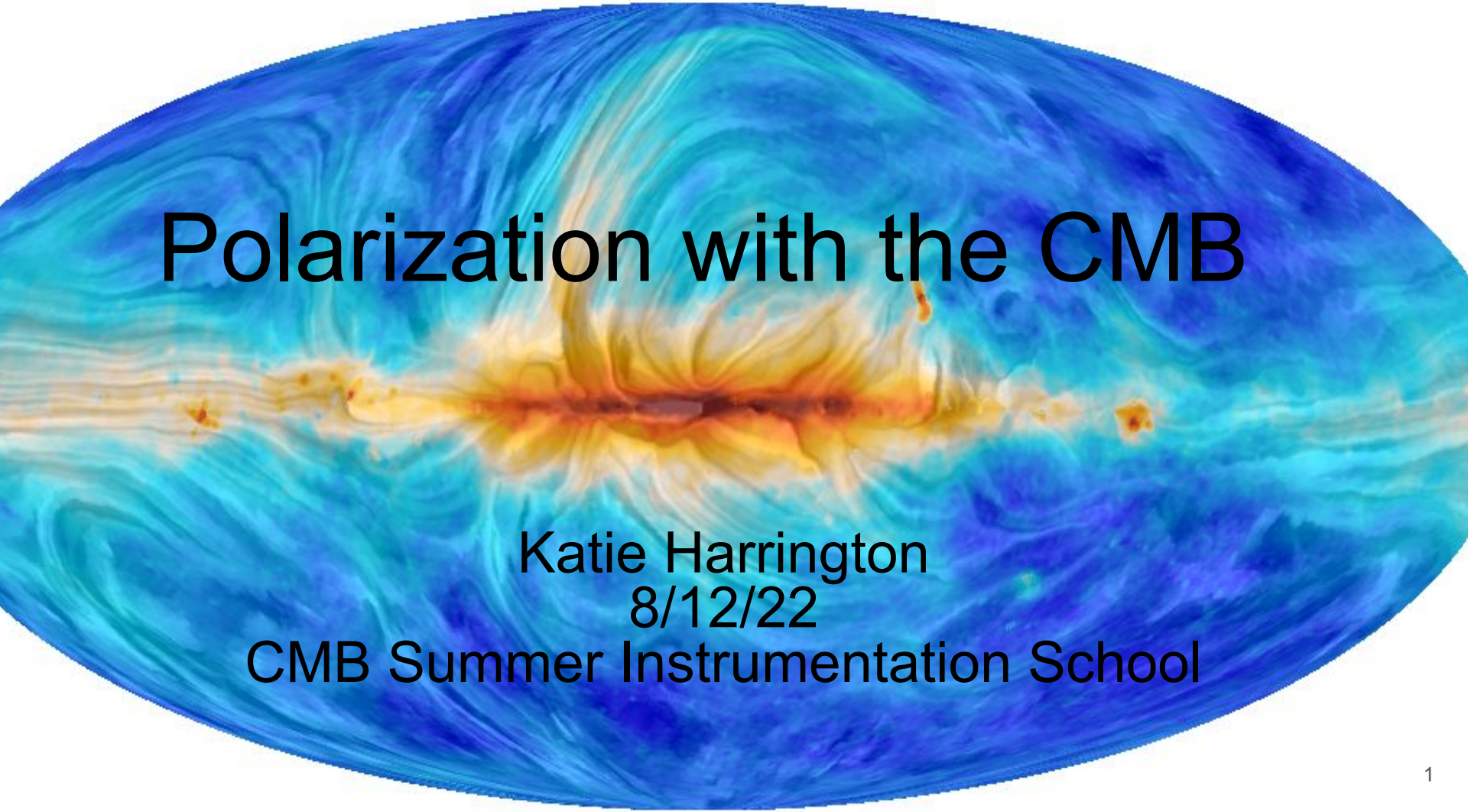


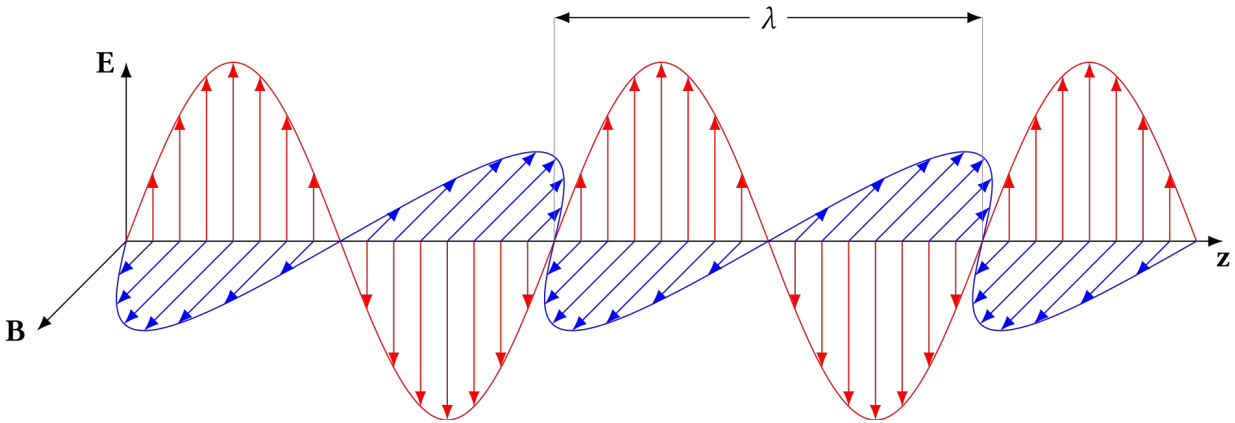
Polarization with the CMB

Katie Harrington
8/12/22
CMB Summer Instrumentation School

Outline

- **What is polarization?**
- Why do we want to measure CMB polarization?
- How do we measure polarization?
  - Polarization Systematics
  - Polarization Modulation

Electromagnetic Waves



Direction the wave is traveling

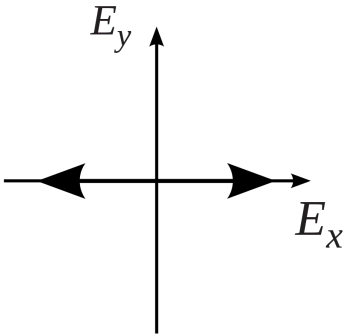
$$\vec{E}(\vec{r},t) = \vec{E}_0 \exp\left(i(\omega t - \vec{k}\cdot\vec{r})\right)$$

Amplitude and **polarization** of the wave. Complex Vector.

Image from Wikipedia

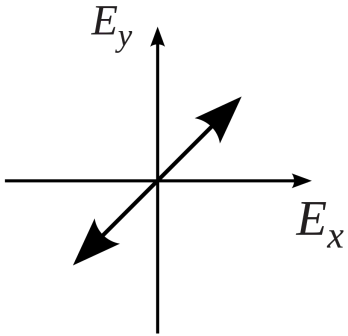
Polarization States

$$\vec{E}_0 = E_x e^{i\delta_x} \cdot \hat{x} + E_y e^{i\delta_y} \cdot \hat{y}$$



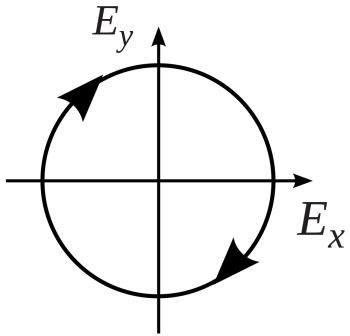
$E_y = 0$

Horizontal



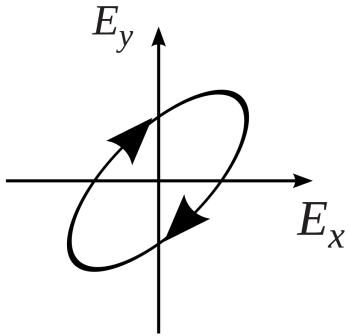
$E_x = E_y, \delta_x = \delta_y$

±45°



$E_x = E_y, \delta_x = \delta_y \pm \frac{\pi}{2}$

Circular



$E_x \neq E_y, \delta_x \neq \delta_y$

Elliptical

Image from Wikipedia

Polarization Vectors

$$\vec{E}_0 = \begin{bmatrix} E_x e^{i\delta_x} \\ E_y e^{i\delta_y} \end{bmatrix}$$

Jones Vectors

- Often more intuitive
- Complex Numbers
- Single Frequency
- Fully polarized light **only**

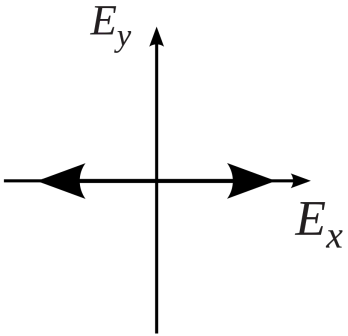
Stokes Vectors

- Real Numbers
- Can be integrated over frequency
- Can represent partially polarized light

$$S = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} |E_x|^2 + |E_y|^2 \\ |E_x|^2 - |E_y|^2 \\ 2\mathbf{Re}\left(E_x E_y e^{i(\delta_x - \delta_y)}\right) \\ -2\mathbf{Im}\left(E_x E_y e^{i(\delta_x - \delta_y)}\right) \end{bmatrix}$$

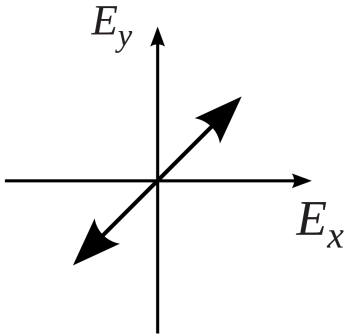
Stokes Vectors

$$S = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} |E_x|^2 + |E_y|^2 \\ |E_x|^2 - |E_y|^2 \\ 2\mathbf{Re}\left(E_x E_y e^{i(\delta_x - \delta_y)}\right) \\ -2\mathbf{Im}\left(E_x E_y e^{i(\delta_x - \delta_y)}\right) \end{bmatrix}$$



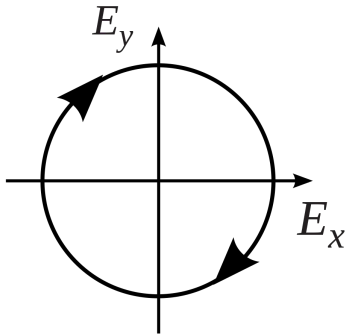
Horizontal

$$I = +Q$$
$$U = V = 0$$



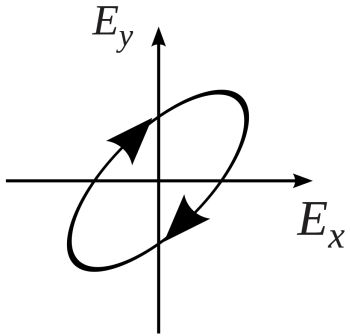
±45°

$$I = +U$$
$$Q = V = 0$$



Circular

$$I = +V$$
$$Q = U = 0$$



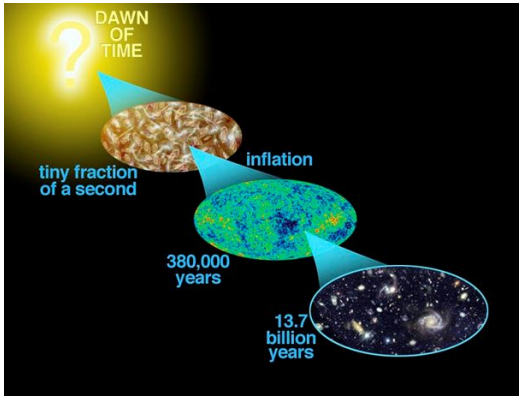
Elliptical

$$I = \sqrt{Q^2 + U^2 + V^2}$$
$$Q \neq U \neq V$$

Outline

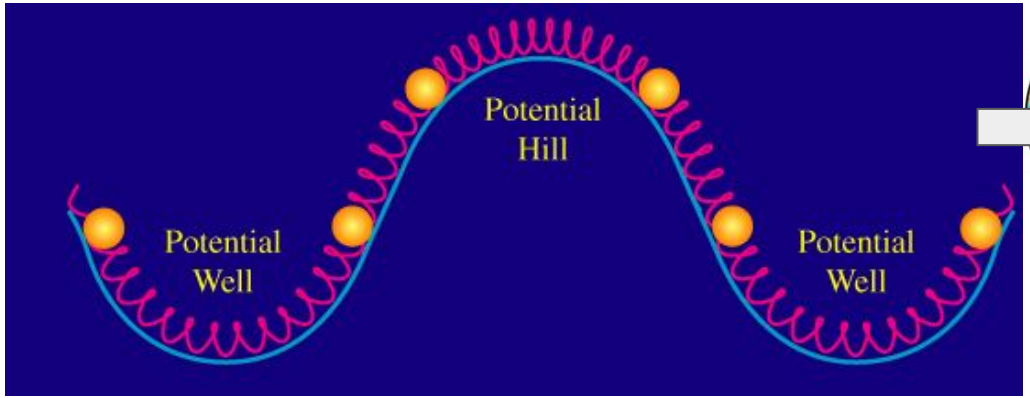
- What is polarization?
- **Why do we want to measure CMB polarization?**
- How do we measure polarization?
  - Polarization Systematics
  - Polarization Modulation

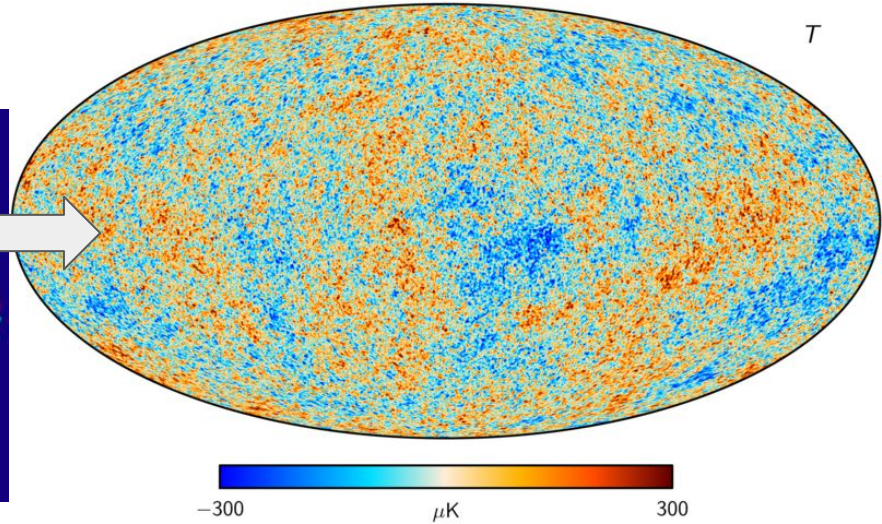
Cosmic Microwave Background



Inflation seeds initial scale-invariant **quantum fluctuations** in the early universe.

Density perturbations → Temperature Anisotropies





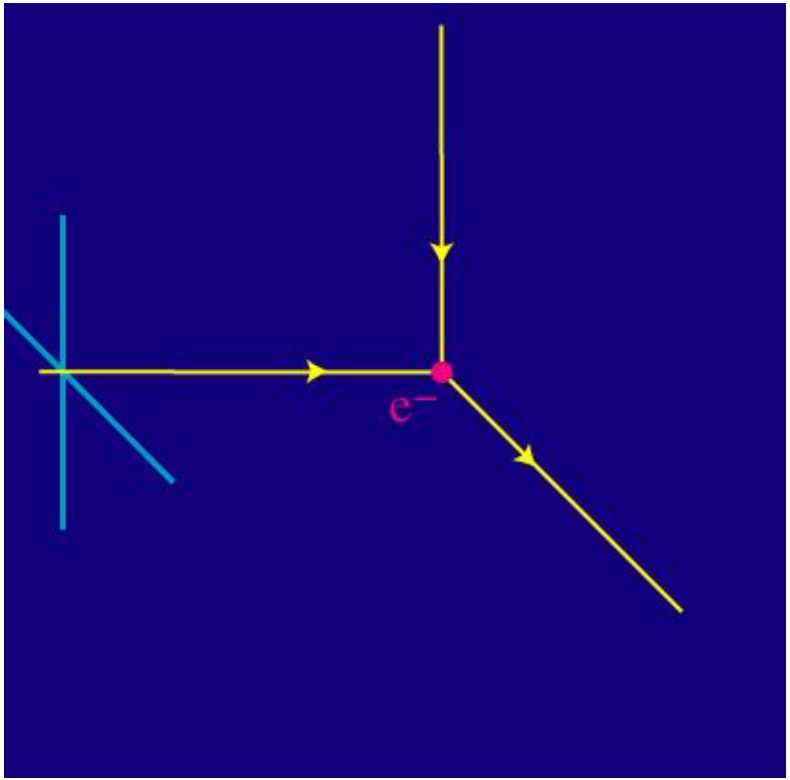
Gif by Wayne Hu

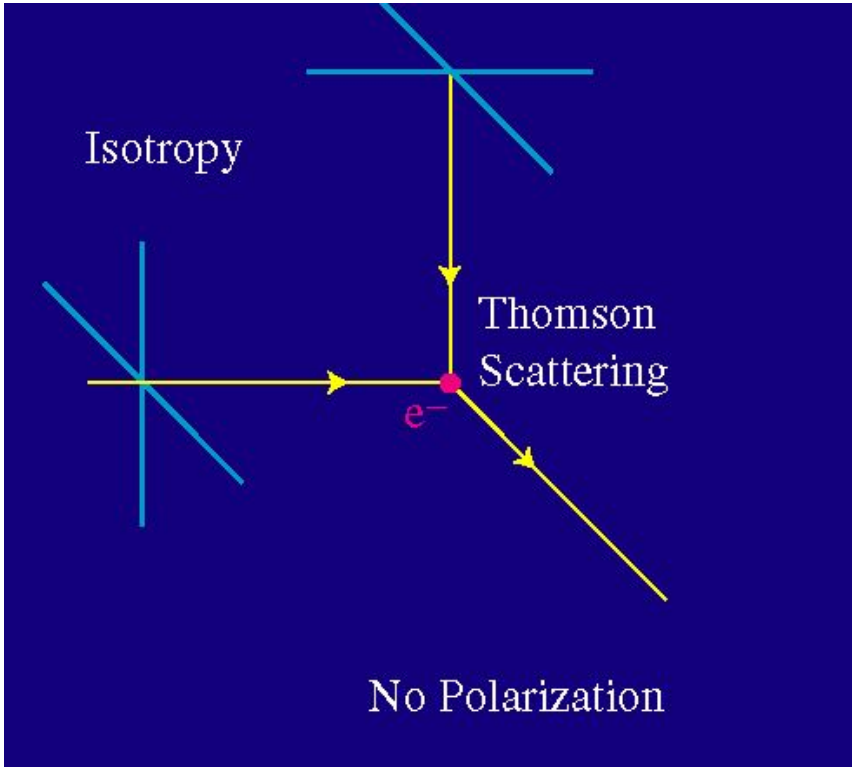
Planck CMB Temperature Map

gifs by Wayne Hu

CMB Polarization

Polarization from the early universe comes from Thomson scattering.

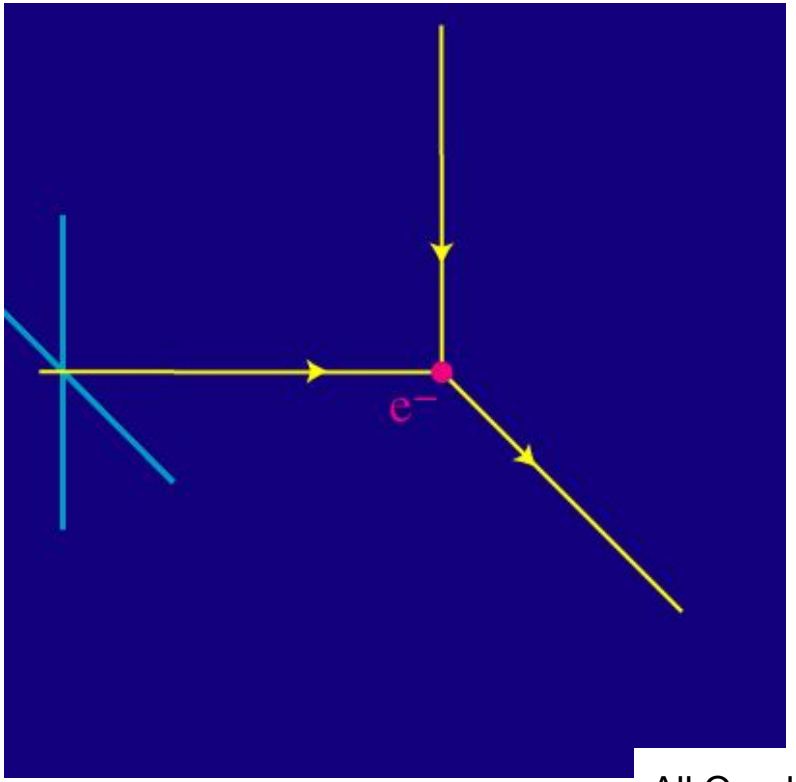


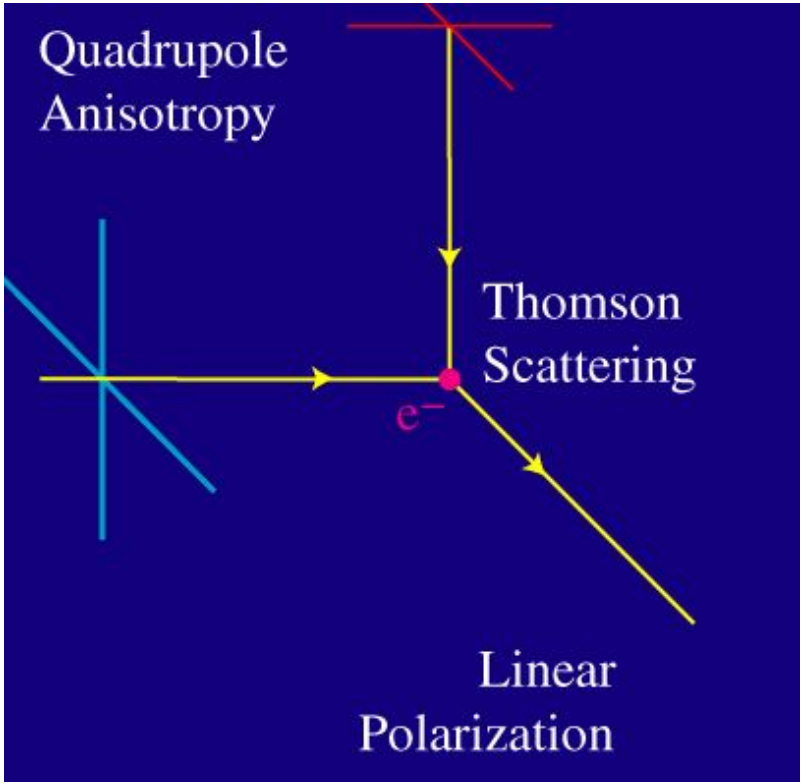


CMB Polarization

gifs by Wayne Hu

Polarization from the early universe comes from Thomson scattering.

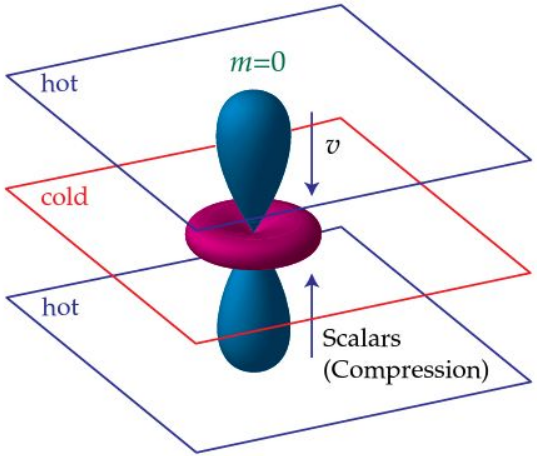




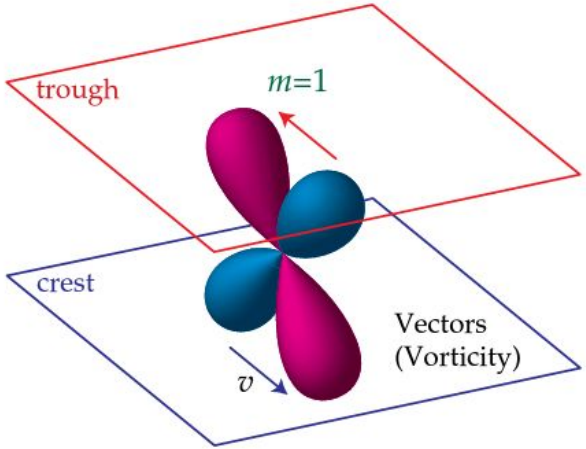
All Quadrupole Anisotropies lead to net linear polarization

Types of Quadrupole Moments

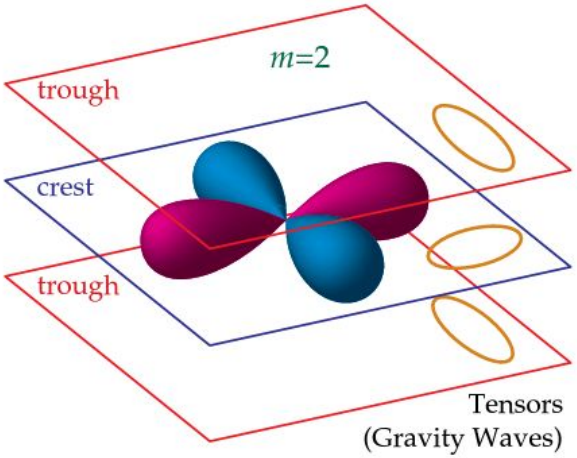
Scalar



Vector

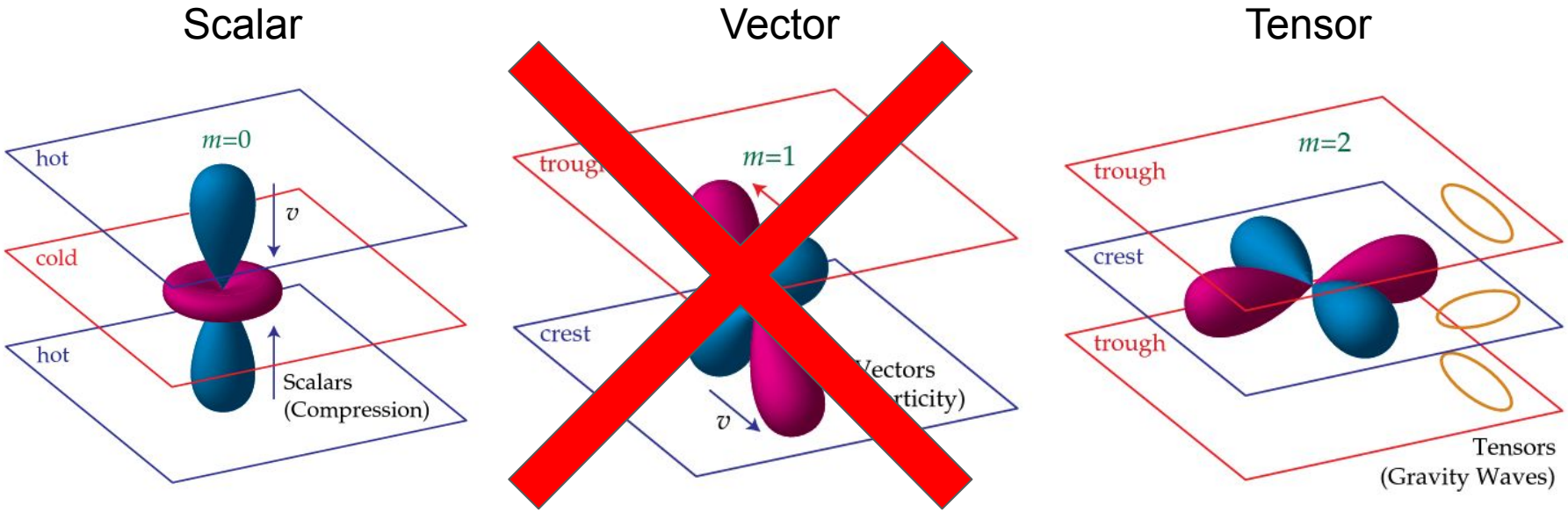


Tensor



(Adapted from Hu, W. and White, M., 9706147)

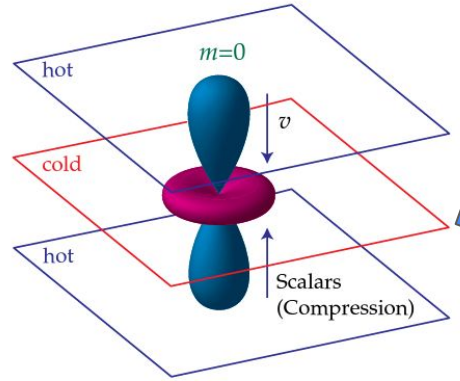
Types of Quadrupole Moments

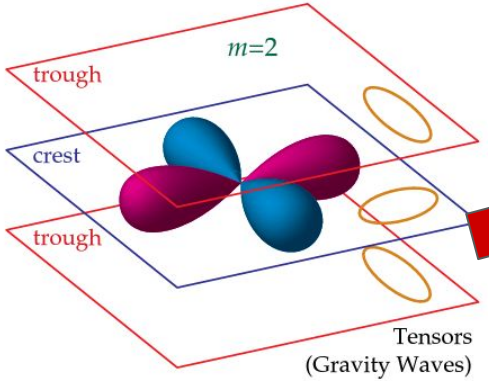


Early universe plasma physics damps out vector quadrupole moments

(Adapted from Hu, W. and White, M., 9706147)

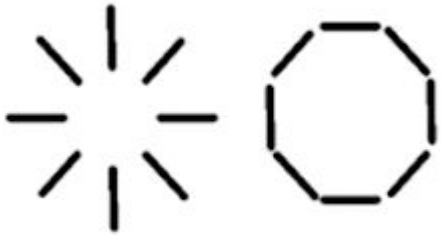
Cosmic Microwave Background Polarization



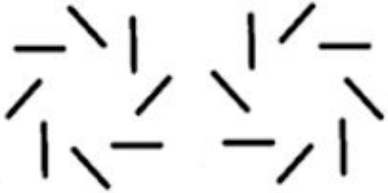


Thomson Scattering during periods of changing ionization states.

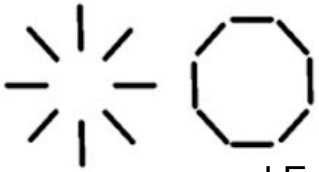
Take 3D universe and convert to what we see on the sky.



E-Modes

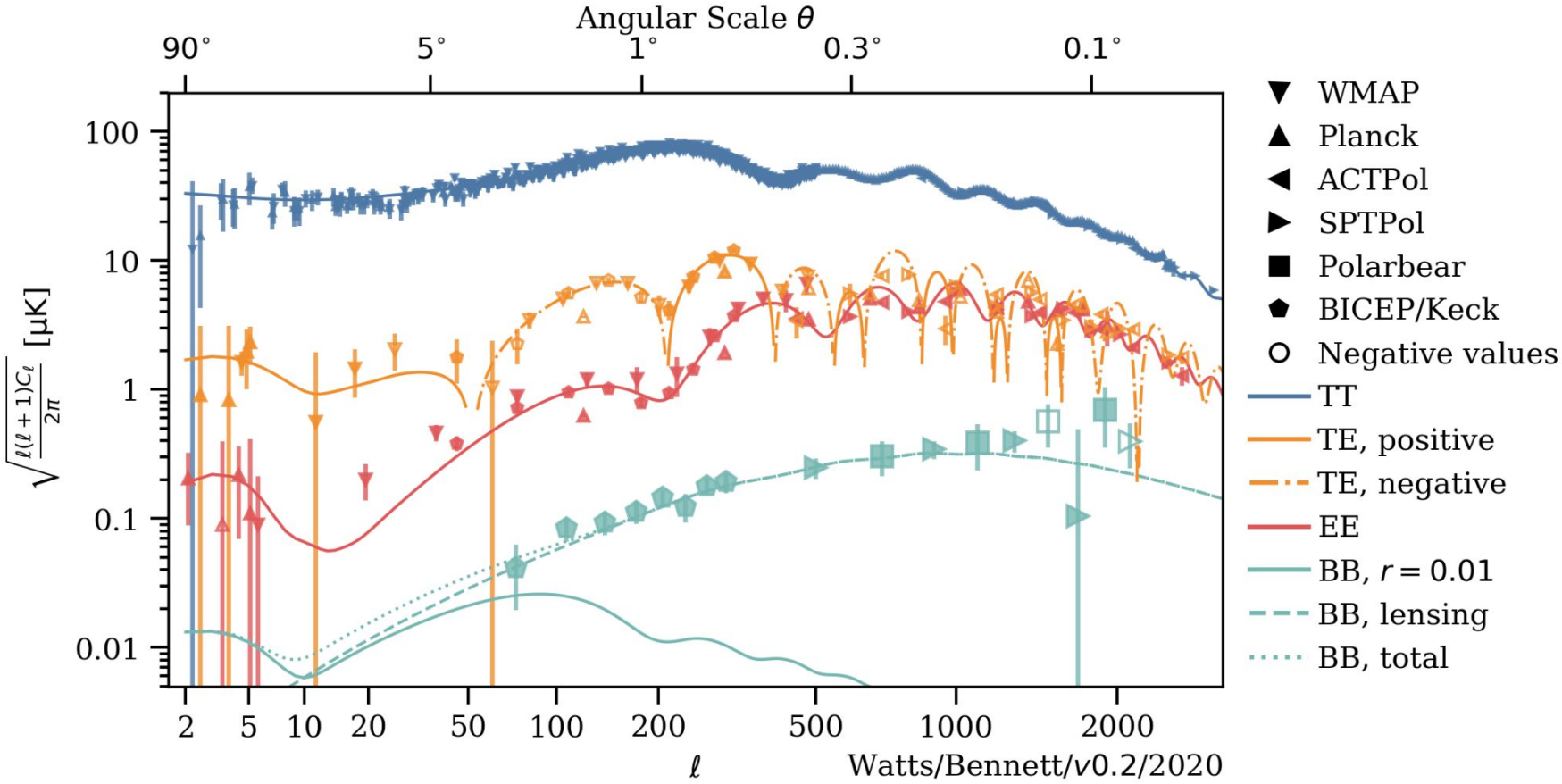


B-Modes



and E-Modes

CMB Power Spectrum



Observational Challenge

Polarized CMB
Fluctuations
~ nK - uK

Unpolarized CMB
Fluctuations
~100s uK

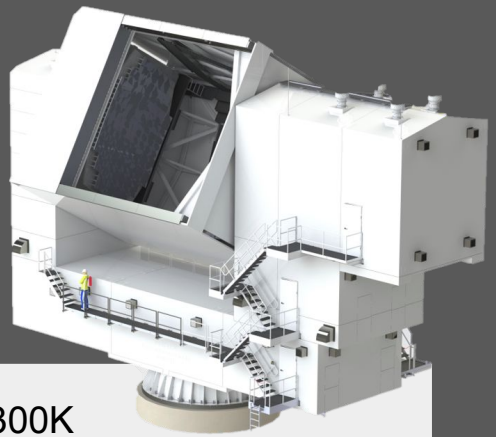
Galactic Emission
~100s uK

Polarized Galactic Emission, ~10uK

CMB
Monopole
2.7 K

Atmosphere,
Wind,
Clouds
~15 K

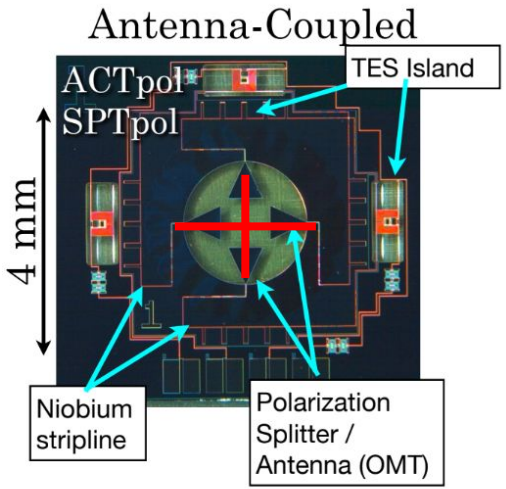
Ground, 300K

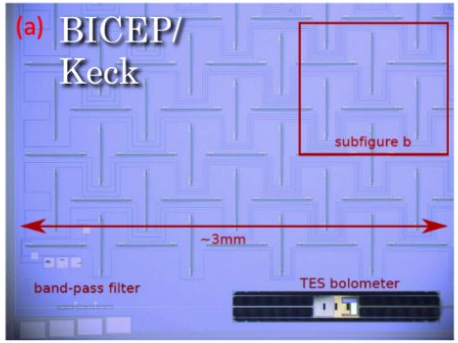


Outline

- What is polarization?
- Why do we want to measure CMB polarization?
- **How do we measure polarization?**
  - Polarization Systematics
  - Polarization Modulation

Detecting Polarization with CMB Instruments





Both TES and KID detectors are *power* detectors
→ Need polarization selection before detectors

$$d_1 = \frac{1}{2}(I + Q)$$

$$d_2 = \frac{1}{2}(I - Q)$$

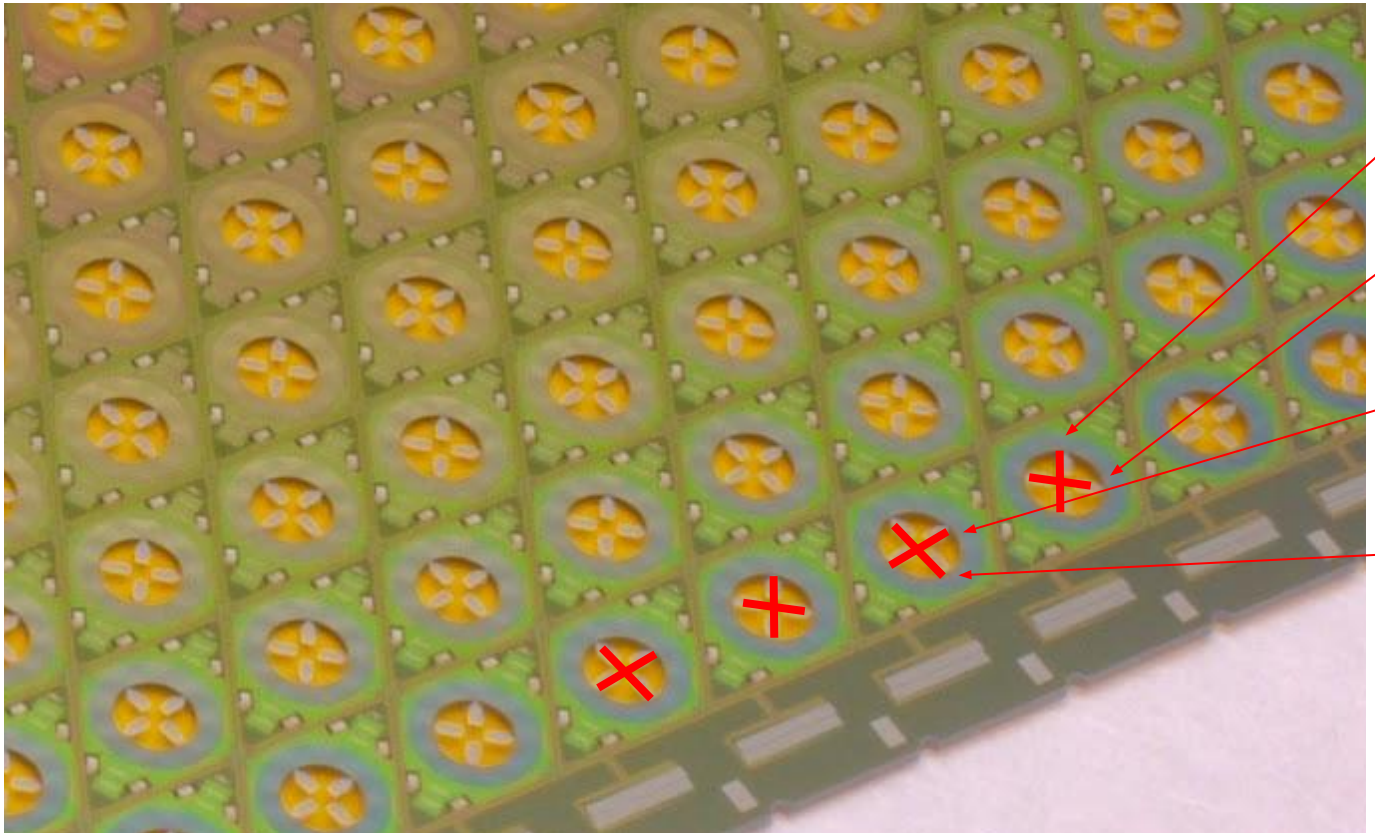
Two Orthogonal Detectors can be differenced to get one of the linear polarization states.

In a perfect world:

$$I = d_1 + d_2$$

$$Q = d_1 - d_2$$

Getting Complete Polarization Angle Coverage



$$d_1 = \frac{1}{2}(I + Q)$$

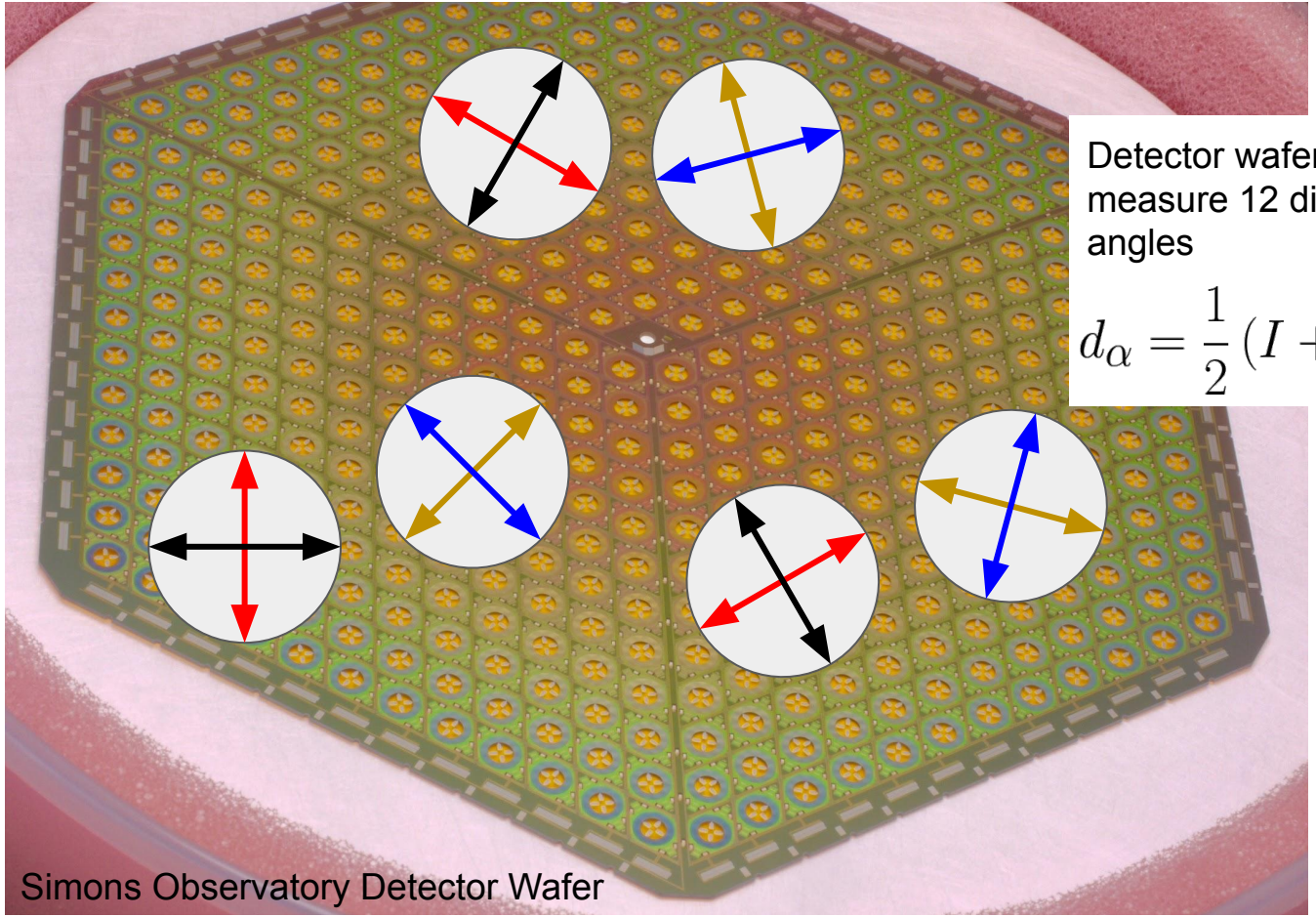
$$d_2 = \frac{1}{2}(I - Q)$$

$$d_3 = \frac{1}{2}(I + U)$$

$$d_4 = \frac{1}{2}(I - U)$$

Simons Observatory Detector Wafer

Getting Complete Polarization Angle Coverage



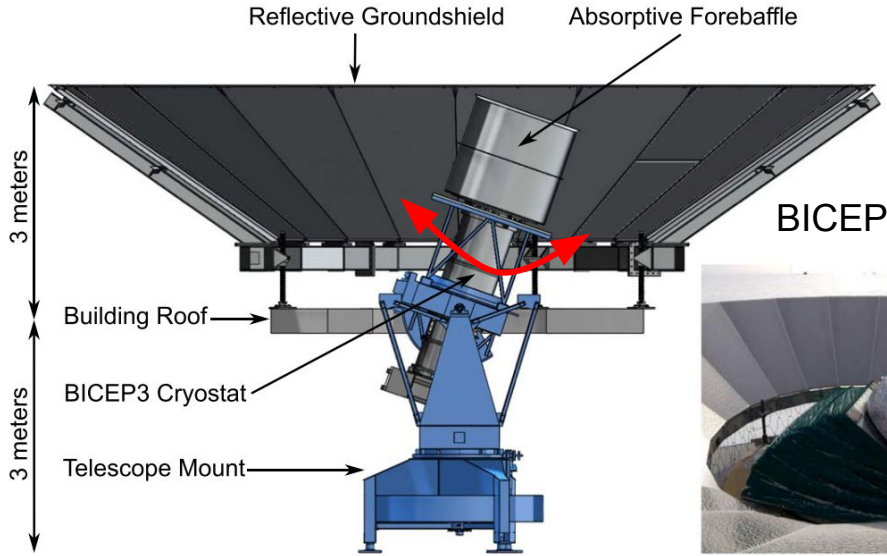
Detector wafer designed to simultaneously measure 12 different linear polarization angles

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

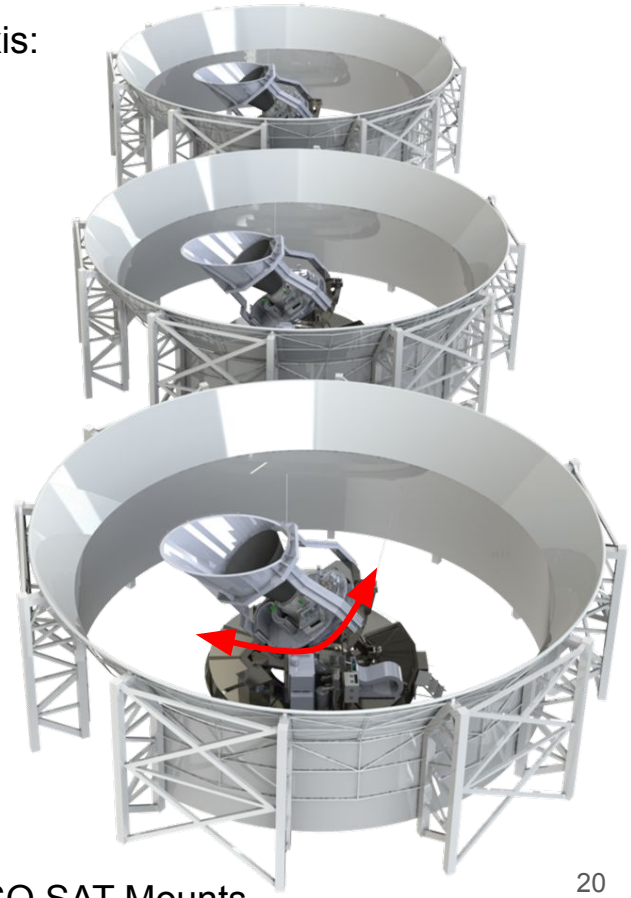
Getting Complete Polarization Angle Coverage

Boresight Rotation: Rotate Telescope *Around* the Optical Axis:

- Rotates detector polarization angles w.r.t the sky
- Per detector properties remain the same.



BICEP3 Mount



SO SAT Mounts

[BICEP/Keck Collaboration, ApJ 927,77 (2022)]

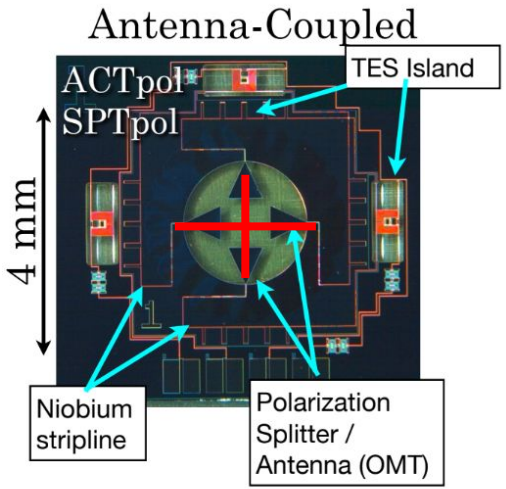
Outline

- What is polarization?
- Why do we want to measure CMB polarization?
- How do we measure polarization?
  - **Polarization Systematics**
  - Polarization Modulation

Differential Efficiencies

Each Detector has slightly different efficiencies due to:

- Detector Efficiency
- Optical Efficiency
- Placement in Focal Plane
- …



$$d_1 = \frac{1}{2}(I+Q) \rightarrow d_1 = \frac{\eta_1}{2}(I+Q)$$

$$d_2 = \frac{1}{2}(I-Q) \rightarrow d_2 = \frac{\eta_2}{2}(I-Q)$$

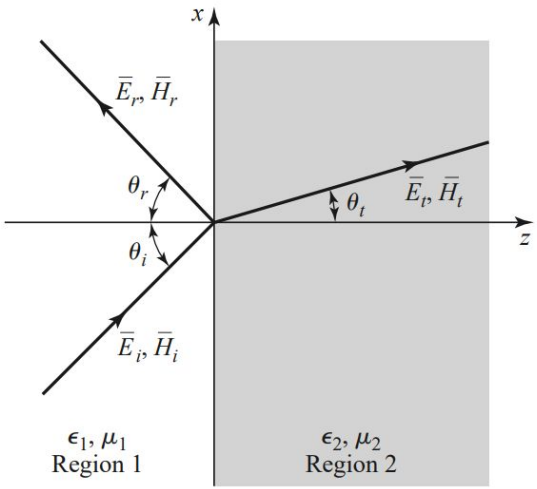
In the real world

Relative detector efficiencies mean pair differencing requires careful calibration.

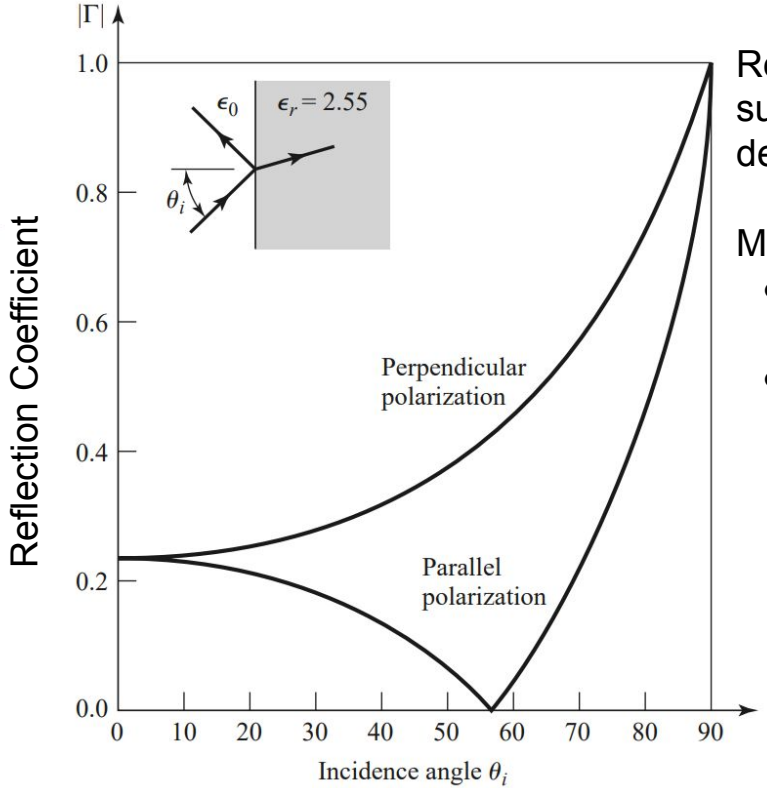
$$d_1 - d_2 = \left(\frac{\eta_1 - \eta_2}{2}\right) I + \left(\frac{\eta_1 + \eta_2}{2}\right) Q$$

Instrument Polarization

Unpolarized Light In → Partially Polarized Light Out



Angled incidence off a dielectric



Reflections off angled surfaces are polarization dependent.

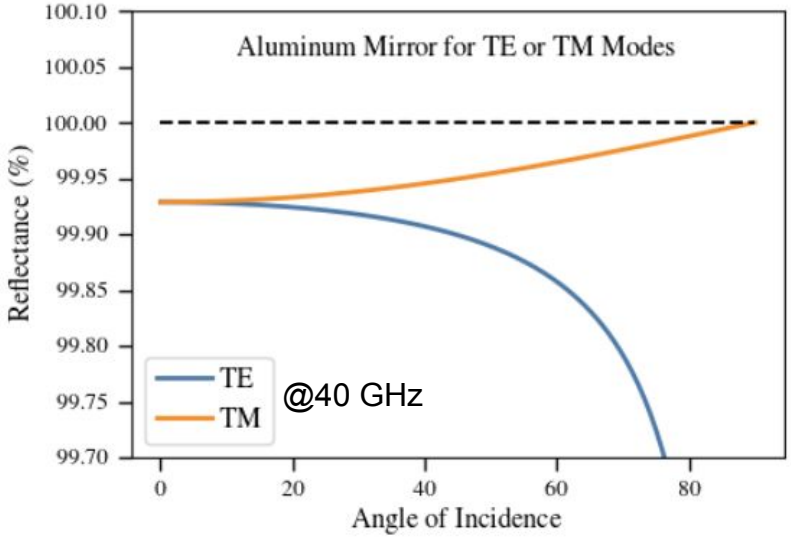
Mitigations:

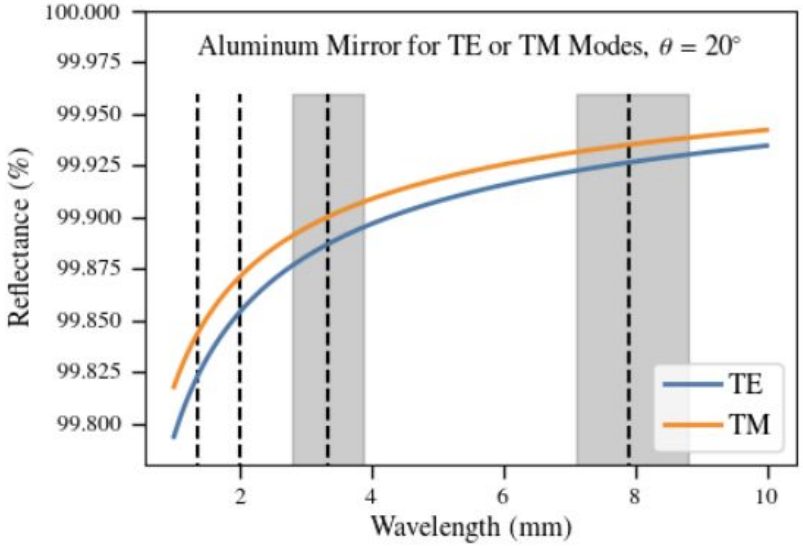
- Anti-reflection coatings
- Use one reflection to counteract another, ex: Crossed-dragone Telescopes

Figures from Pozar, Microwave Engineering, 4th Edition

Instrument Polarization

Unpolarized Light In → Partially Polarized Light Out





@90 GHz and 20 deg incidence, ~10^{-4} effect for an Aluminum flat mirror

- Small effects add up while looking for tiny signals.
- Polarization signal proportional to input unpolarized signal.
  - One source of T→ P Leakage

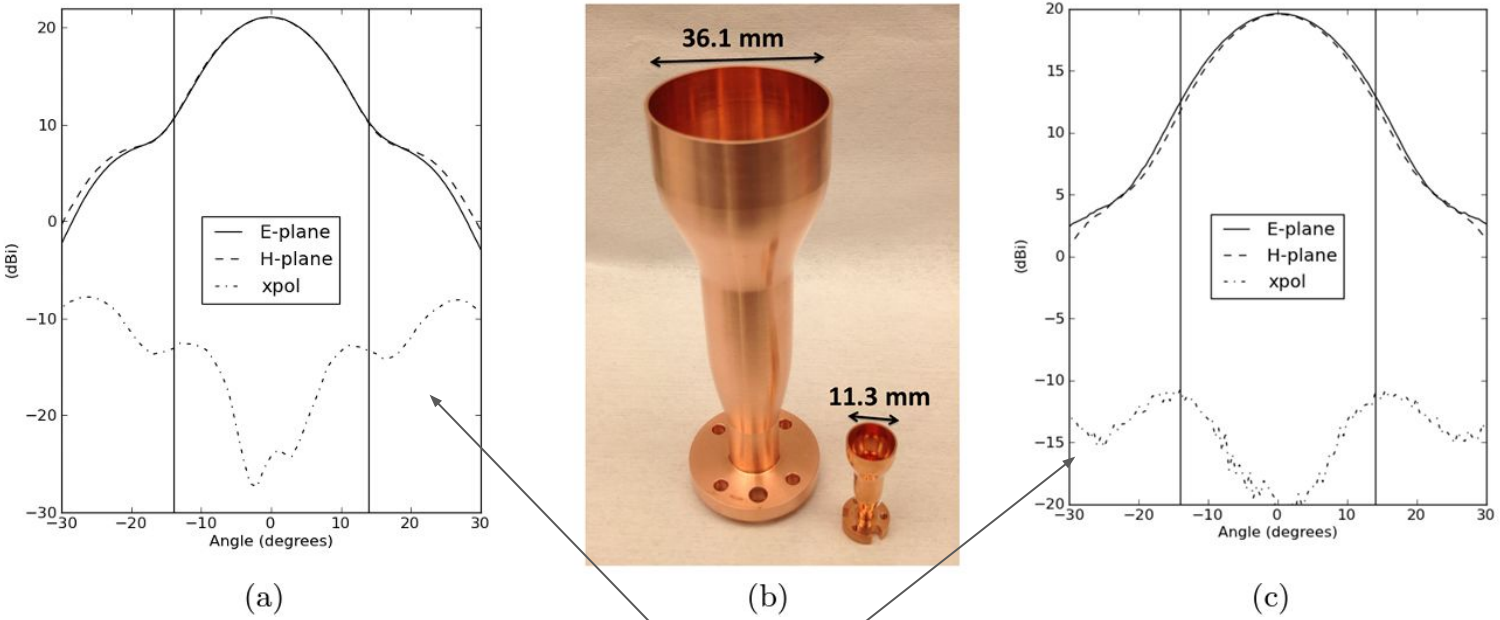
Figures from Harrington, 2018

Cross-Polarization

Detecting some polarization orthogonal to the intended polarization.

ie. detecting some E_y when aligned along E_x

All antennas / horns / optical coupling devices have some cross-pol



Feedhorn cross-pol from CLASS 40 GHz and 90 GHz telescopes.

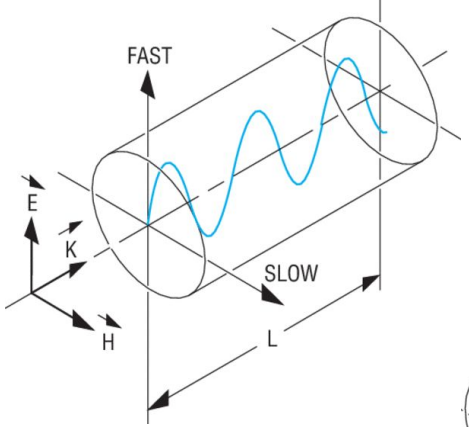
Figure from Essinger-Hileman et. al., 2014

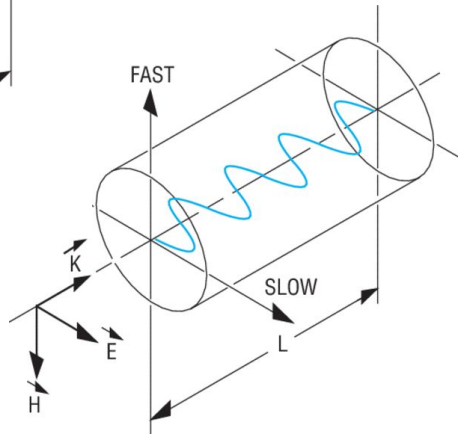
Outline

- What is polarization?
- Why do we want to measure CMB polarization?
- How do we measure polarization?
  - Polarization Systematics
  - **Polarization Modulation**

Polarization Modulation

- Using a polarization selective devices to change or modify the incoming polarization in known ways.
  - Half waveplates (HWPs)
    - Stepped
    - Continuously Rotating
  - Variable-delay polarization modulators (VPMs)

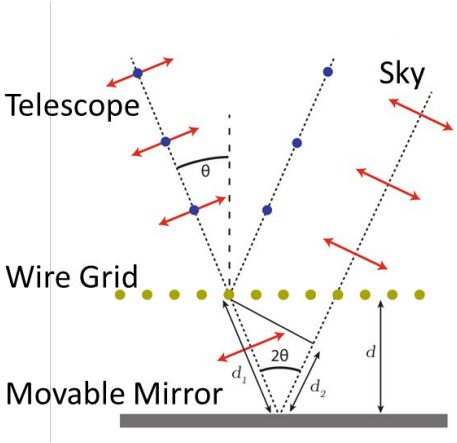




HWP are birefringent materials with a fast and slow axis. Slow axis delayed by π phase compared to fast axis.

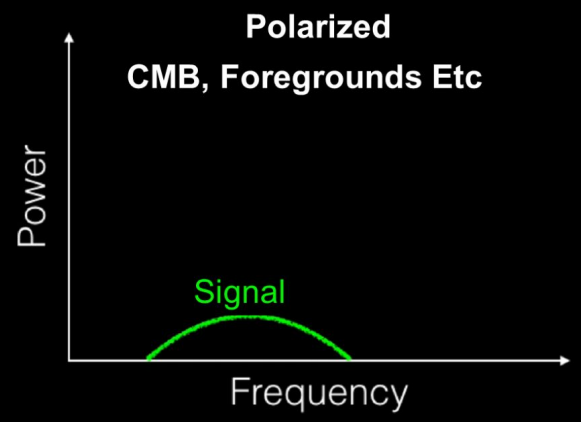
If x is fast axis, HWP takes +Q → -Q

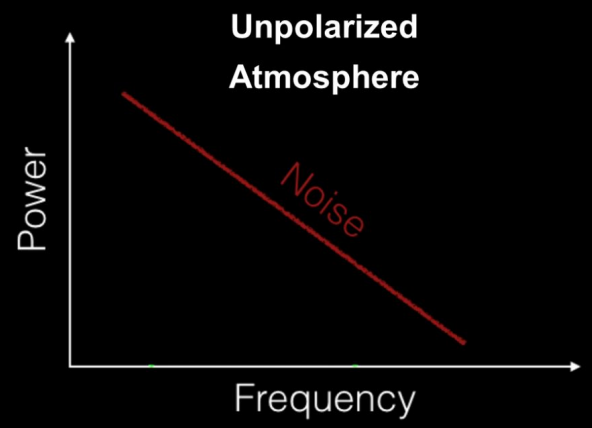
Rotating a HWP mixes Q and U.



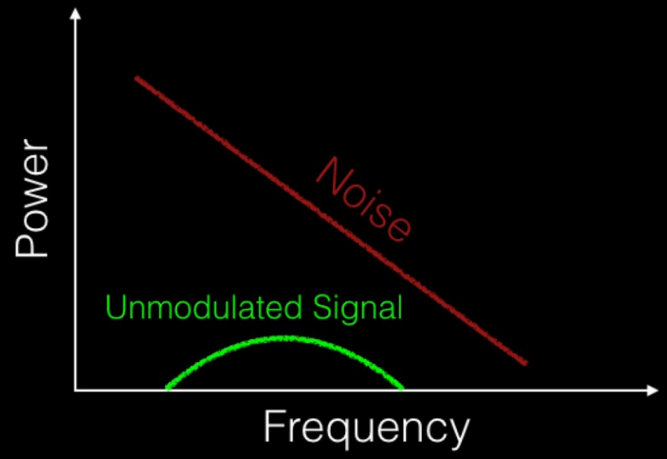
VPMs have wire grid + moveable mirror
Change mirror position → Mix Q and V

Polarization Modulation



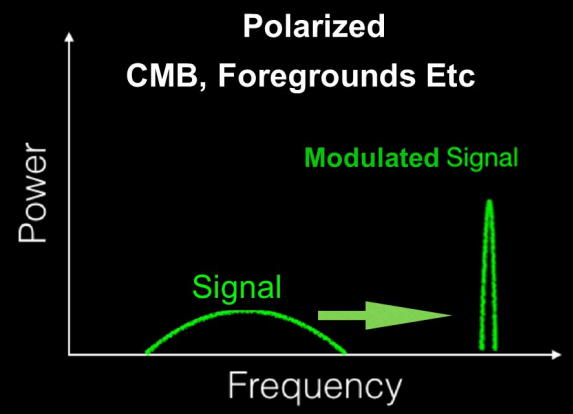


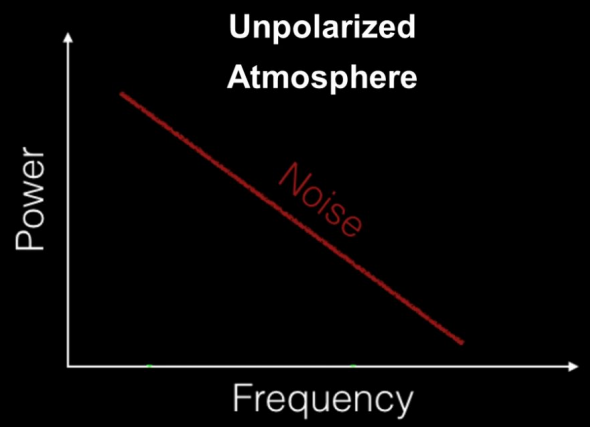
Telescope without modulation



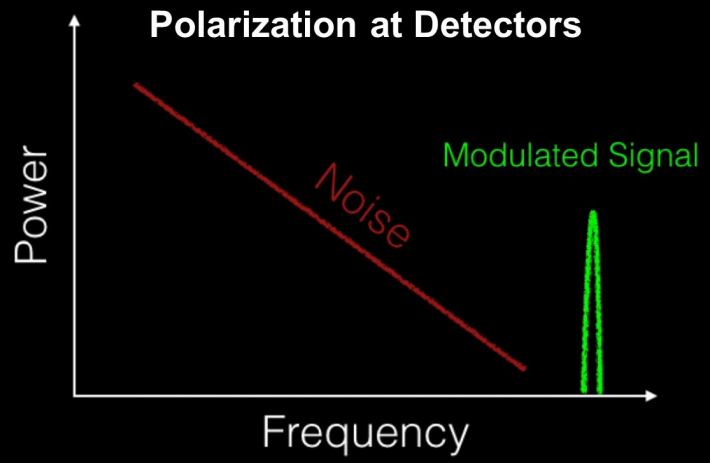
Slides from Toby Marriage

Polarization Modulation





Telescope **with** modulation

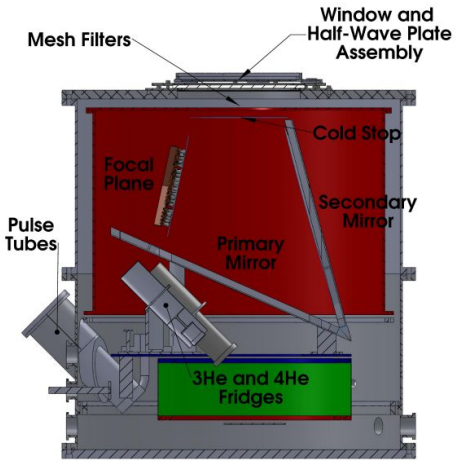


Slides from Toby Marriage

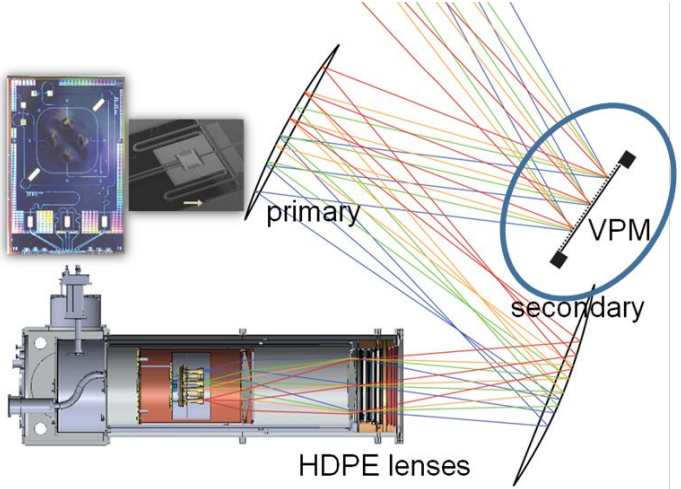
Slides from Toby Marriage

Polarization Modulation

- Modulate Polarization at the front of the telescope optics.
  - Before the effects of instrument polarization.

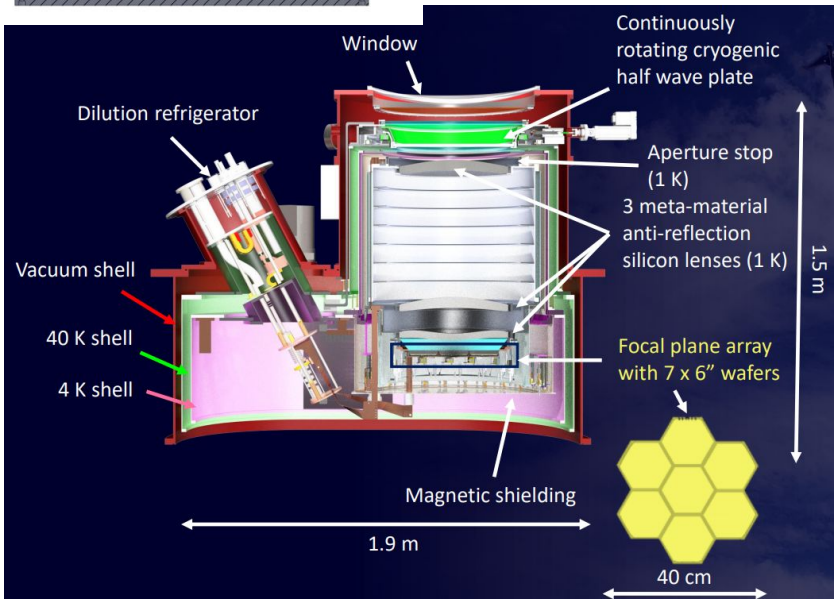


ABS



CLASS

SO SATs

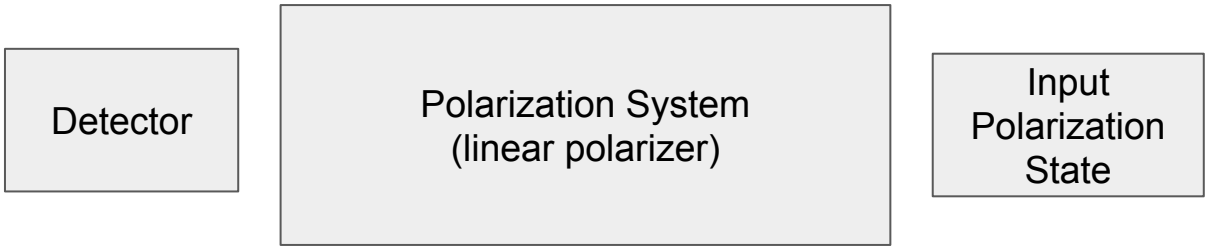


Outline

- What is polarization?
- Why do we want to measure CMB polarization?
- How do we measure polarization?
  - Polarization Systematics
  - Polarization Modulation

Thanks!

Modeling Polarization Selective Devices



Jones Calculus Uses Jones Vectors

- 2x2 Matrices
- Complex Numbers
- Single Frequency
- Fully polarized light **only**

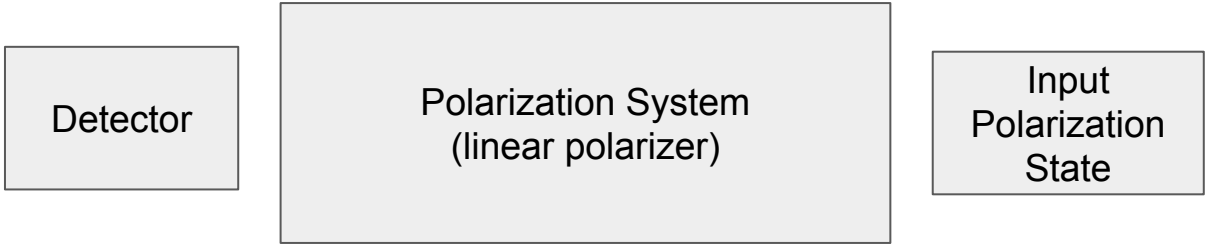
$$\vec{E}_{out} = J \cdot \vec{E}_{in}$$

$$\vec{E}_{out} = \begin{bmatrix} E_{xx} & E_{yx} \\ E_{xy} & E_{yy} \end{bmatrix} \vec{E}_{in}$$

$$\vec{E}_0 = \begin{bmatrix} E_x e^{i\delta_x} \\ E_y e^{i\delta_y} \end{bmatrix}$$

$$\vec{E}_{out} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \vec{E}_{in}$$

Modeling Polarization Selective Devices



Mueller Calculus Uses Stokes Vectors

- 4x4 Matrices
- Real Numbers
- Can be integrated over frequency
- Can represent partially polarized light

$$\vec{S}_{out} = M \cdot \vec{S}_{in}$$

$$\vec{S}_{out} = \frac{1}{2}\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \vec{S}_{in}$$

There is a standard conversion for going from Jones Matrices to Mueller Matrices