A few minutes on measuring polarisation

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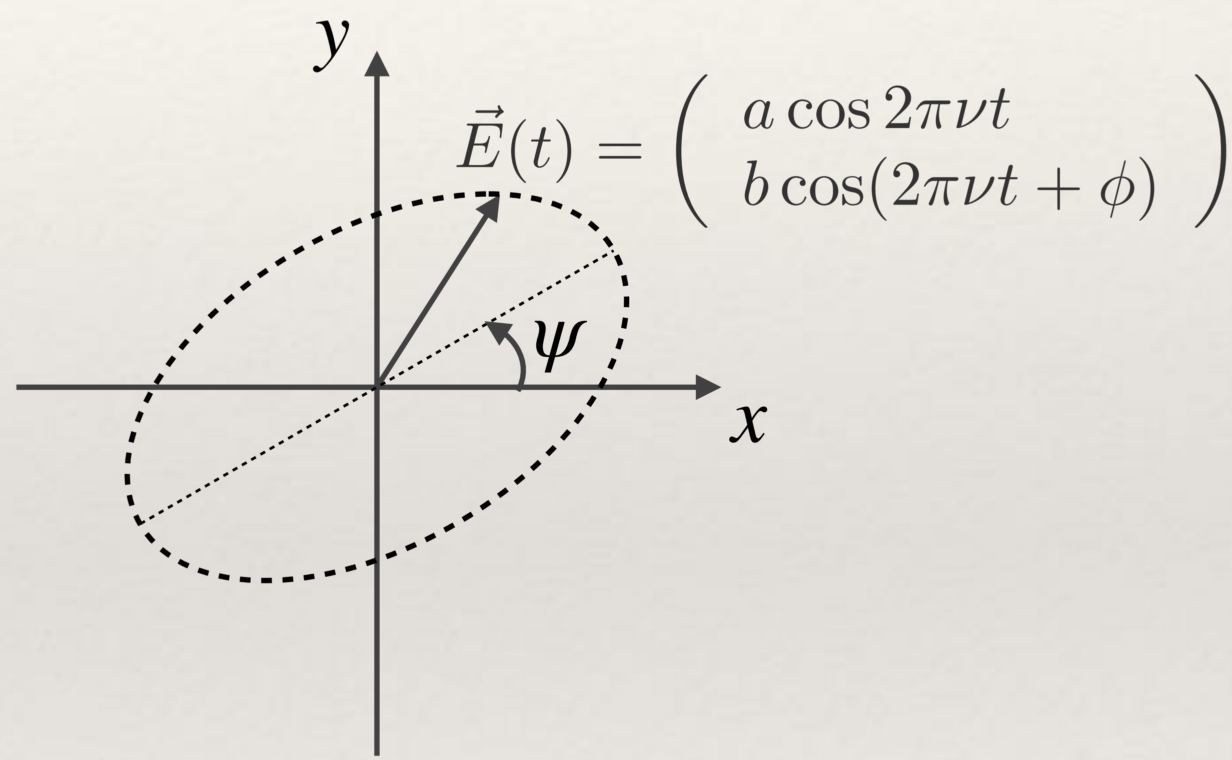
Intention

- Models of star or galactic emissions refer to degree and angle of polarisation, CMB cosmology refers to “E and B modes”… but these are not directly measurable by incoherent detectors
- The science cases are addressed in other talks of this workshop, so here I’ll focus on
  - ***What*** we actually measure
  - ***How*** it affects the design of a polarimeter and observations
- Not a review but rather an attempt to be pedagogical and illustrate principles on a particular case
- Experts may skip this talk ;-)

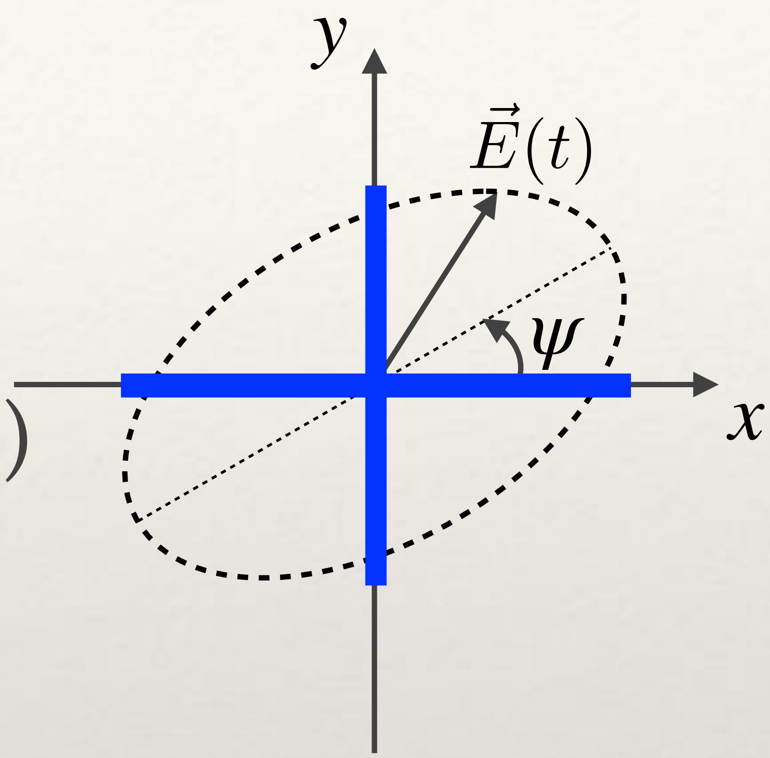
Polarisation basics

- Light travels towards us along the z axis
- Polarimetry aims at characterising the trajectory of the E field in the (x,y) plane
- Two particular (canonical) states are *circular* and *linear* polarisations
- Instruments can either detect the electric field ***or the intensity I=E²***



Polarisation basics

- I = "total intensity" is basis independent
- Two extra parameters (Q,U) are needed to describe the projection of the ellipse
- A last parameter (V) measures the rotation of E, but will be ignored hereafter.



$$I = I_x + I_y$$

$$Q_\psi = I_x - I_y$$

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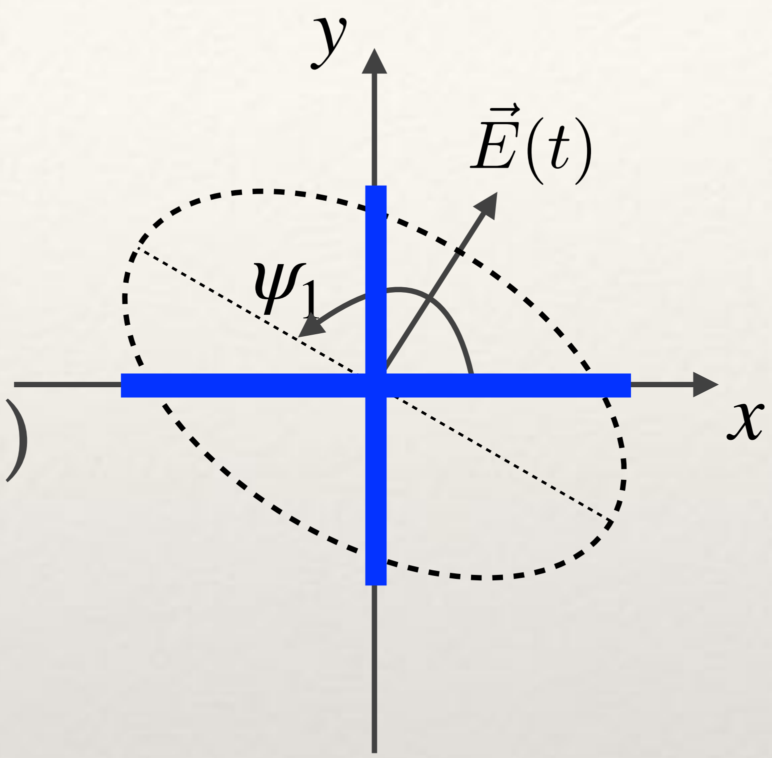

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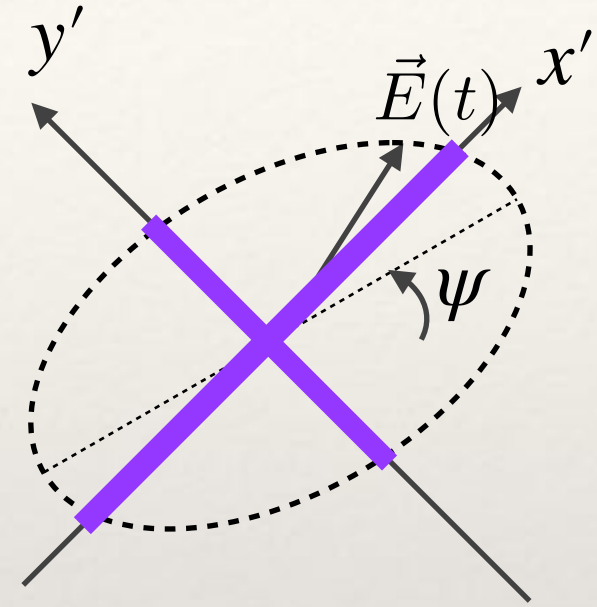

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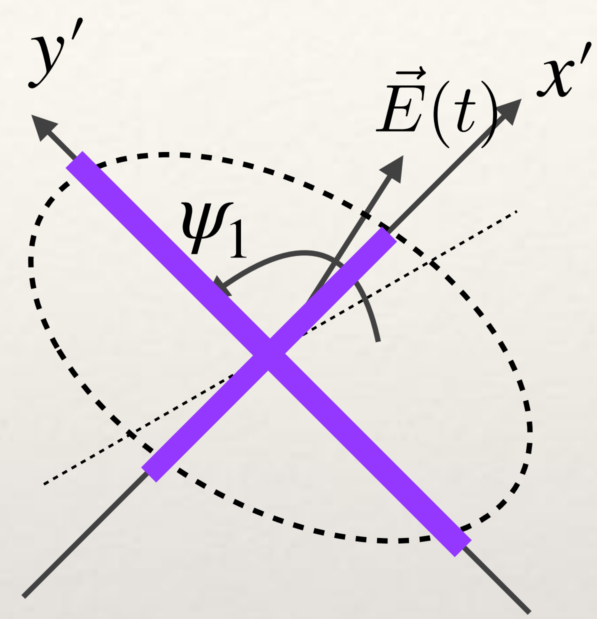


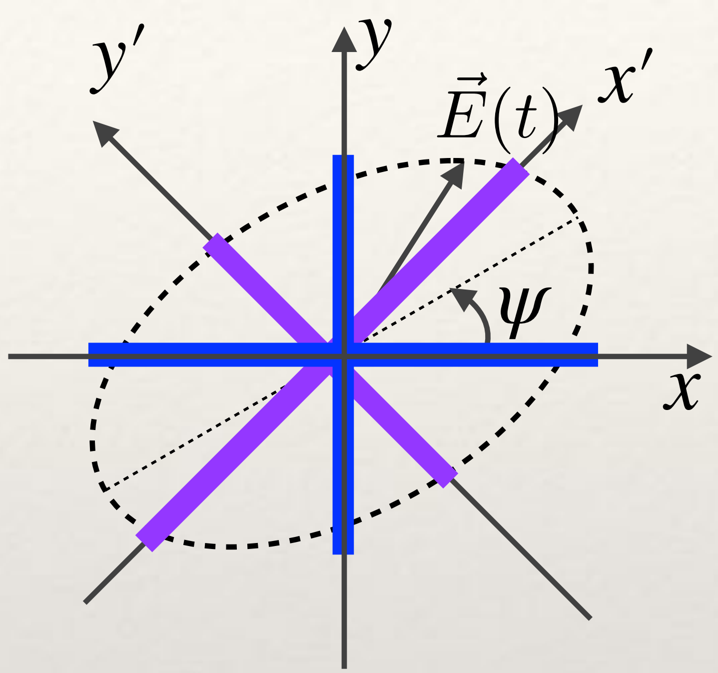
$$I = I_x + I_y$$

$$Q_{\psi_1} = I_x - I_y = Q_\psi$$

$$U_{\psi_1} = I_{x'} - I_{y'} \neq U_\psi$$

Polarisation basics

- I, Q, U, V are the Stokes parameters (G. G. Stokes, 1819-1903)
- Operations on these parameters are described by Mueller matrices (H. Mueller, 1900-1965)
- They relate to the degree and angle of polarisation:



$$I = I_x + I_y$$

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$$p = \frac{\sqrt{Q^2 + U^2 + V^2}}{I} \qquad \psi = \frac{1}{2}\arctan(U, Q) \qquad Q = pI\cos 2\psi \qquad U = pI\sin 2\psi$$

- **An incoherent detector sensitive to polarisation measures, with its direction oriented at alpha w.r.t. x measures:**

$$m = \frac{1}{2}(I + Q\cos 2\alpha + U\sin 2\alpha)$$

Polarisation basics

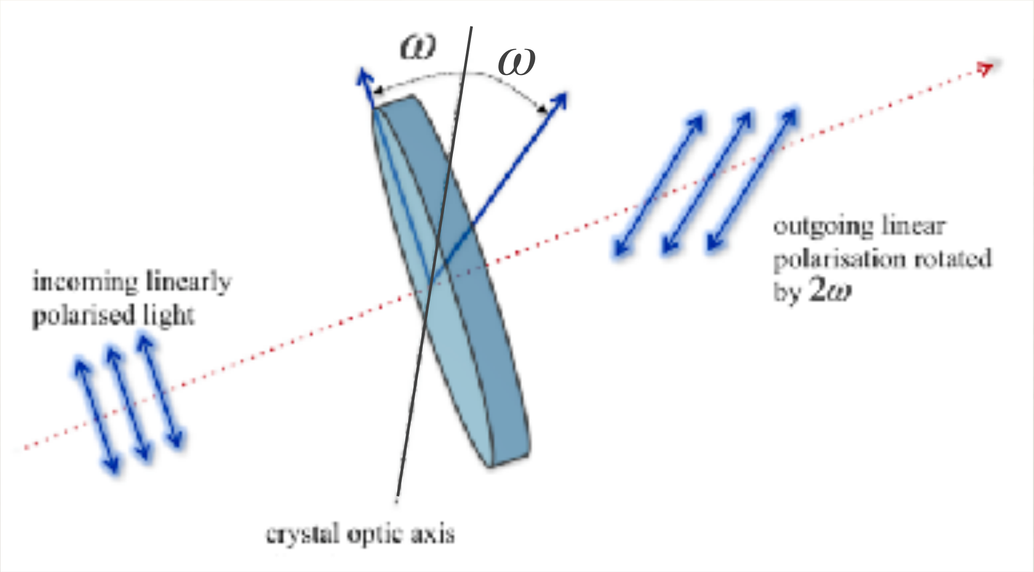
$$m = \frac{1}{2}(I + Q\cos 2\alpha + U\sin 2\alpha)$$

- For each map pixel, we need at least 3 different angles in [0,180[to derive I, Q and U. Minimum covariance is attained when these angles are evenly distributed.
  - 1/Different orientations of the polarised detectors and combine them (e.g. Archeops, Planck, BICEP/Keck, QUaD, SPT3G…)
  - Or 2/Enough angle variation per detector to make a map of I, Q, U per detector, and then combine them.
- To vary the orientation of a detector:
  - 1/Let the sky rotate w.r.t. the instrument: simple instrumental design, but slow compared to sky noise and electronic noise
  - Or 2/Actively rotate the sky polarisation: Maxipol, SCUpol, CLASS, ACT, Simons O., PILOT, NIKA2, LiteBIRD

Half Wave Plate polarimetry

HWP + polariser —> $m = \frac{1}{2}(I + Q\cos 4\omega + U\sin 4\omega)$

- On the bright side
  - The same detector can measure I, Q and U
  - Releases constraints on the focal plane design
  - Releases constraints on the scanning strategy
  - Offers huge angular redundancy and homogeneity, so optimal covariance
  - Enables null tests
  - Rejects the sky noise
  - Rejects the electronic noise



Example: NIKA2 @IRAM's 30m

	Array 1&3	Array 2
Reference Wavelength [mm]	1.15	2.00
Reference Frequency [GHz]	260	150
Number of valid detectors[a]	952&961	553
FWHM[c] [arcsec]	11.1 ± 0.2	17.6 ± 0.1
NEFD[i] $[\mathrm{mJy} \cdot \mathrm{s}^{1/2}]$	30 ± 3	9 ± 1
M_s[j] $[\mathrm{arcmin}^2 \cdot \mathrm{mJy}^{-2} \cdot \mathrm{h}^{-1}]$	111 ± 11	1388 ± 174

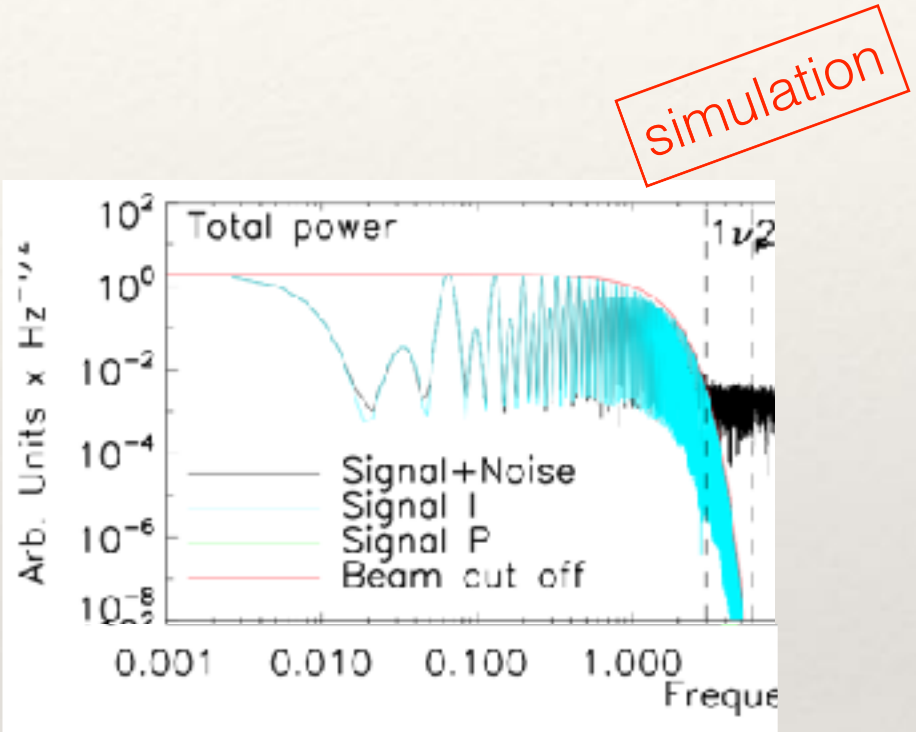
Perotto+20

- Kinetic Inductance Detectors
- 6.5 arcmin FOV
- Linear polarisation at 1.2mm
- HWP continuously rotating at 3Hz

HWP polarimetry

$$m = \frac{1}{2}(I + Q\cos 4\omega + U\sin 4\omega)$$

- Total intensity is at low frequencies, damped by the beam



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HWP polarimetry

$$m = \frac{1}{2}(I + Q\cos 4\omega + U\sin 4\omega)$$

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- Q and U are pushed to frequencies around 4 times the HWP rot. freq.
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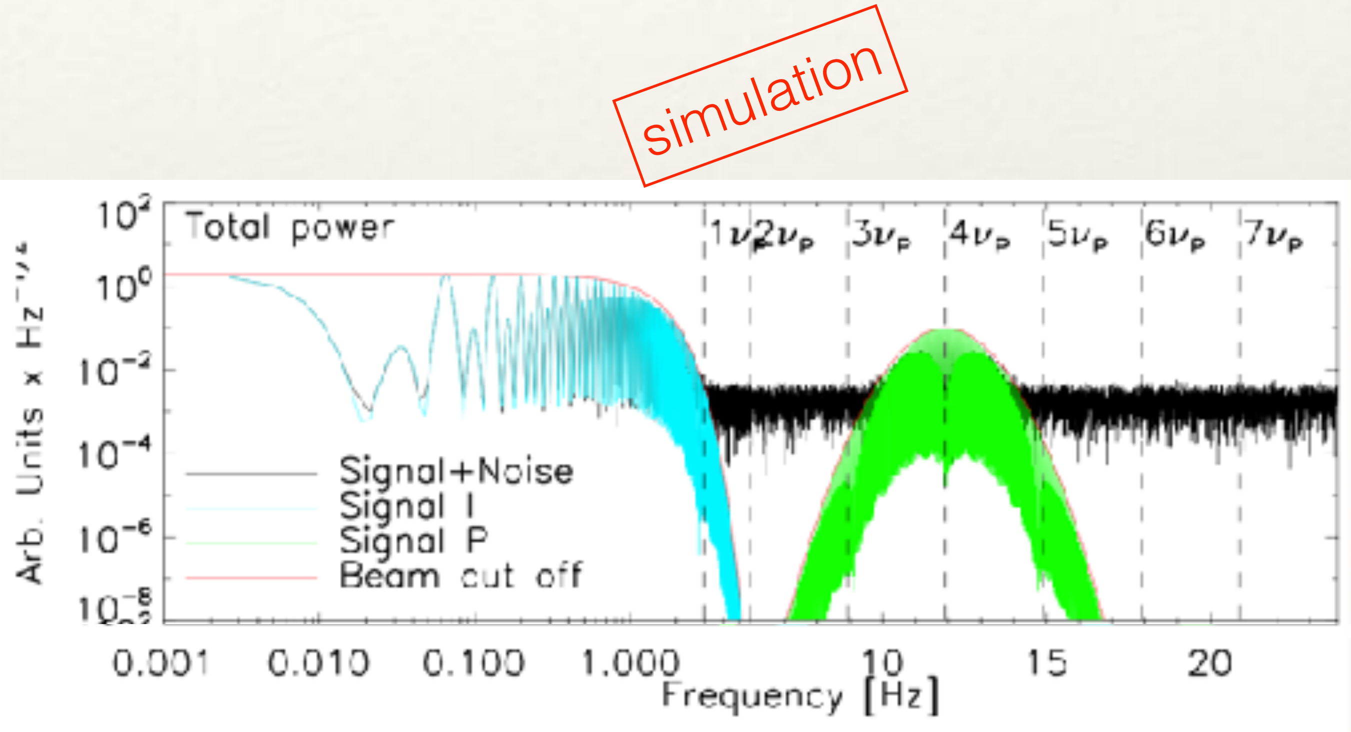

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- Locking-in + low-pass filtering allow to separate and recover I, Q, U per detector timeline.
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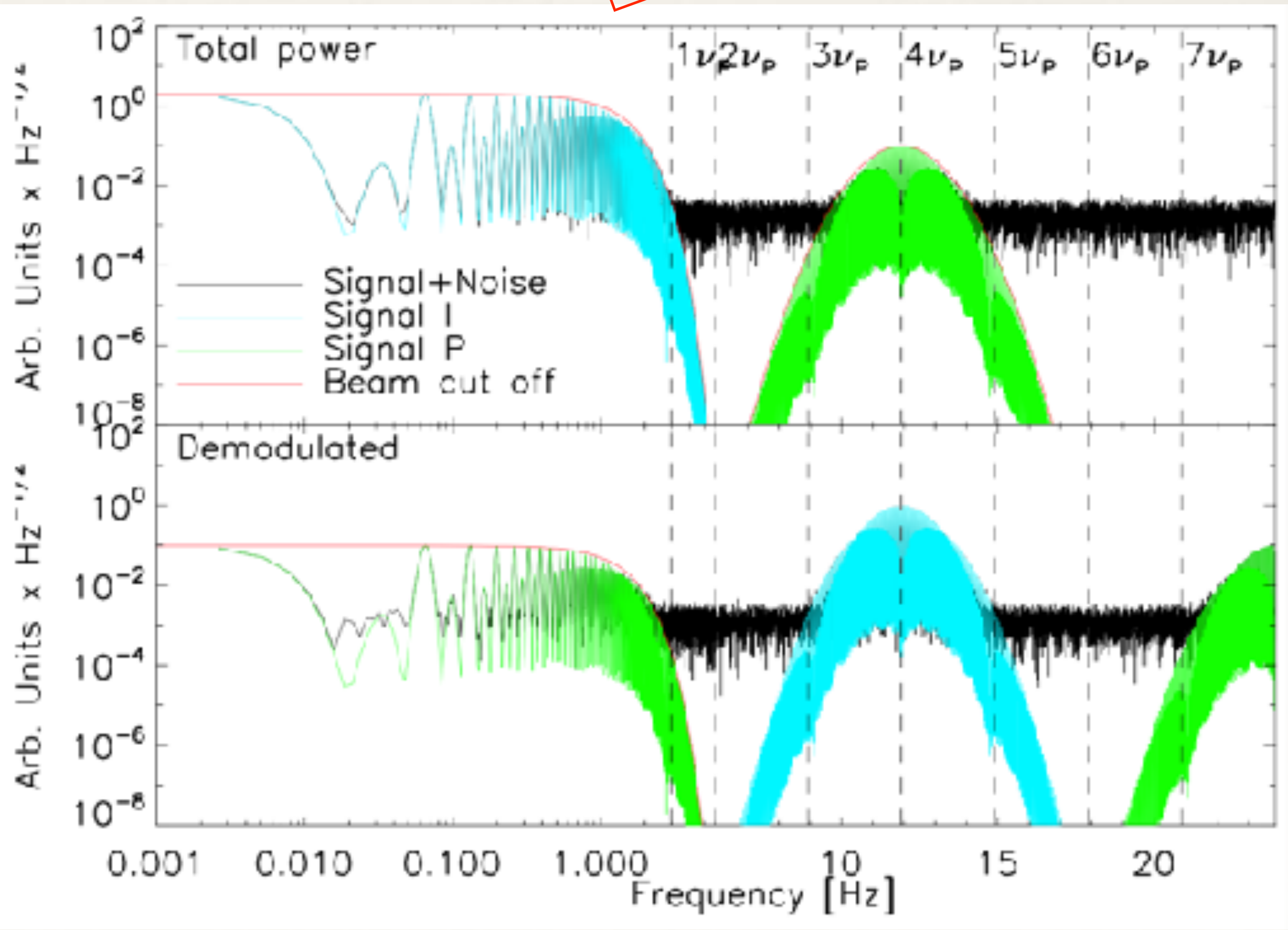
simulation



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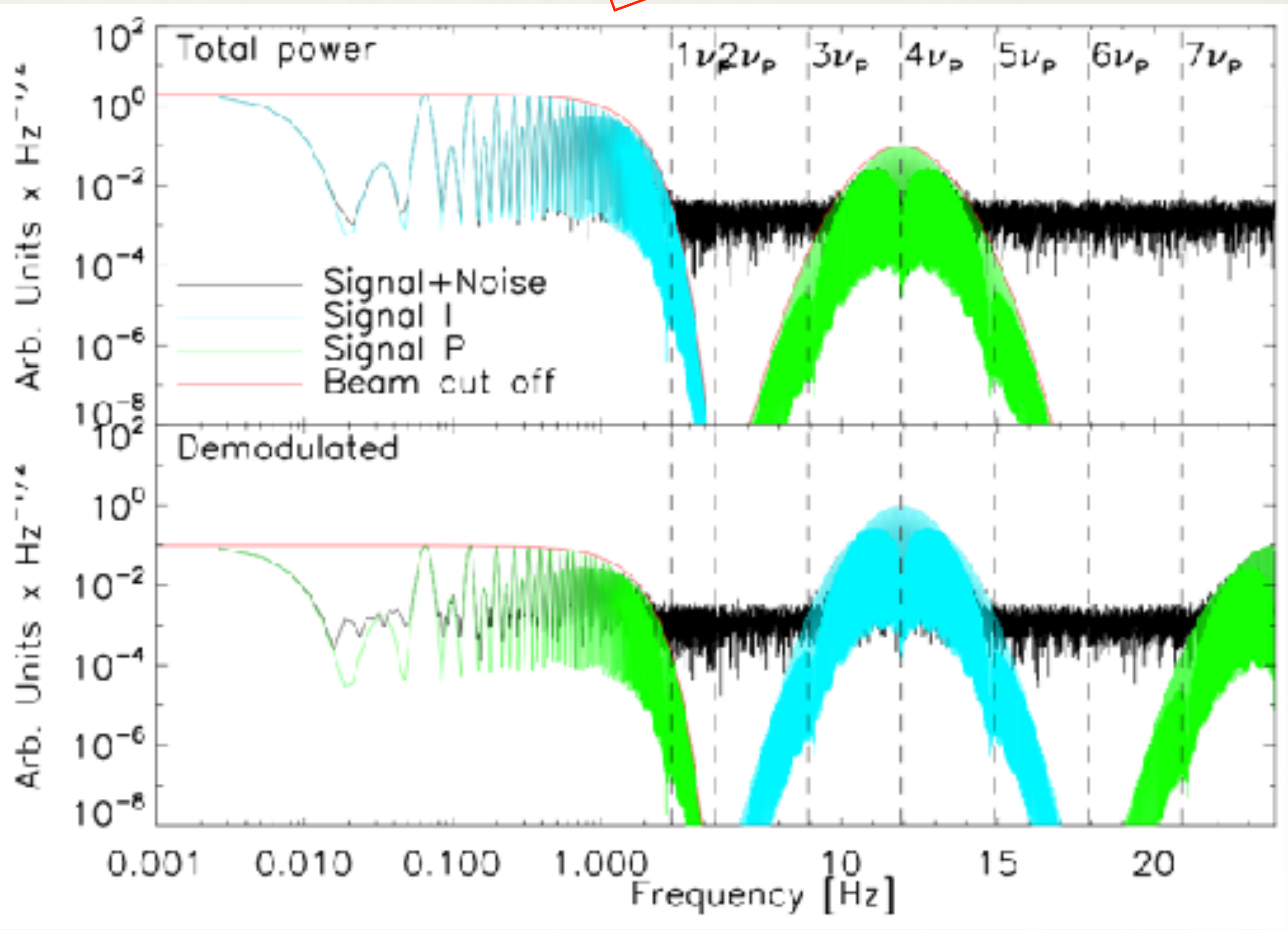
HWP polarimetry

$$m = \frac{1}{2}(I + Q\cos 4\omega + U\sin 4\omega)$$

- Total intensity is at low frequencies, damped by the beam
- Q and U are pushed to frequencies around 4 times the HWP rot. freq.
- Locking-in + low-pass filtering allow to separate and recover I, Q, U per detector timeline.
- Rotating the HWP above 1Hz puts polarisation at frequencies where sky noise is negligible and instrumental noise is white
- Note: constraints on the observation scanning speed vs HWP rotation frequency to prevent I and P bandpasses overlap

simulation



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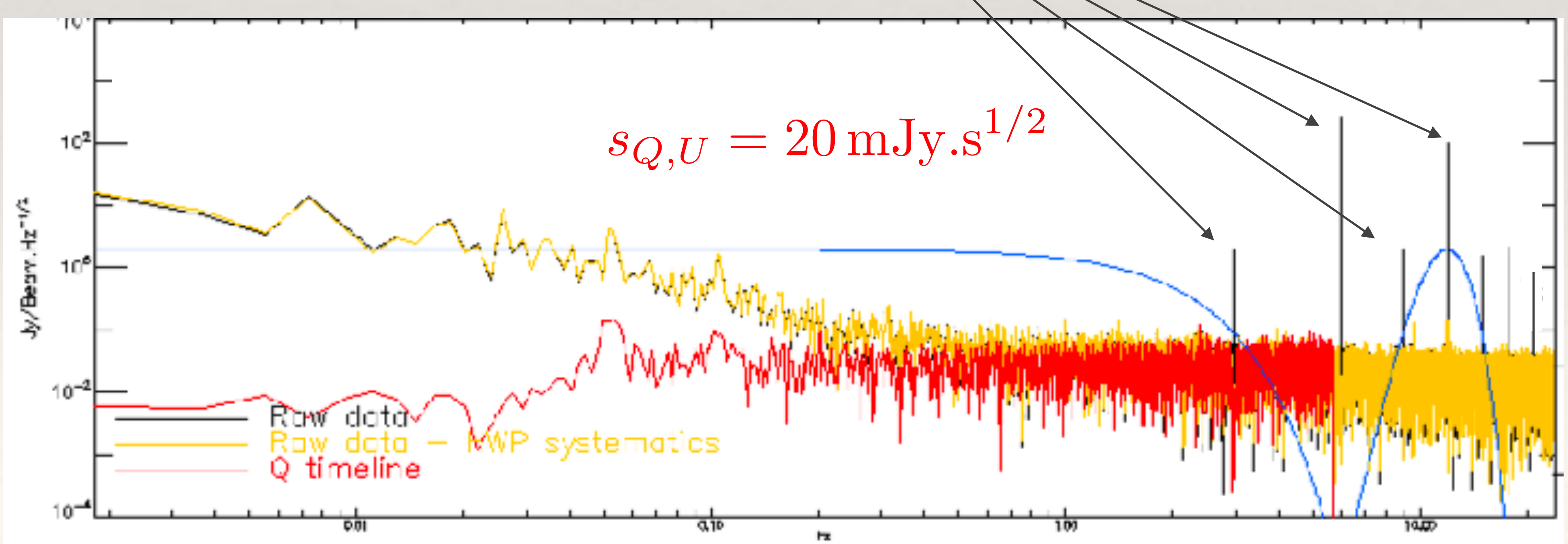
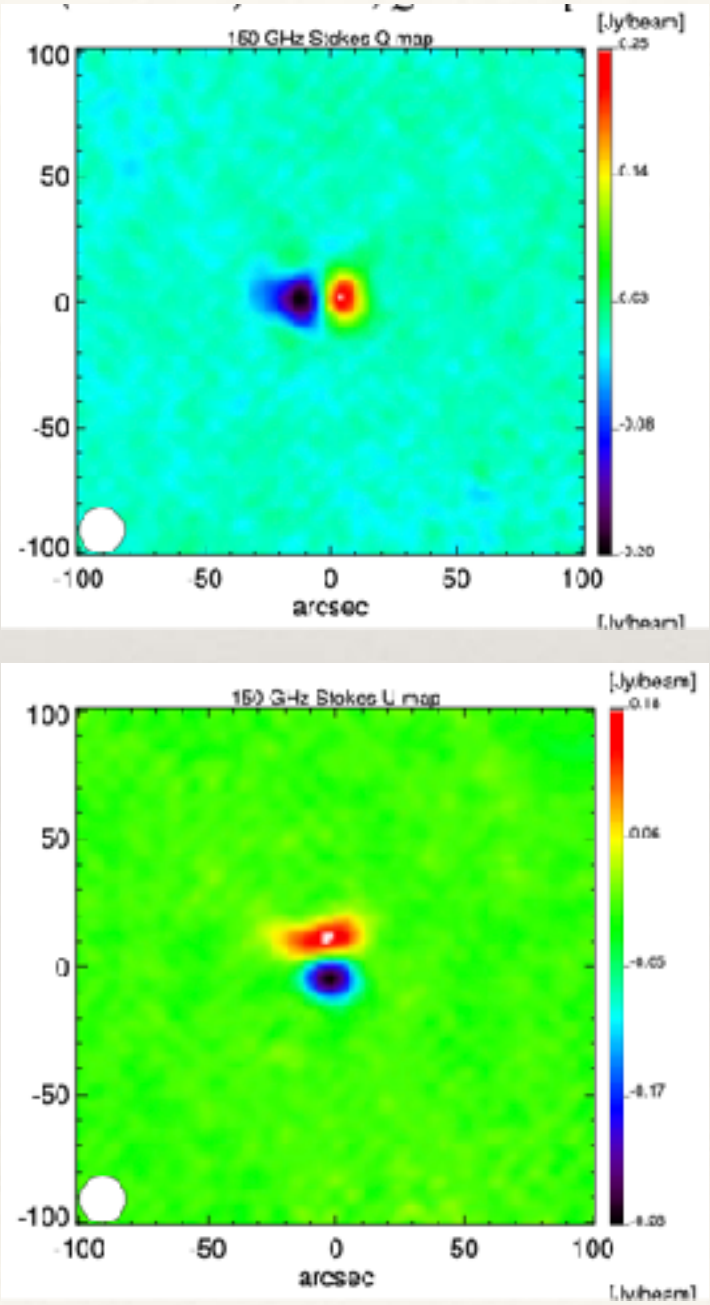
HWP polarimetry

- On the dark side
  - Extra piece of hardware
  - Extra constraints on the electronics, the acquisition rate and thus the volume of data to reduce.
  - Need fast detectors
  - Strong additional systematic signal due to background modulation and reflections at the HWP level
- But the bright side prevails !



Systematic effects

- I to P: instrumental polarisation.
  - Hard to design and build telescope/instruments with less than a few % IP. Comparable to many science cases. Hard to characterise
  - IP can vary with the telescope's focus, elevation, temperature…
- Rotation Q-U mixing:
  - Absolute orientation of instrument on the sky ?
  - For local observables, it's "just" a parameter, but for non local observables (e.g. CMB E-B modes), it is more problematic.
- Polarisation efficiency m = 0.5*(I+**r***(Qcos2a + Usin2a))
- Need for *calibrators* ==> PROTOCALC and COSMOCAL (A. Ritacco's talk)



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Measuring polarisation in short

- 3 parameters I, Q, U instead of only one
- Continuously rotating a HWP at about 1 Hz
  - Allows high angular redundancy, homogeneity and null tests. Not to mention beam related IP systematics.
  - Requires fast detectors
  - Produces a systematic modulation of the background, that, although huge, can be controlled.
- Usually, I is 10 to 100 times (at least…) larger than Q and U, so instrumental polarisation I to P in general is the most critical and may vary in time in a way that is non trivial and difficult to assess. It relates to beams.
- Strong need for calibrators in the far field, unpolarised (for the beam and IP), polarised for the orientation and efficiency

Being sensitive to polarisation doesn't make a polarimeter

R. H. Hildebrand