Modulation in CMB Polarization Experiments

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Measurement

- Most measurements are made by comparing the signal from an unknown source to that from stable or known sources.
- In a properly conceived calibration scheme, both the transfer function of the instrument and the unknown signals are measured with respect to the stable standards.
- The photometric system is put into SI units using an absolutely known calibrator

Time Scales

- If the comparison is done at a low temporal rate, the measurement is considered to be a “total power” measurement.
- If the comparison is done at a high rate, the signal is said to be modulated

Null Experiments

- The reference signal may come from an internal source (FIRAS) or another point on the sky (WMAP, DMR, Planck).
- For CMB Polarization measurements, one can use adjacent locations on the sky (SPIDER, EPIC) or modulate the polarization state of the input light (EBEX, Poincare).

Null Experiments

- It is useful to design experiments which are null, that is, have a reference signal nearly equal to the expected input to be measured.
  - Relaxes gain stability requirements
    - Low S/N per measurement.
  - Reduces required dynamic range.

Calibration Process

- Simplest Data Model:

$$D(x,t) = (S(x) + O_r)G(t) + O_e(t)$$

- Our ability to calibrate depends on the correlation time of the calibration functions G(t) and O(t); we have to “Nyquist sample” these calibration functions. We thus need to compare the unknown to a reference at this Nyquist frequency. We must know *a priori* that O(t) and G(t) are appropriately band limited. This must be assured by experiment design, and verified by validation measurements.

Required Stability

- If the comparison of signals occurs on a time scale t, the required gain stability can be written:

$$D(x,t) - D(0,t) < \frac{e_n}{\sqrt{t}}$$

  - If offsets are stable over time t,

$$\delta G < \frac{e_n}{S(x)\sqrt{t}}$$

Measuring the Signature of Inflation

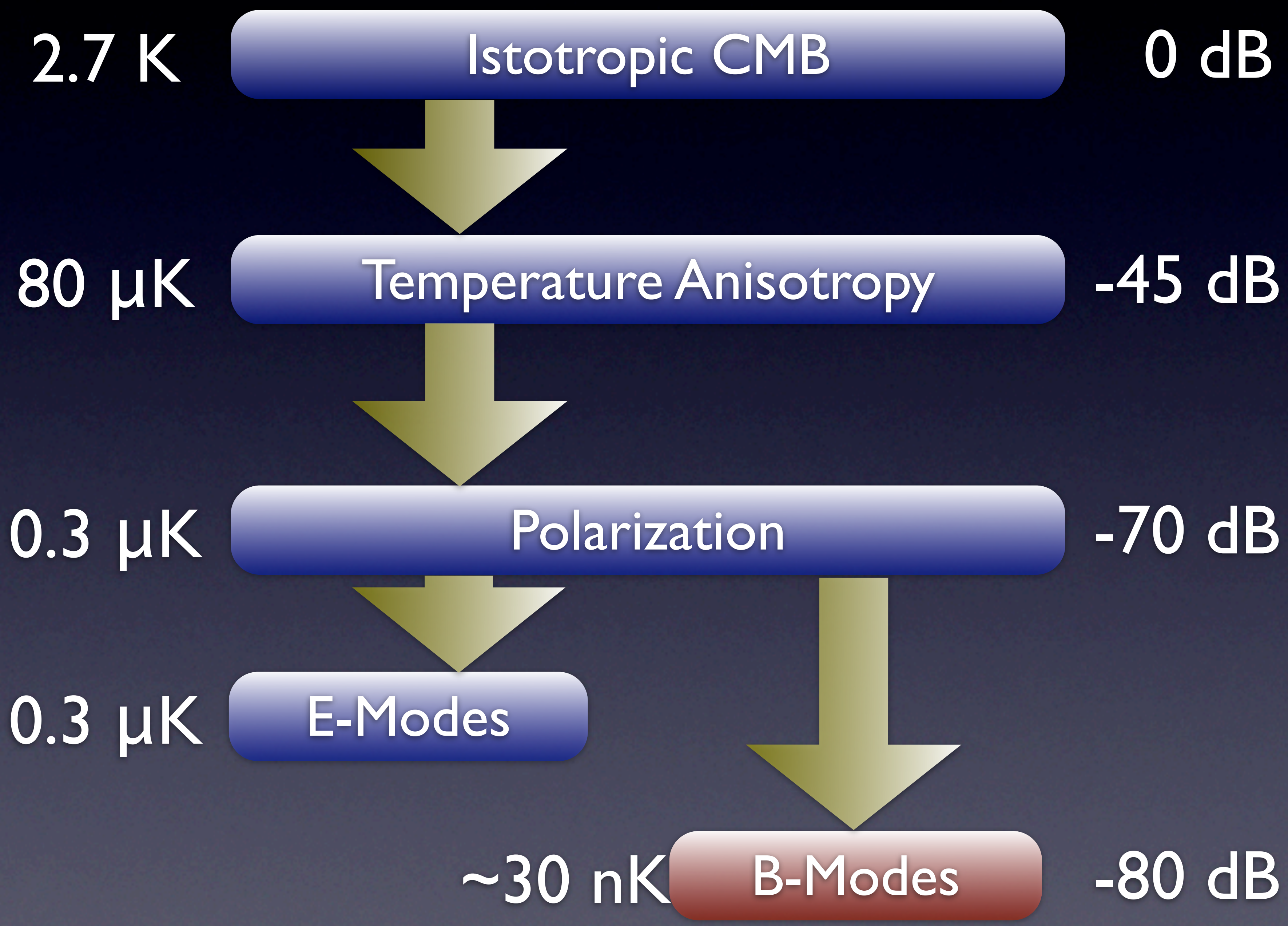
Instrument Concept- enabling technologies must be developed.

Instrument Design- studies of potential trade-offs guide the placement of channels

Separate Polarization from Unpolarized Flux → Use Multi-frequency Maps to separate Galactic from CMB Polarization → Angular Spectrum Separates Inflation Sigature from "E-modes"

The instrument should measure "Zero" for an unpolarized source

CMB Signal Hierarchy



Polarization Measurement Design

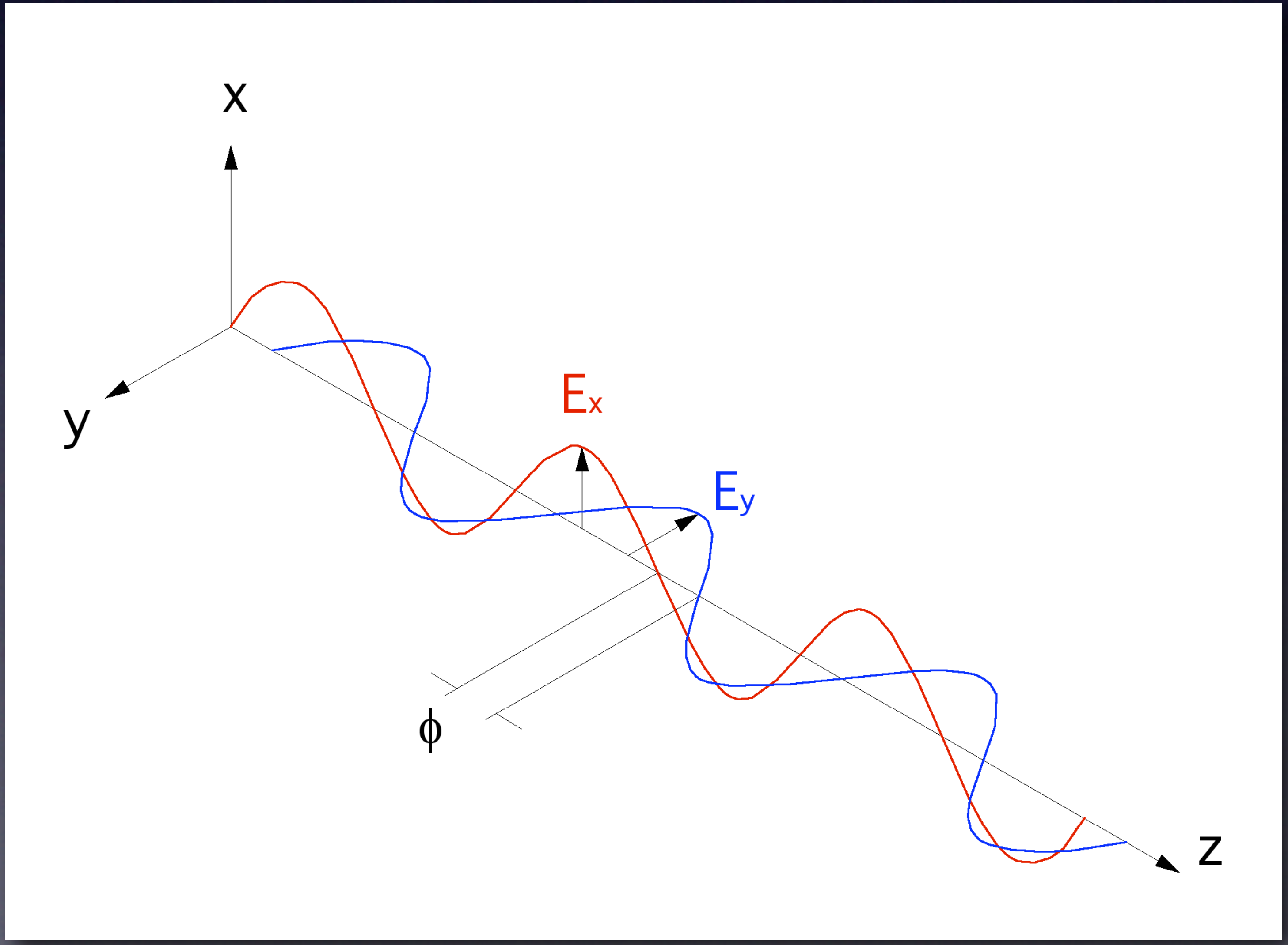
- We measure a vector quantity at each field point
  - Can design experiment to spatially modulate or to modulate polarization
  - Different modulation schemes require different degrees of instrument stability on differing time scales
  -

Spatial Modulation

- Advantages
  - Small “offsets” (primarily CMB fluctuations)
  - Simplicity
- Disadvantage
  - Sensitivity to beam shape, etc.

Polarization Modulation- systematic variation of the polarization state of the incoming signal for subsequent demodulation and detection.

Modulating polarization without mapping $T \rightarrow Q,U$ requires the introduction of a phase between 2 orthogonal polarizations



2 free parameters:

1. Orientation of the basis (eg. HWP)

2. Magnitude of phase shift (eg. Faraday Rotator, VPM)

Polarization Modulation Choices

- Speed: The speed of modulation will determine which noise sources can by "Nyquist Sampled" by the modulation.

- Location: *"The closer a modulator is to the sky in the signal path, the more potential systematic effects it can modulate and thus stabilize."* -TFCR 2005

- Orthogonality: Polarization modulation must be orthogonal to other time-varying signals that are potential systematics

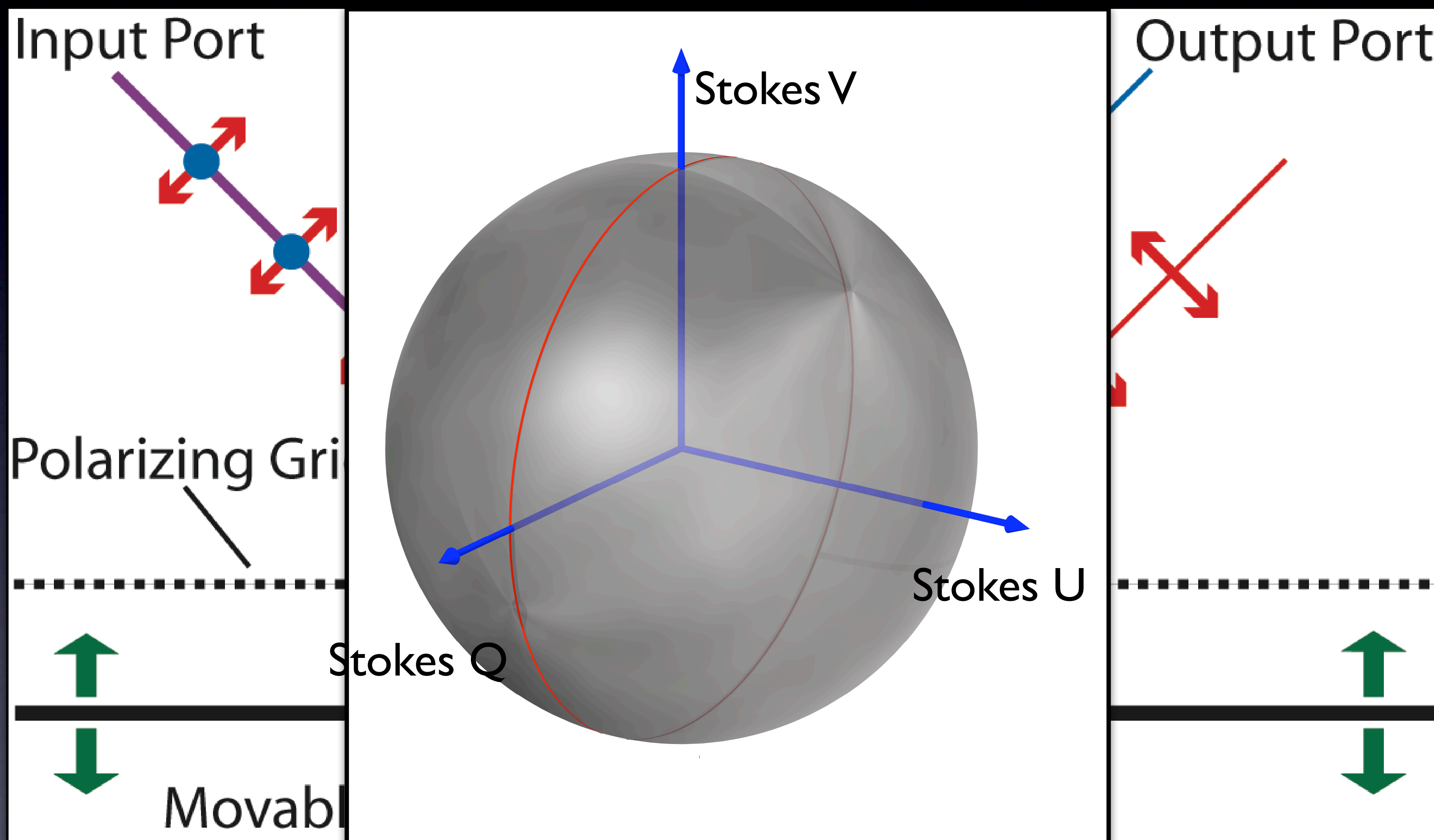
Candidates

- Rotating half wave plate
- VPM

Similarities and Differences

- Similarity
  - Both change the state of polarization by delaying V with respect to H
- Differences
  - Half wave plate rotates the polarization from Q to U, changes the basis coming into the instrument
  - VPM Modulates the amplitude of Q by going from Q to -Q through V. No change in basis
    - To what degree is this an advantage?

Variable-delay Polarization Modulators (VPMs)



$$Q_{detector} = Q\cos\phi + V\sin\phi$$

Polarization Modulation

- Advantages
  - Insensitivity to polarizaton properties, beam details of instrument
  - Null experiment - no sensitivity to spatial fluctuations
  - No spatial scanning requred
    - Each point independently measured

Polarization Modulation

- Disadvantages
  - Some designs provide no sensitivity to I
  - Offset must be minimized
    - Easy for cryo inst.

Summary

- Modulation, either spatial or polarization, is necessary to stabilize system response
- The order of modulation is a key design choice, and will drive the experiment design
- Alternatives should be tested to provide deeper understanding of the costs and benefits