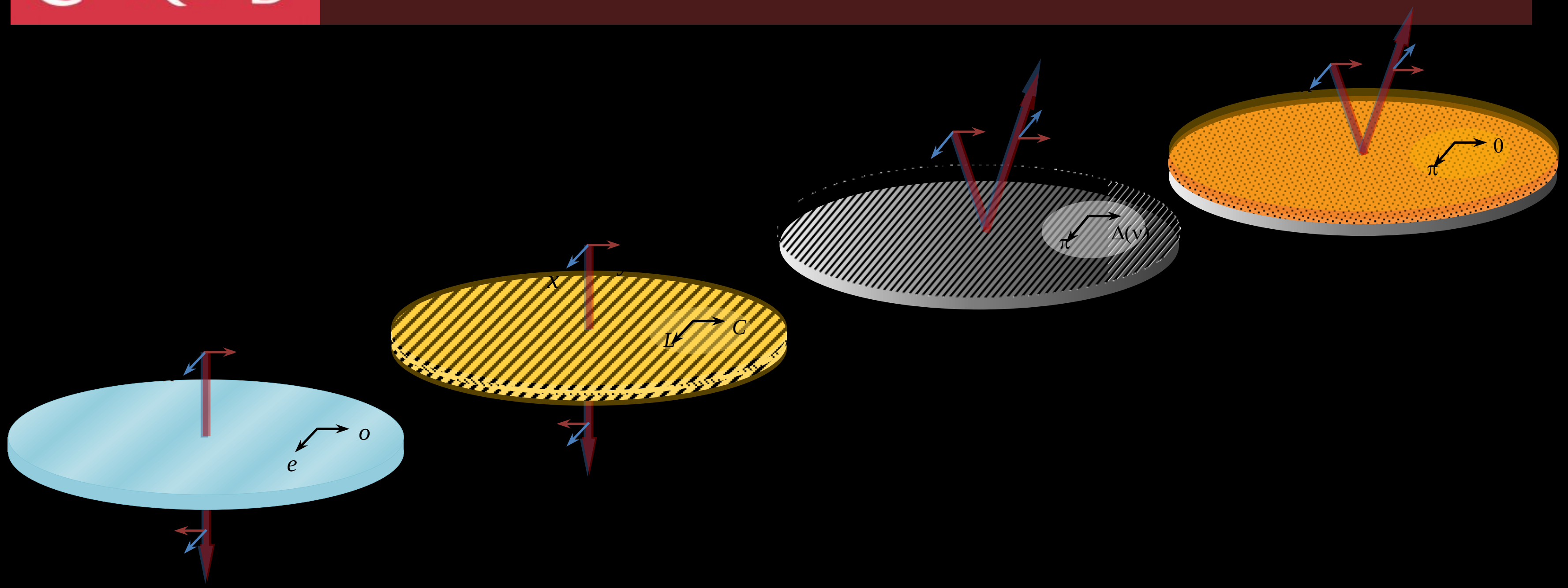
Polarisation Modulators



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1) Cardiff University, 2) APC Université Paris 7 Denis Diderot

Towards the European Coordination of the CMB programme, Villa Finaly, Firenze, 7/9/2017

Why polarisation modulation? 1/2

Polarisation modulation

- We mean rotation of the linear polarisation sensitivity of an instrument
- Modulation of the signal by the detectors

Unpolarised light

- In principle unaffected
- Intensity and polarised signals separated in the frequency domain

Extraction from low frequency 1/f noise

- Detected signals are shifted into a user-defined band far from:
  - 1/f unpolarised atmospheric noise leaking into polarisation
  - Unpolarised ground pickup
  - 1/f detector/electronic noise, gain drifts
  - Long term instabilities, changes of the instrument response

Why polarisation modulation? 2/2

➢ Mitigation of systematics effects

- A single polarisation-sensitive detector measures the modulated Q and U
- Beam mismatches, asymmetries
- Differential gain of the orthogonal polarisation detectors of the same pixel
- In general:

  → Temperature-to-polarisation and polarisation-to-polarisation leakage

➢ Scanning strategy

- Best polarisation sensitivity is achieved by observing each pixel in the sky with the same detector with many different, and possibly evenly spread, polarisation angles

Without a polarisation modulator

Instruments without polarisation modulators

- Polarisation modulation achieved via rotation of the instrument with respect to the sky or sky rotation (scanning)

Detector pairs differencing techniques required

- Detectors sensitive to orthogonal polarisations need to be well characterised and have stable responsivity ratios
- Spurious signals arising from inaccurate detector calibrations, time dependent responsivities, independent noises, different antenna patterns

Projects:

- Planck
- ACTPol
- BICEP, Keck array, BICEP Array
- QUaD, QUIET, QUIJOTE
- SPTPol, SPT-3G

Polarisation modulator milestones

➢ MAXIPOL

- First CMB experiment using a rotating HWP

➢ EBeX

- So far the only one exploiting the magnetic levitation technology

➢ ABS

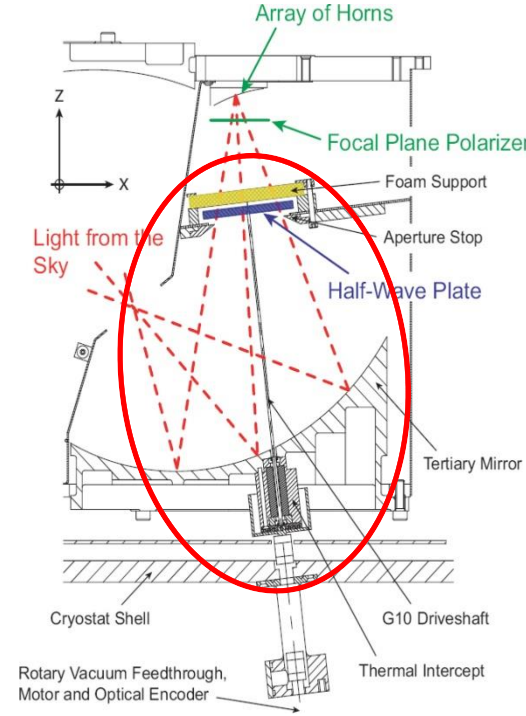
- First CMB ground experiment using a 300K continuos rotating HWP, first demonstrating the capability of suppressing 1/f noise due to unpolarised atmosphere

→ It is possible to recover CMB polarization signal over large angular scales from CMB ground experiments

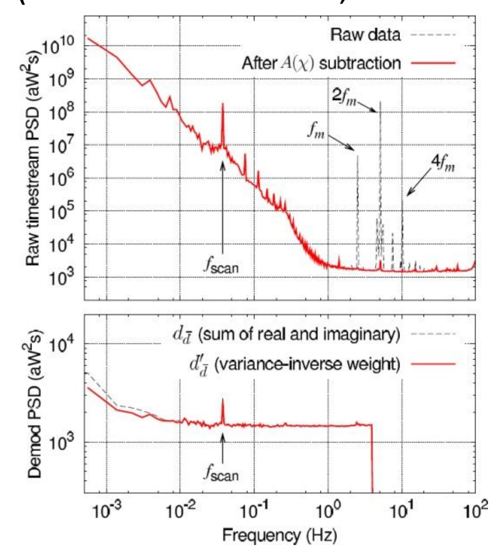
➢ LiteBIRD

- Currently the only satellite proposal (phase A) with HWPs
- It is implementing the experience gained with EBeX

MAXIPOL (Johnson B.R. et al., 0308259, 2003)



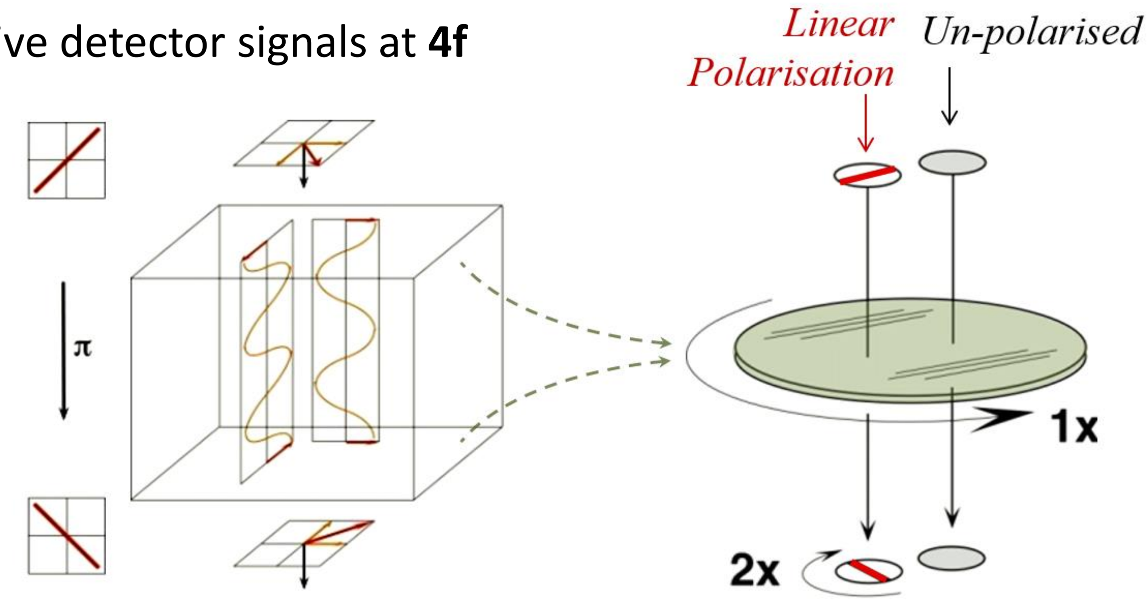
ABS (Kusaka A. et al. 2014,1310.3711)



How to modulate linear polarisation

➢ Quasi-optical modulation of linearly polarised light

- Rotating Half-Wave Plate (HWP) + fixed polariser + detectors <u>or</u>
- Rotating HWP + polarisation-sensitive detectors
- Mechanical rotation at **f**
- Polarised signal rotates at **2f**
- Polarisation sensitive detector signals at **4f**



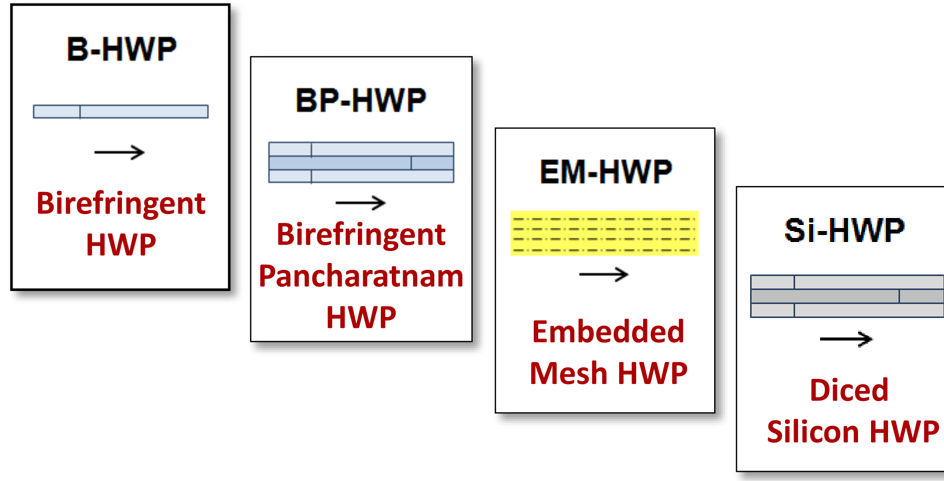
➢ Projects with polarisation modulators

- HERTZ, SCUPOL, SHARP, POLARBEAR, SMA
- POLKA, ABS, NIKA, NIKA2, CLASS, AdvACTPol
- MAXIPOL, EBEX, PILOT, BLASTPol, SPIDER, PIPER, …

Quasi-optical polarisation modulators

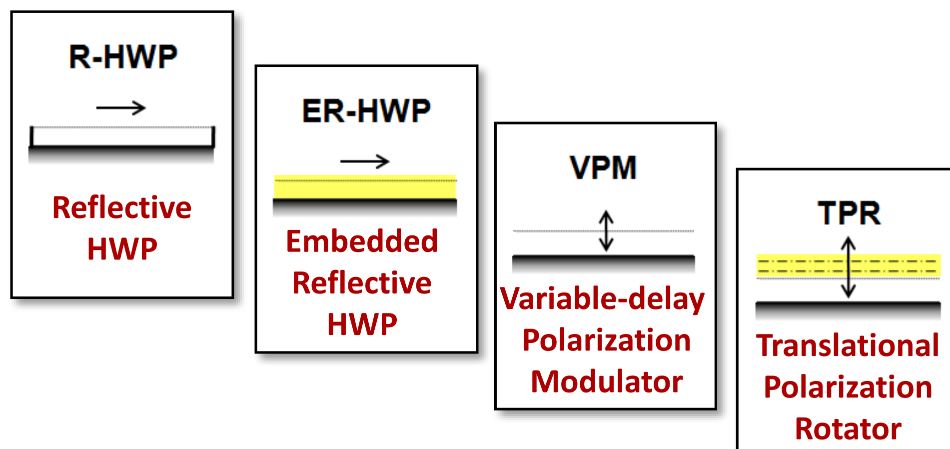
➢ Transmissive modulators

- Single plate birefringent HWP
- Multi-plate Pancharatnam HWP
- Embedded Mesh HWP
- Diced Silicon HWP

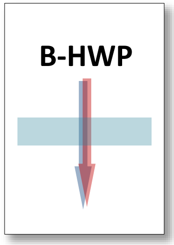


➢ Reflective modulators

- Reflective HWP
- Embedded Reflective HWP
- Variable-delay Polarisation Modulator
- Translation Polarisation Rotator

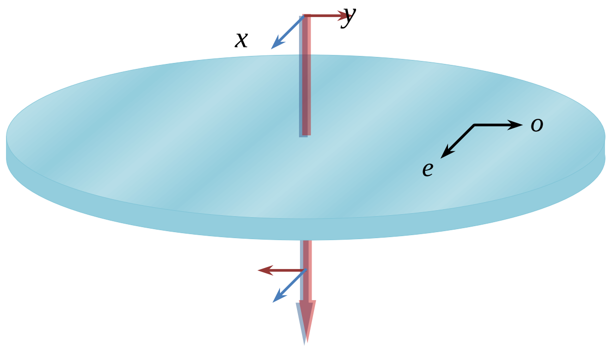


Transmissive modulators 1/2



➢ Single plate

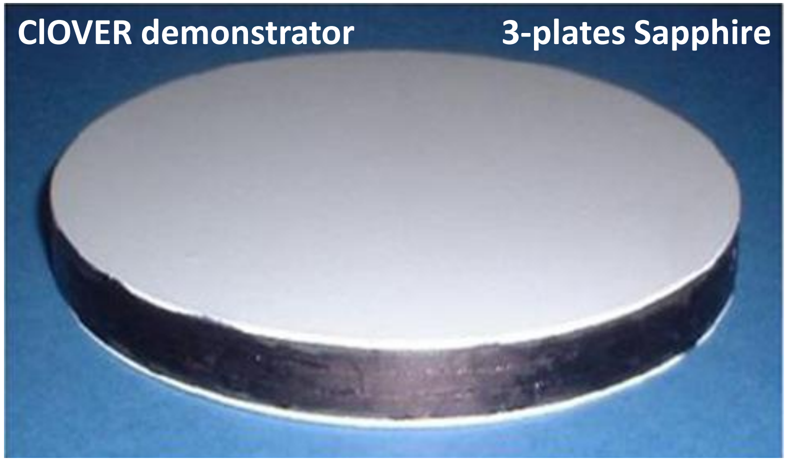
- Sapphire slabs
- Available up to 500mm diameter



➢ Multi-plate Pancharatnam

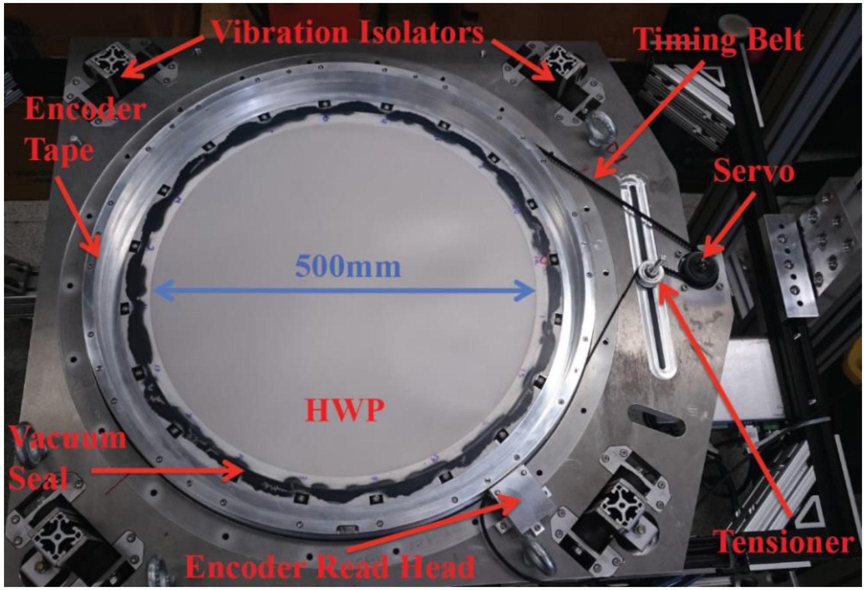
- Single plate birefringent HWP
- Multi-plate Pancharatnam HWP
- Large bandwidths proportional to the number of plates

Projects: SCUPOL, POLARBEAR, ABS, MAXIPOL, EBEX, PILOT, BLASTPol, SPIDER

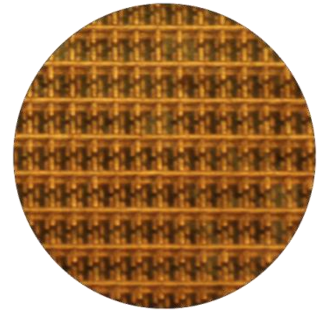


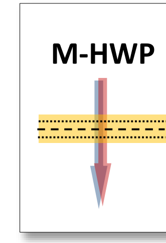
Hill et al. 2016, 1607.07399

POLARBEAR2



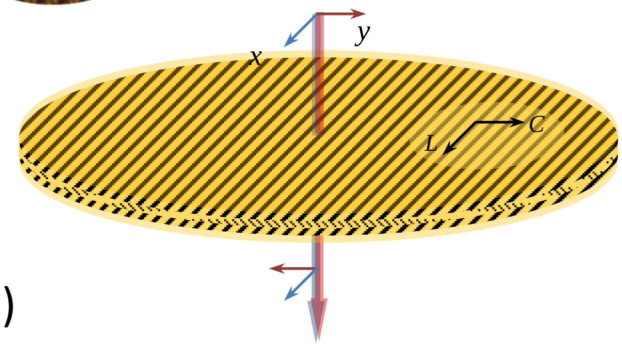
Transmissive modulators 2/2





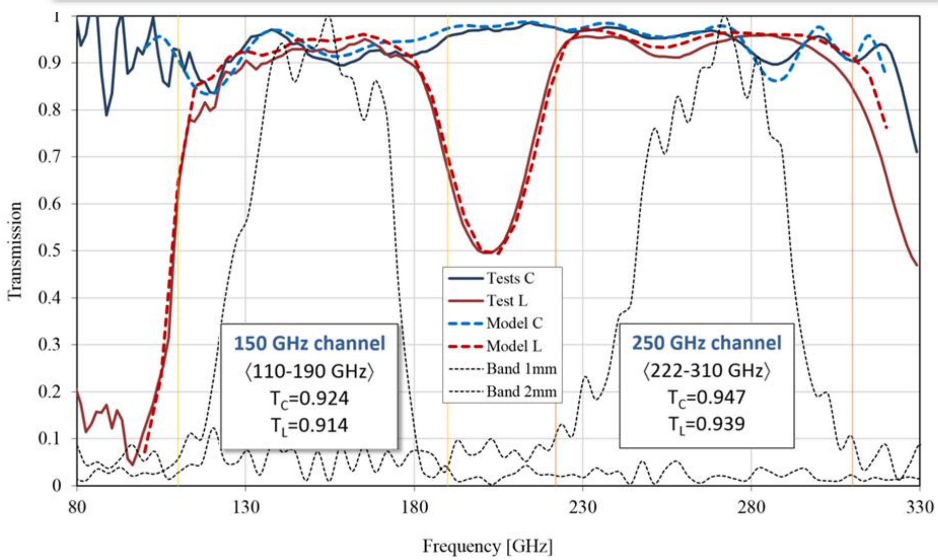
➢ Mesh HWP

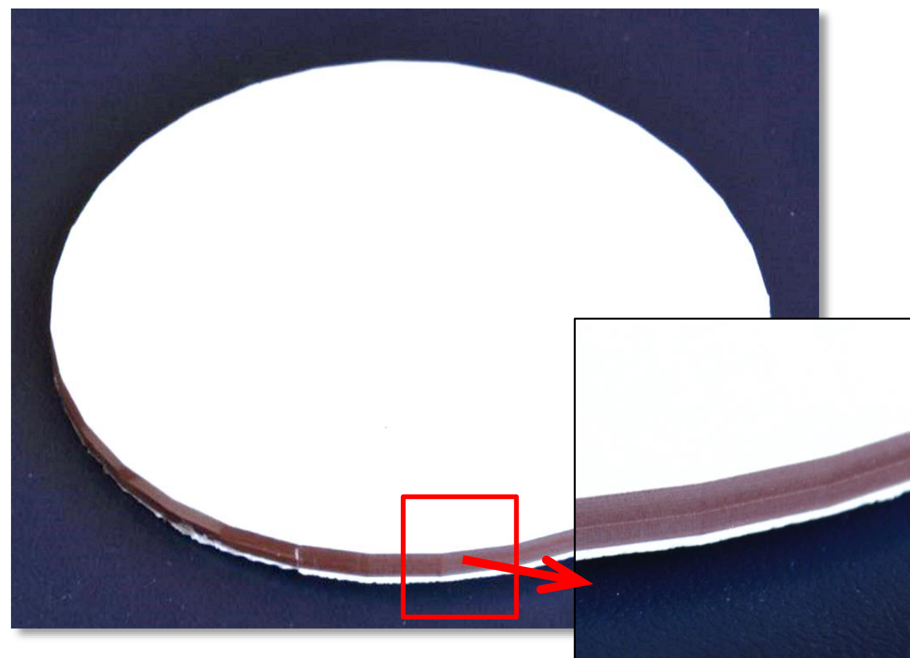
- Based on embedded mesh-filter technology
- Anisotropic mesh-filters
- Capacitive and inductive stacks
- Bandwidths ~100% (3:1)
- HWP axes defined photolithograpically



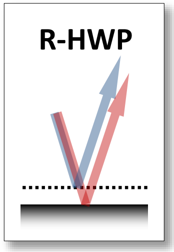
Projects: NIKA, NIKA2, BlastTNG, ASTE, CLASS (QWPs)
QUBIC, LSPE, LiteBIRD HFT (?)

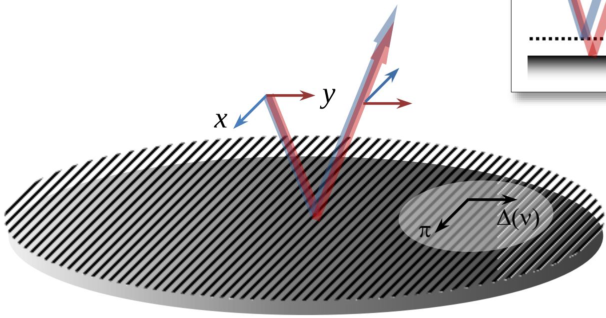
Transmissions along the inductive and capacitive axes





Reflective modulators 1/2



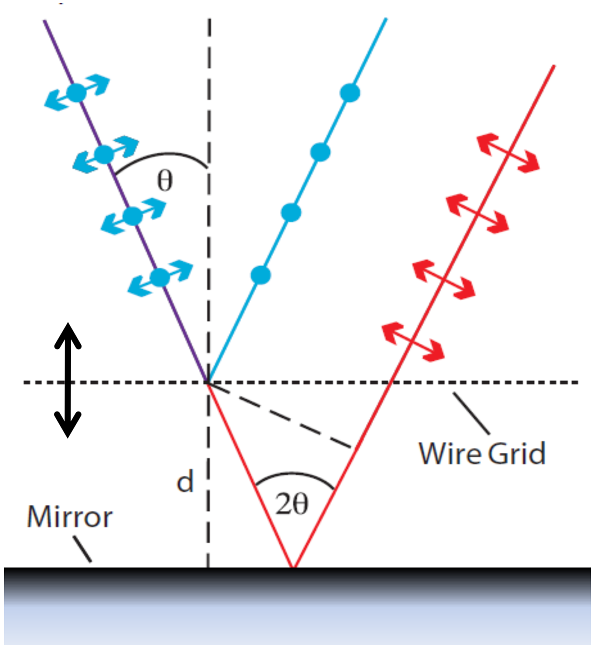


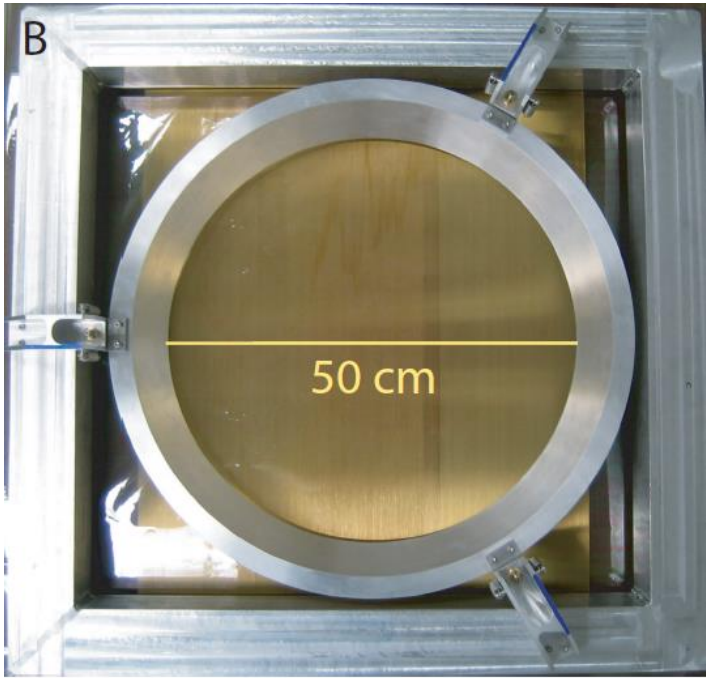
➢ Variable-delay Polarisation Modulator (VPM)

- Periodic displacement of a free-standing wire grid parallel to a mirror
- Modulation of Q <u>or</u> U
- VPM 45 deg rotation to switch from Q to U sensitivity

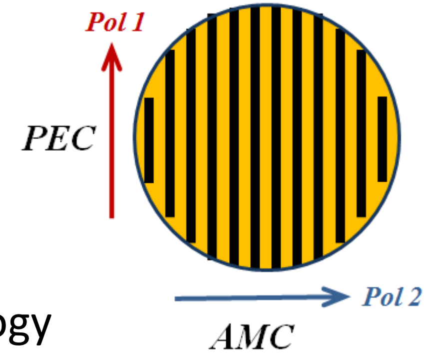
Projects: CLASS, PIPER

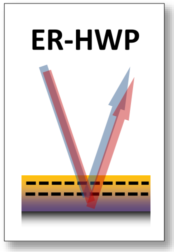
D.T. Chuss et al. 2006

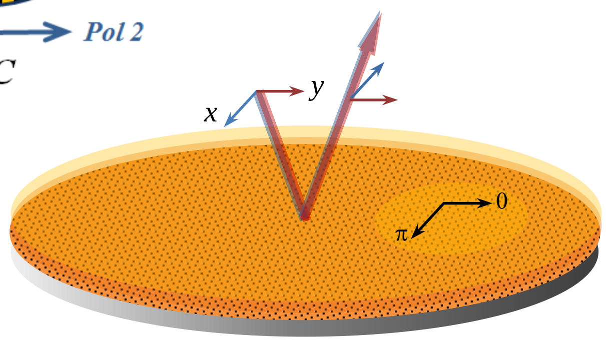




Reflective modulators 2/2





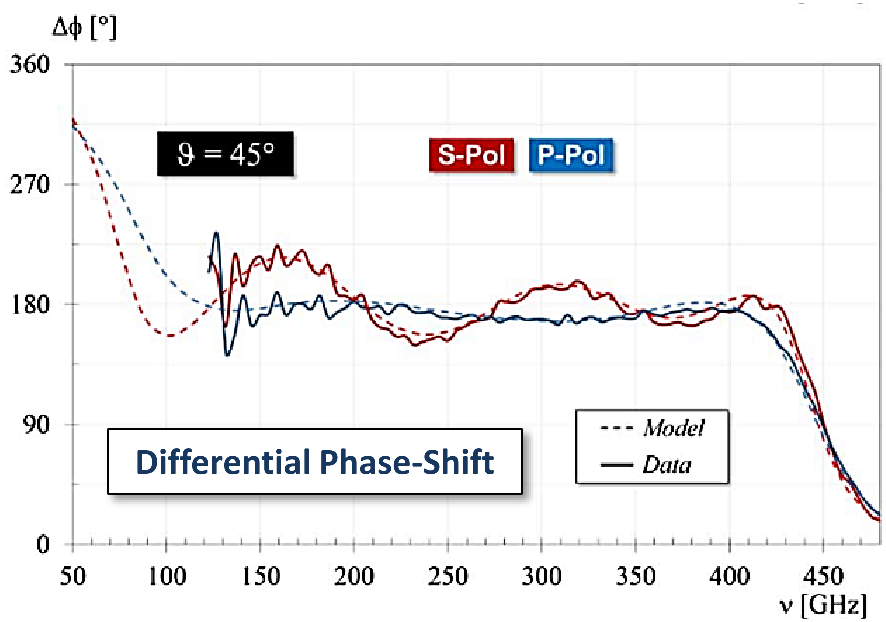


➢ Embedded Reflective HWP

- Based on embedded mesh-filter technology
- Working principle based on artificial magnetic surface
- Very large bandwidths achievable

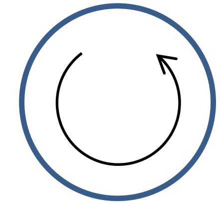
  → ~156%, 8:1 ratio or 3 octaves
- Large diameters

Projects: GISMO2 (?), LiteBIRD (?)



Polarisation modulation strategies

➢ Continuous rotation (fast)



- Ideal case (many samplings of the polarization vector)
- Modulation sky polarisation above the 1/f knee of atmospheric emission
- Rapid modulation in general more robust against systematic errors
- Need development of demodulation techniques
- Useful for mitigating calibration errors

Projects: ABS, MAXIPOL, EBeX, POLKA, NIKA, NIKA2, POLARBEAR1,2, AdvACTPOL

ABS: - Significant reduction of atmospheric noise down to 1-2 mHz

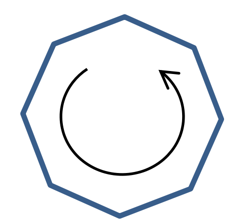
NIKA: - Significant reduction of atmospheric noise in the polarised signal

- Developed algorithm to correct/reduce I → P leakage

- Potential to measure polarisation at large angular scales

LiteBIRD: proposal of a continuous polarisation modulation

➢ Stepped rotation (slow)



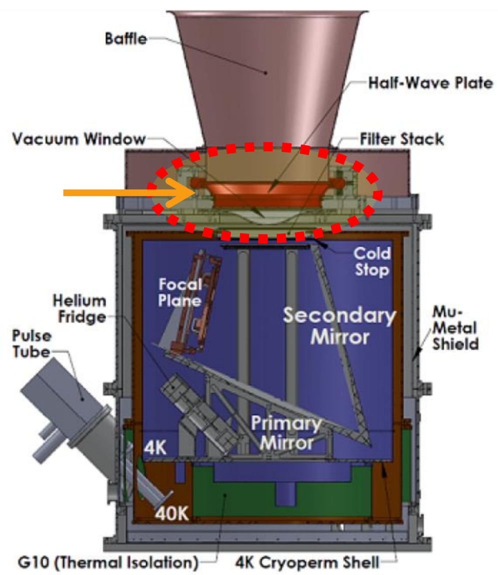
- Periodic changes of the polarisation modulator angle followed by instrument scan and integration
- Fewer number of samplings polarisation vector
- Less dissipated power

Projects: HERTZ, SCUPOL, SHARP, PILOT, BLASTPol, SPIDER, POLARBEAR, SMA, QUBIC

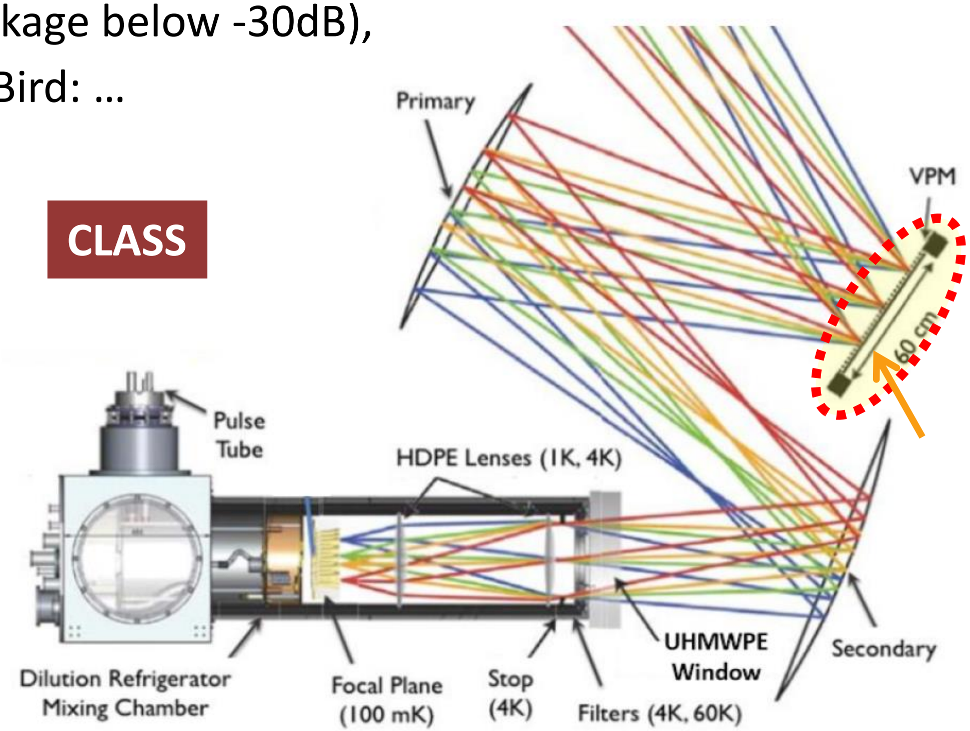
Polarisation modulator location

- **Pol modulator as first element of the optical chain**
  - **Advantages**:
    - Complete decoupling between sky and instrumental polarisation, no need to deal with modulation of beam systematics
    - Ambient temperature rotation mechanism, no problems with heat dissipation
  - **Disadvantages**:
    - Operating at ambient temperature → PM higher (differential) emissivity
  - **Projects**: ABS (cold mirrors, I > P leakage below -30dB), PIPER, CLASS, SPIDER, LiteBird: …

ABS



CLASS

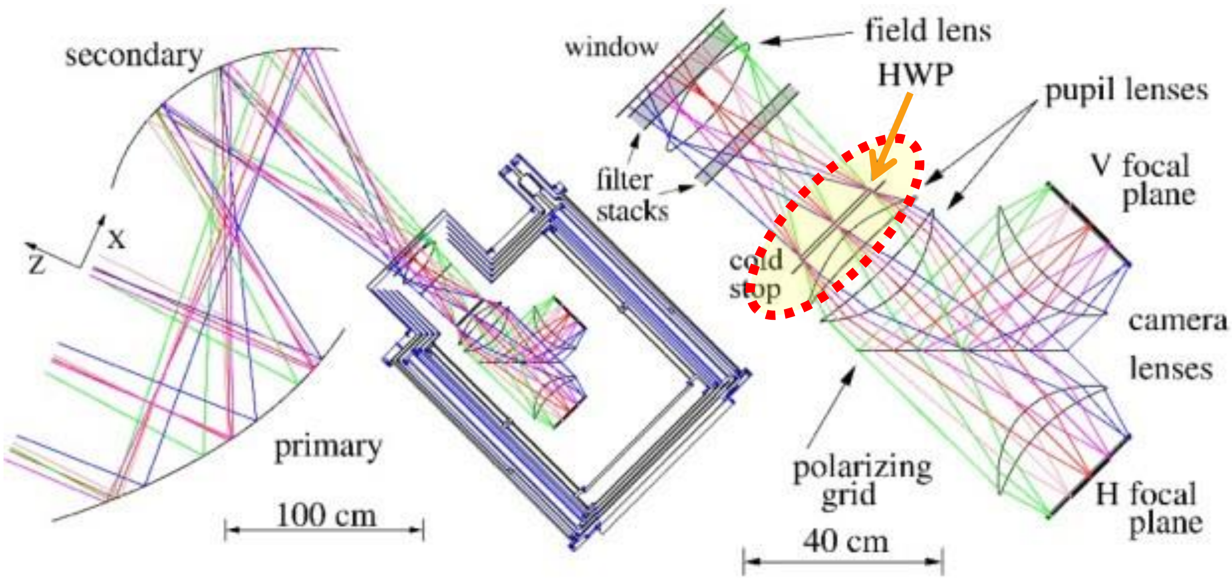


Polarisation modulator location

➢ **Pol modulator within optical system / at pupil image (Lyot stop)**

- **Advantages**:
  - **<u>If</u>** the PM is located at the pupil image (Lyot stop) the detectors will see the same portion of the HWP → Some of the HWP systematics can be removed as a common mode between detectors
  - **<u>If</u>** PM operating at cryogenic temperatures → PM lower (differential) emissivity
- **Disadvantages**:
  - Modulation of instrumental polarisation from optics on the sky side
  - **<u>If</u>** PM at cryogenic temperatures → need low dissipation cryo-mechanism
- **Projects**: MAXIPOL, EBEX, NIKA, NIKA2

EBEX

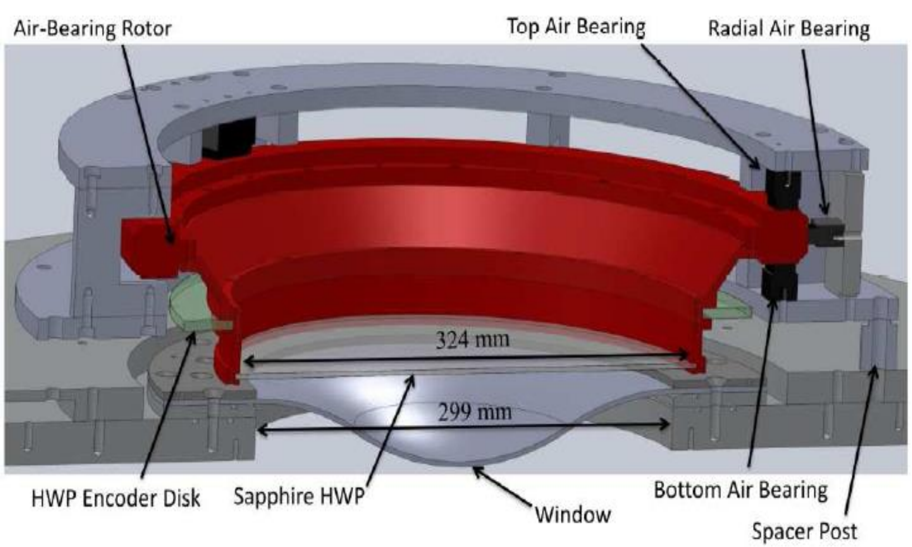


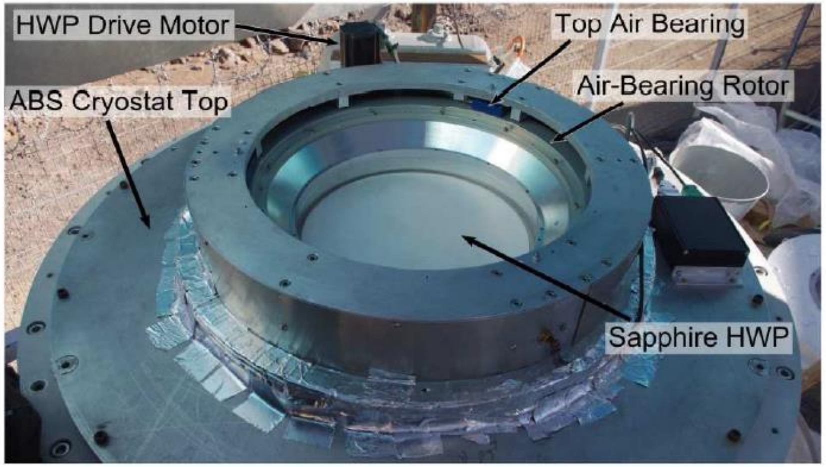
Rotation mechanisms 1/2

➢ **Ambient temperature continuous rotation**

- **External motor with rotary vacuum feedthrough**
  - Cryogenic rotating HWP → MAXIPOL
- **Ball bearings**
  - Thin-section ball bearings → POLARBEAR
- **Air bearings**
  - Ambient temperature rotating HWP → ABS
- **Projects**: POLARBEAR 1-2a, AdvACTPol, NIKA, NIKA2, Brain(QWP)

ABS





Kusaka A. et al. 2014, 1310.3711

Rotation mechanisms 2/2

For a review:
CMB-S4 Technological Book
(sec. 3.6.5), 1706.02464 (2017)

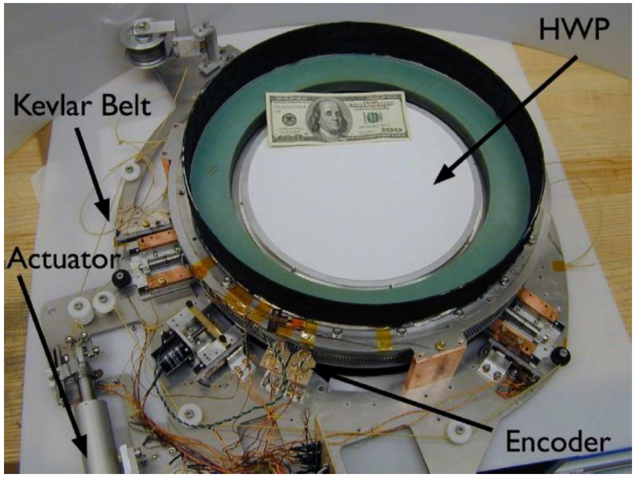
➢ Cryogenic stepped rotation

- **Mechanical system**:
  - Worm gear + worm screw + magnetic coupling
- **Projects**: PILOT, QUBIC, SPIDER

➢ Cryogenic continuous rotation

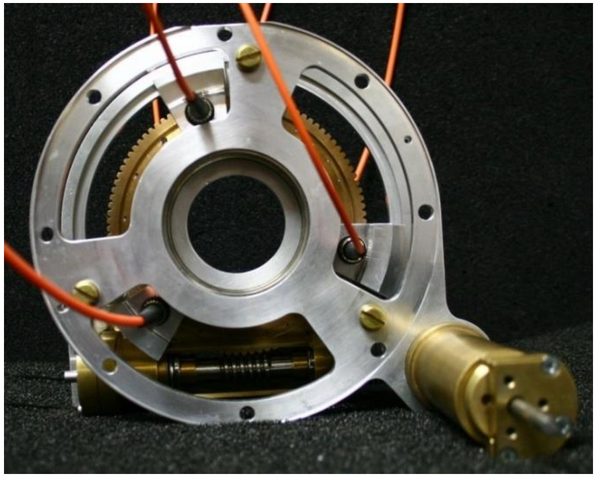
- **Magnetic levitation**:
  - Systematics due to Eddy currents
- **Projects**: EBeX, POLARBEAR2b,2c, LSPE/SWIPE, LiteBIRD

EBeX



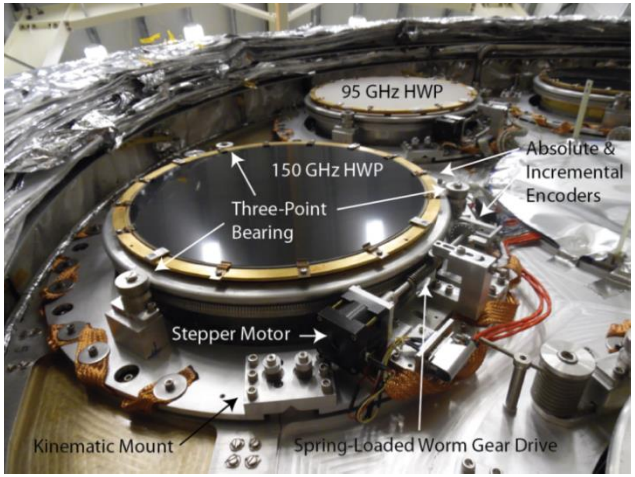
Klein J. et al. SPIE, 2011, 8150, 815004

PILOT



Salatino M. et al., 2011, 1006.5392

SPIDER



Bryan S. et al., 2016, 87, RSI 014501

Half Wave Plate systematics 1/4

➢ Performance parameters

- Transmission & Reflection
- Absorption/emissivity
- Bandwidth
- Modulation efficiency

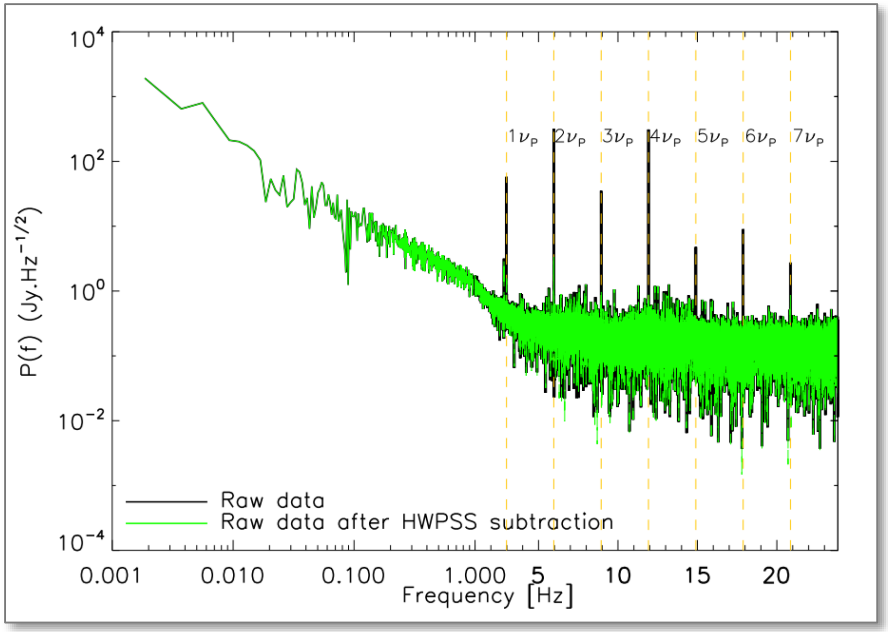
➢ Jones matrix for a non-ideal HWP

$$\mathbf{J}_{\rm hwp} = \begin{pmatrix} 1+h_1 & \zeta_1 e^{i\chi_1} \\ \zeta_2 e^{i\chi_2} & -(1+h_2)e^{i\beta} \end{pmatrix}$$

NIKA - Ritacco A. et al. (2016)

➢ Spurious signals

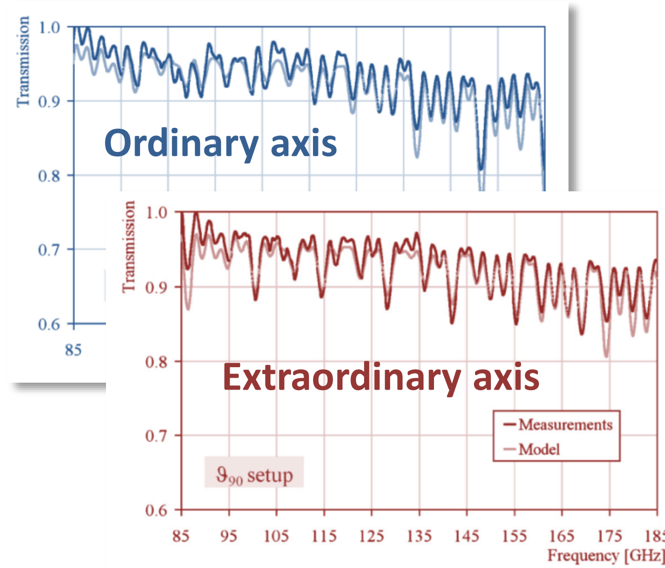
- On top of the sky polarisation modulation, HWP imperfections can lead to background modulation and spurious signals at higher harmonics (**nf**)



Half Wave Plate systematics 2/4

➢ **Differential transmission**

- **Origins**:
  - Birefringent crystal with non-birefringent ARC
  - Different transmissions along mesh C and L axes
- **HWP Instrumental Polarisation**:
  - Linear pol from unpolarised sky emission
  - HWP synchronous, detected at **2f**
- **Note:** <u>If</u> IP produced on the sky side of the HWP, e.g. by mirrors/windows, it will be detected at **4f** (I > Q/U leakage)



Pisano et al, Appl. Opt. (2006)

➢ **Differential emissivity**

- **Origins**:
  - Different absorption coefficient along axes
    → Polarised emission along axes
  - HWP synchronous, detected at **2f** (0.3% in the **ABS** experiment)
- **Note:** <u>If</u> differential emissivity produced on the sky side of the HWP it will be detected at **4f** (I > Q/U leakage)

Half Wave Plate systematics 3/4

- **Temperature variations**
  - Drifts of the HWP temperature with time → Different emissivities
- **HWP cross-polarisation**
  - Leakage of polarisation from one axis to the other
- **Beam impact**
  - Deterioration of the beam passing through the HWP (ellipticity)
- **Multiple reflections**
  - Within detectors and HWP → detected at **2f**
  - Reflections at non-normal incidence can be detected at **4f** (I > Q/U)
- **Non-uniform optical properties**
  - HWP or ARC surface inhomogeneities → can be detected at **4f**
- **Driving mechanism**
  - HWP-synchronous signals can arise from the HWP drive mechanism (observed, among others, in MAXIPOL and EBeX)
  - **If** HWP and rotation mechanism misaligned (wobbling) → detected at **4f**

Half Wave Plate systematics 4/4

➢ HWP axes orientation frequency dependence

- Effect arising in birefringent rotated multi-plate designs
- Phase offset of the intensity-vs-angle modulation at different frequencies
- Dependent on the stack construction parameters
- Overall in-band response dependent on the instrument spectral response and the incident radiation spectrum

➢ Polarisation angle reconstruction errors

- HWPs in stepped mode might have slight oscillations around a median point before settling at each step; these errors adds up to the detector angle uncertainties:

→ This is an issue both for C_l reconstruction as well as for polarisation calibration on the sky

Note:

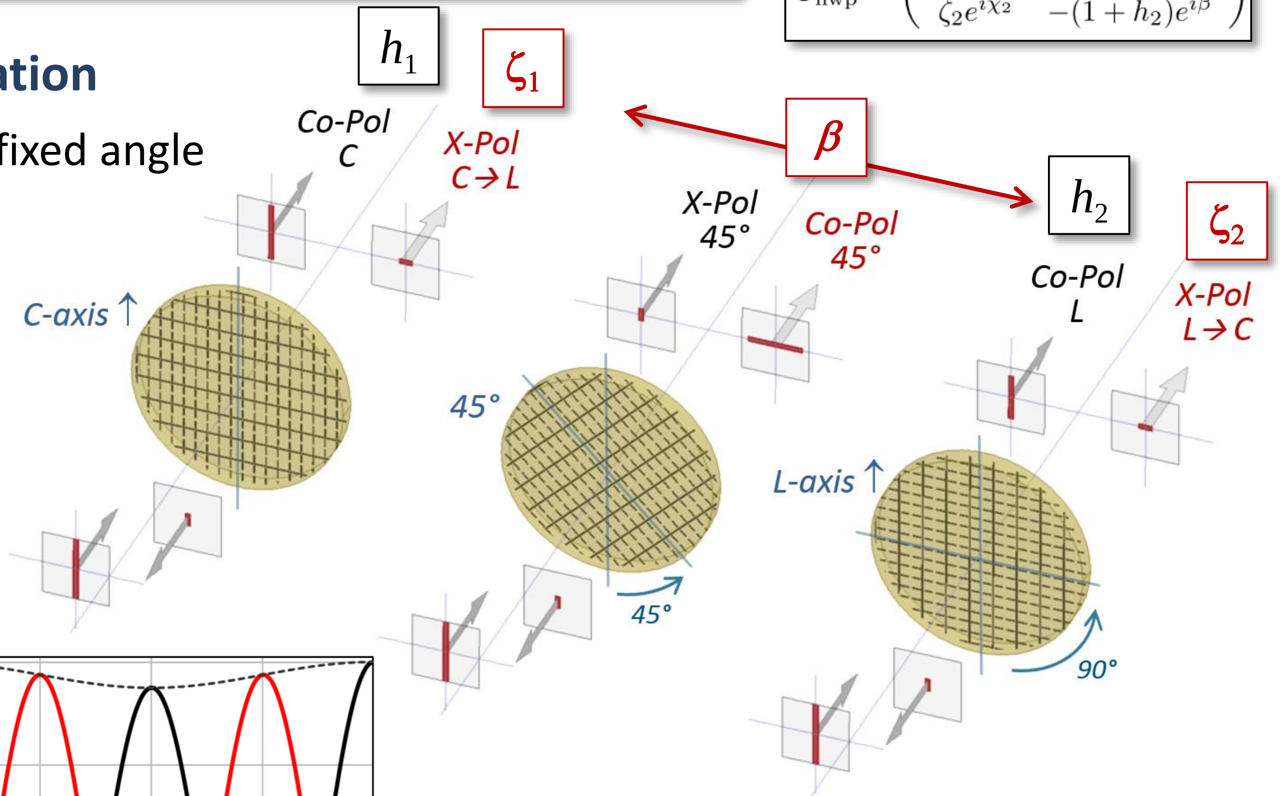
- The HWP induced **I > Q/U leakage** affects the recovery of our polarisation signal and are especially problematic at large angular scales
- **However**:
  - HWPs mitigates I > Q/U leakage due to beam systematics (differencing) in HWP-less experiments
  - **If** the HWP effects are quantified (via measurements and/or simulation), they can be assessed in the demodulation and successive mapmaking/parameter extraction phases

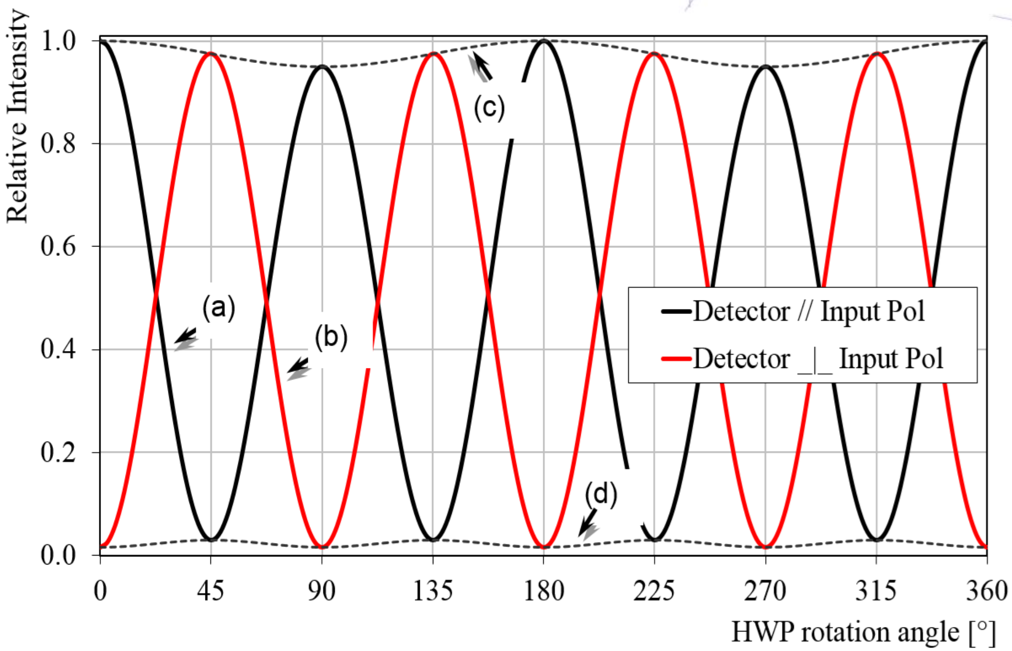
Modulator characterisation: Transmissive HWP

$$\mathbf{J}_{\rm hwp} = \begin{pmatrix} 1+h_1 & \zeta_1 e^{i\chi_1} \\ \zeta_2 e^{i\chi_2} & -(1+h_2)e^{i\beta} \end{pmatrix}$$

➢ Polarised signal modulation

- Polarised input signal at fixed angle
- HWP rotation (0-360°)

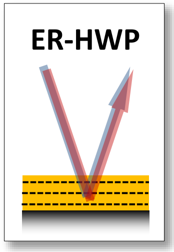




➢ Measured parameters

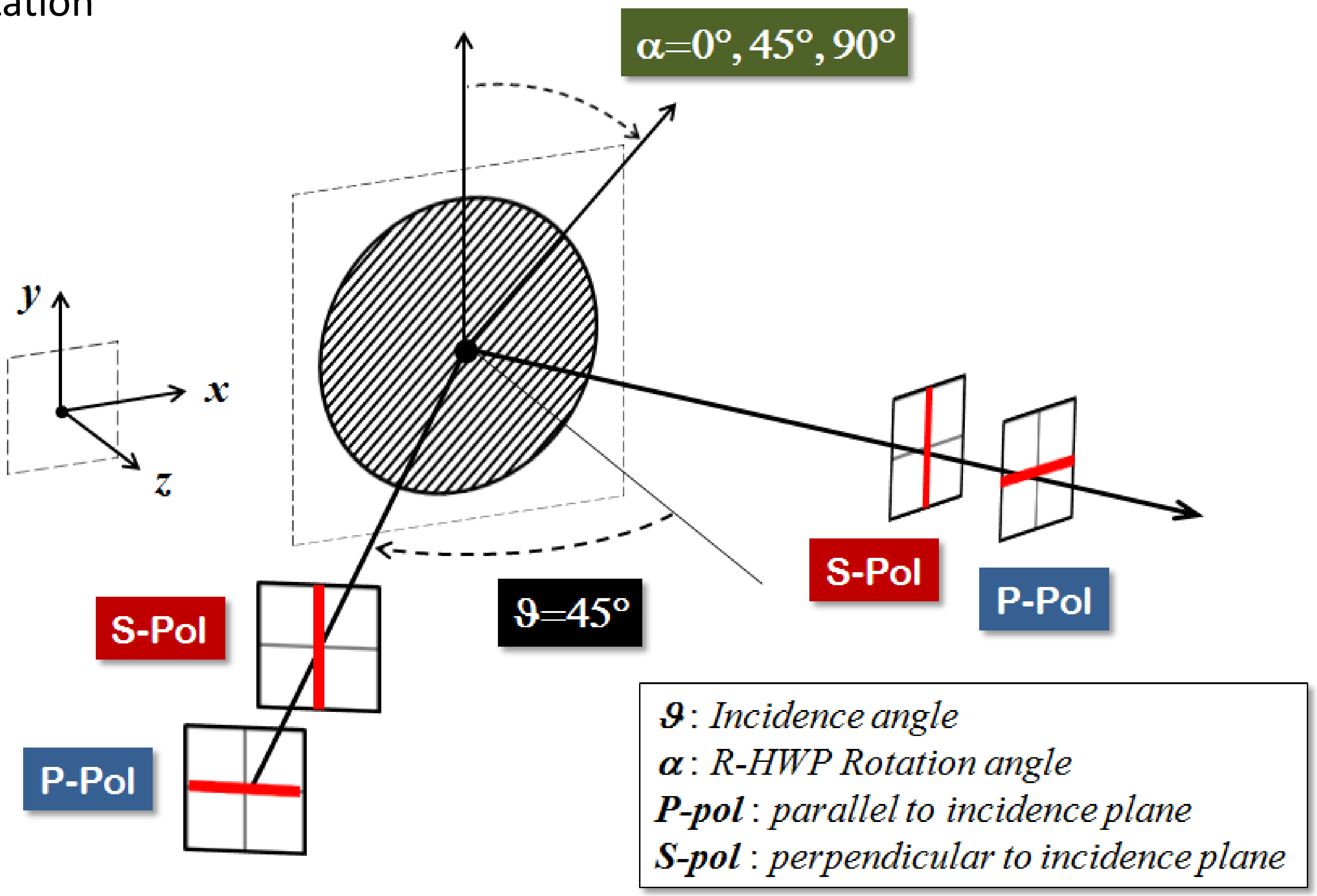
- Polarisation modulation efficiency
- Instrumental Polarisation (IP)
- Cross-pol leakage along axes
- 45 deg cross-pol

Modulator characterisation: Reflective HWP



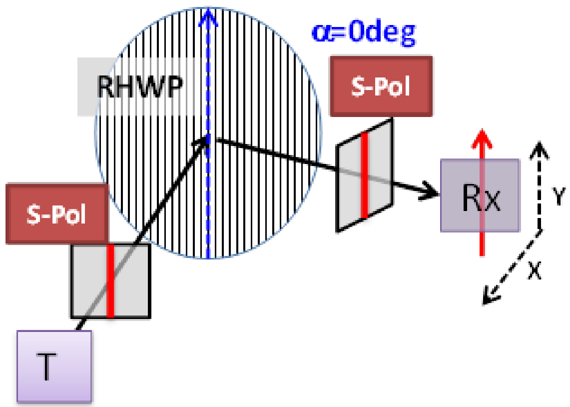
➢ Polarised signal modulation

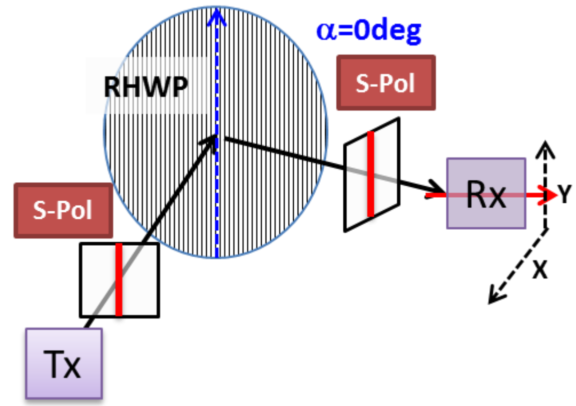
- Off-axis operation breaks the symmetry
- S & P polarised input signals at fixed angle
- HWP rotation

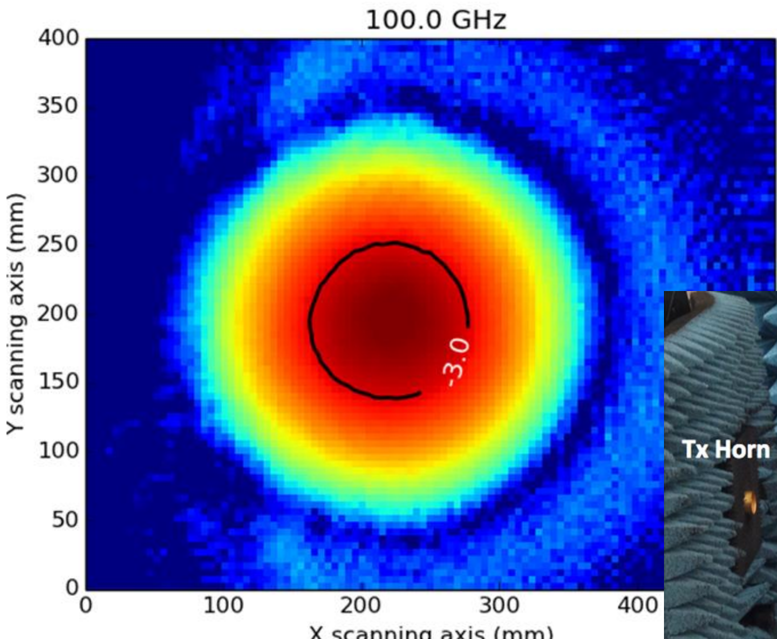


Modulator characterisation: ER-HWP beam effects

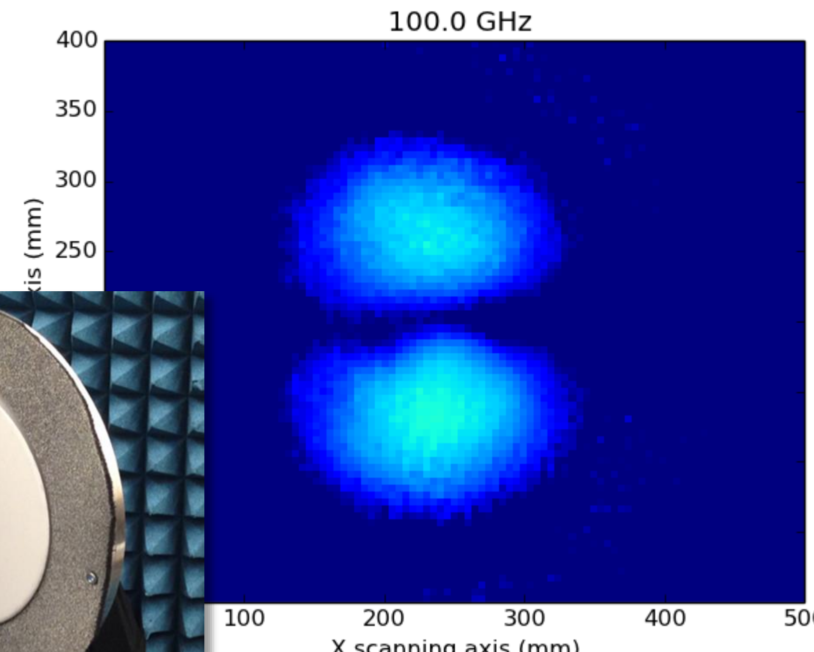
Bruno Maffei







Co-polar beam



Cross-polar beam

Modulator characterisation: Requirements

$$\mathbf{J}_{\rm hwp} = \begin{pmatrix} 1+h_1 & \zeta_1 e^{i\chi_1} \\ \zeta_2 e^{i\chi_2} & -(1+h_2)e^{i\beta} \end{pmatrix}$$

- Conversion of laboratory measurements into Jones' parameters
- HWP performance requirements from instrument requirements

Systematic	Parameters	Requirement	Goal
HWP efficiency	η_{HWP}		
Phase shift	β		
	σ_β	....	
Transmission	$\lvert\Delta h\rvert = \lvert h_1 - h_2\rvert$		
	$\lvert h_1\rvert, \lvert h_2\rvert$		
	$\sigma_{h_1}, \sigma_{h_2}$		
	T_C	....	
	T_L		
	$\lvert T_C - T_L\rvert$		
	σ_{T_C,T_L}		
Cross polarization	ζ_1, ζ_2		
	σ_{ζ_1,ζ_2}		
	σ_{ζ_1,ζ_2}	....	
	x-Pol		
	$\sigma_{\text{x-Pol}}$		
HWP induced ellipticity	ε_{HWP}		
Flatness[a]	Δx		
Modulated dis-homegeneity	$h^{\rm mod}$	....	
Thermal stability	NET_{HWP}		

➢ **Constraints on HWP's performance parameters and their knowledge accuracy**

Conclusions

- Many CMB projects are now successfully employing polarisation modulators. There is also a proposal to employ them on the satellite mission LiteBIRD.
- Proven reduction of unpolarised atmospheric 1/f noise leaking into polarisation
- Proven mitigation of instrumental systematics
- Many modulator technologies with increasing larger diameters are now available
- Difficult to define the best configuration due to the multiple options and the related and combined pros and cons