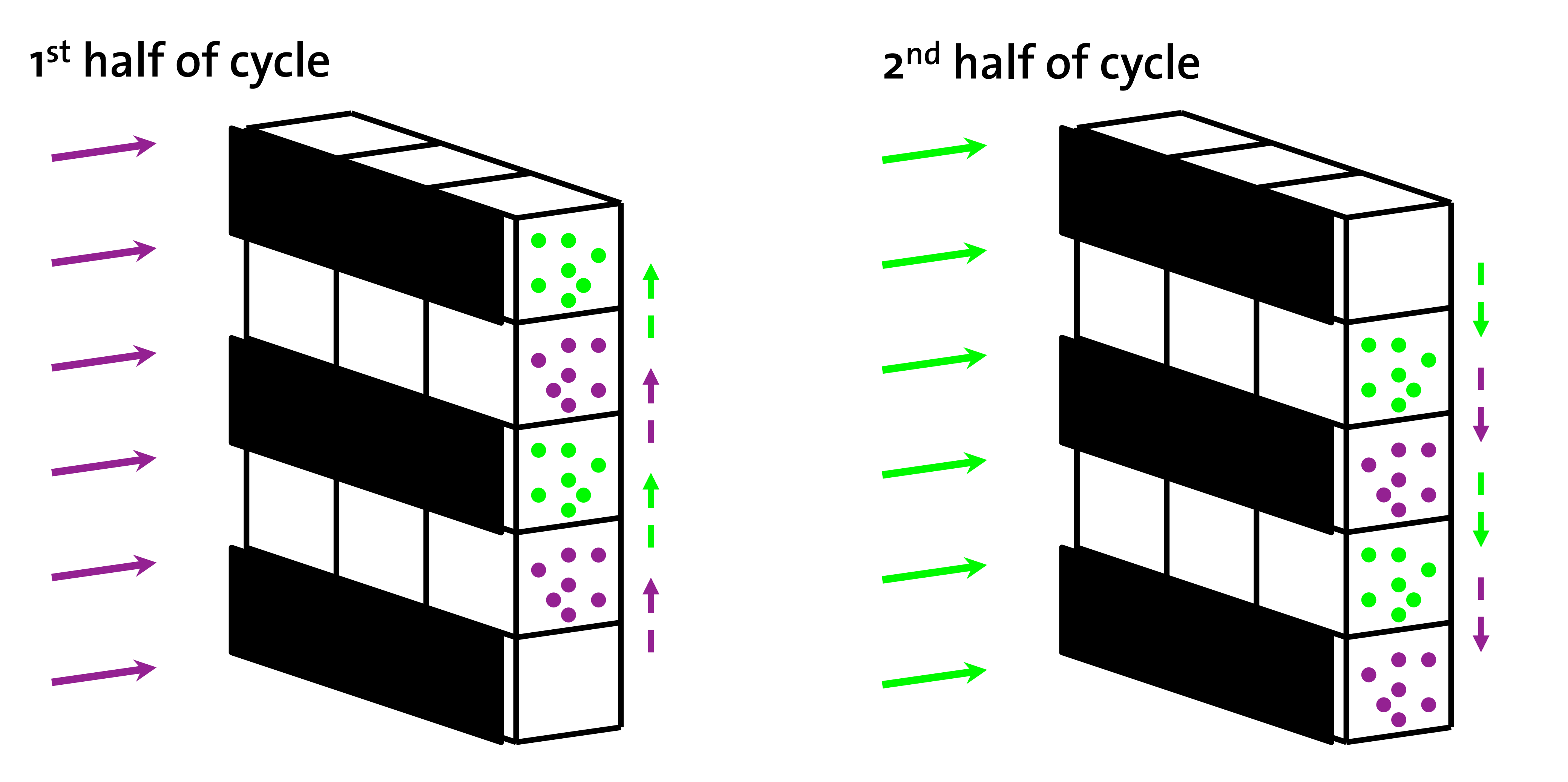
$I = I_0 + I_{90}$
$Q = I_0 - I_{90}$

both images are created simultaneously
⟹ modulation faster than seeing variation

both images recorded with the same pixels
⟹ minimal differential aberrations
⟹ no dependence on single pixel sensitivity

demodulation phase-switch
⟹ compensation of fixed-pattern-noise

Two-phase demodulation



1st exposure: start demodulation with shift up: $Q_1 = 0.5\,(I_\perp - I_{\parallel}) = 0.5\,(+Q + FPN^A) - (-Q + FPN^B))$

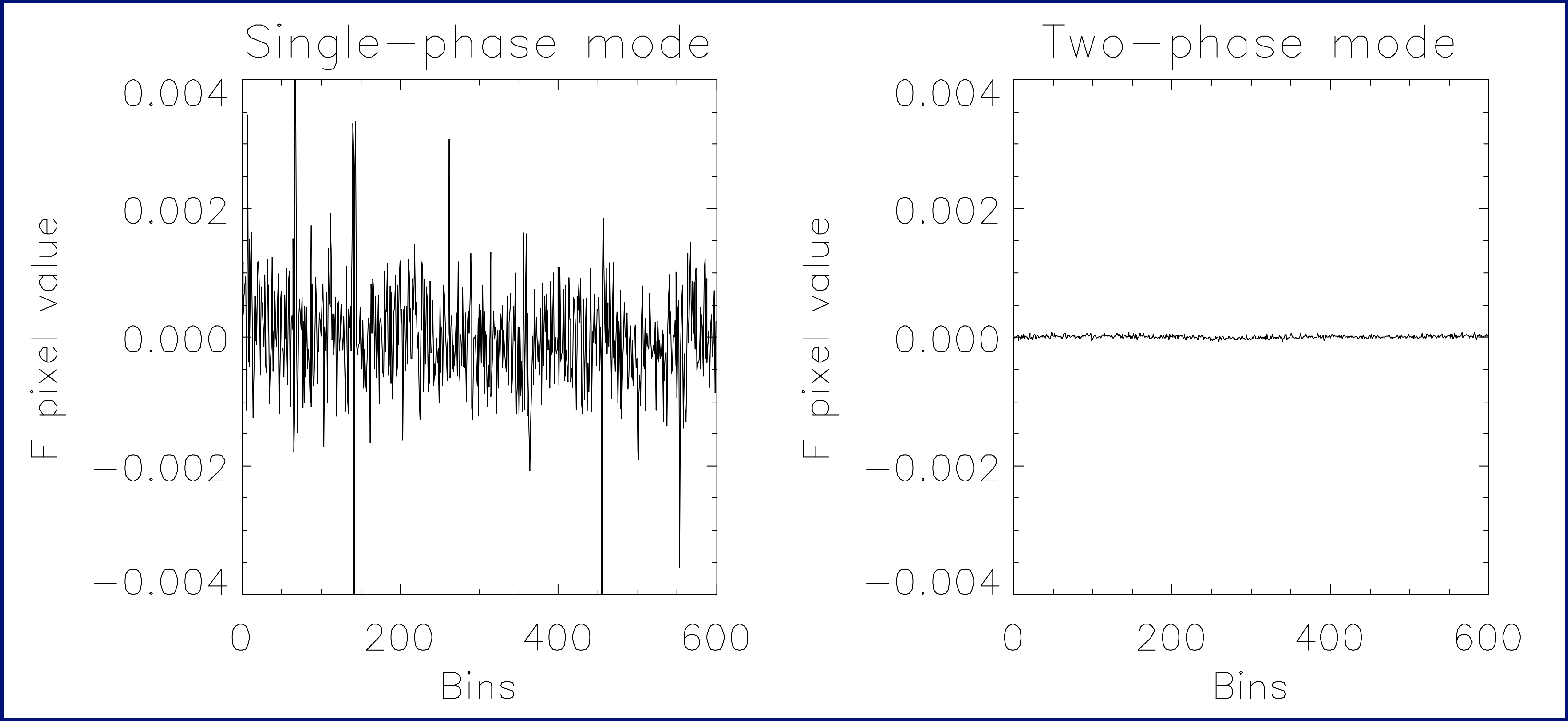
2nd exposure: start demodulation with shift down: $Q_2 = 0.5\,(I_{\parallel} - I_\perp) = 0.5\,(-Q + FPN^A) - (+Q + FPN^B))$

$$Q = Q_1 - Q_2 = I_\perp - I_{\parallel}$$

$\Longrightarrow$ effects due to different buffer pixels cancel out!

Fixed pattern noise

Pixel to pixel fixed pattern noise of σ = 0.04 %



Buffer pixels are not identical for both polarization images

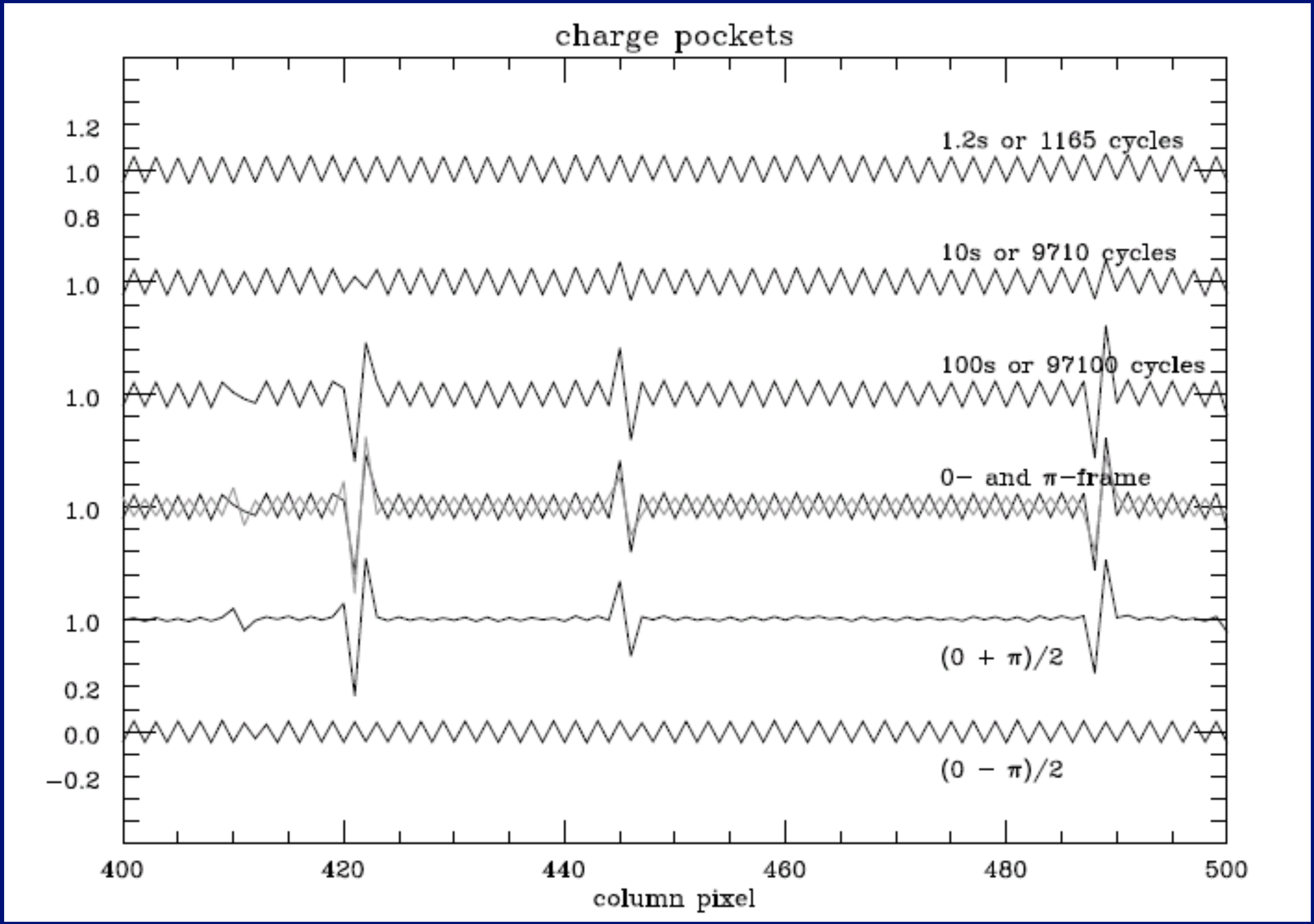
⟹ pixel to pixel cross-talk

⟹ stray light

⟹ charge transfer efficiency / charge pockets

Charge traps

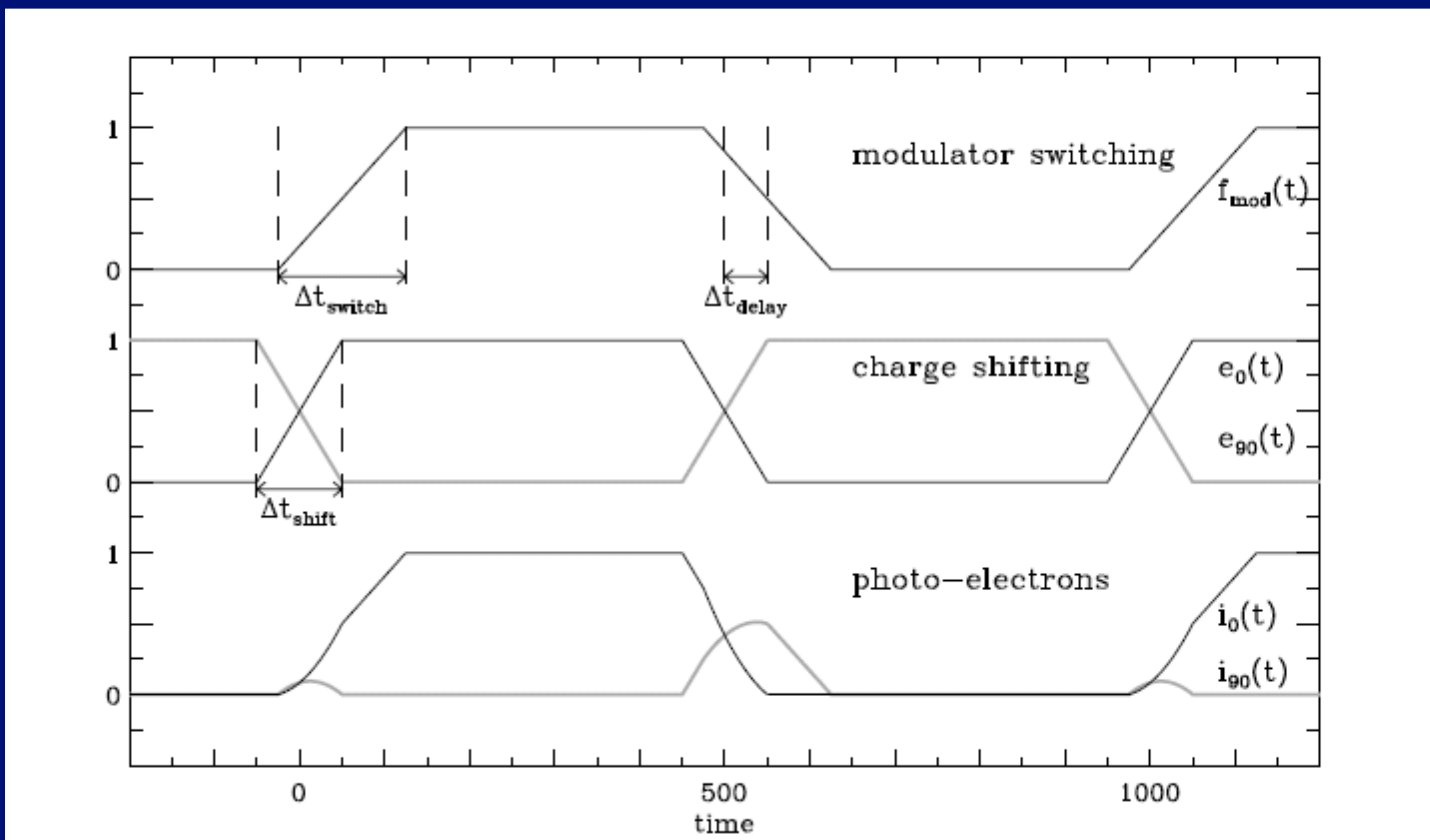
strong pocket pumping due to up and down shift



Two-phase mode ⟹ effects cancels out!

Synchronization errors

- ⟹ finite time for polarimetric modulation / demodulation (75 μs / 55 μs)
- ⟹ time delay between modulation / demodulation
- ⟹ depends on polarimetric mode (modulation frequency)



$\varepsilon_{time} = |I_0 - I_{90}| \, / \, (I_0 + I_{90})$

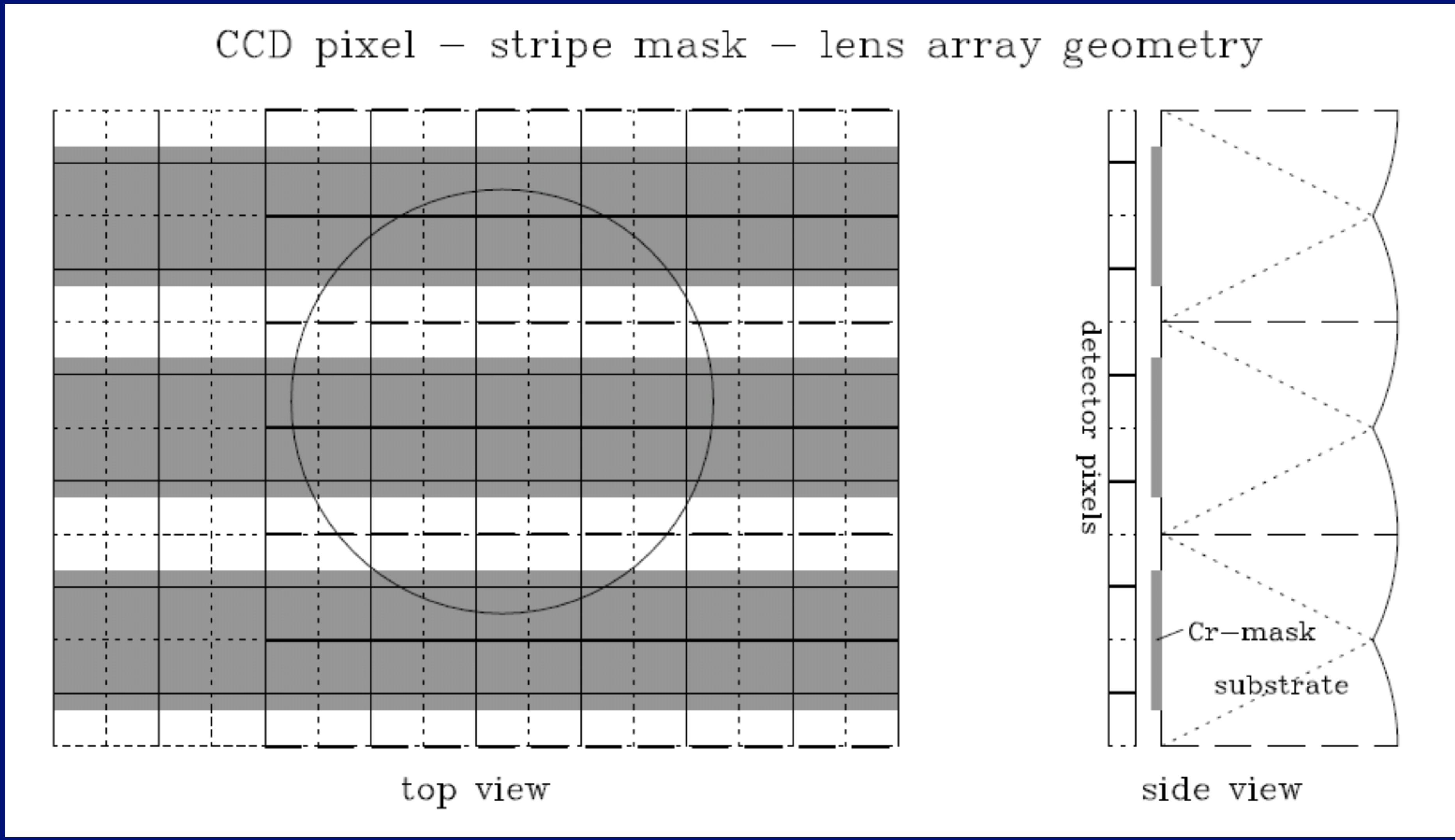
$\varepsilon_{time} \sim \Delta t / t_{cycle}$

⟹ $\varepsilon_{time,slowpol} \approx 1$ (>0.99)

⟹ $\varepsilon_{time,fastpol} = 0.927$

Static charge and light leakage

⟹ light pollution = photo-electrons produced in covered rows
⟹ charge diffusion (especially for short wavelength photons)
⟹ large overlap of the occulting mask reduces both effects



$L = I_{cov} / I_{open}$

	CCD1	CCD2
V	4.4%	5.1%
R	3.3%	3.7%
I	2.6%	3.0%

$\varepsilon_{mask} = (I_{open} - I_{cov}) / (I_{open} + I_{cov})$

⟹ $\varepsilon_{mask} \approx 0.95$ (L=2.5%)

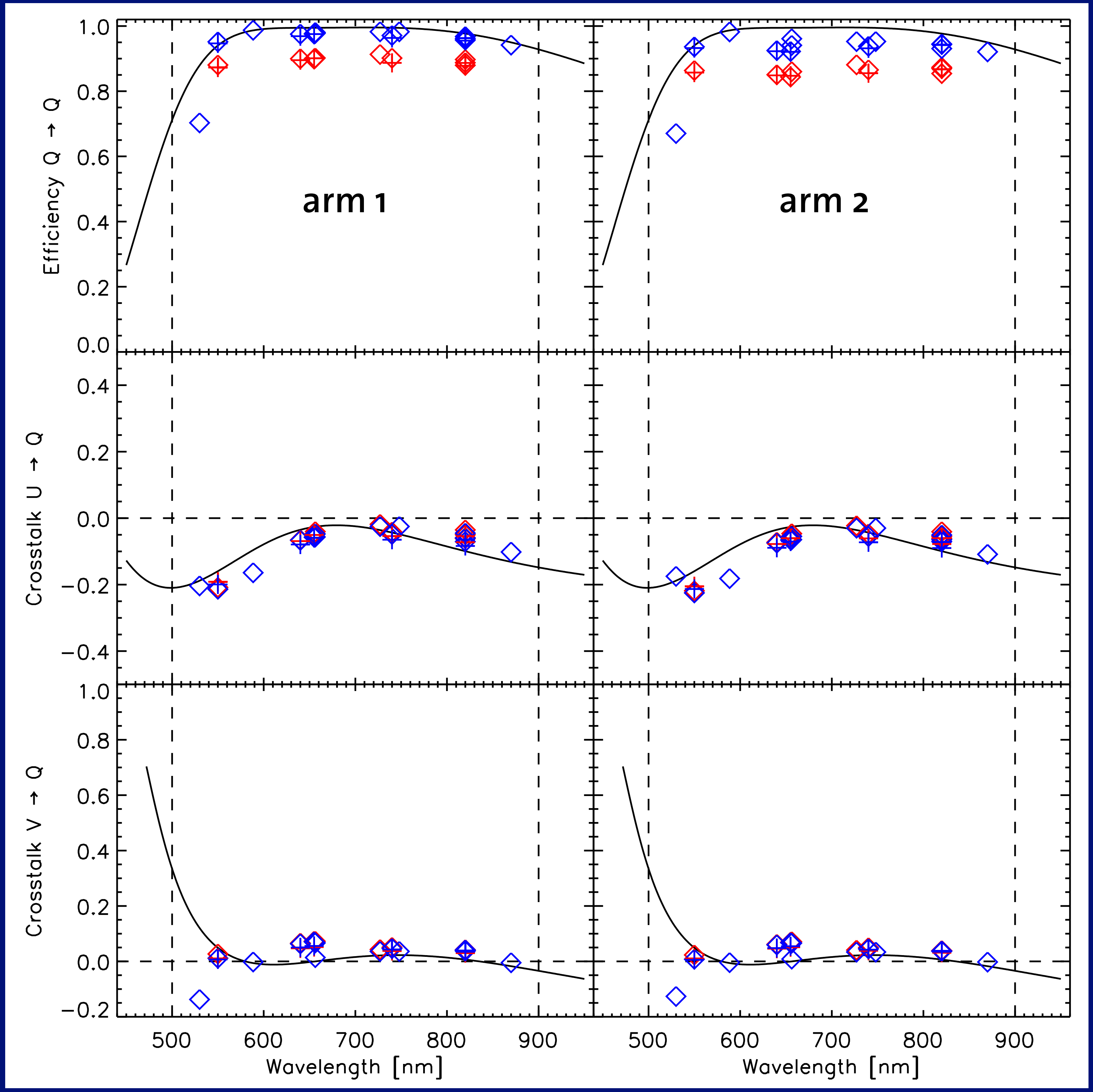
FLC modulator package

ferro-electric liquid crystal modulator

FLC retardance ~ 0.5 λ_0/λ
$\Longrightarrow$ similar to zero-order HWP

„achromatic FLC“:
$\Longrightarrow$ combine 0-HWP with FLC

	FLC	0-HWP
Switch angle	45.8° ± 0.5°	-
Switch time	75 µs	-
Design wavelength	662.3 nm	689.5 nm
T operation range	25°C	0-15°C
Position angle fast axis	-26.3°	64.4°



BEAMSPLITTER leakage $\Longrightarrow$ reduced polarization in arm2

transmitted beam: fully polarized (>99.9%)
reflected beam: 1-3% light from opposite channel

Modulation/Demodulation Efficiency

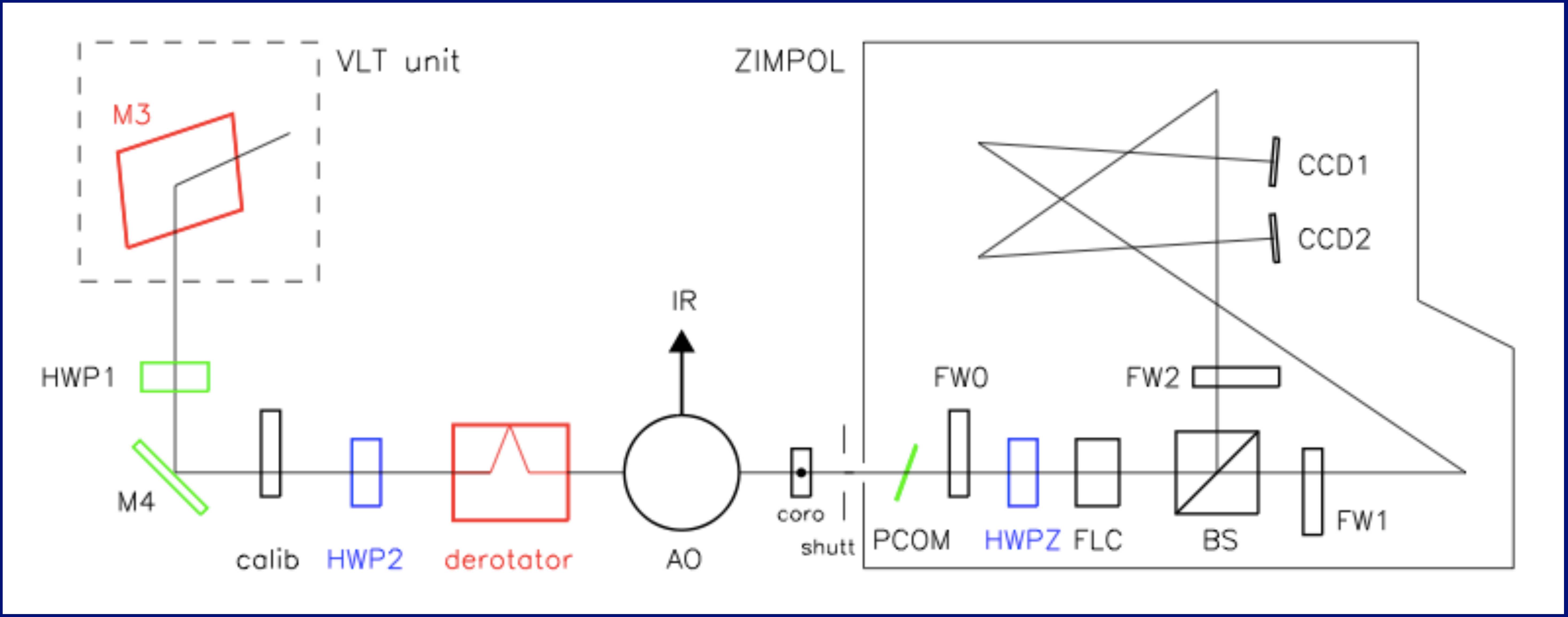
$$(Q/I)_m \longrightarrow (Q/I)_0$$

$$\varepsilon_{MoDem} = \varepsilon_{time} \cdot \varepsilon_{mask} \cdot \varepsilon_{FLC}$$

$$\varepsilon_{MoDem}(\lambda,\vec{x}) \approx 0.80 \quad \text{(fast polarimetry)}$$

$$\varepsilon_{MoDem}(\lambda,\vec{x}) \approx 0.90 \quad \text{(slow polarimetry)}$$

ZIMPOL/SPHERE instrument overview

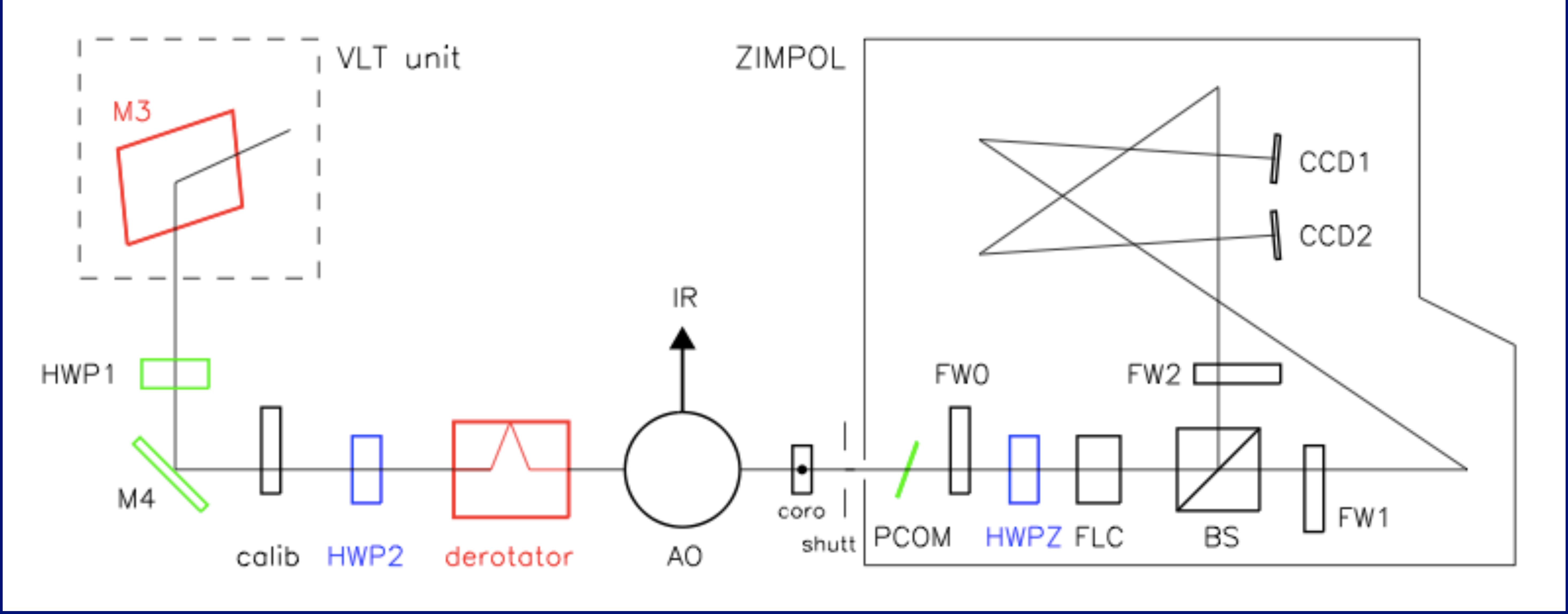


ZIMPOL achieves a high precision only if polarization is less than 1%

$\Longrightarrow$ required:

p (tel. + sky) < 0.5 %
p (instr.) < 0.5 %
no polarization signal loss (Q,U → V cross-talks)

CPI calibration



red: components introducing substantial instrumental polarization (>1 %)

blue: rotate polarization into the derotator system and back into the ZIMPOL system

green: components which compensate instrumental polarization

Telescope polarization

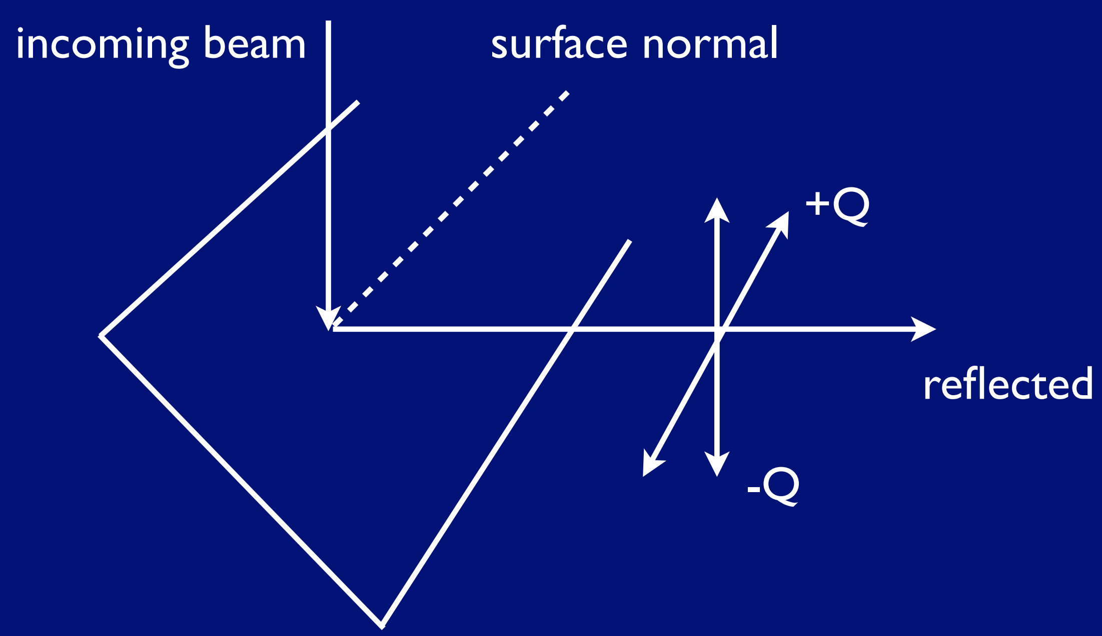
M3 produces ~5 % polarization

polarization only in +Q direction (perp. to scattering plane)
⟹ compensation by „crossed mirror" M4

polarization direction moves with zenith angle (M_3 rotation)
⟹ use HWP1 to stabilize polarization direction

$$\alpha_{HWP1} = 0.5\ \alpha_{zenith}$$

$$M_{tel} = M_{M4}\ M_{HWP1}\ M_{M3}$$



Mueller matrix for an inclined mirror

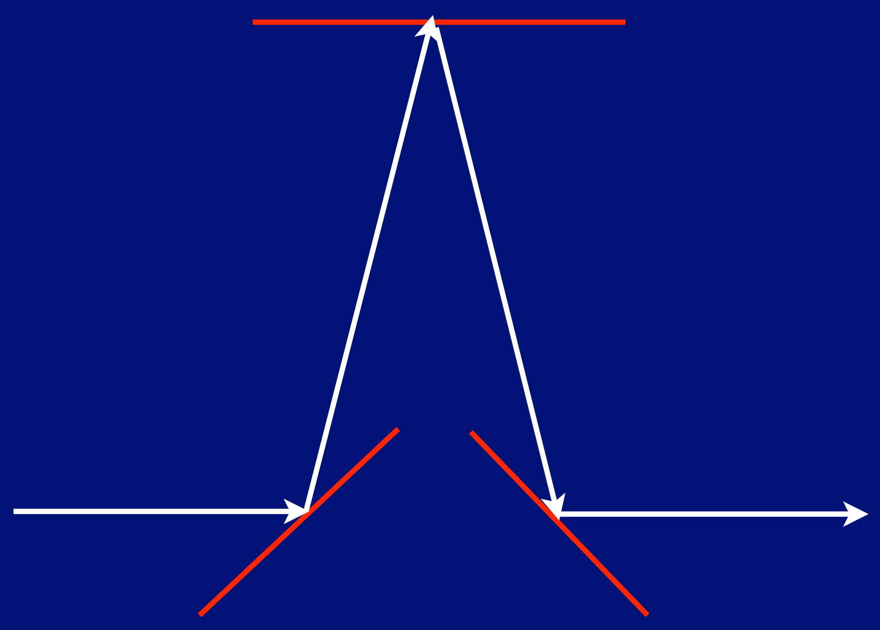
$$M = c \begin{pmatrix} I\rightarrow I & Q\rightarrow I & 0 & 0 \\ I\rightarrow Q & Q\rightarrow Q & 0 & 0 \\ 0 & 0 & U\rightarrow U & V\rightarrow U \\ 0 & 0 & U\rightarrow V & V\rightarrow V \end{pmatrix}$$

Derotator cross-talks

Derotator produces strong cross-talk U→V

Mueller matrix for an inclined mirror

$$M = c \begin{pmatrix} I\rightarrow I & Q\rightarrow I & 0 & 0 \\ I\rightarrow Q & Q\rightarrow Q & 0 & 0 \\ 0 & 0 & U\rightarrow U & V\rightarrow U \\ 0 & 0 & U\rightarrow V & V\rightarrow V \end{pmatrix}$$



⟹ selected polarization needs to be rotated into a direction parallel or perpendicular to derotator

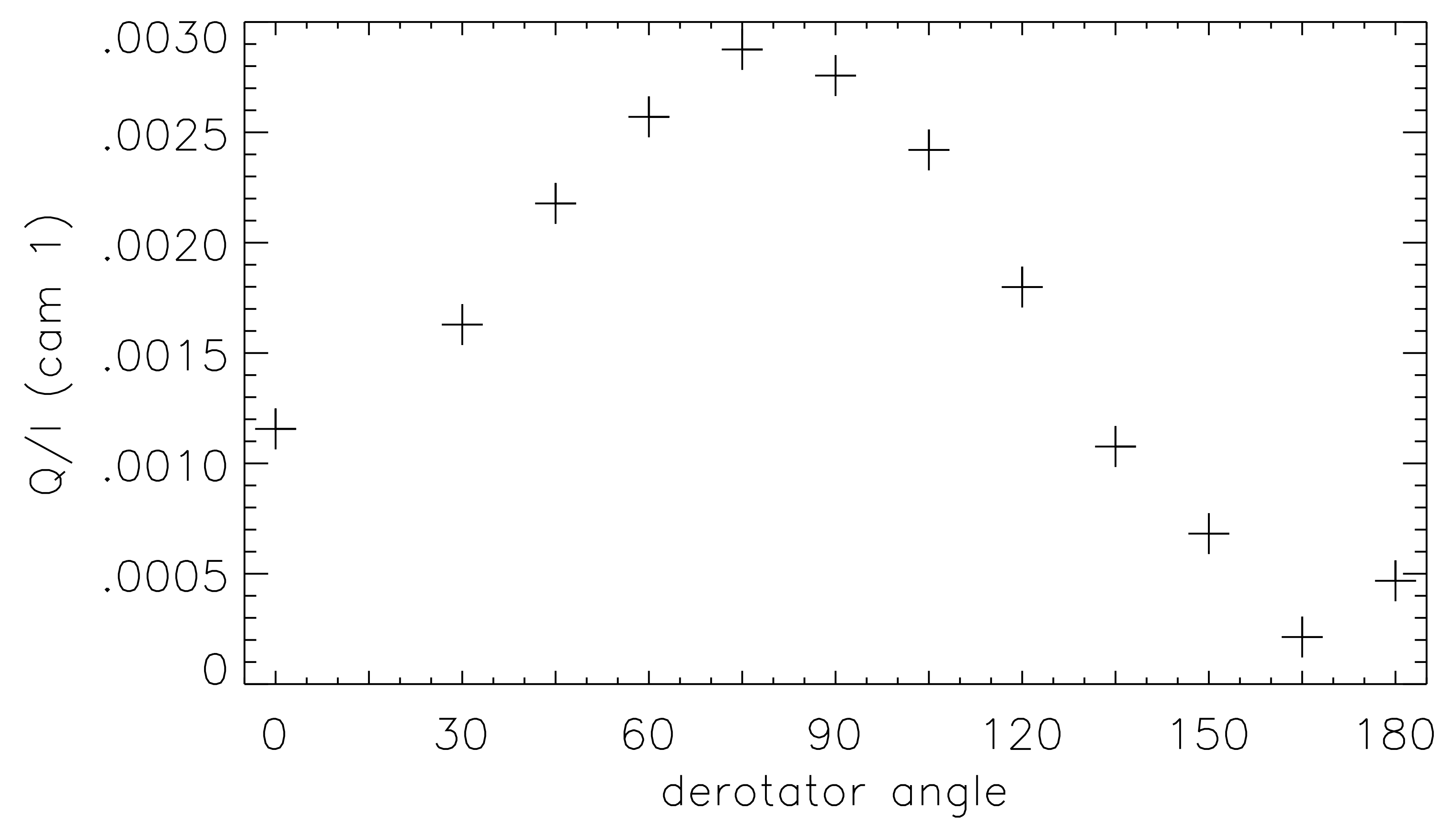
⟹ use HWP2 to select and rotate polarization direction into „derotator system"

Derotator polarization

Derotator produces ~2-3 % polarization

polarization only perp. to scattering plane
⟹ polarization direction moves with derotator orientation

⟹ compensation to p_{inst} < 0.5 % by a co-rotating tilted dielectric-plate („glass plate“)



Polarimetric beamshift

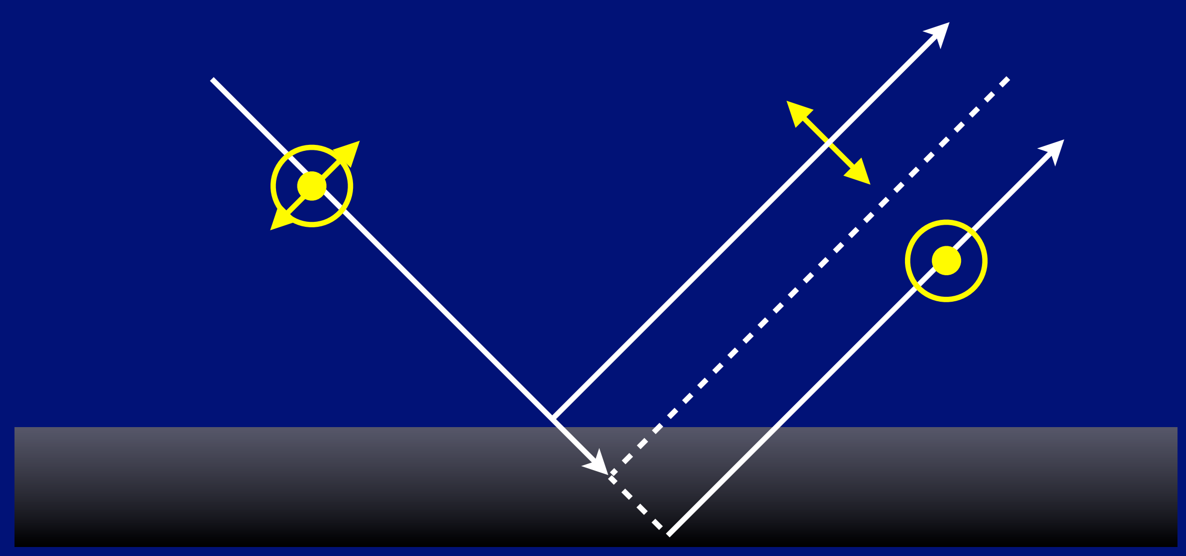
~0.1-0.3 mas shift between opposite polarization modes

⟹ limits the speckle suppression capabilities of ZIMPOL

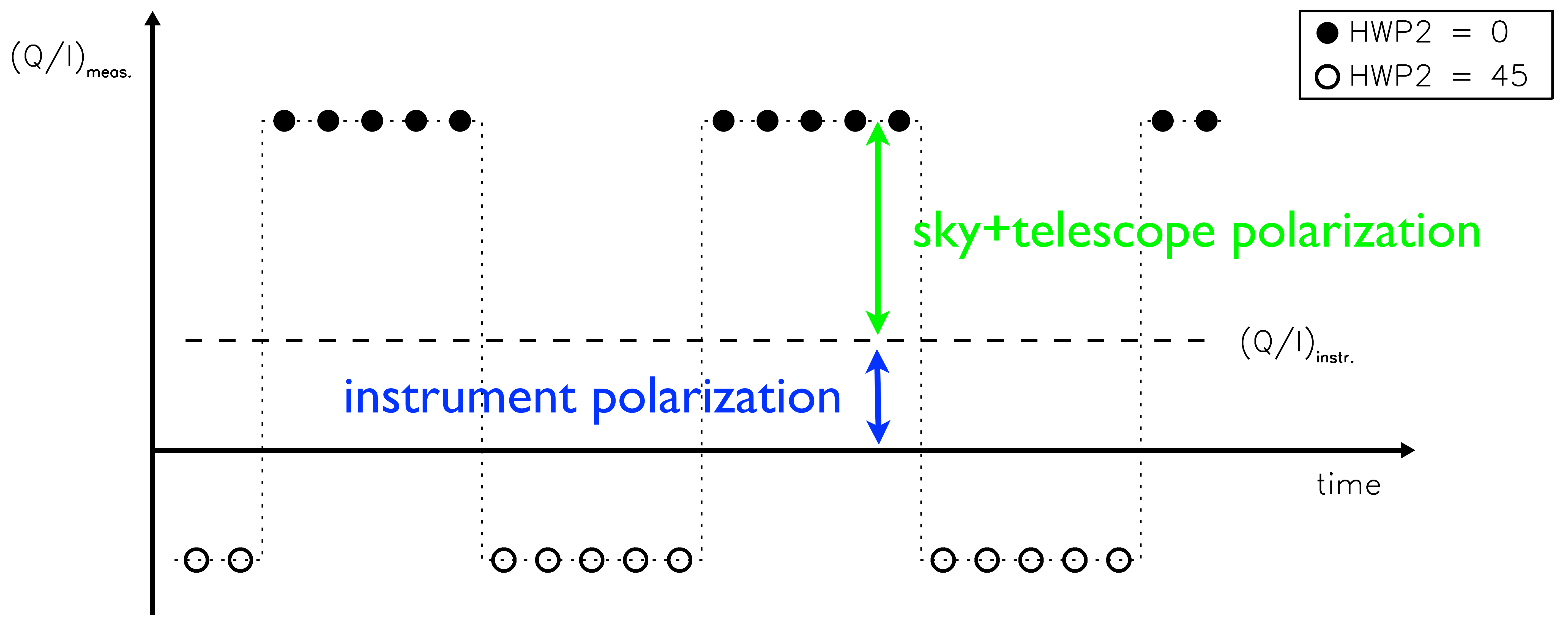
- ~0.2-0.6 μm in focal plane of telescope
- strong beamshift producers (inclined mirrors): Derotator (TBC: M3, M4)
- beamshift changers: HWPs, FLC

theoretical background

- birefringence effects: probably weak as producers (TBC)
- reflection effects: Goos-Hänchen effect
- other effects?



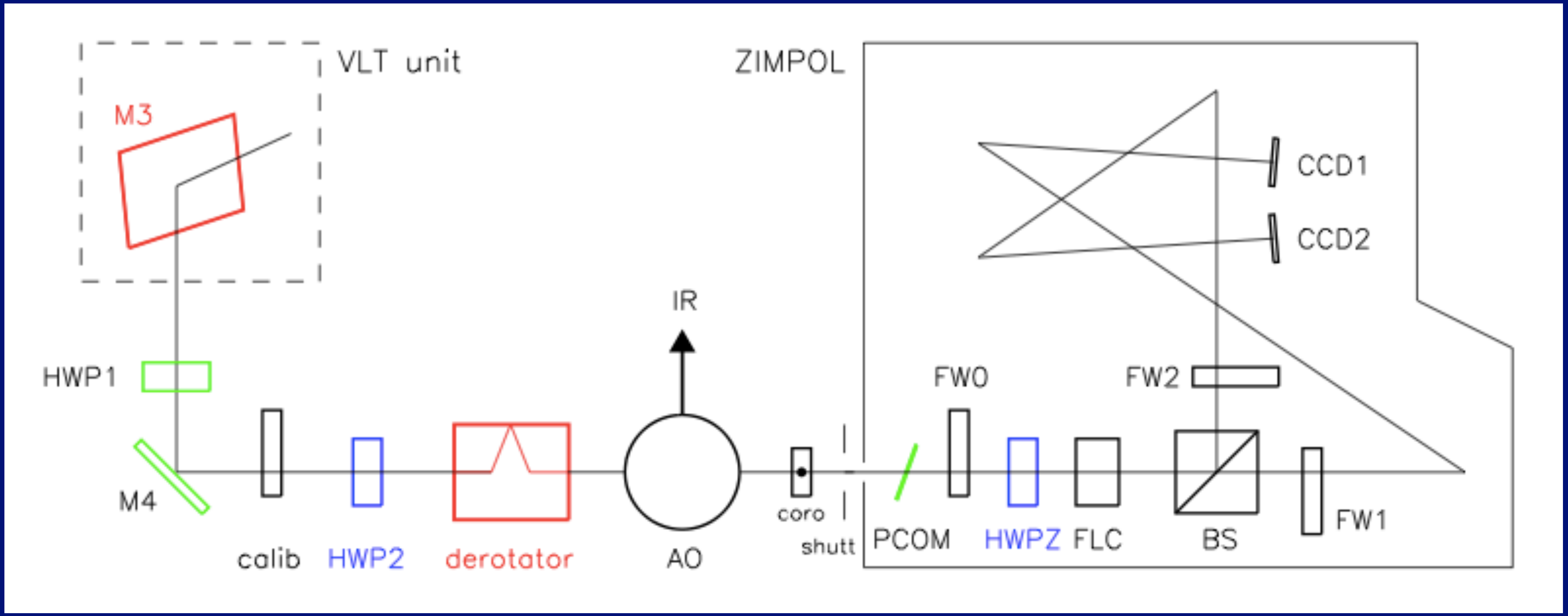
HWP2 polarization switch



- residual polarization from derotator
- residual polarization from 8 CPI mirrors (small angle deflections, < 5°)
- residual detector effects

⟹ polarization switch to separate polarization from
- sky + telescope
- instrument

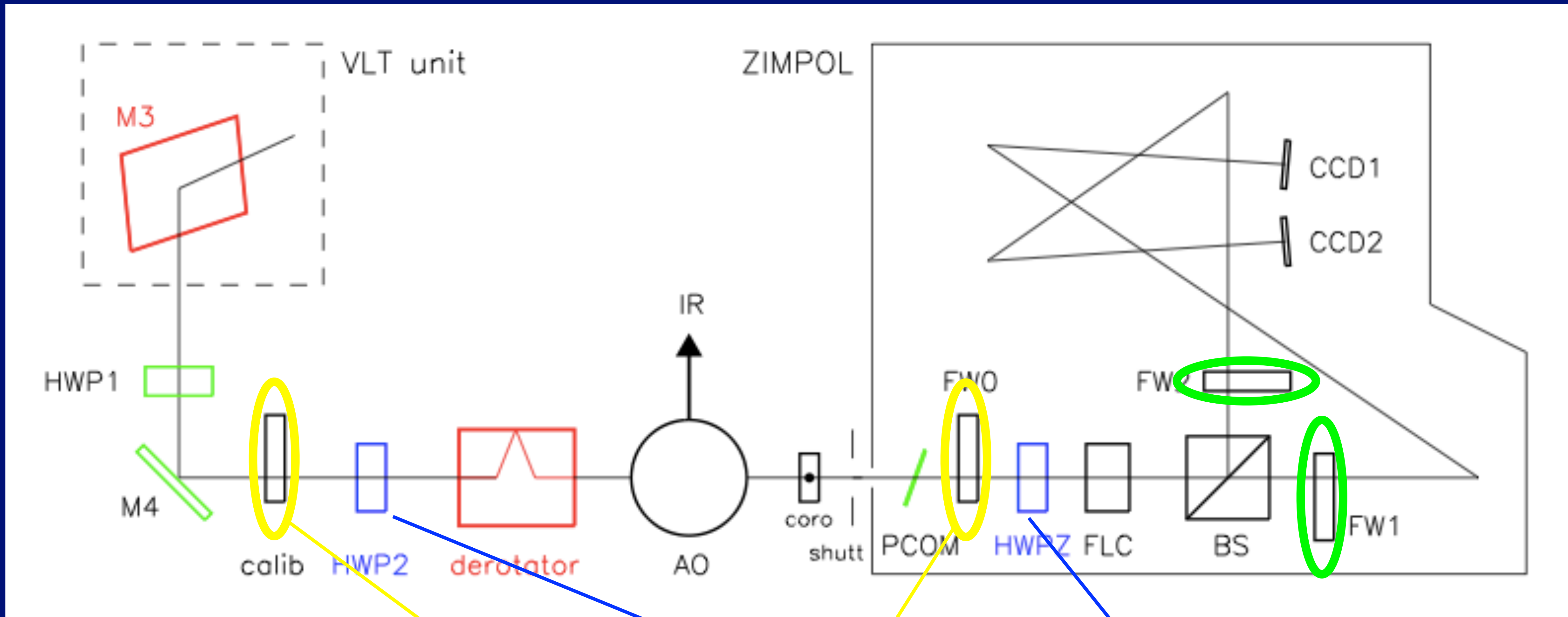
CPI calibration



- ZIMPOL measures polarization of
  - sky + telescope + instrument
- p_{inst} required to be < 0.5 %
- telescope polarization is compensated by
  - M4 HWP1 M3
- the ZIMPOL reference system is fixed
  - only Stokes I and Q are measured

- HWP2
  - selects polarization direction to be measured
  - rotates polarization into derotator system
  - switches $p_{tel+sky}$ to measure instrument residuals
- Polarization compensator plate
  - compensates derotator polarization
- HWPZ
  - rotates selected polarization into ZIMPOL system

Polarimetric calibration measurements



wavelength

Telescope / sky

Calibration unit
⟹ flatfield-lamp (IS)
⟹ point-source
(⟹ HWP1)

+

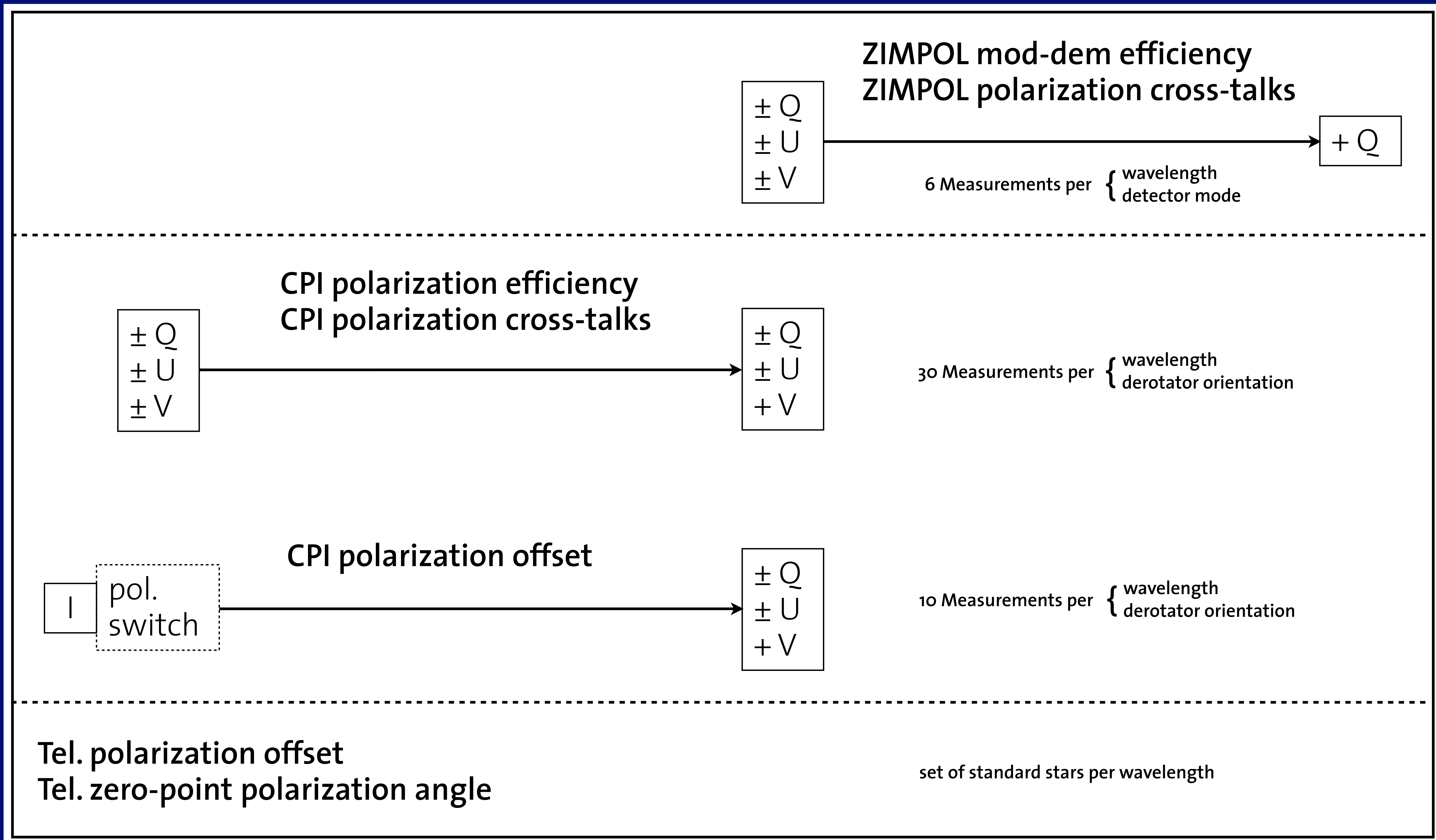
⟹ linear polarizer
⟹ quarter-wave plate
⟹ circular polarizer

+

⟹ half-wave plate

ZIMPOL

Polarimetric calibration measurements



Calibration plan for ZIMPOL/SPHERE

Science Calibrations

- Astrometric calibration
- Photometric calibration
- Telescope polarization (unpolarized standard stars)
- Telescope zero point polarization angle (polarized standard stars)

Technical Calibrations

- Bias
- Dark
- (Polarization flat)
- Intensity flat (bad pixels)
- Sky flat
- Modulation/Demodulation efficiency

Instrument Monitoring

- AO+C polarization efficiency
- AO+C polarization offset
- AO+C polarization cross-talks
- ZIMPOL modulation cross-talks
- Telescope cross-talk

Final polarimetric efficiency

$$\begin{pmatrix} 1 \\ (Q/I)_m \\ (U/I)_m \end{pmatrix} \longrightarrow \begin{pmatrix} 1 \\ (Q/I)_0 \\ (U/I)_0 \end{pmatrix}$$

$$\varepsilon_{pol} = \varepsilon_{MoDem} \ \varepsilon_{CPI} \ \varepsilon_{tel}$$

$$\varepsilon_{MoDem}(\lambda,\vec{x}) \approx 0.80 \quad \text{(fast polarimetry)}$$

$$\varepsilon_{MoDem}(\lambda,\vec{x}) \approx 0.90 \quad \text{(slow polarimetry)}$$

$$\varepsilon_{CPI}(\lambda) > 0.95$$

$$\varepsilon_{tel}(\lambda) > 0.98$$

Summary

- Telescope polarization is compensated by HWP1 and mirror M4
- HWP2 is used:
  - to select polarization direction to be measured
  - to rotate selected polarization into derotator system
  - as polarization switch to separate instrument polarization and sky+telescope polarization
- Derotator polarization is corrected by a co-rotating polarization compensator
- HWPZ rotates the polarization into the ZIMPOL system
- Extensive calibration measurements using internal lamps and sky observations are needed to determine the polarimetric efficiency and cross-talks
- Open issue: polarimetric beamshift effect (high-performance goal)

Conclusions

SPHERE polarimetry provides:

- polarimetric sensitivity of 10^{-5} (ZIMPOL)
- unprecedented contrast capabilities
- unprecedented inner working angle
- dedicated coronagraphs
- a wide range of different filters (simultaneous polarimetry in two bands)
- $\lambda = 0.5 - 2.3\ \mu m$

→ A wide range of solar and extra-solar applications

→ Any suggestions are very welcome!

APPENDIX

ZIMPOL observing modes

fast polarimetry (967 Hz)
slow polarimetry (27 Hz)
window mode polarimetry

standard imaging
snapshot imaging (for DIT ~0.01 s)

P1: No field derotation

- for bright targets
- all components fixed (except HWP1)
- highest precision polarimetry

P2: Active field rotation

- for fainter targets
- moving components (HWP2-Derotator-HWPZ)
- small drifts of instrumental polarization

P3: Pseudo derotation

- combination of P1 and P2
- field fixed for about 5-10 minutes
- derotator is kept close to P1 orientation

I: Imaging mode

- field stabilized imaging
- pupil stabilized imaging

ZIMPOL/SPHERE requirements

Planet search (e.g. α Cen, ε Eri)	circumstellar disk (PSF of a star of 8 magnitude at 1 arcsec)
• photon flux: 10^6 s^{-1} per 10 mas x 10 mas • planet signal / PSF flux: 10^{-4} • polarimetric sensitivity: 10^{-5} • fast modulation (1 kHz)	• photon flux: 10 s^{-1} per 10 mas x 10 mas • polarimetric sensitivity: 10^{-3} • photon noise limited • slow modulation (30 Hz)

★ huge flux range

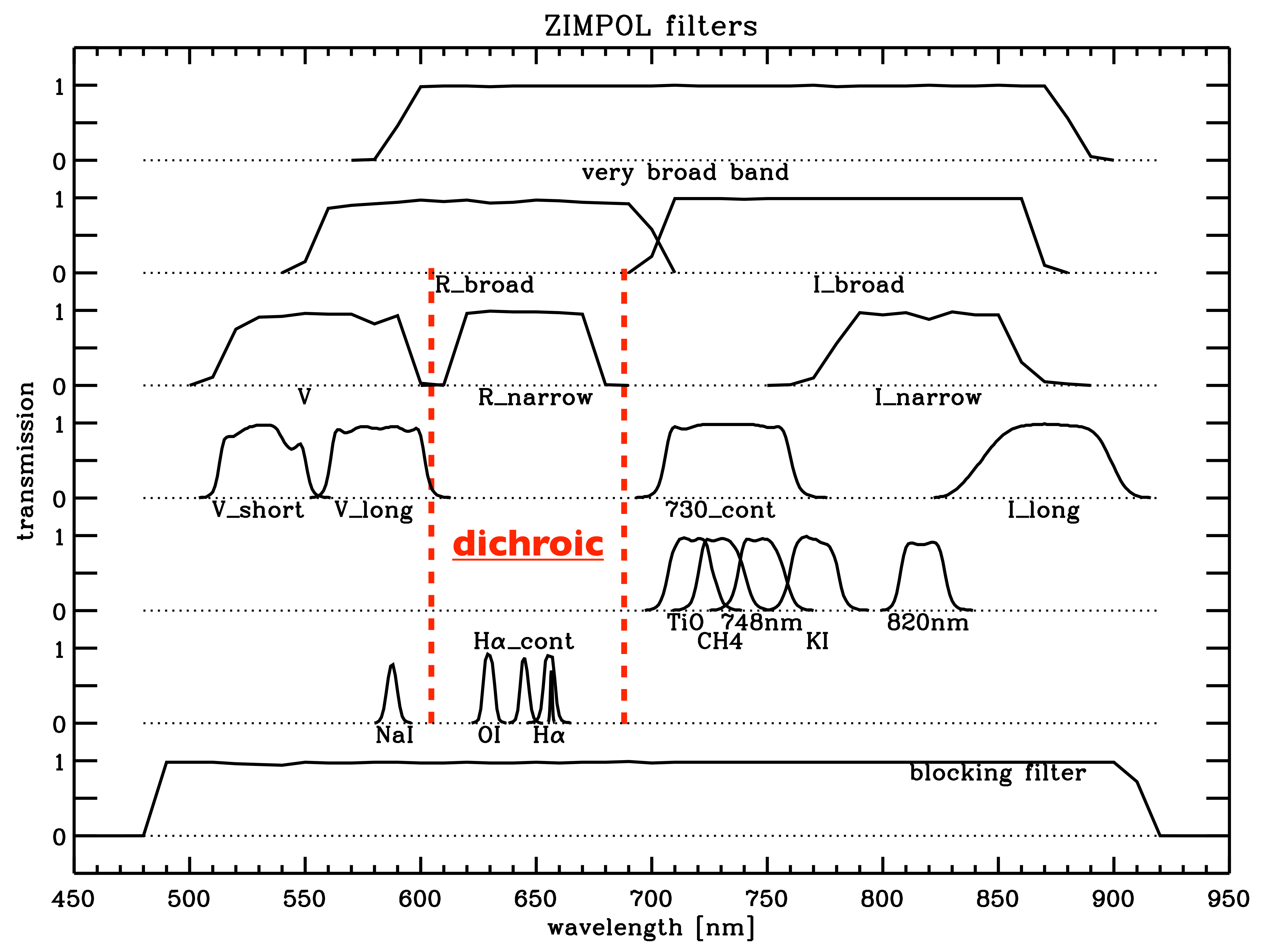
★ high photon efficiency

★ good detector gain linearity

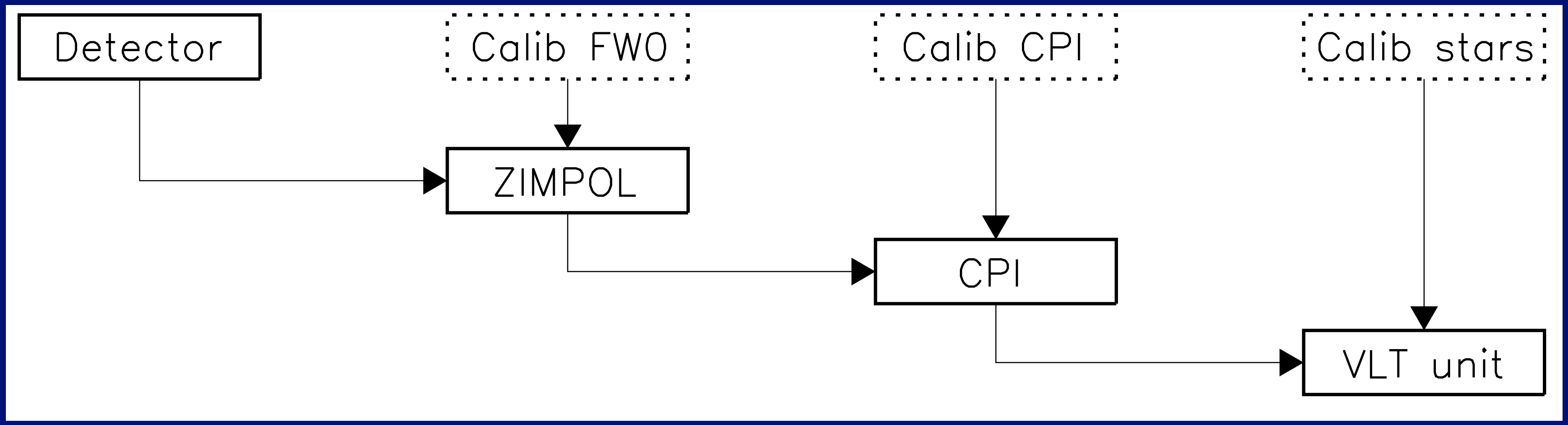
★ high polarimetric sensitivity

★ small detector overheads

Filters


ZIMPOL filters
transmission
wavelength [nm]
450
500
550
600
650
700
750
800
850
900
950
1
0
very broad band
R_broad
I_broad
V
R_narrow
I_narrow
V_short
V_long
730_cont
I_long
dichroic
TiO
748nm
CH4
KI
820nm
Hα_cont
NaI
OI
Hα
blocking filter

Mueller matrix chain



⟹ ZIMPOL only measures Q

⟹ HWP2 selects Q or U direction

$$X = Z \cdot C \cdot H \cdot T = \begin{pmatrix} 1 & * & * & * \\ x_{IQ} & x_{QQ} & x_{UQ} & * \\ * & * & * & * \\ * & * & * & * \end{pmatrix}$$

H = HWP(rel. 0°)

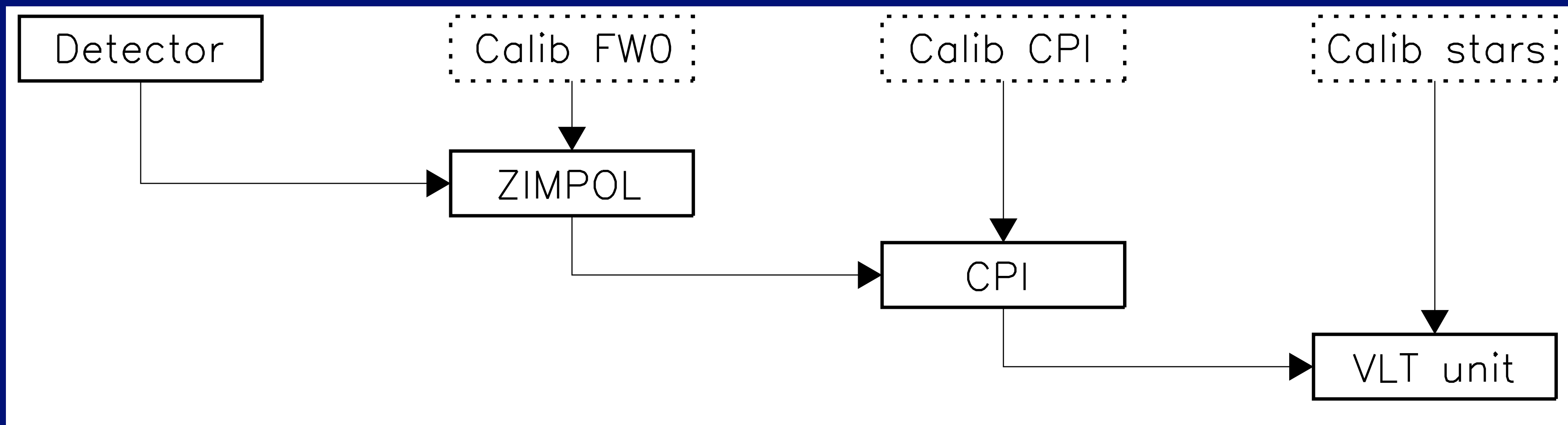
$$X = Z \cdot C \cdot \tilde{H} \cdot T = \begin{pmatrix} 1 & * & * & * \\ \tilde{x}_{IQ} & \tilde{x}_{QQ} & \tilde{x}_{UQ} & * \\ * & * & * & * \\ * & * & * & * \end{pmatrix}$$

$\tilde{H}$ = HWP(rel. 22.5°)

$$\begin{pmatrix} 1 \\ (Q/I)_m \\ (U/I)_m \end{pmatrix} = \begin{pmatrix} 1 & * & * \\ x_{IQ} & x_{QQ} & x_{UQ} \\ \tilde{x}_{IQ} & \tilde{x}_{QQ} & \tilde{x}_{UQ} \end{pmatrix} \cdot \begin{pmatrix} 1 \\ (Q/I)_0 \\ (U/I)_0 \end{pmatrix}$$

no V but 2^{nd} order cross-talks included:
e.g. Q → V → U

Mueller matrix chain



$$\begin{pmatrix} 1 & * & * & * \\ * & z_{QQ} & z_{UQ} & z_{VQ} \\ * & * & * & * \\ * & * & * & * \end{pmatrix}$$

$$\begin{pmatrix} 1 & * & * & * \\ * & c_{QQ} & c_{UQ} & (c_{VQ}) \\ * & c_{QU} & c_{UU} & (c_{VU}) \\ * & c_{QV} & c_{UV} & (c_{VV}) \end{pmatrix}$$

$$\begin{pmatrix} 1 & * & * & * \\ t_{IQ} & t_{QQ} & t_{UQ} & * \\ t_{IU} & t_{QU} & t_{UU} & * \\ * & * & * & * \end{pmatrix}$$