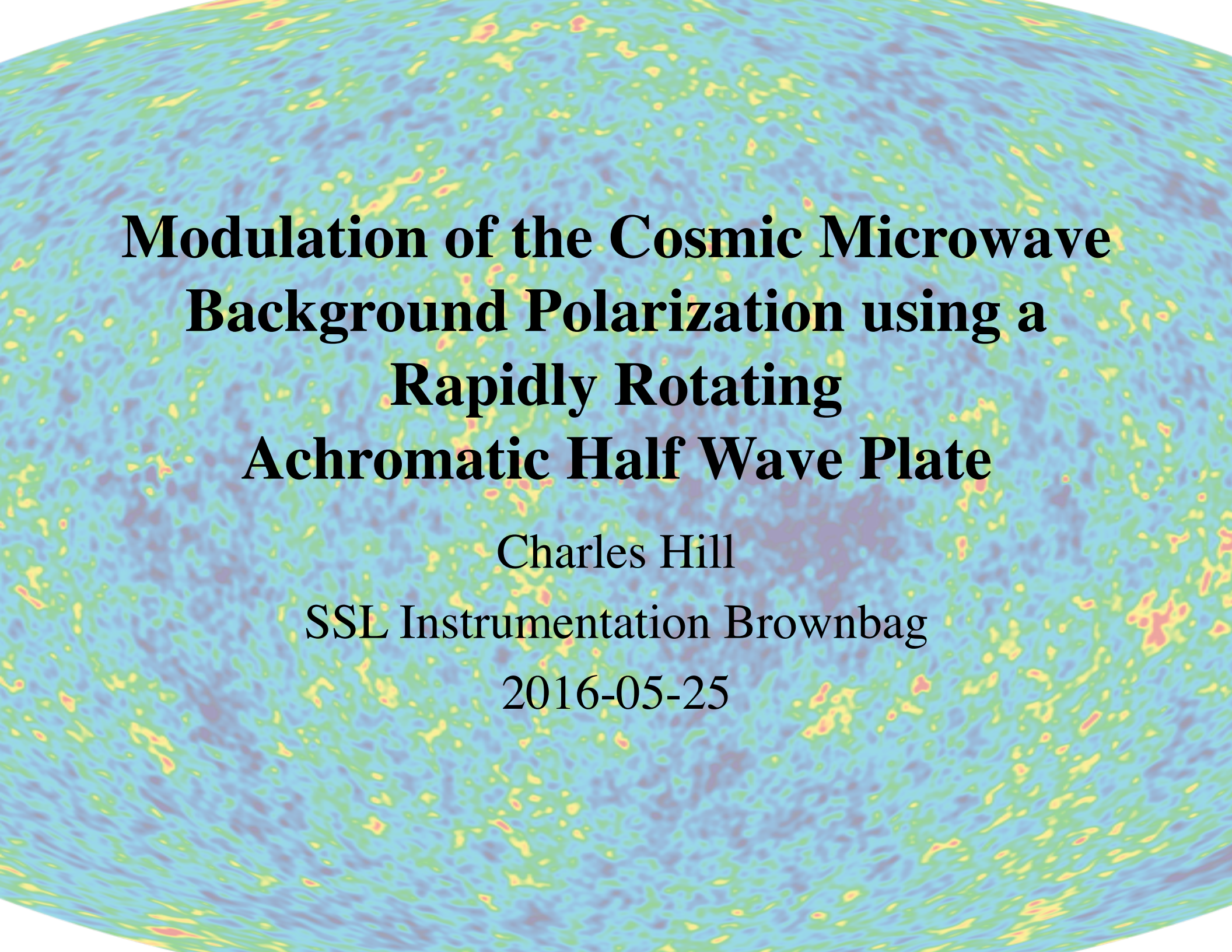


The background of the slide is a full-page image of a Cosmic Microwave Background (CMB) polarization map. It shows a complex, grainy pattern of colors (blue, green, yellow, and red) representing the polarization of the CMB. The pattern is somewhat circular, suggesting a map of the sky.

Modulation of the Cosmic Microwave Background Polarization using a Rapidly Rotating Achromatic Half Wave Plate

Charles Hill

SSL Instrumentation Brownbag

2016-05-25

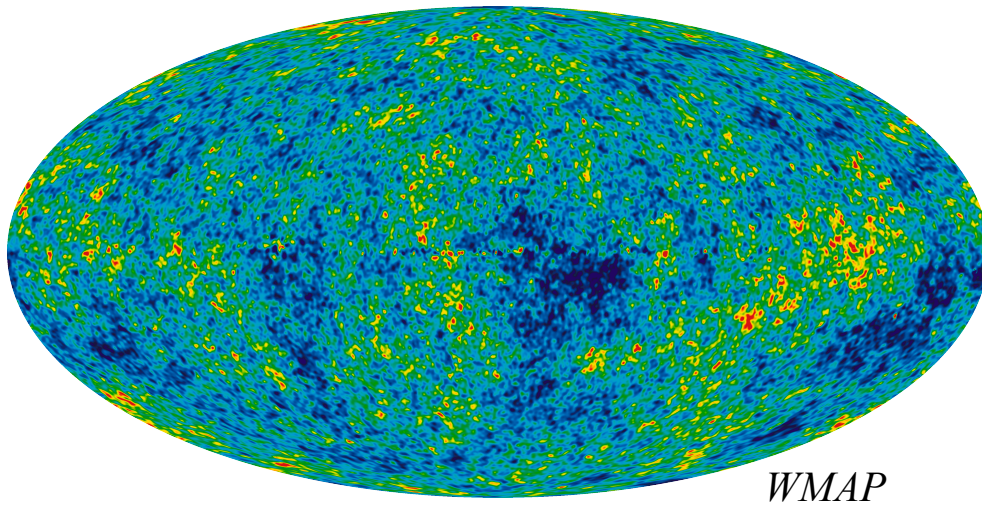
Overview

1. Cosmic Microwave Background Review
2. The Simons Array Experiment
3. Polarization modulation for Simons Array
4. A Warm Half Wave (HWP) Plate for PB2a
5. A Cold HWP for PB2b/c
6. A HWP for the LiteBIRD Satellite

CMB Overview

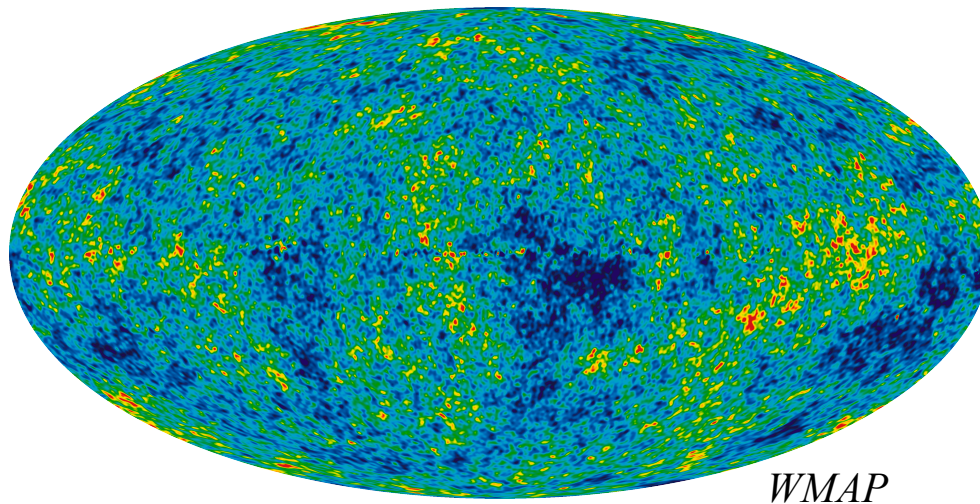
Generating CMB Polarization

CMB Temperature Anisotropy



Generating CMB Polarization

CMB Temperature Anisotropy



Thomson Scattering

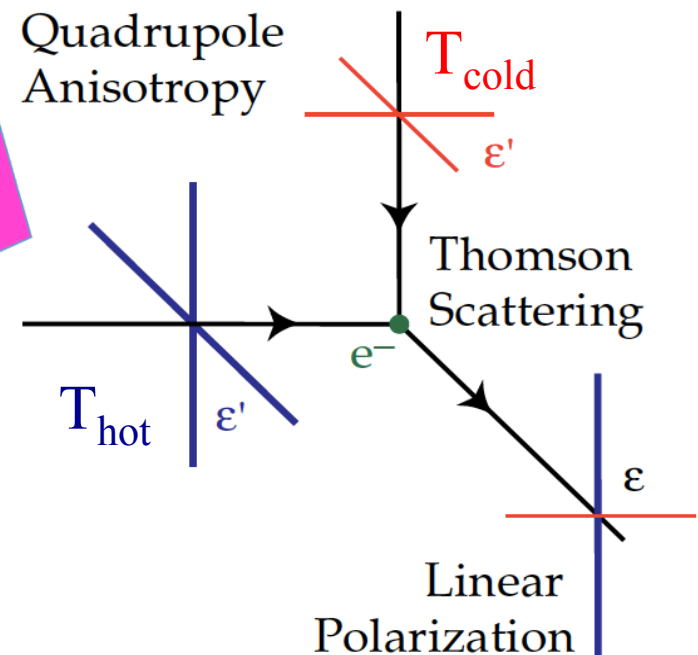
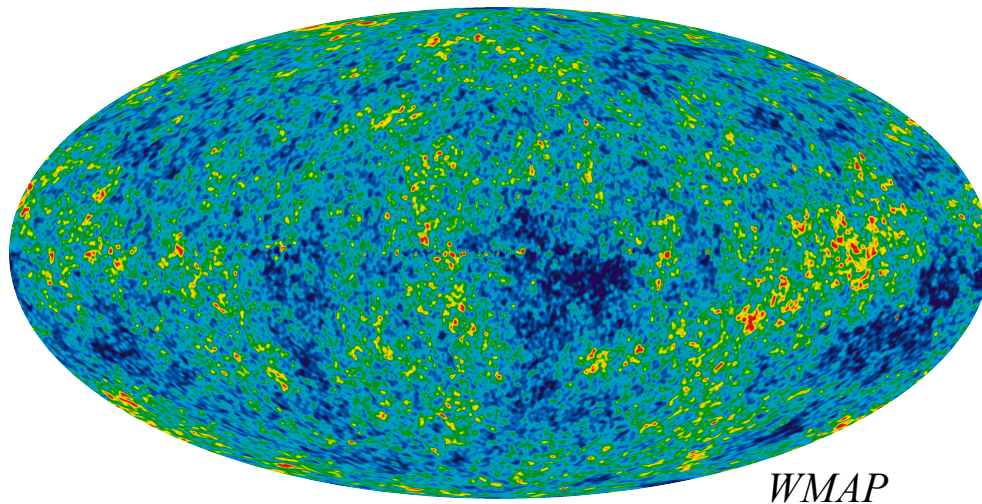


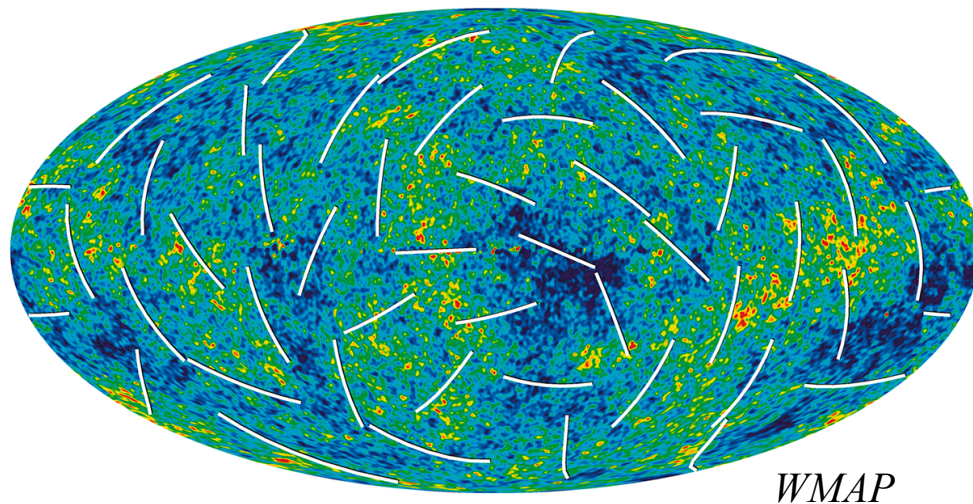
Fig: Hu and White (1997)

Generating CMB Polarization

CMB Temperature Anisotropy



CMB Polarization Anisotropy



Thomson Scattering

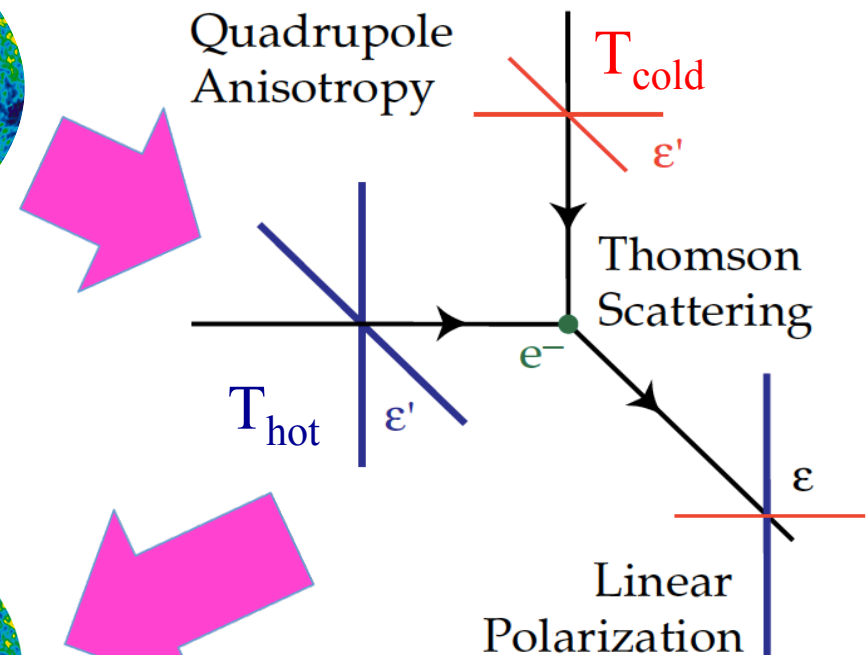
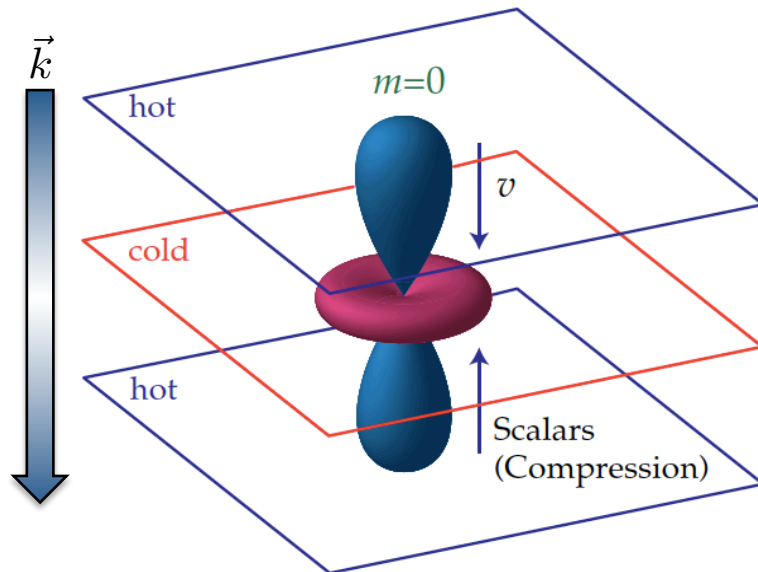


Fig: Hu and White (1997)

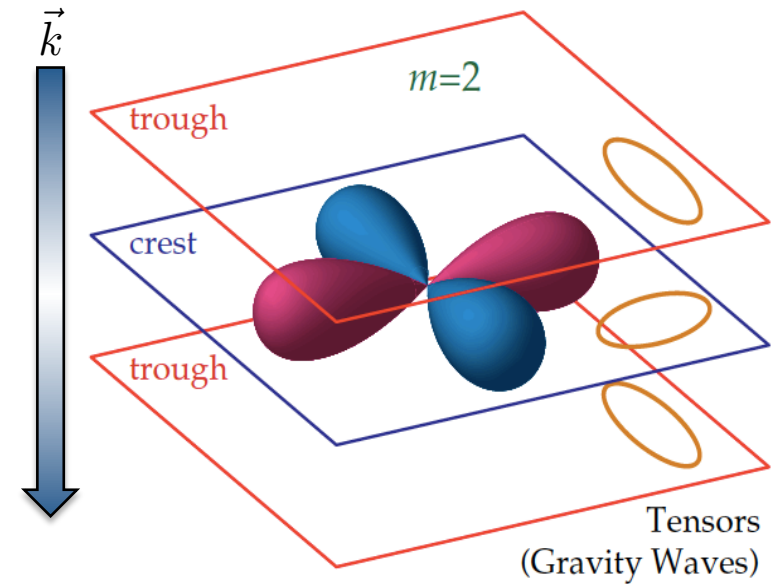
Sources for Polarization Patterns

Scalar Perturbations



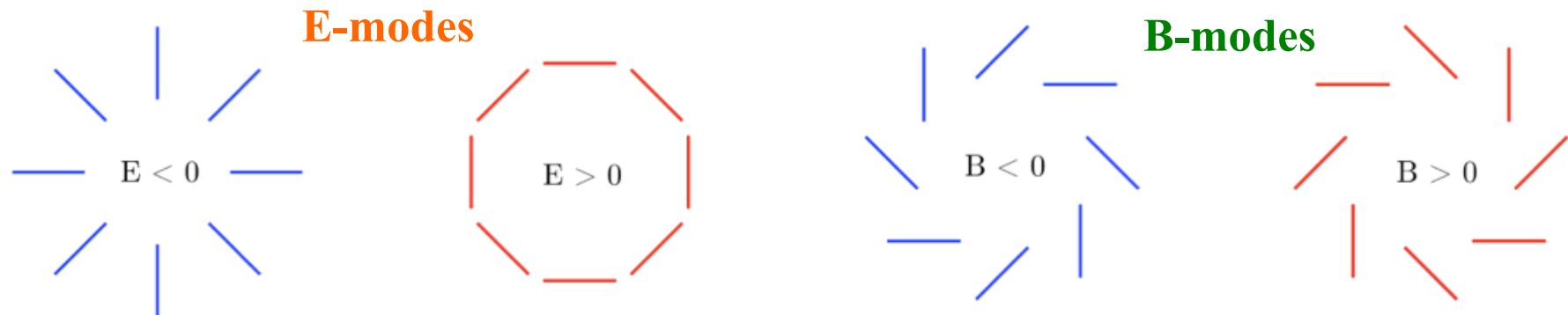
Figs: Hu and White (1997)

Tensor Perturbations



Sources for Polarization Patterns

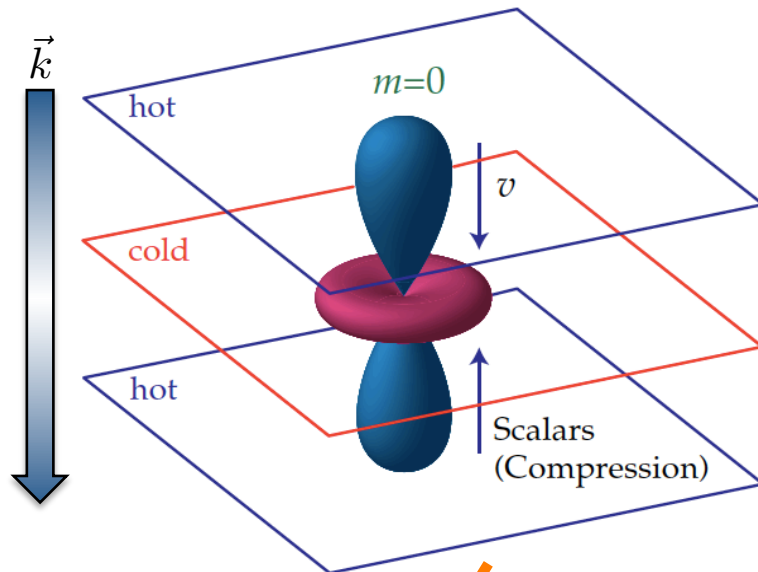
Convenient Polarization Basis



Seljak and Zaldarriaga (1997)

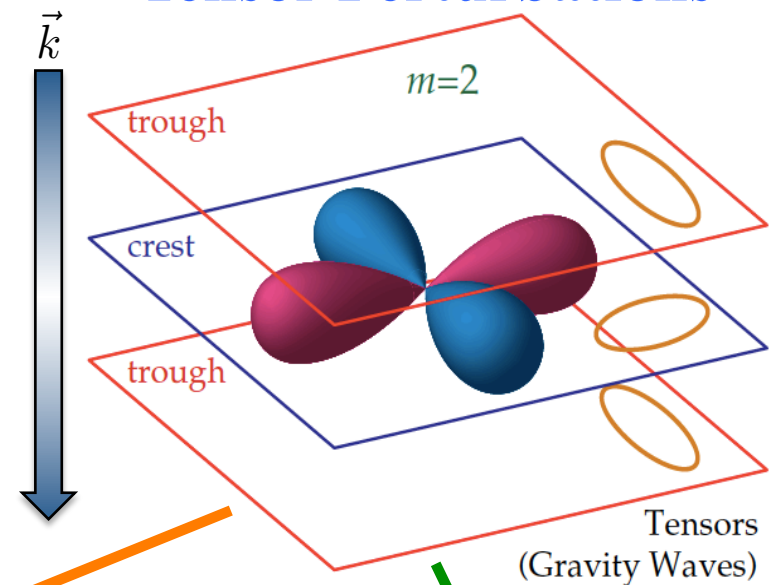
Sources for Polarization Patterns

Scalar Perturbations

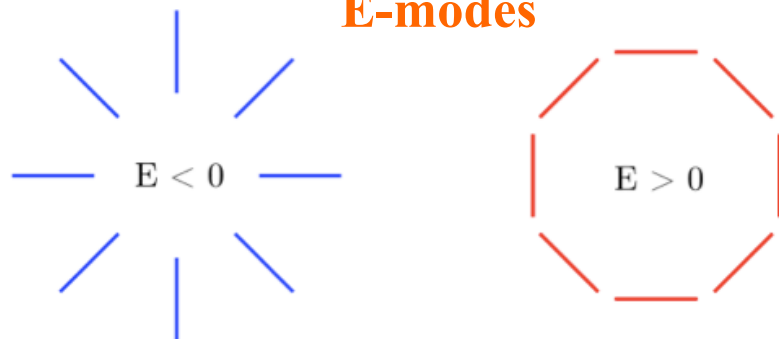


Figs: Hu and White (1997)

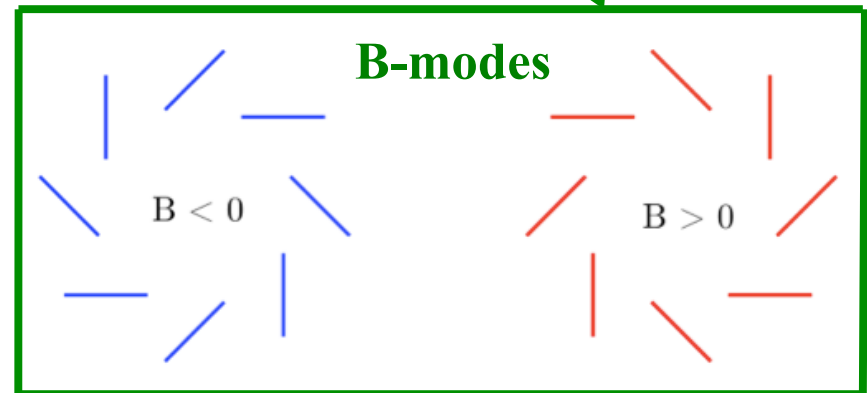
Tensor Perturbations



E-modes



B-modes



Seljak and Zaldarriaga (1997)

Sources for Polarization Patterns

INFLATION!

**Exponential
Expansion**

**Standard
Cosmology**

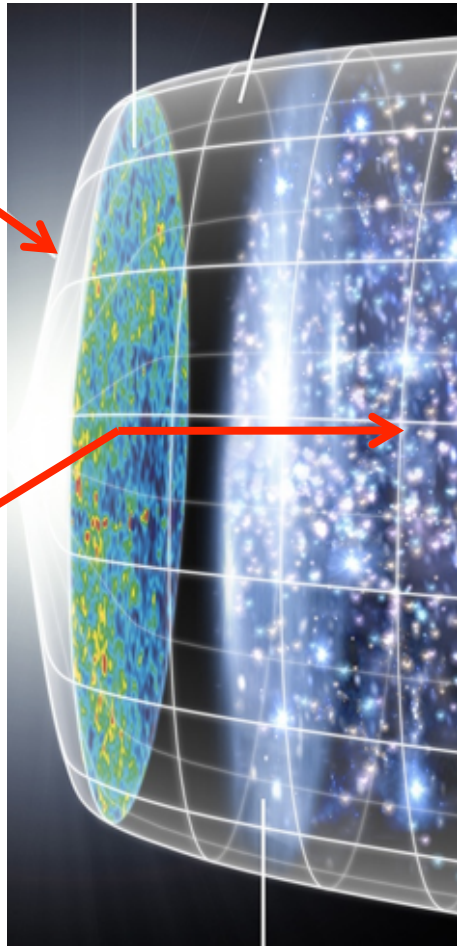
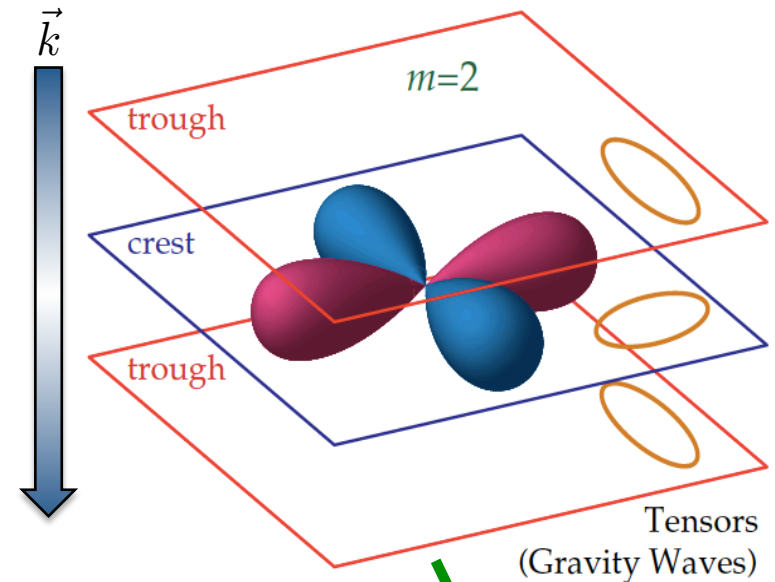
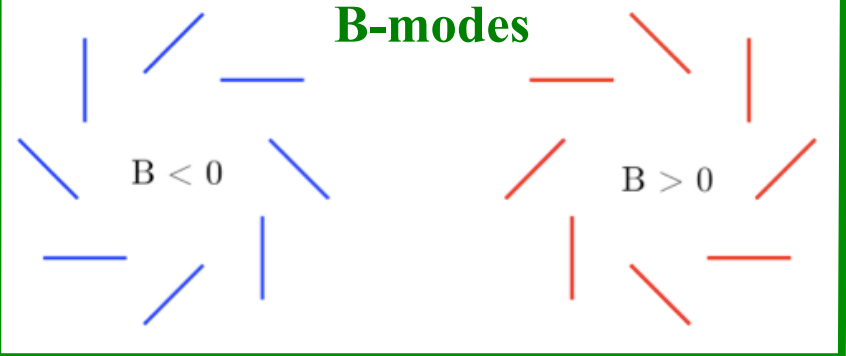


Fig: WMAP

Tensor Perturbations



B-modes

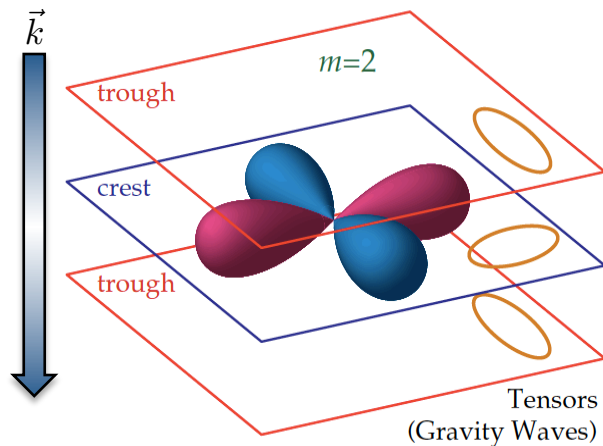


Seljak and Zaldarriaga (1997)

B-mode Science

Inflationary physics

Primordial Gravitational Waves



$$r = \frac{\mathcal{P}_{\text{Tensor}}}{\mathcal{P}_{\text{Scalar}}} \propto E_{\text{Inflation}}^4$$

Structure formation

Gravitational Lensing of E-modes into B-modes

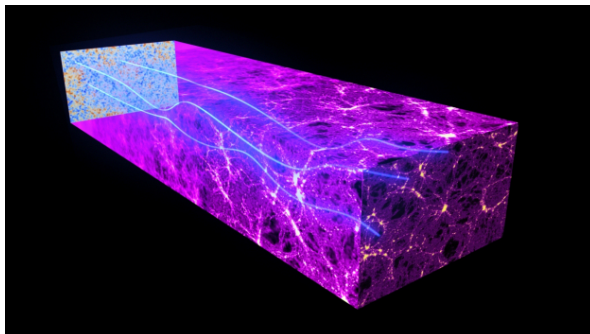


Fig: Planck

$$\sum m_\nu$$

Some Terrestrial Experiments

Atacama Desert

Chajnantor Science Preserve



South Pole



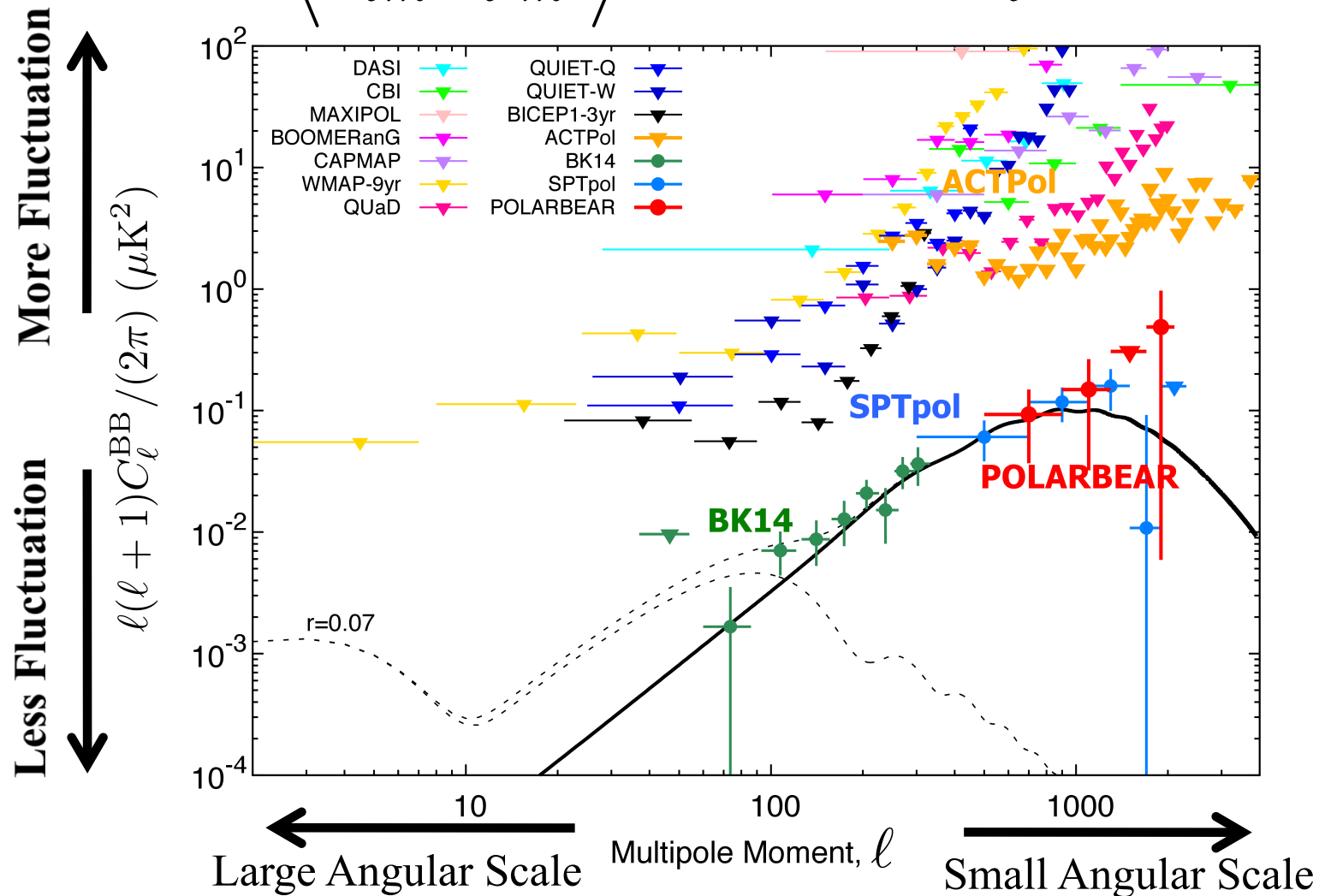
Balloons



B-mode Measurement Status

B-mode Power Spectrum

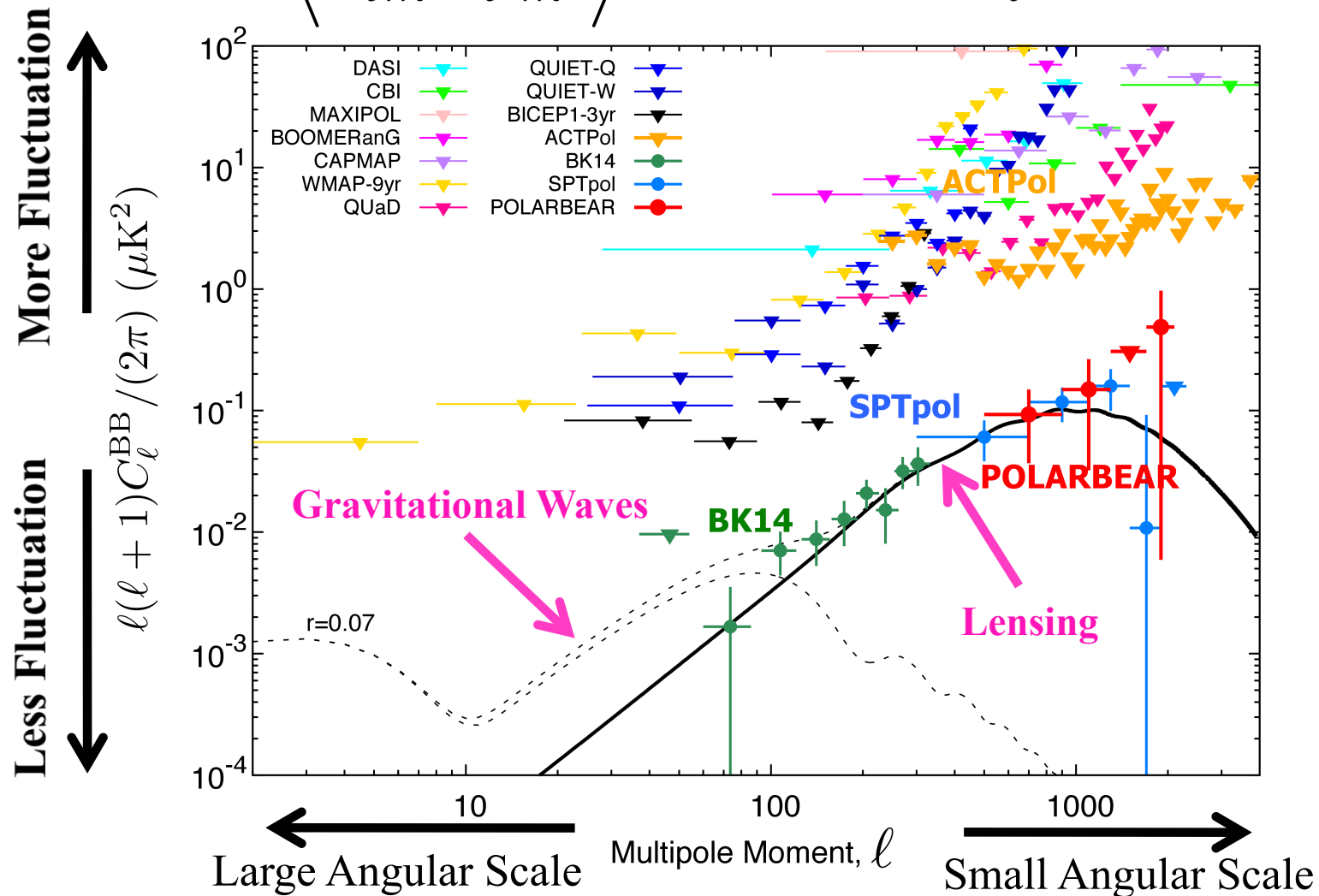
$$\langle a_{\ell m}^B a_{\ell' m'}^{B*} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_{\ell}^{BB}$$



B-mode Measurement Status

B-mode Power Spectrum

$$\langle a_{\ell m}^B a_{\ell' m'}^{B*} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_{\ell}^{BB}$$

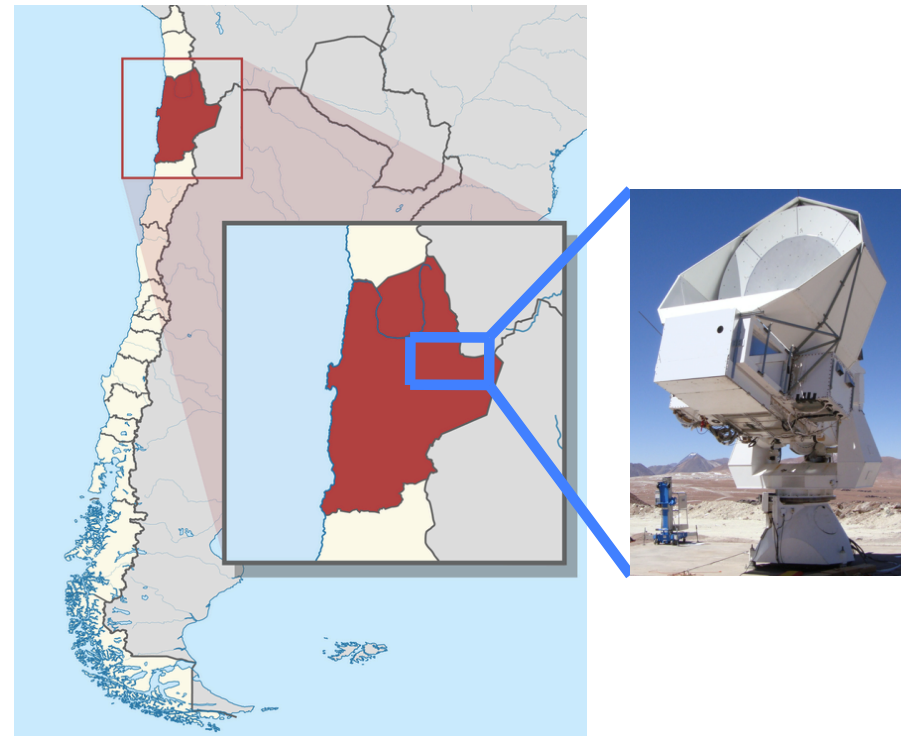
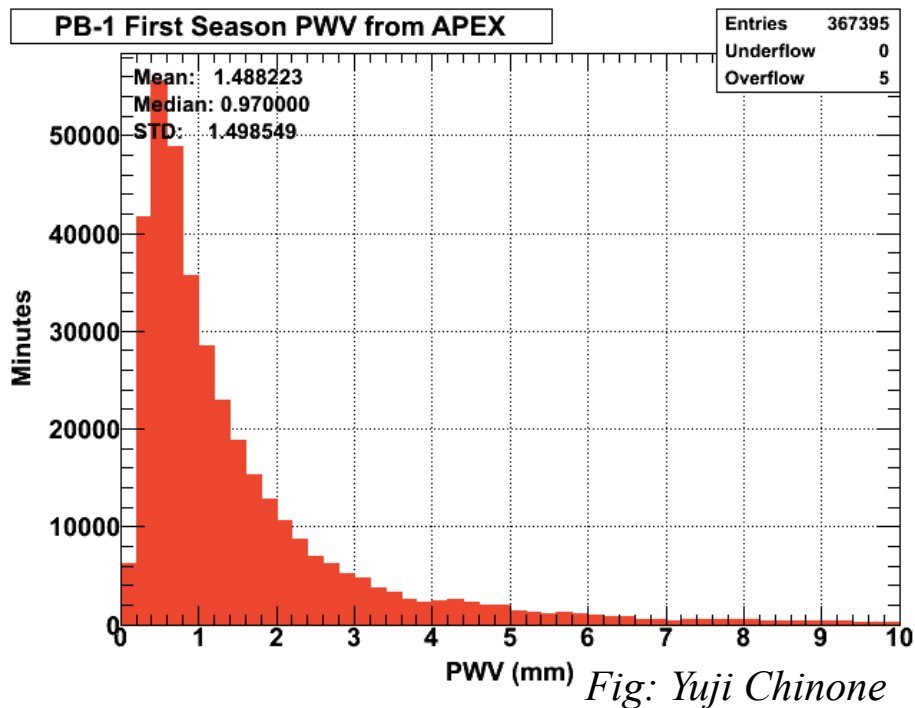


POLARBEAR-2 and Simons Array



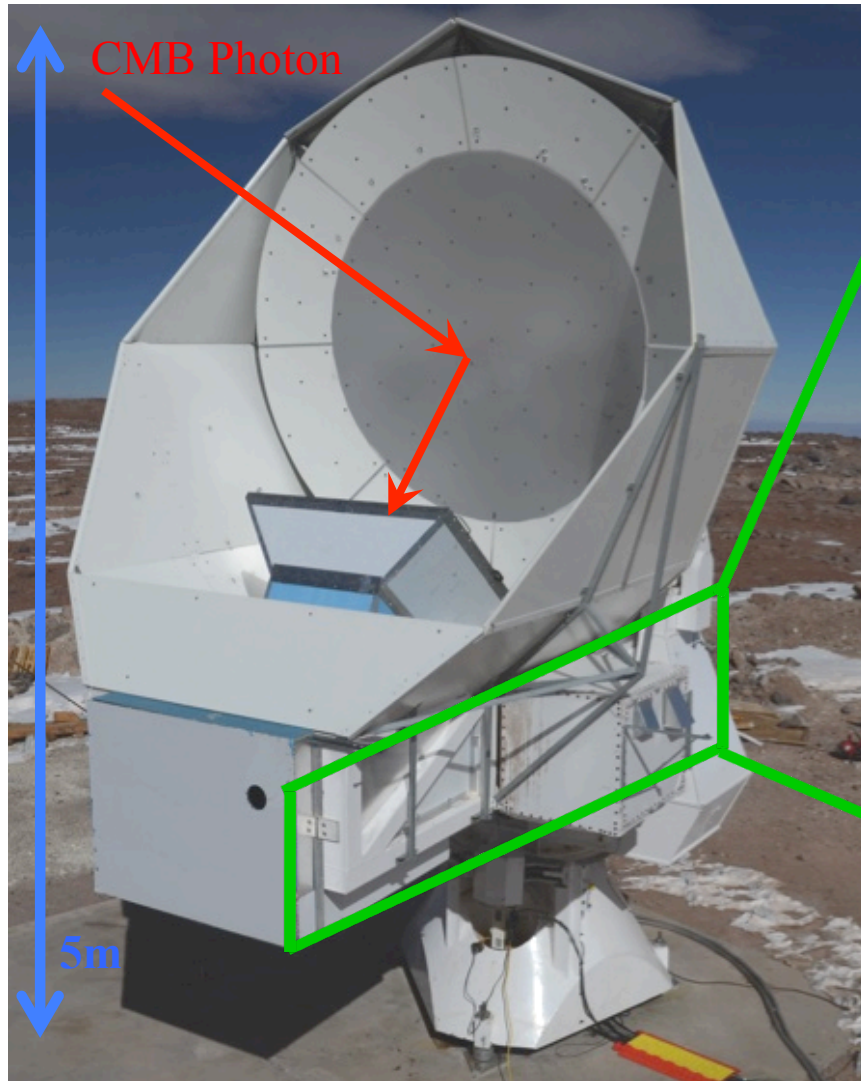
Observation Site

- Atacama Desert, Chile
- 5200 m (17,000 ft) altitude
- 1.0mm median precipitable water vapor

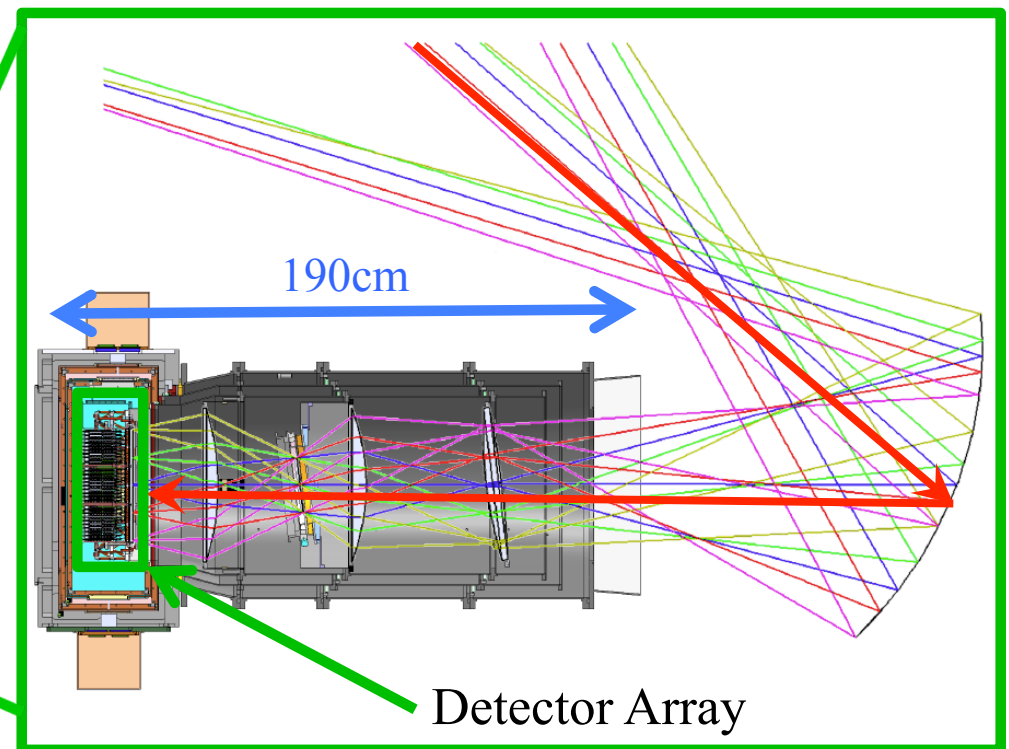


Huan Tran Telescope and Receiver

Telescope

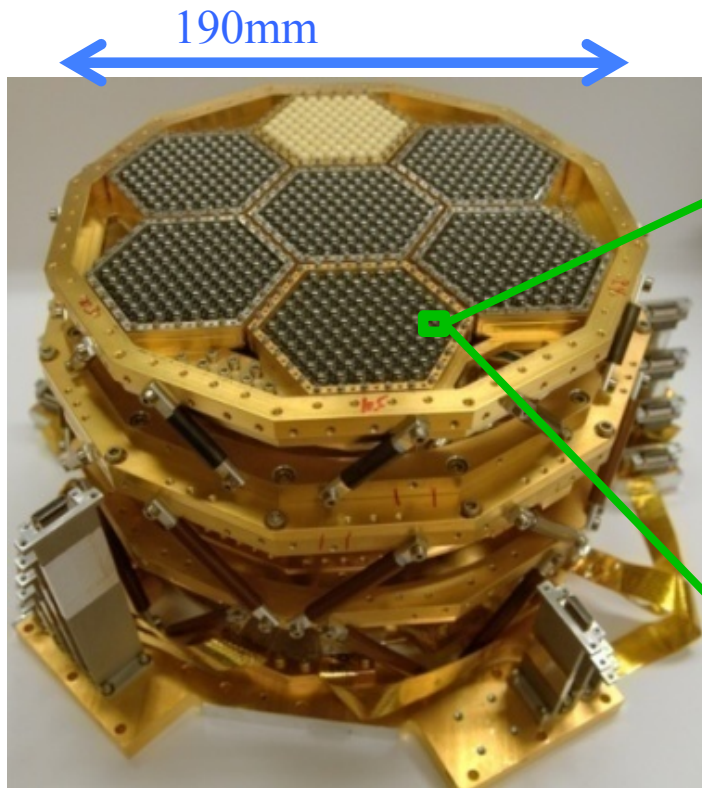


Receiver



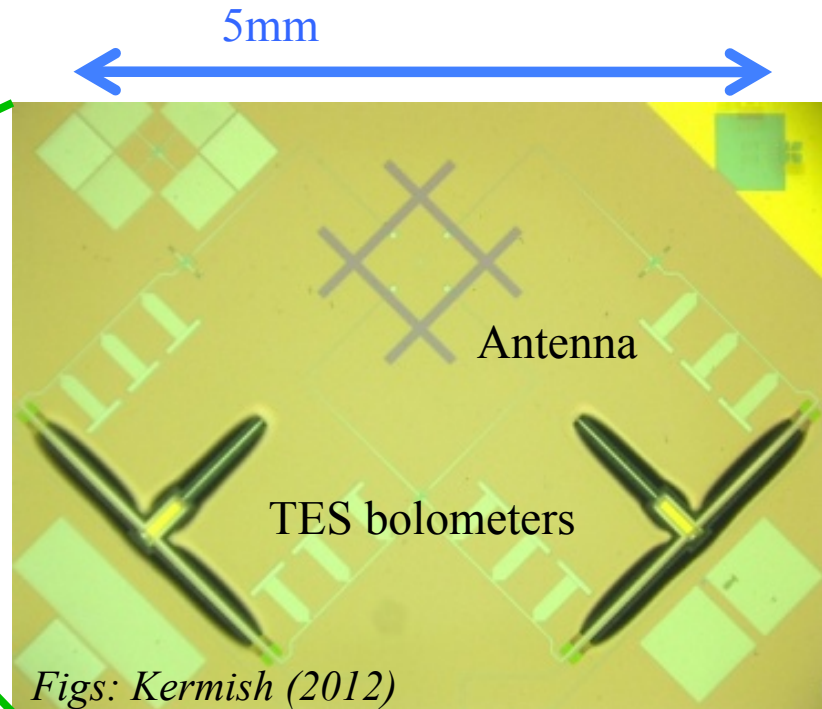
Legacy: POLARBEAR-1

Detector Array



- 1,274 Detectors
- 2.2-degree field of view

Detector Pixel



- Two polarizations
- Single frequency $\rightarrow$ 150GHz

Deployed in 2012

Next Generation: POLARBEAR-2

Detector Array

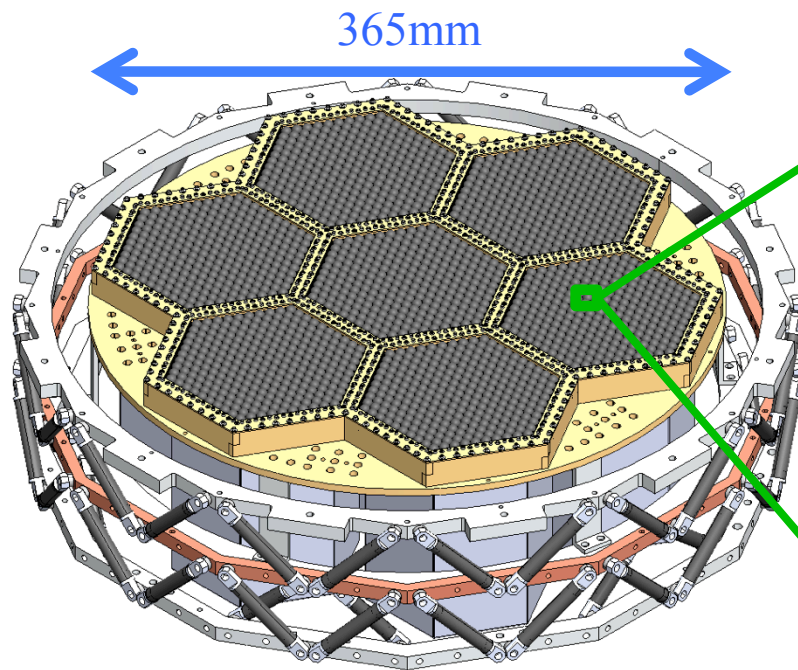
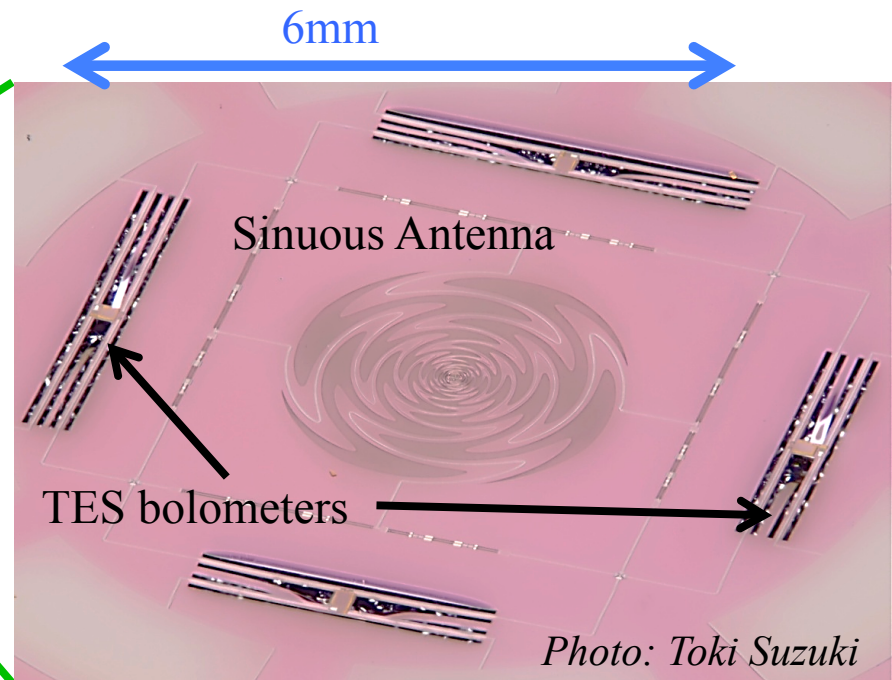


Fig: Ari Cukierman

- 7,588 Detectors
- 4-degree field of view

Detector Pixel

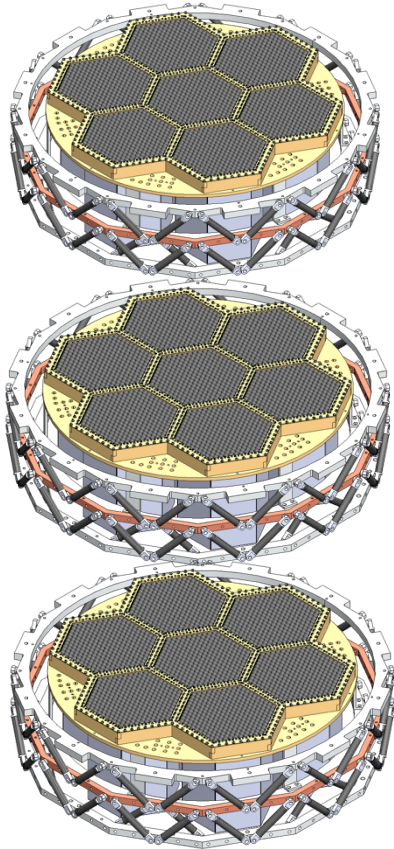


- Two polarizations
- Two frequencies → 95 and 150GHz

Deploys spring 2017

Simons Array

Three PB2-style Experiments



PB2a

95/150 GHz

PB2b

95/150 GHz

PB2c

220/280 GHz

Photos: KEK

Three HTT-style Telescopes



- 22,764 TES bolometers
- 95 GHz, 150 GHz, 220 GHz, and 280GHz
- Deployment schedule: PB2a (2017), PB2b (2018), PB2c (2018)

Polarization Modulation for Simons Array

Motivation for Modulation

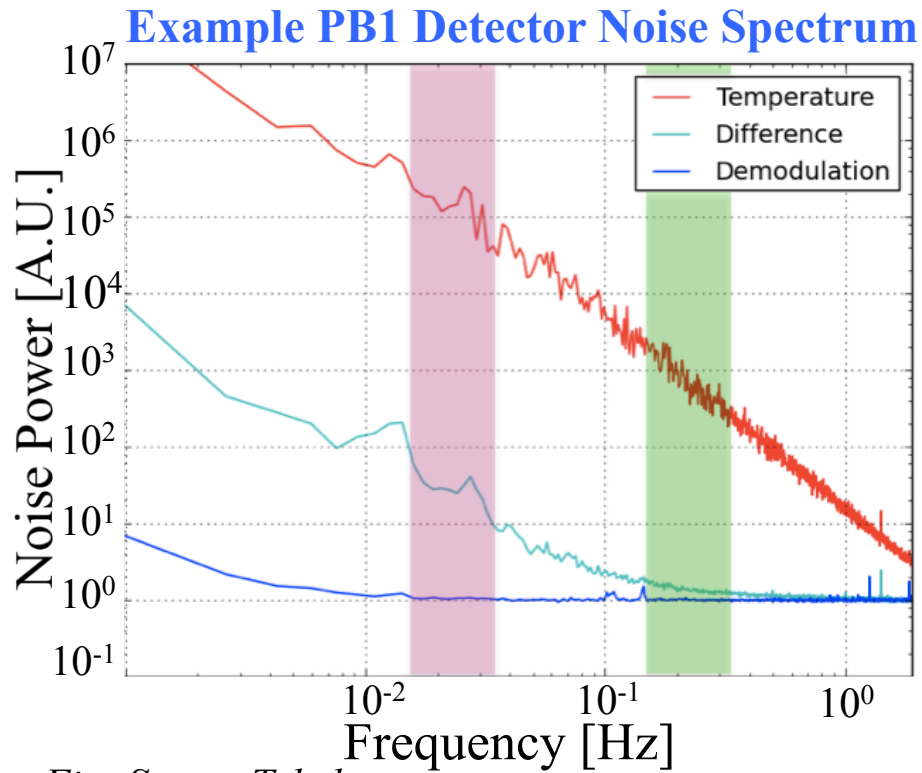


Fig: Satoru Takakura

Motivation for Modulation

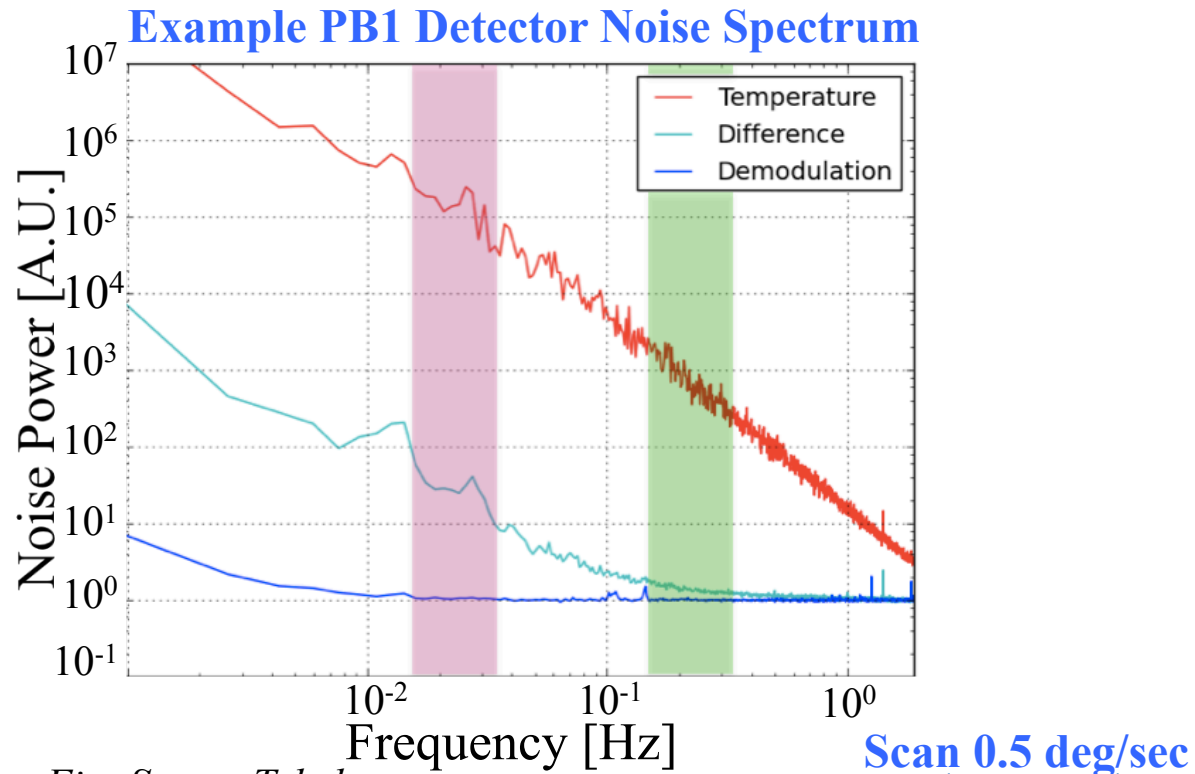


Fig: Satoru Takakura



Motivation for Modulation

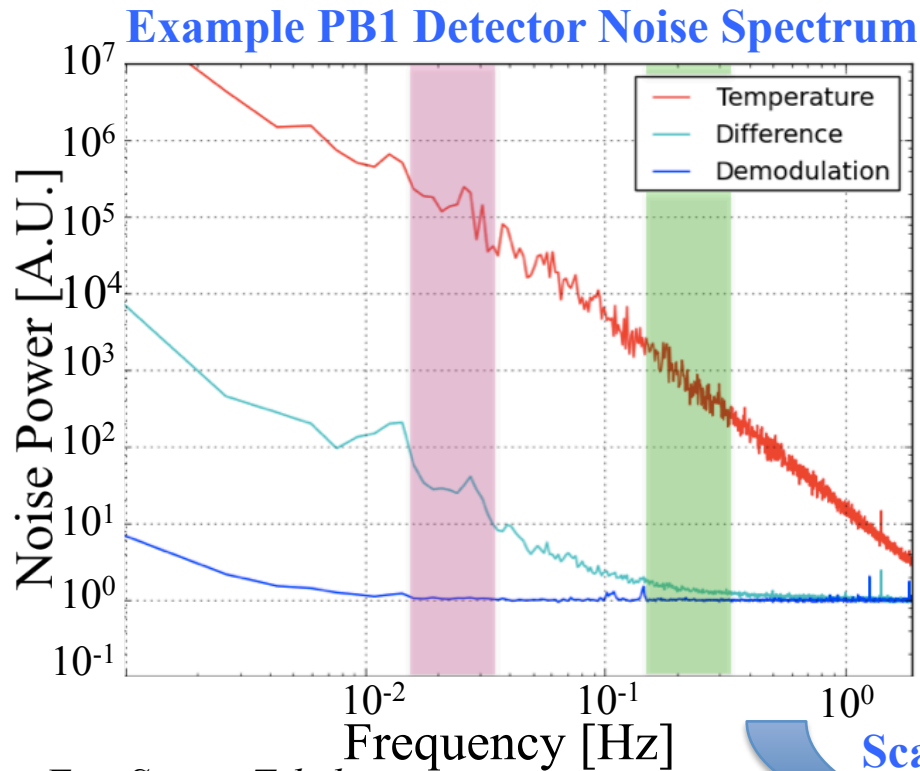


Fig: Satoru Takakura

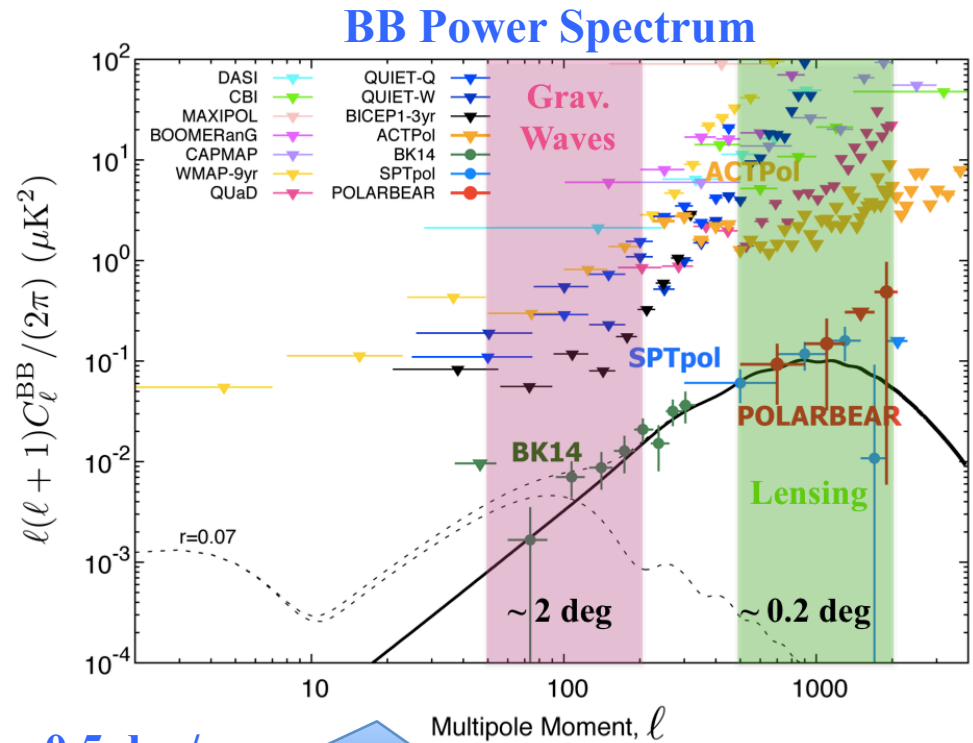


Fig: Yuji Chinone

Scan 0.5 deg/sec



Motivation for Modulation

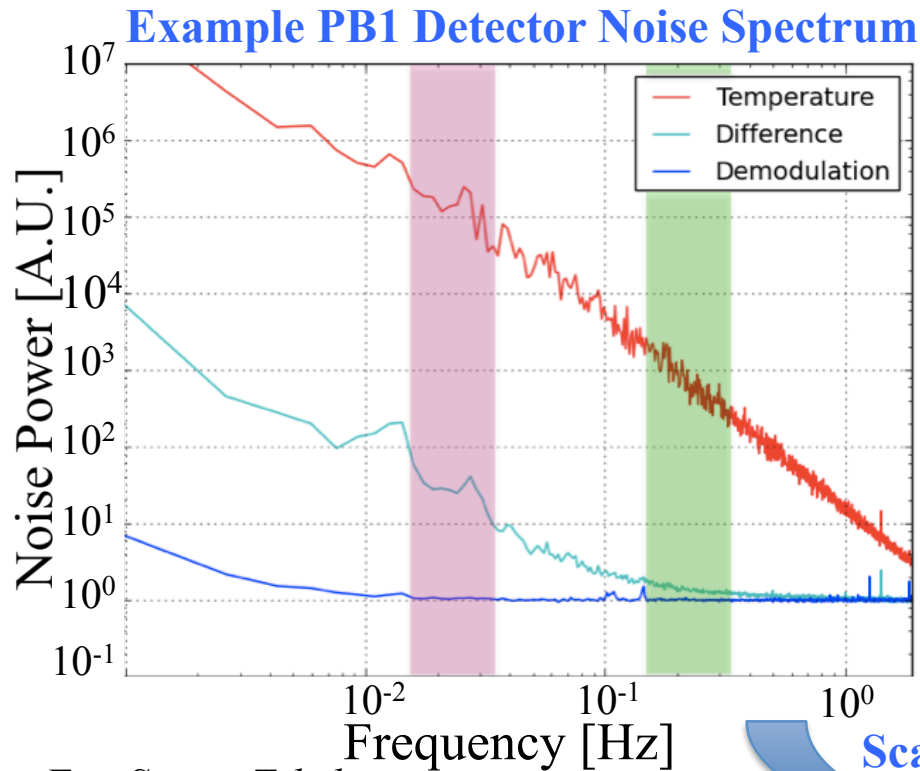


Fig: Satoru Takakura

Scan 0.5 deg/sec

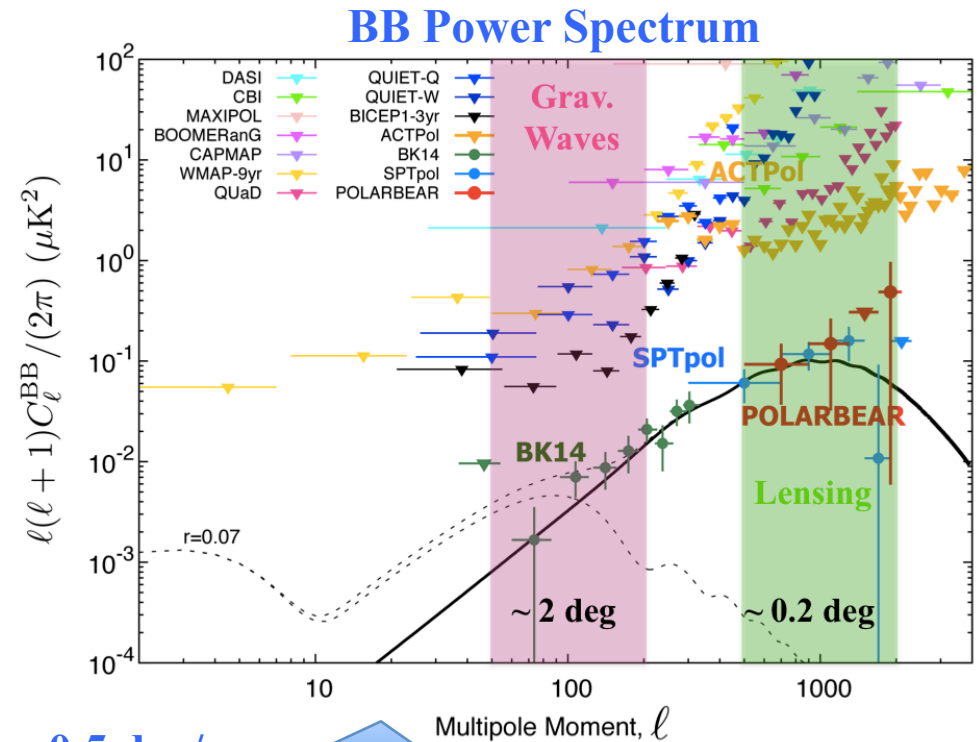
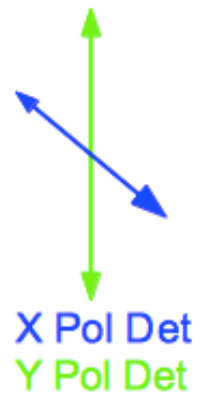
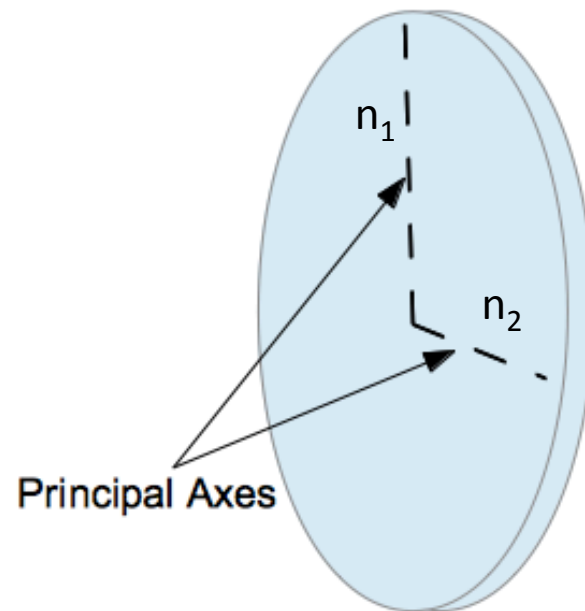


Fig: Yuji Chinone

- 1/f noise decreases sensitivity on large angular scales
- Modulation suppresses 1/f knee to regain sensitivity on large angular scales

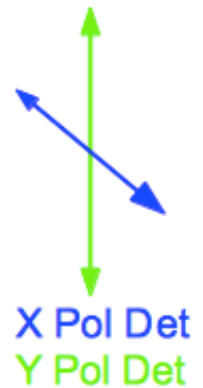
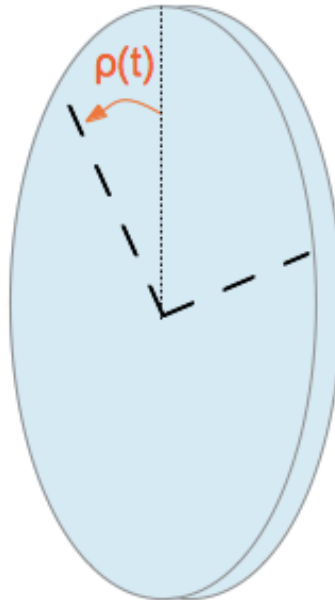
Continuously Rotating Half Wave Plate

Birefringent Material

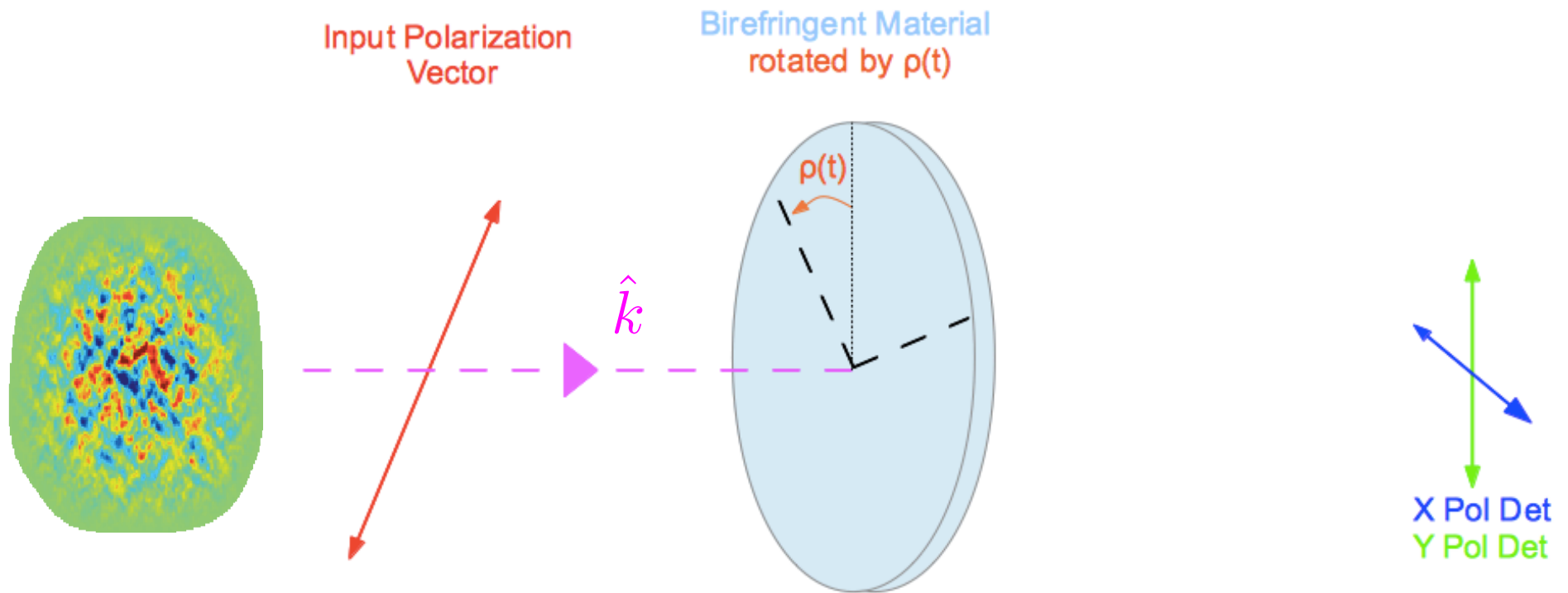


Continuously Rotating Half Wave Plate

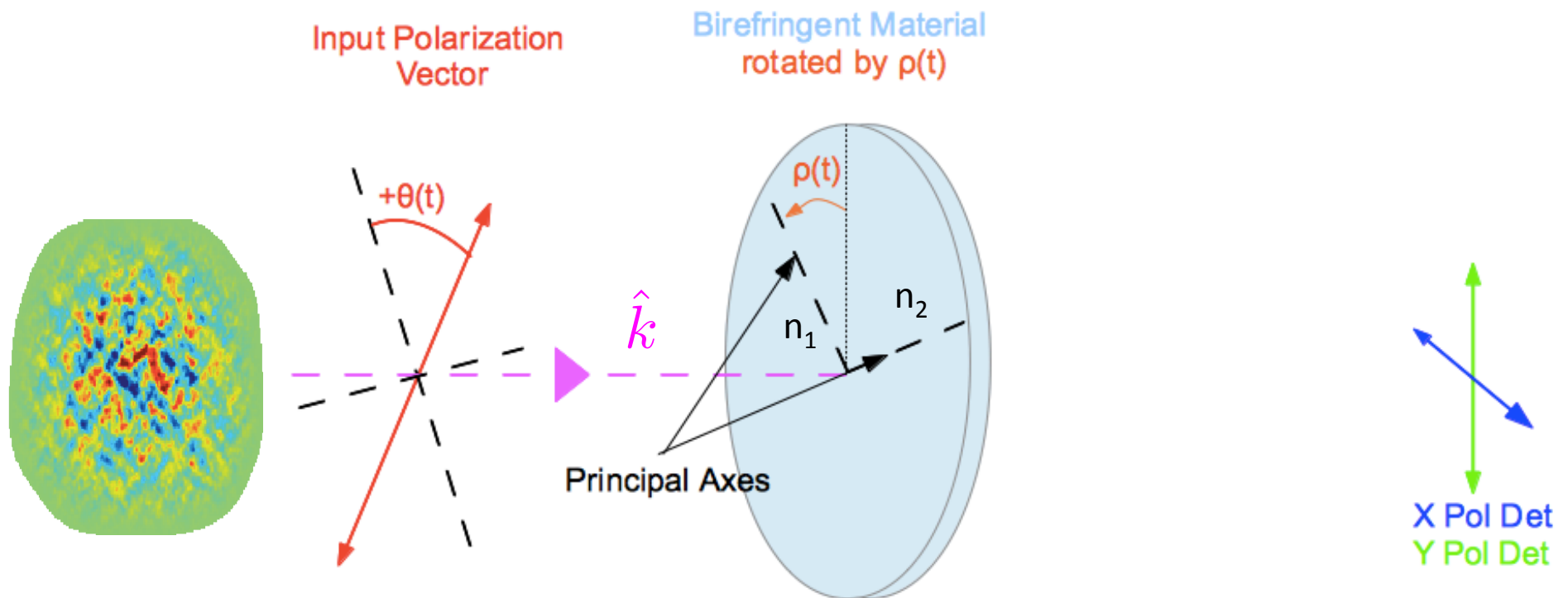
Birefringent Material
rotated by $\rho(t)$



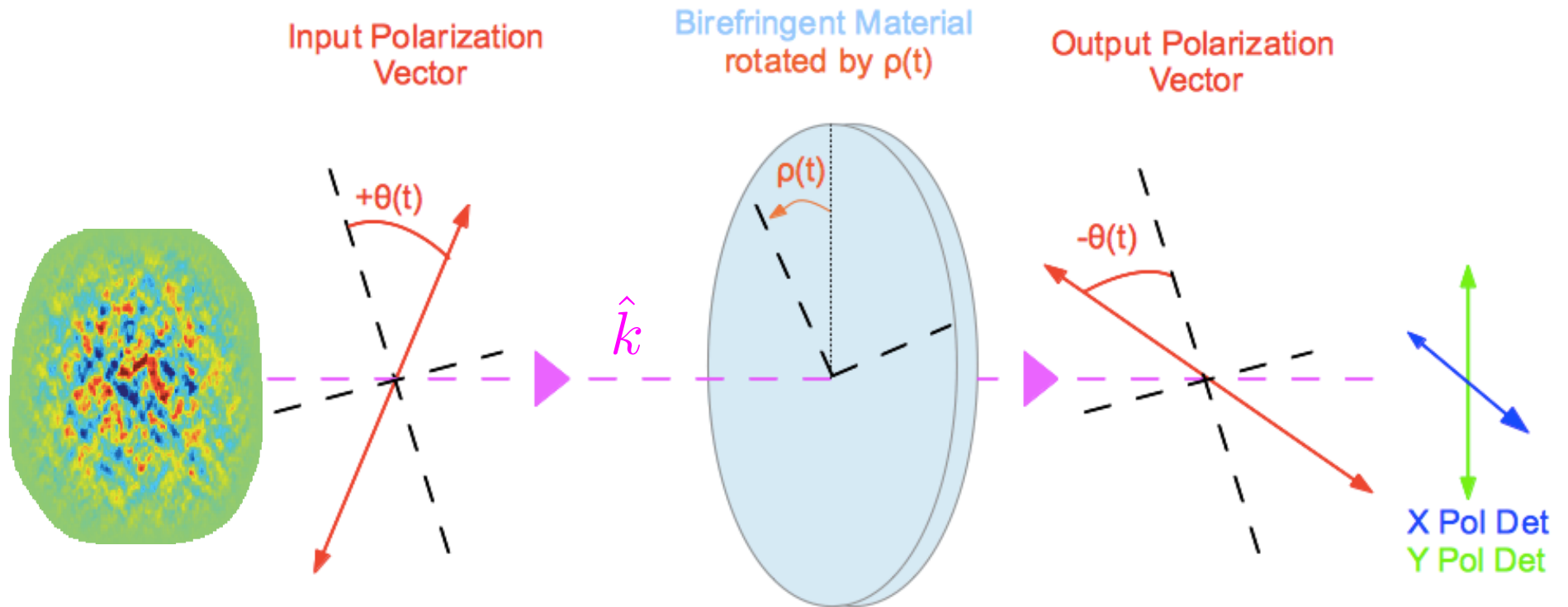
Continuously Rotating Half Wave Plate



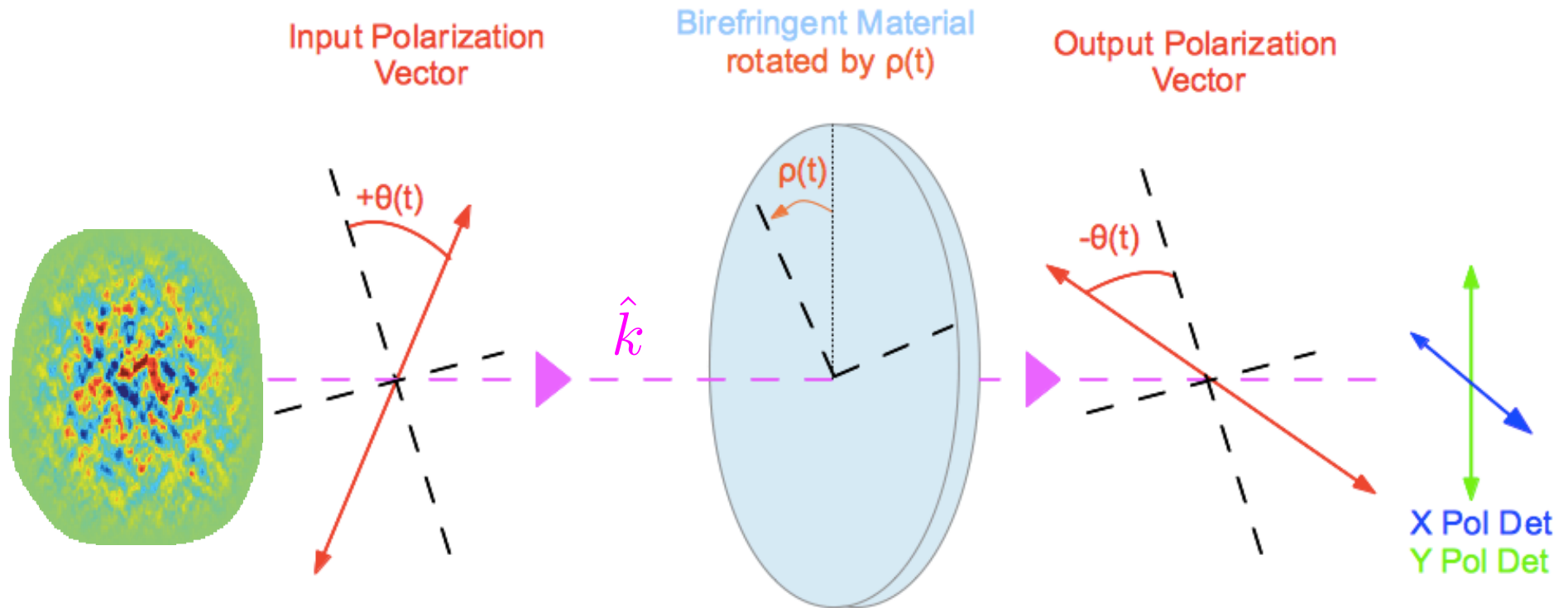
Continuously Rotating Half Wave Plate



Continuously Rotating Half Wave Plate



Continuously Rotating Half Wave Plate



- A continuously rotating HWP modulates linear polarization at “4f”, i.e. 4x the rotation frequency of the birefringent substrate

Polarization Modulation

Example PB1 Detector Noise Spectrum with Modulator

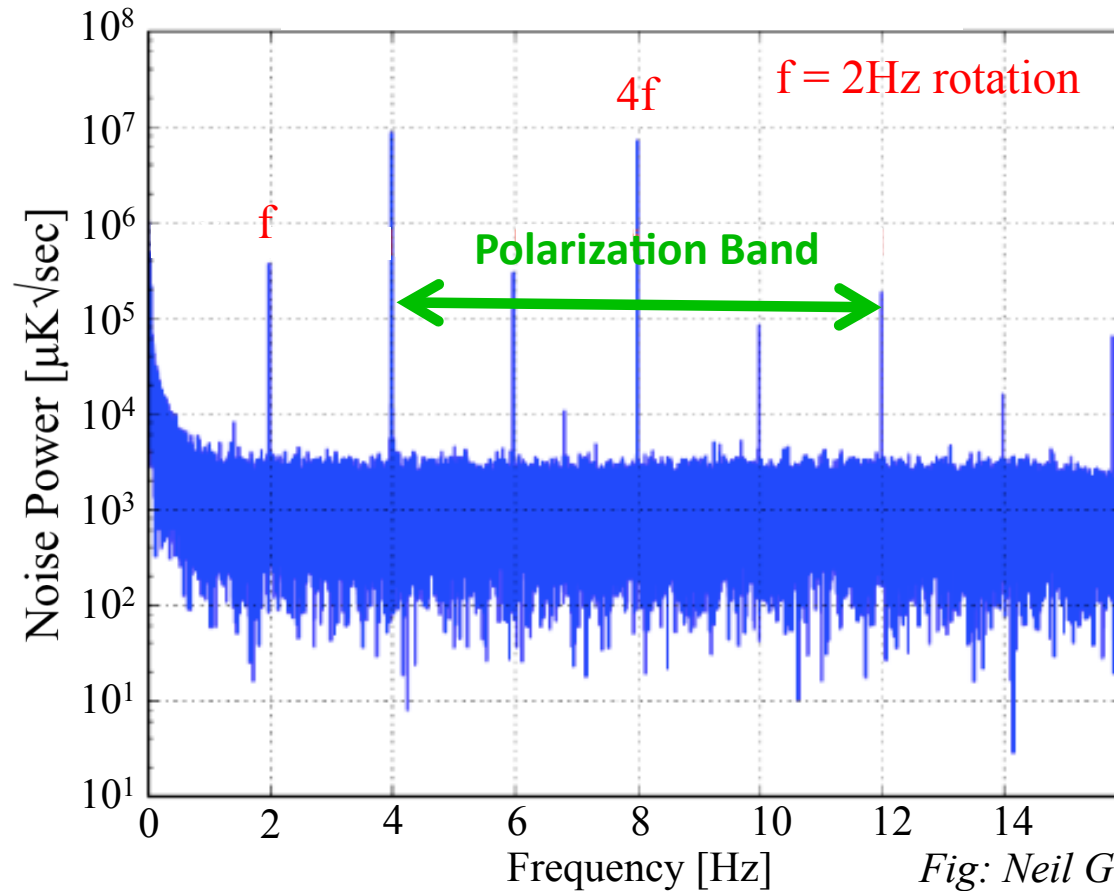


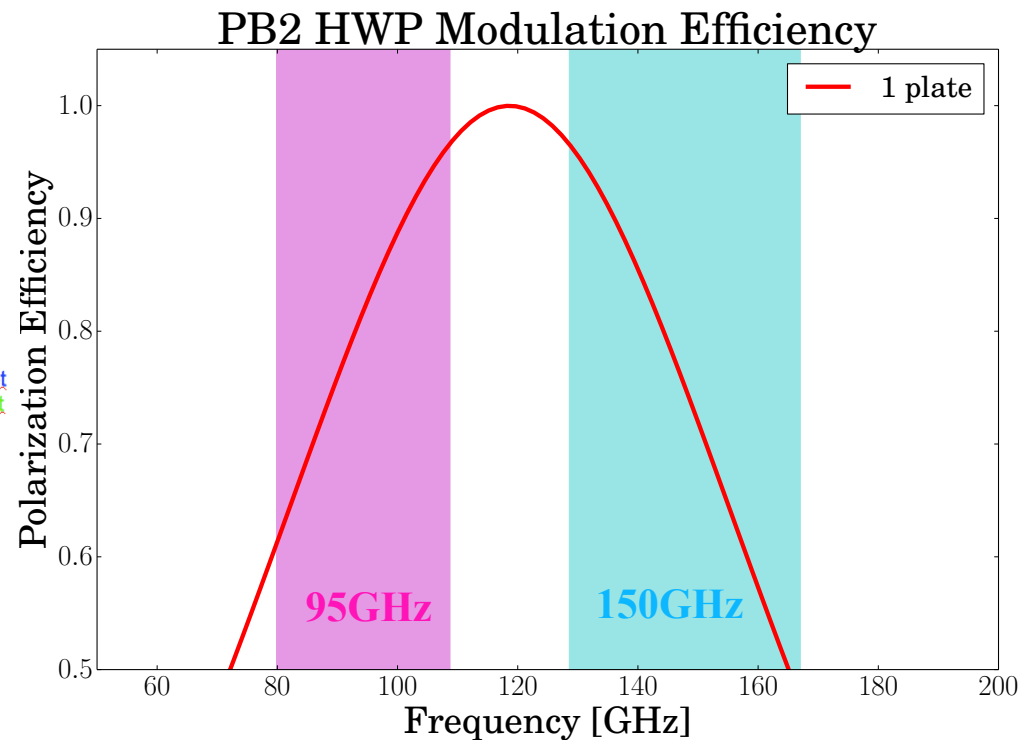
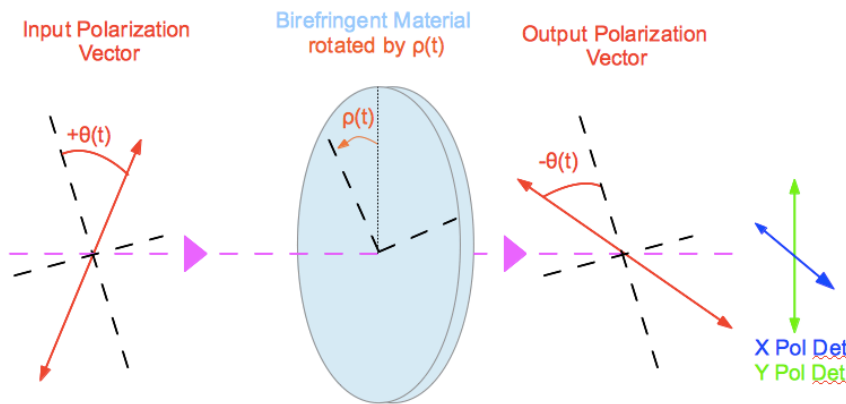
Fig: Neil Goeckner-Wald

- Continuous polarization modulation moves the polarization band into a white-noise-dominated regime

Going Achromatic

Broadband modulation achieved by stacking 3 monochromatic HWPs

Monochromatic HWP

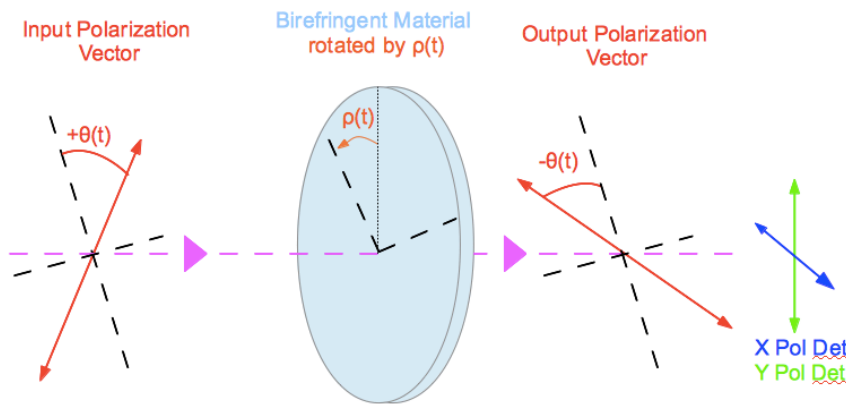


Band	1 plate Efficiency
95 GHz	75.6 %
150 GHz	82.0 %

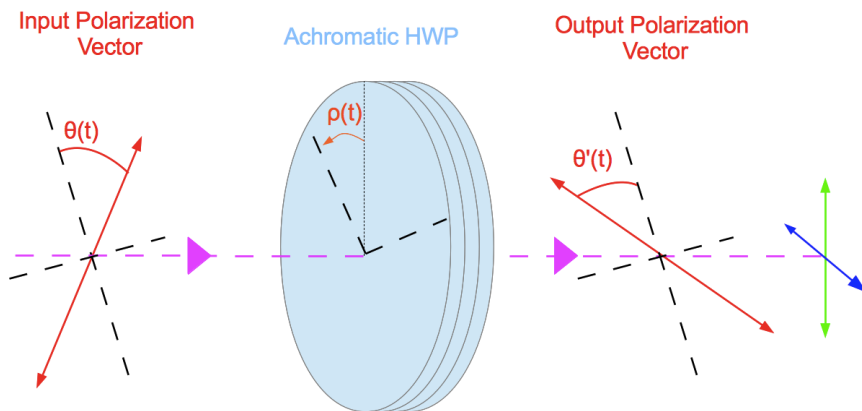
Going Achromatic

Broadband modulation achieved by stacking 3 monochromatic HWPs

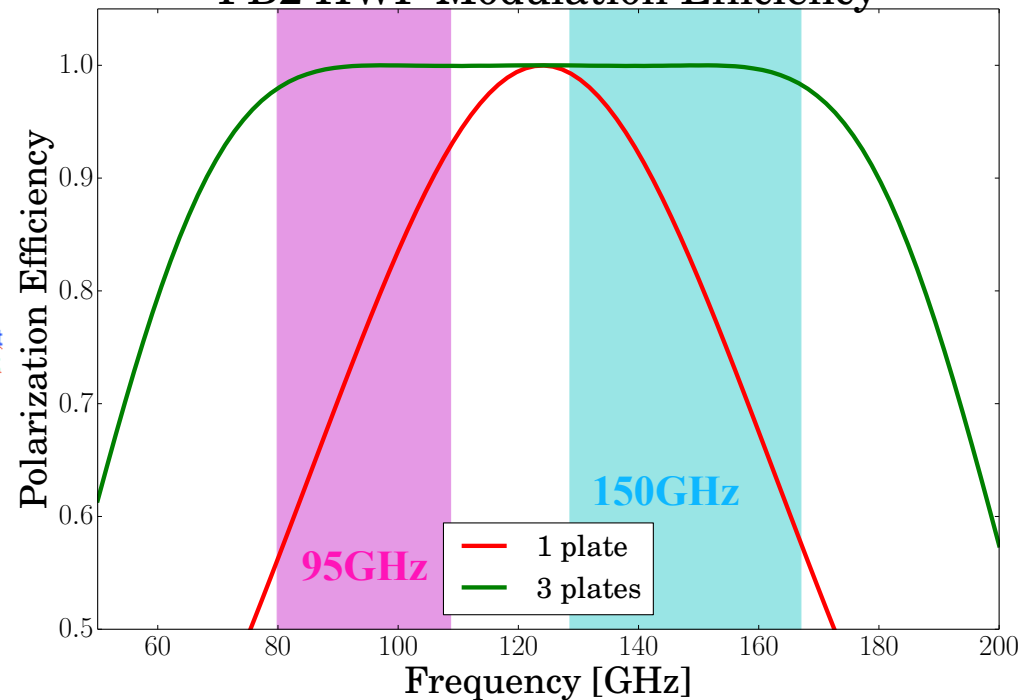
Monochromatic HWP



Achromatic HWP



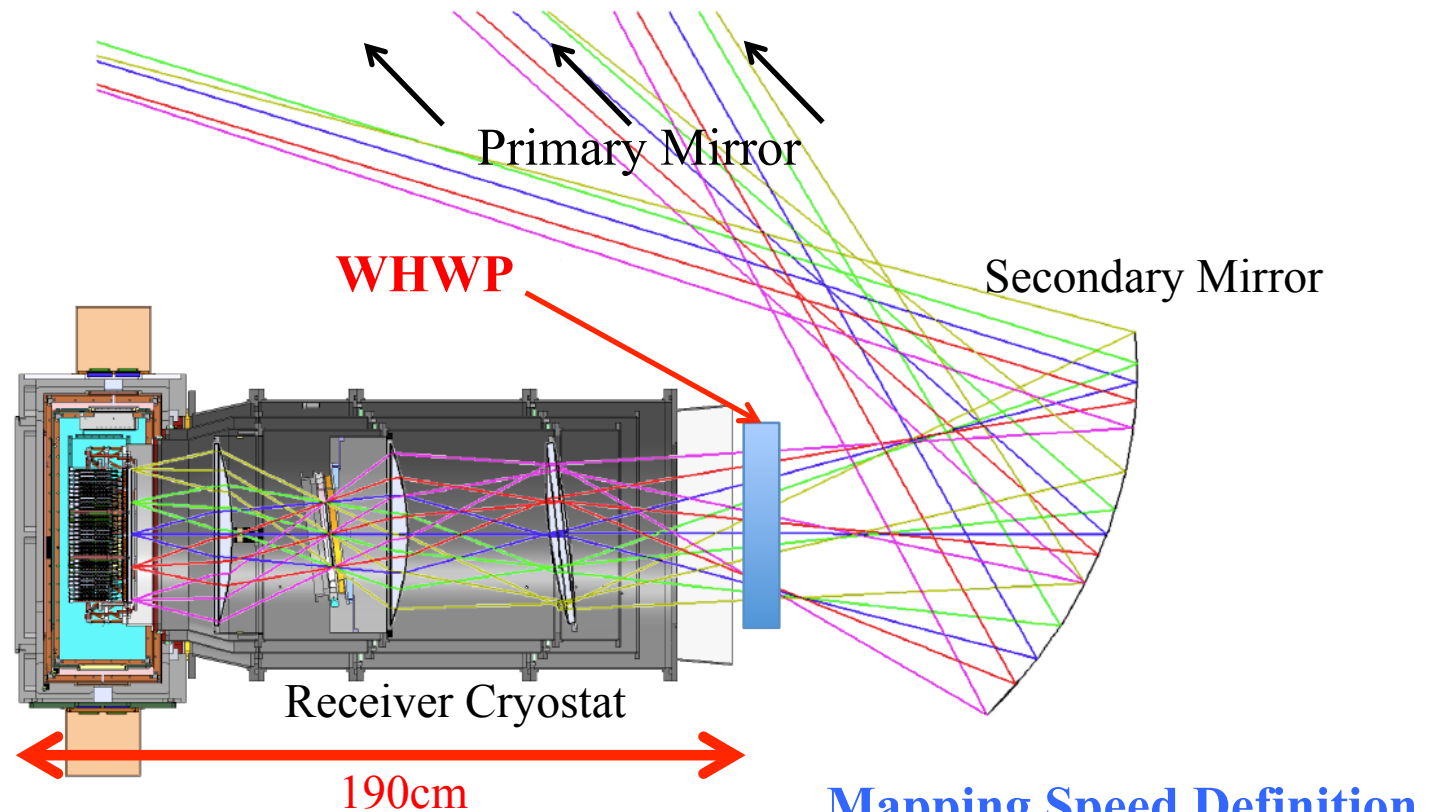
PB2 HWP Modulation Efficiency



Band	1 plate Efficiency	3 plate Efficiency
95 GHz	75.6 %	99.7 %
150 GHz	82.0 %	99.8 %

A Warm HWP for PB2a

WHWP Requirements



- $\geq 470\text{mm}$ clear aperture
- $\leq 40\%$ hit in mapping speed
- 2 Hz rotation, ≥ 100 million revolutions

Mapping Speed Definition

$$MS \sim \frac{N_{\text{det}}}{NEP_{\text{white}}^2}$$

Birefringent Substrate

PB2 will use sapphire as its birefringent material

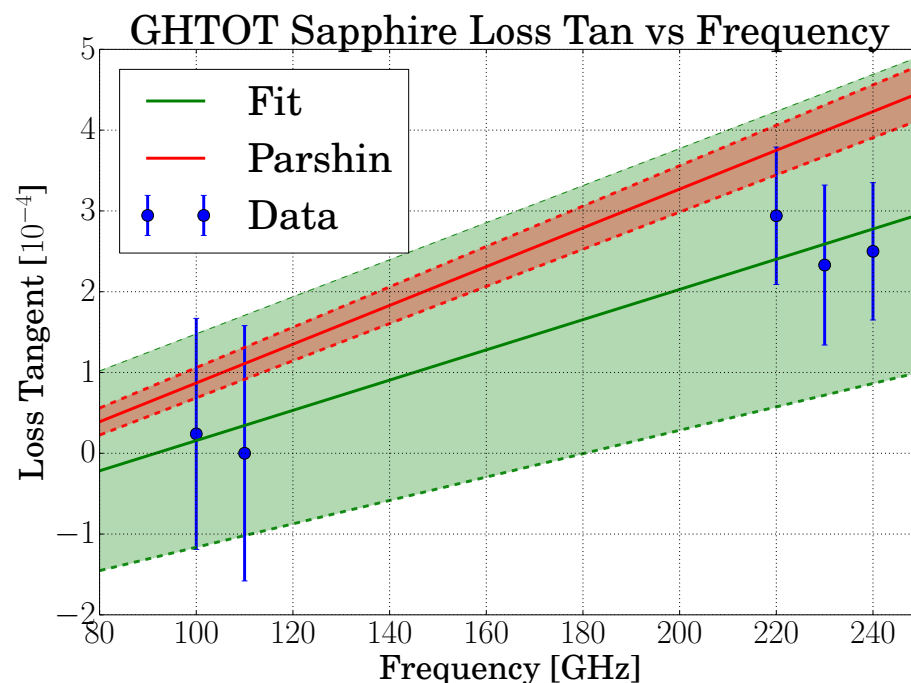
$$t_{\text{HWP}} = \frac{\lambda_0}{2(n_e - n_o)}$$



Photo: Chris Raum

Dimension	Value
Diameter	512.9 +/- 0.6 mm
Thickness	3.75 +/- 0.01 mm

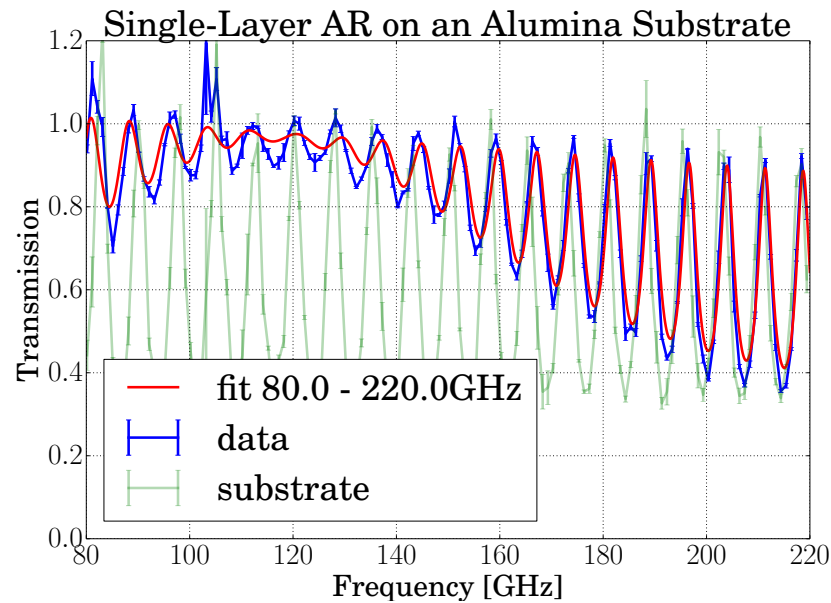
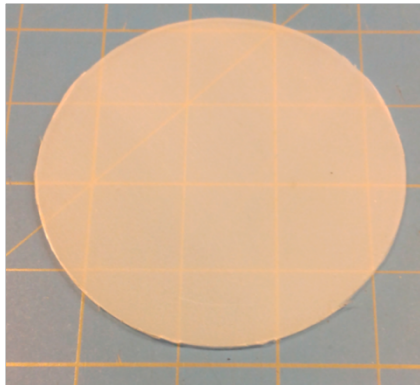
$$\alpha = 1 - \exp[-2\pi z n \tan\delta/\lambda]$$



Band	Loss Tangent [1e-4]
95 GHz	0.5 +/- 1.3
150 GHz	1.1 +/- 1.5

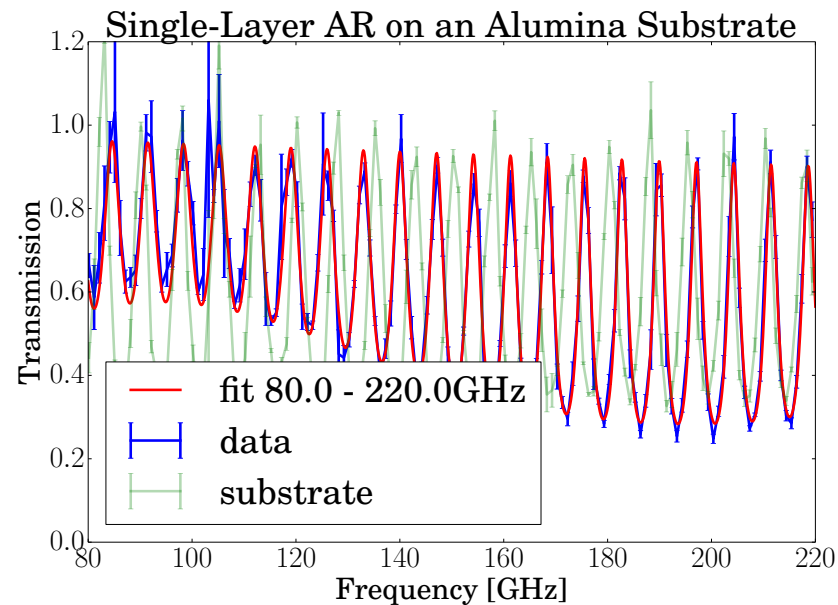
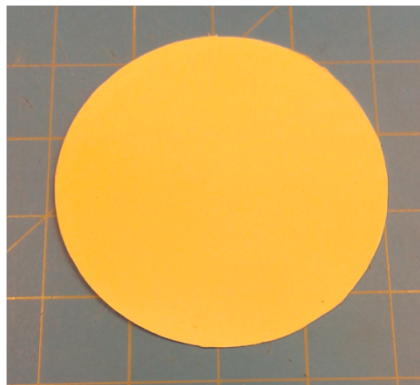
Anti-Reflection Coating

New Process Fibre
HDPE



Index	1.55 +/- 0.01
tan δ	0.5 +/- 0.4 e-4
Thick	0.015 +/- 0.002"

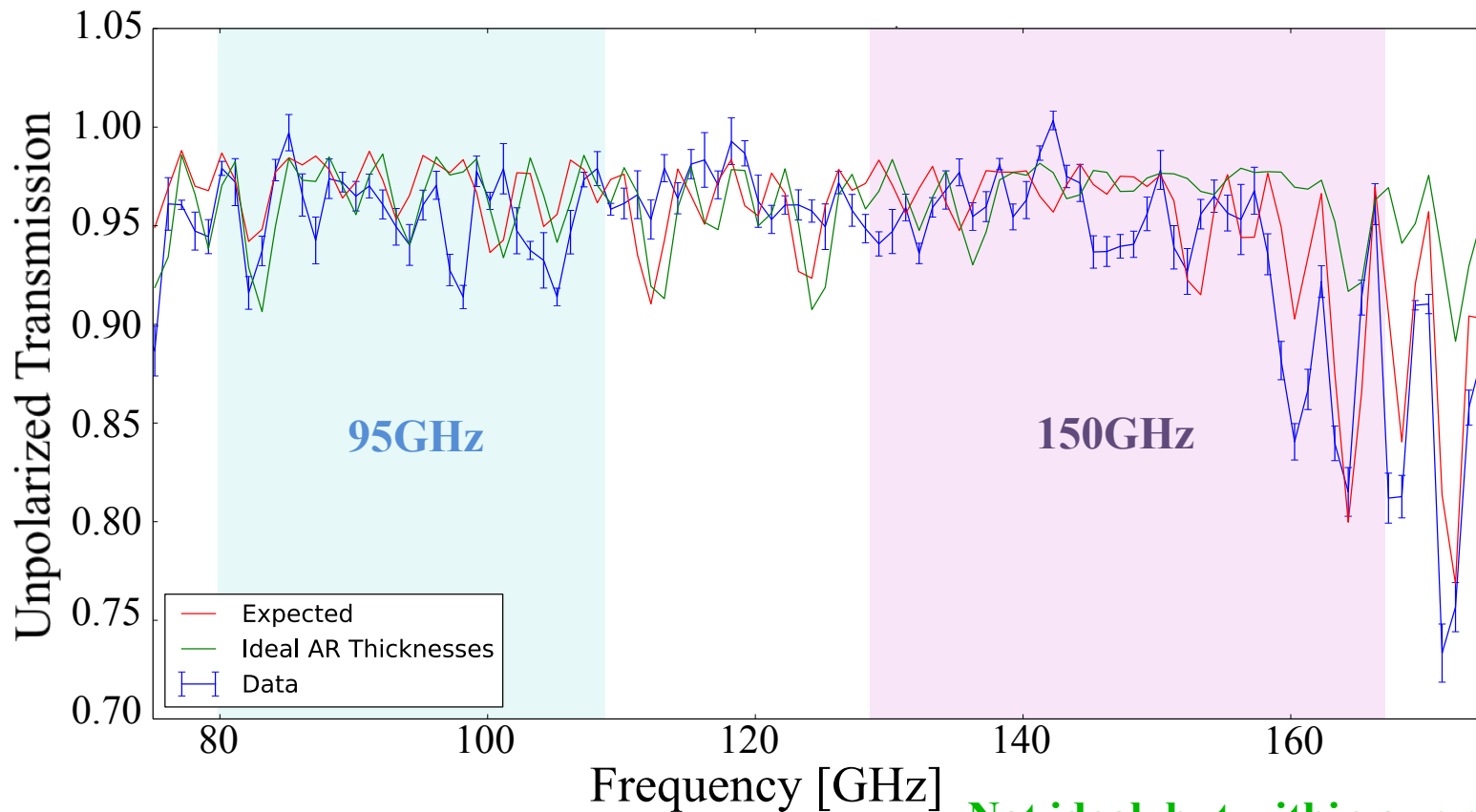
Rogers Corporation
R03006



Index	2.52 +/- 0.01
tan δ	18 +/- 1.4 e-4
Thick	0.010 +/- 0.001"

WHWP Transmission Performance

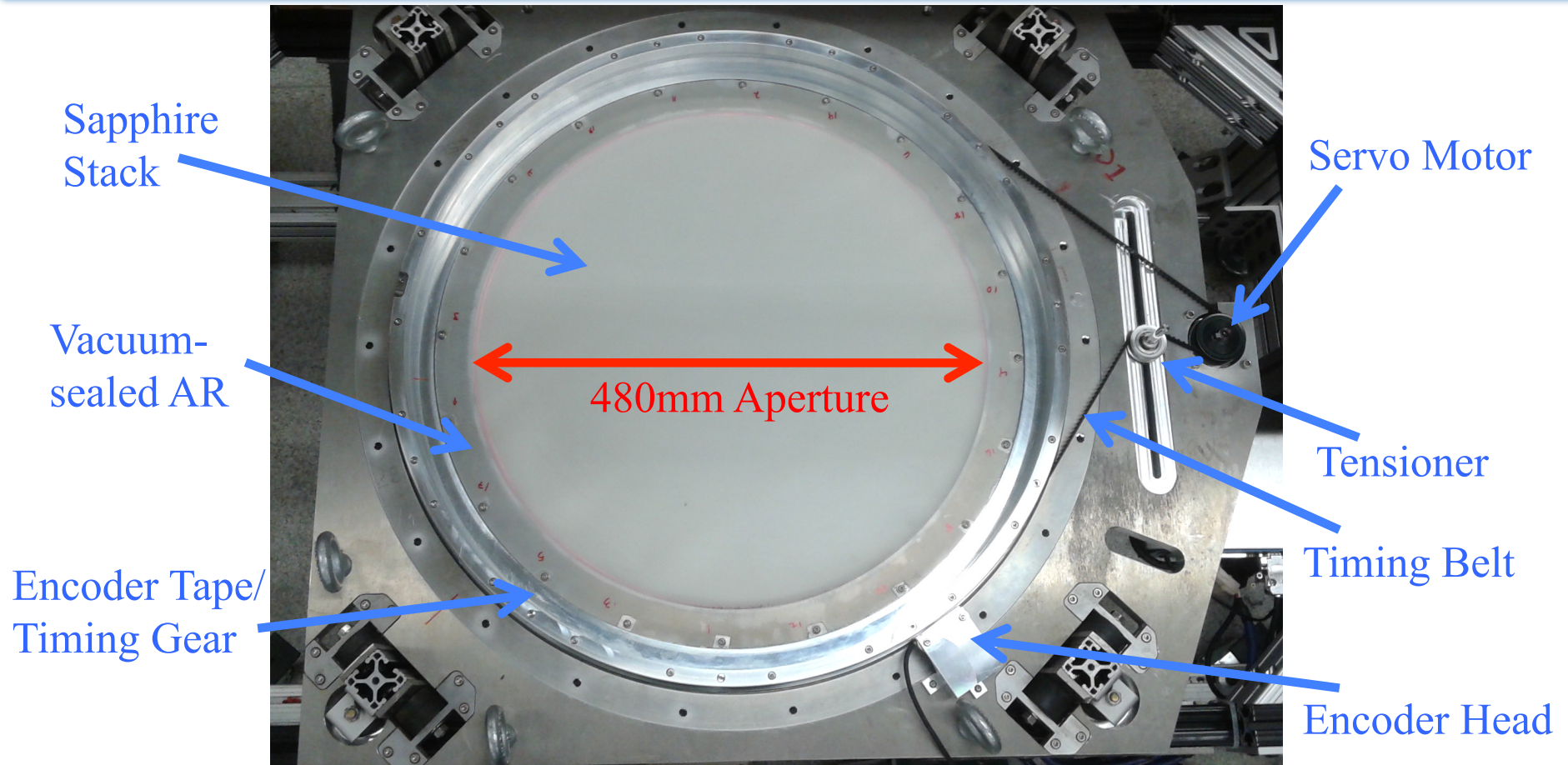
The PB2a WHWP bandpass meets deployment standards



Not ideal, but within our requirement!

Band	Efficiency	Emissivity	Fractional Mapping Speed
95 GHz	95.6 %	1.1 %	82.6 %
150 GHz	94.1 %	1.9%	72.3 %

WHWP Construction

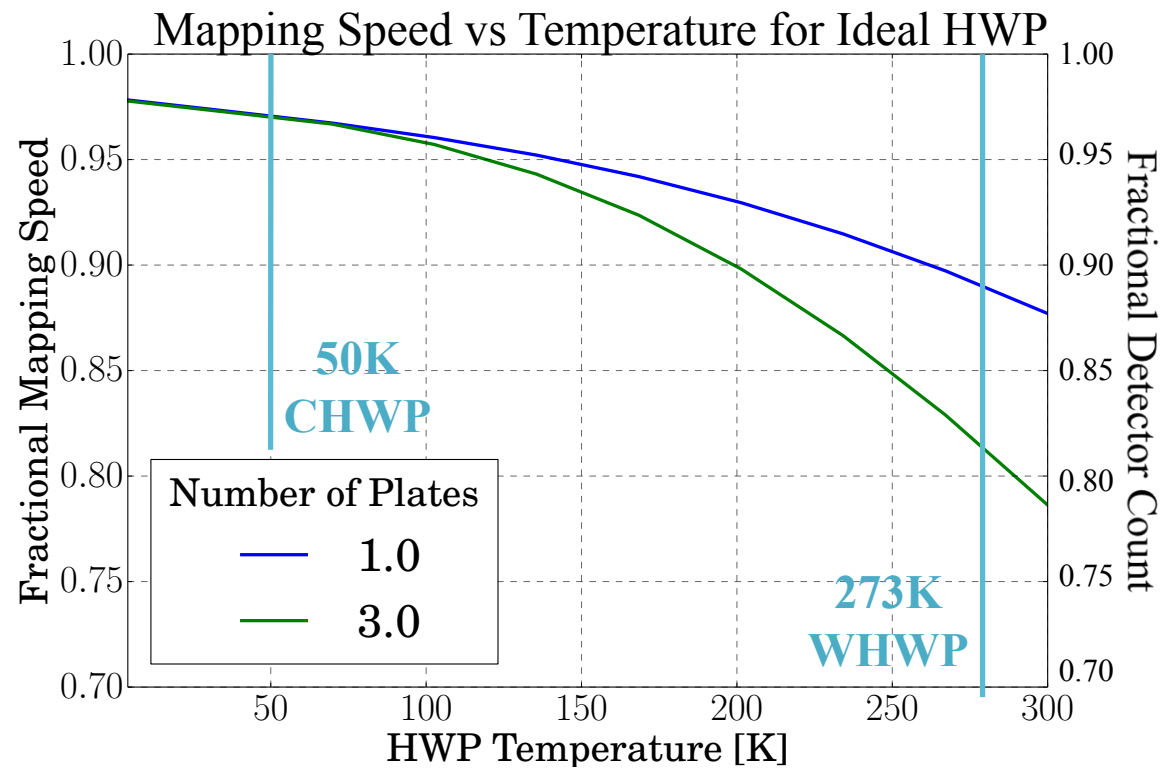


Rig design by Shawn Beckman

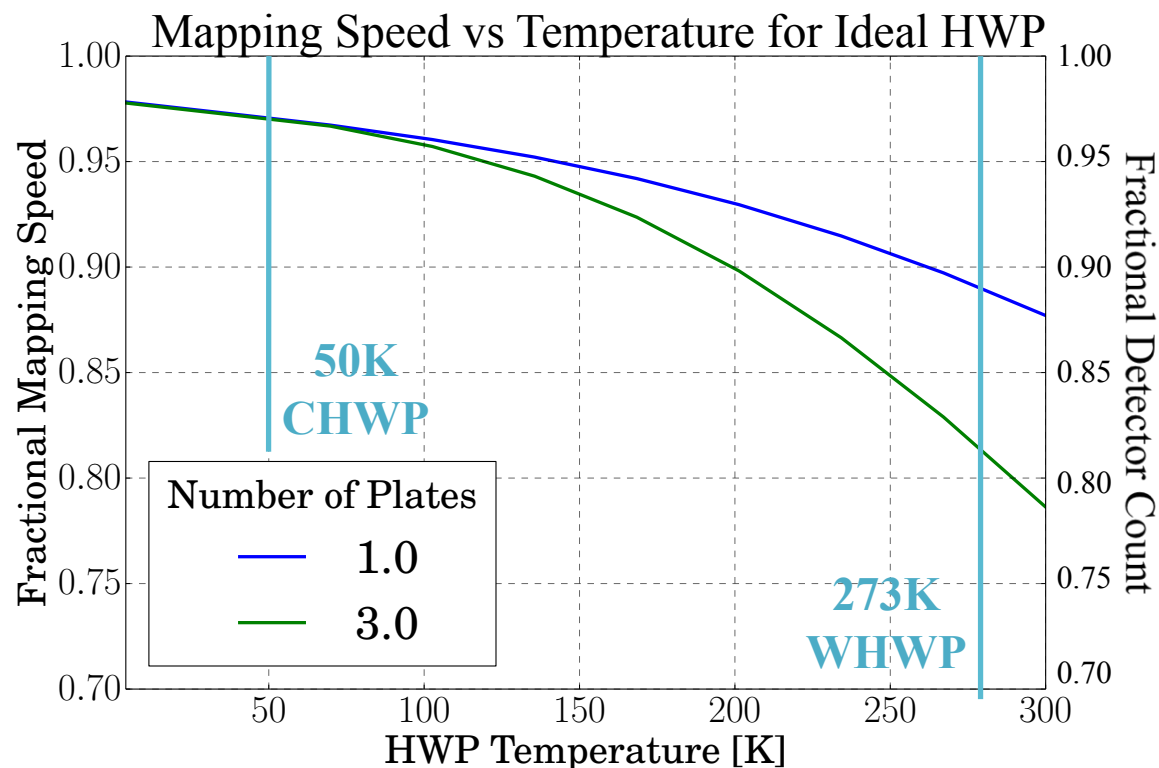
Final local testing in June
Integration with the PB2a receiver this summer

A Cold HWP for PB2b/c

Motivation for Going Cryogenic



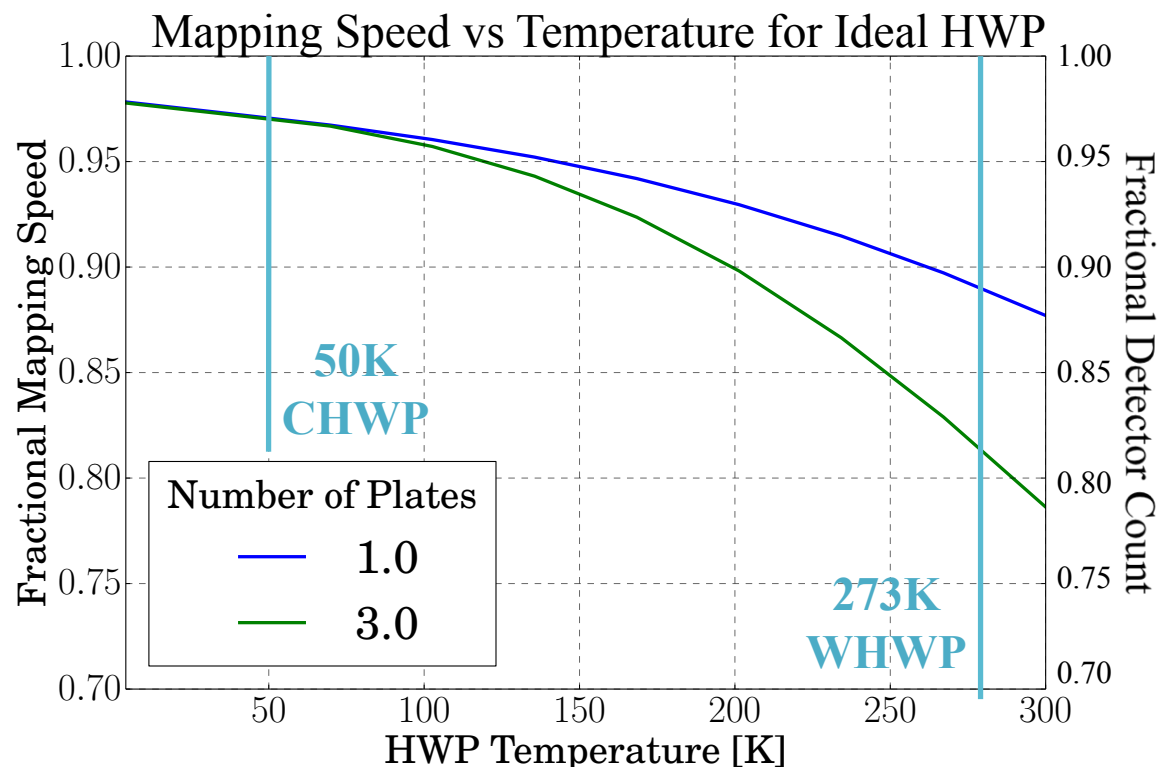
Motivation for Going Cryogenic



Fractional impact on mapping speed in 150GHz Band

Multipole	No HWP	WHWP	CHWP
$\ell \sim 100$	1.0	2.5	2.5
$\ell \sim 1000$	1.0	0.7	1.0

Motivation for Going Cryogenic

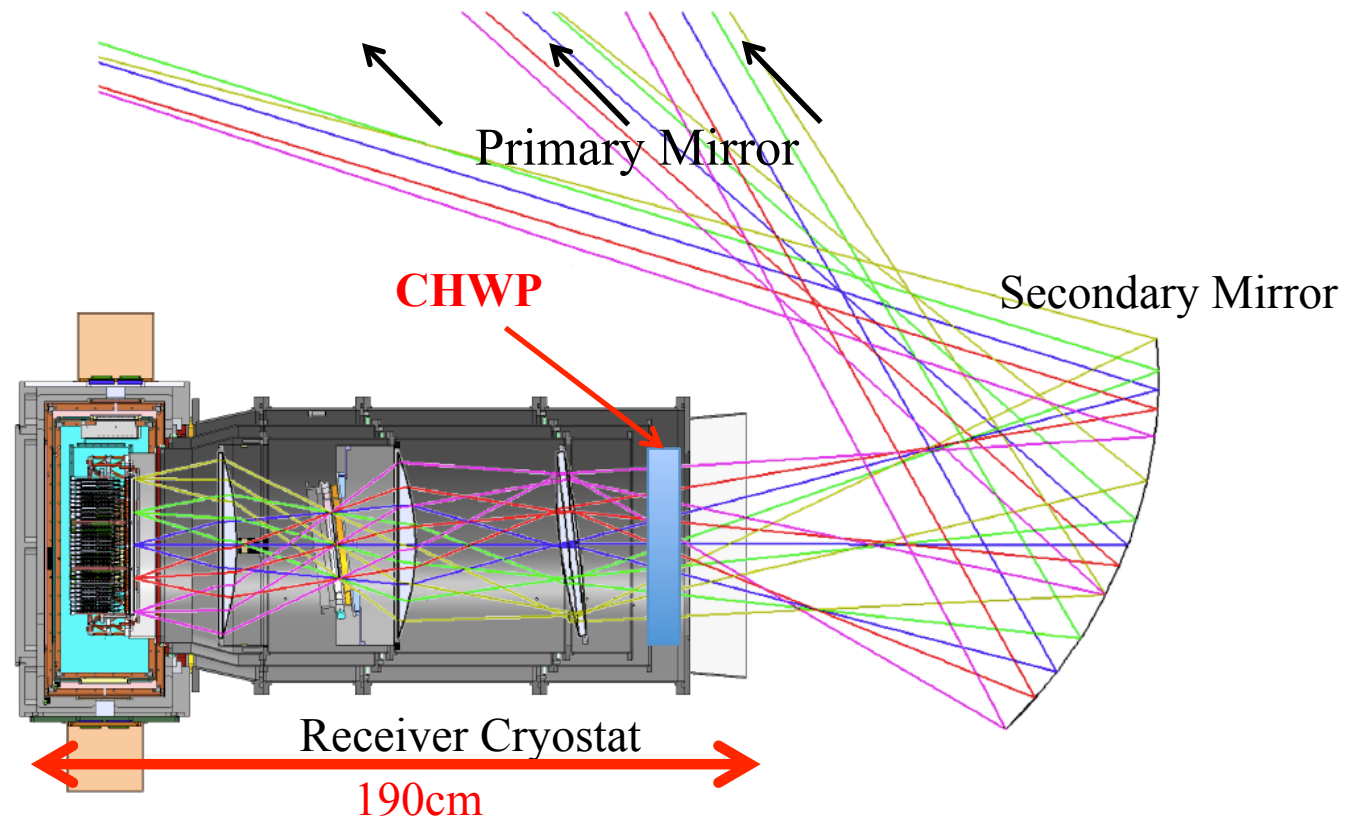


Fractional impact on mapping speed in 150GHz Band

Multipole	No HWP	WHWP	CHWP
$\ell \sim 100$	1.0	2.5	2.5
$\ell \sim 1000$	1.0	0.7	1.0

A CHWP resolves tension between high- ℓ and low- ℓ science!

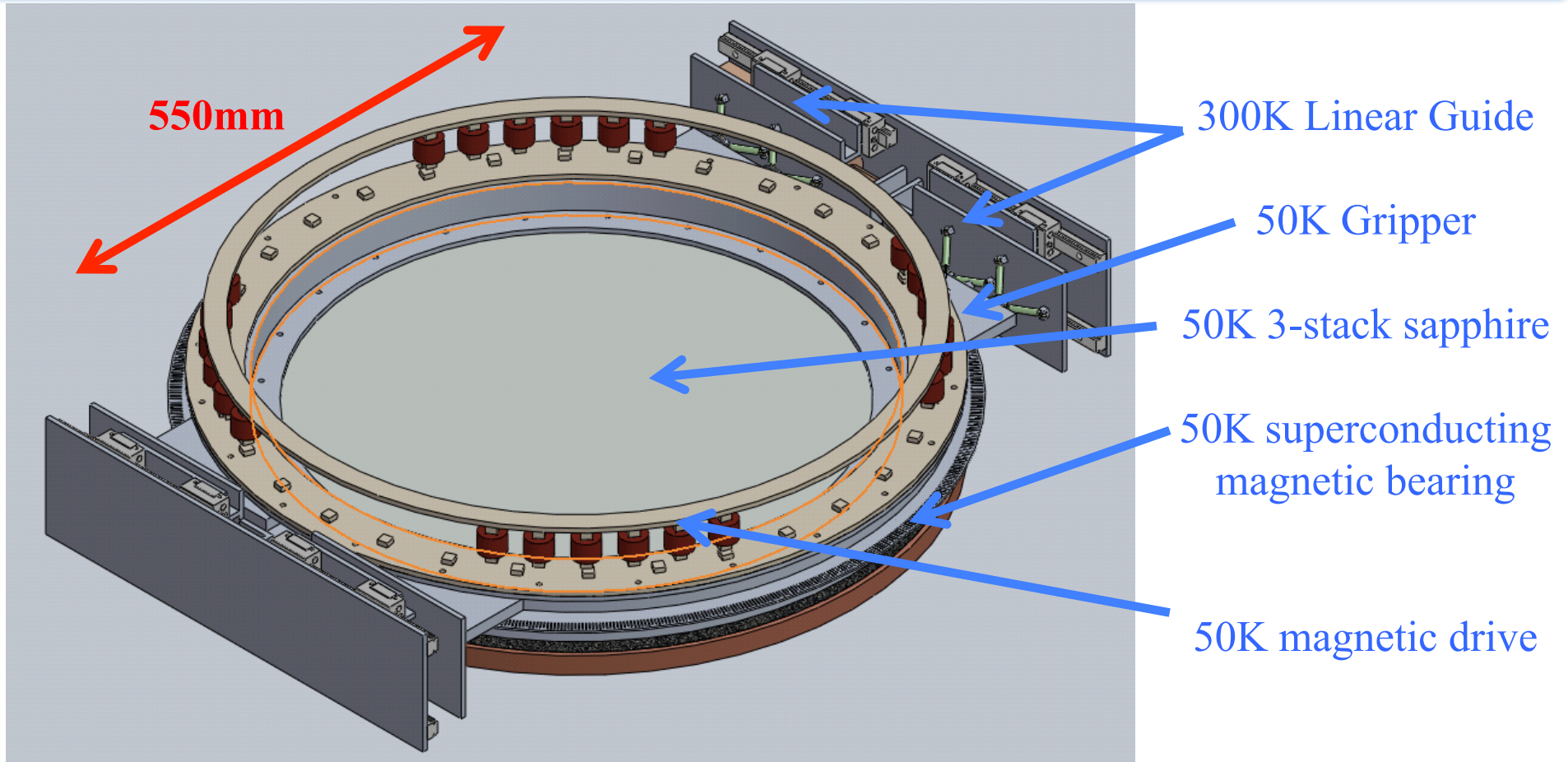
PB2 CHWP Requirements



Science motivations drive engineering challenges

- Minimal photon loading and heat dissipation – low friction
- Minimal microphonic heating of focal plane – low vibration
- Minimal EMI at detectors – controlled EM footprint
- Minimal risk to observation efficiency – robust against failure

PB2 CHWP Design

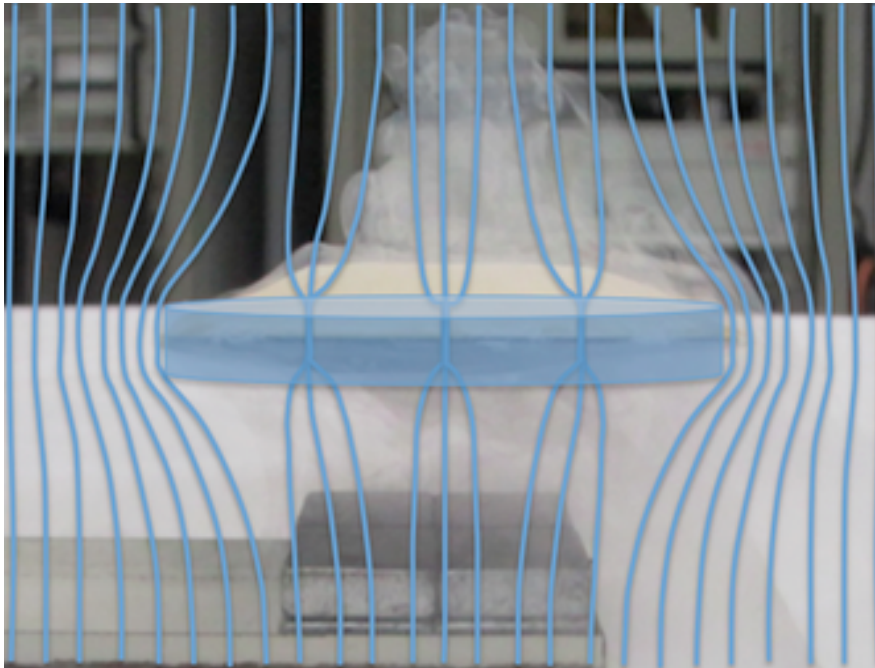


Key Technologies

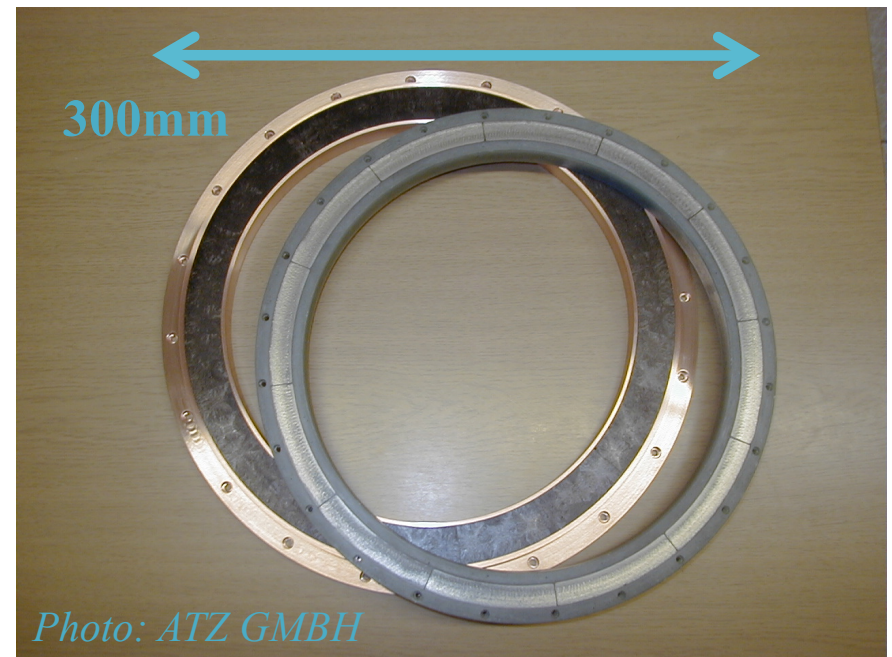
- Bearing: Superconducting magnetic levitation
- Drive: Electromagnets coupled to magnetized sprockets
- Gripper: Warm linear guide coupled to cryogenic gripper

Superconducting Magnetic Bearing

Flux Pinning



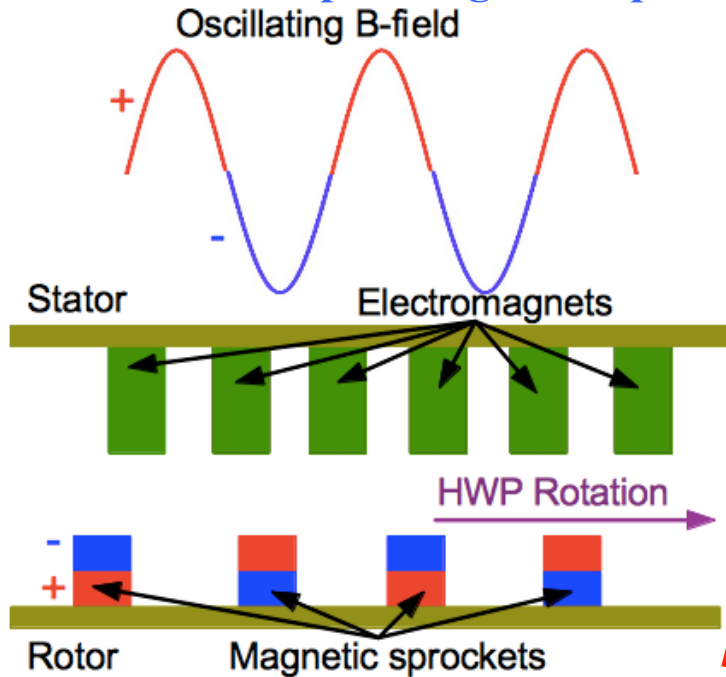
EBEX Superconducting Bearing



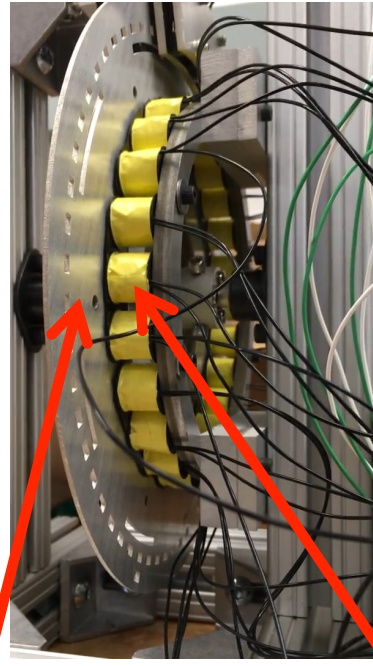
- Rotor – 0.8T Neodymium Magnet
- Stator – YBCO high-T_c superconductor
- PB2 HWP Heating estimate – ~500 mW at 2Hz rotation speed

Electromagnetic Drive

EM Drive Operating Concept



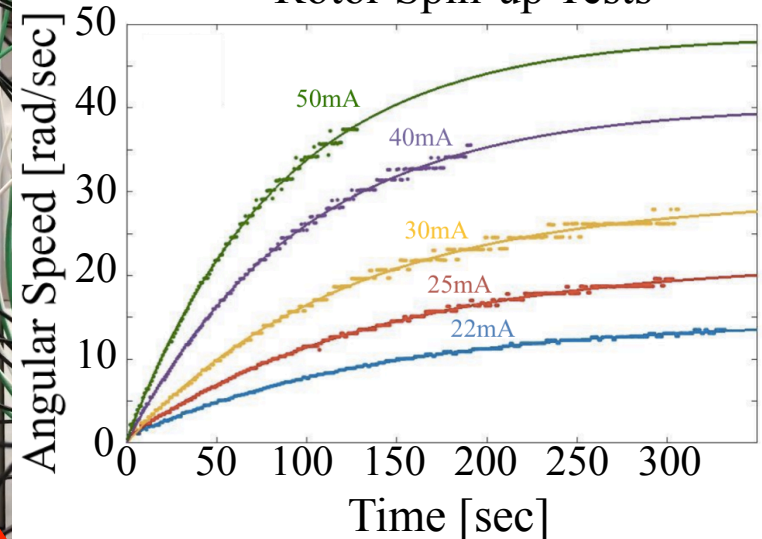
Warm Prototype



Encoder/Rotor Solenoids/Stator

Warm Demonstration

Rotor Spin-up Tests

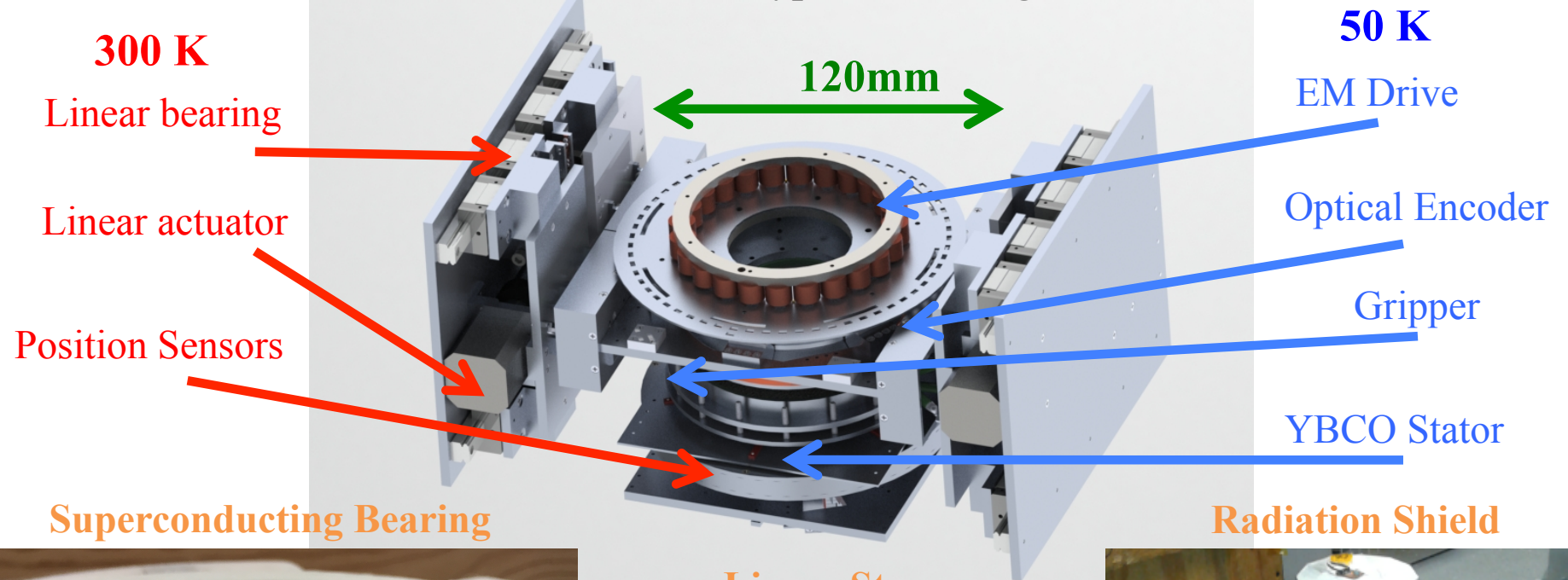


- No moving parts
- No mechanical contacts
- Cryogenically reliable

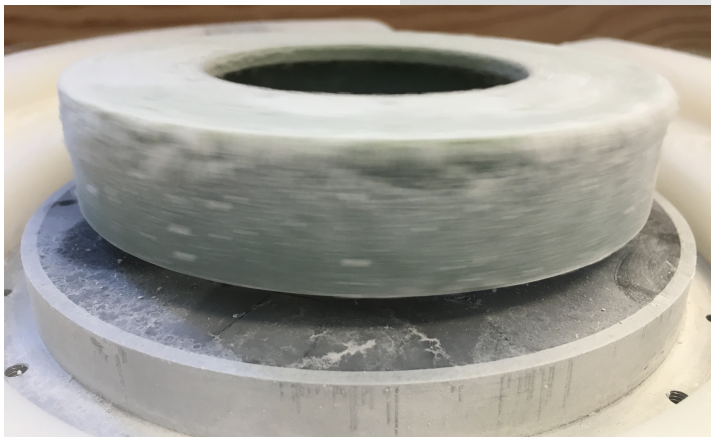
CHWP Prototype

Many design challenges to be addressed via prototyping

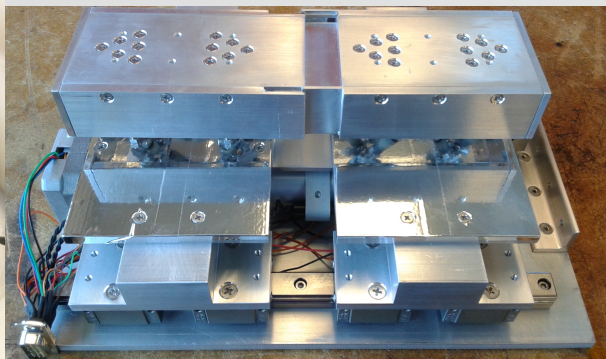
CHWP Prototype CAD Design



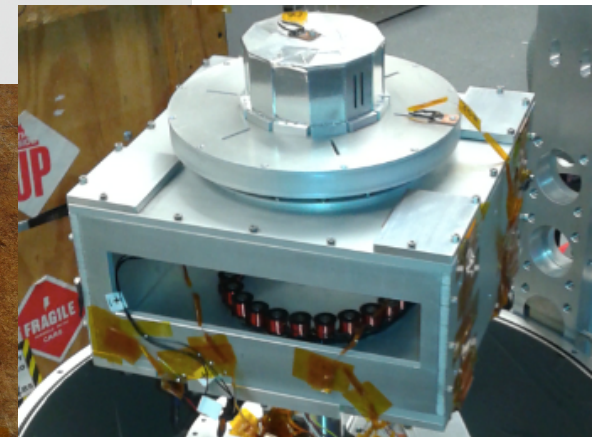
Superconducting Bearing



Linear Stage



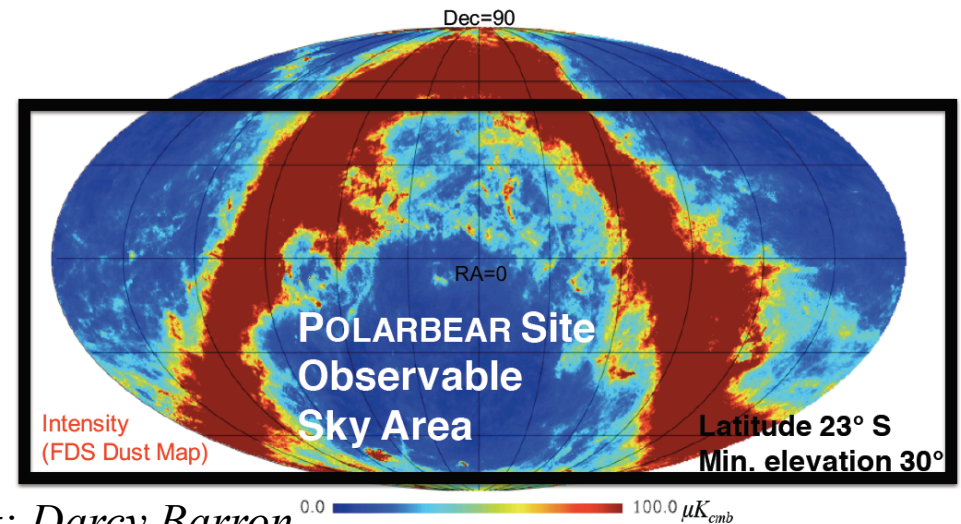
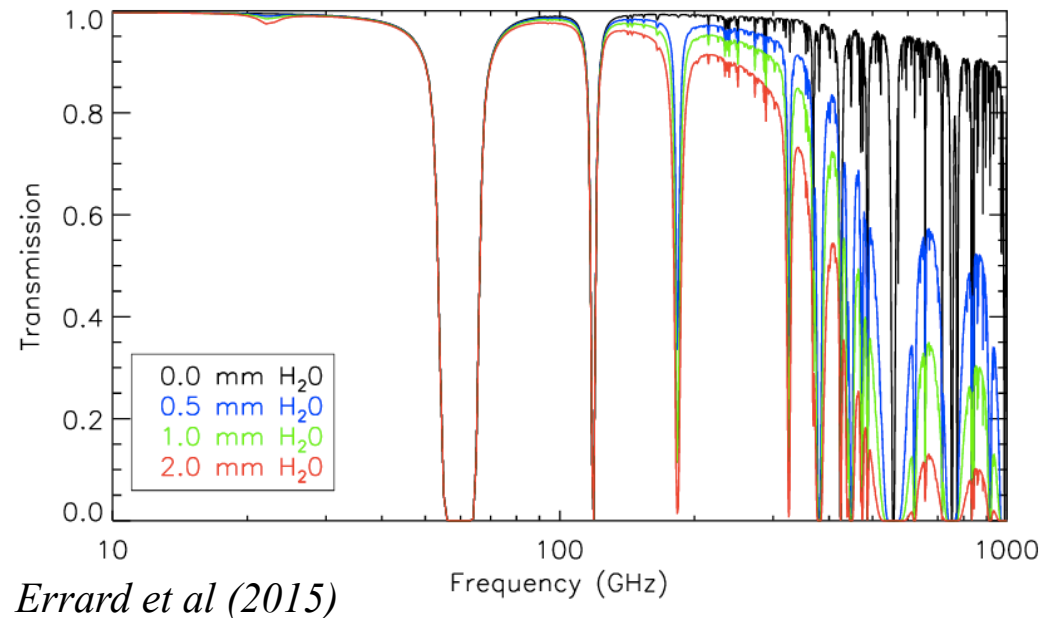
Radiation Shield



A HWP for the LiteBIRD Satellite

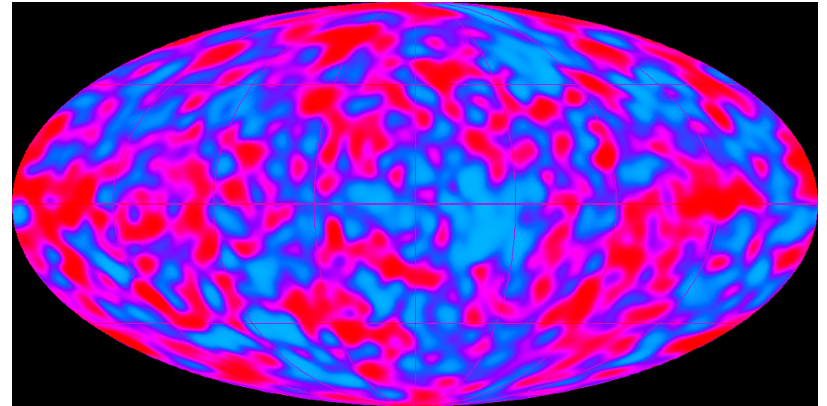
Motivations for B-modes from Space

- No atmosphere
 - Less photon loading on detectors
 - Less fluctuation in optical power
 - Greater frequency coverage
- More available sky
 - Full-sky survey
 - More large-angular-scale modes



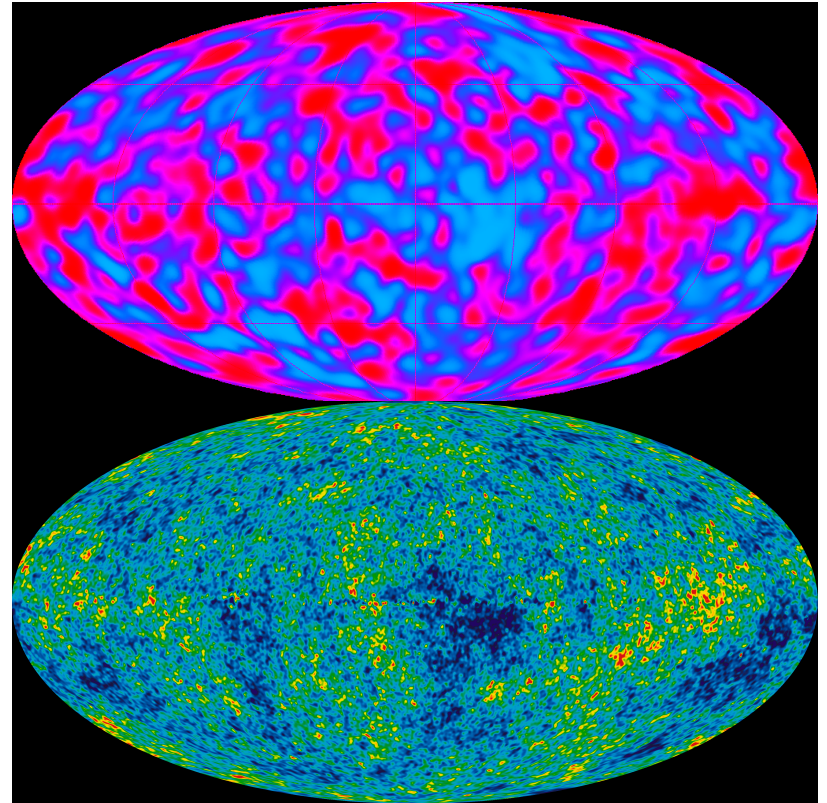
History of CMB Satellite Missions

- COBE (1989 – 1993)
 - Monopole temperature
 - Detection of temperature anisotropies



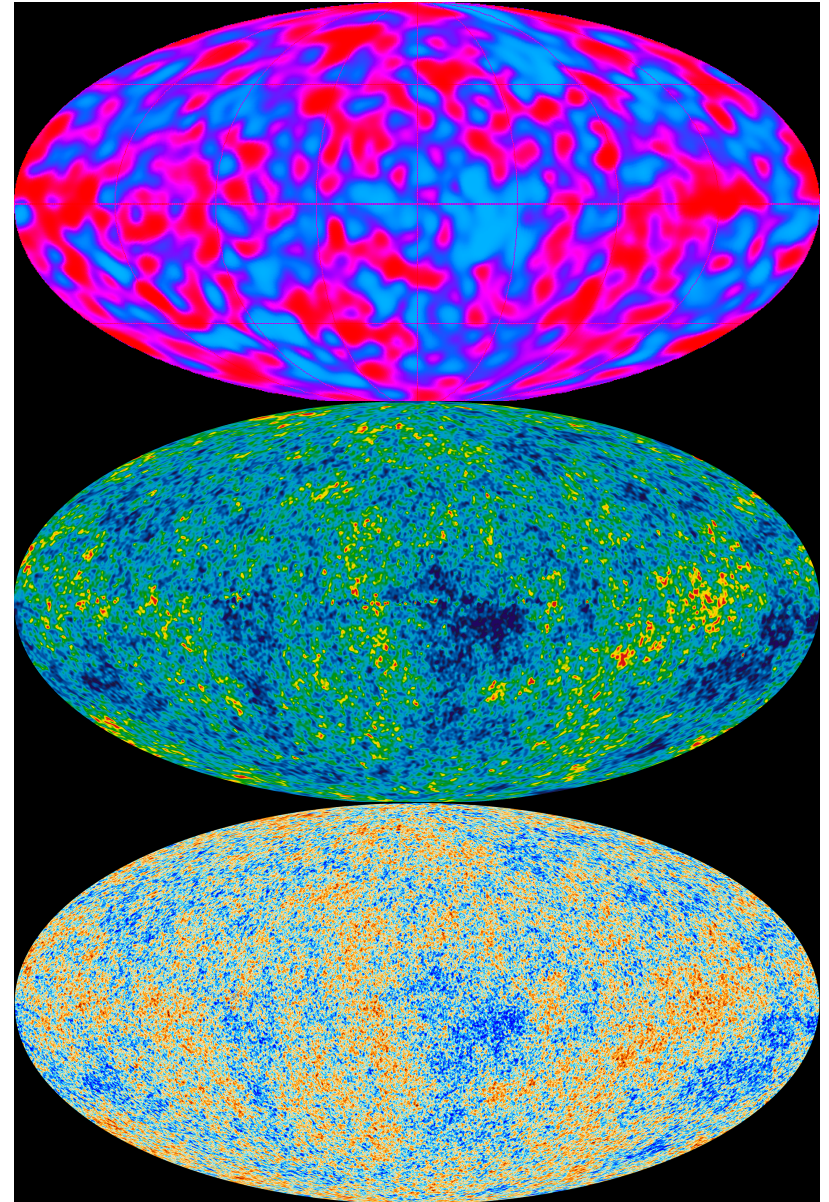
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 - Precise characterization of **temperature anisotropies**
 - Detection of **E-mode polarization**



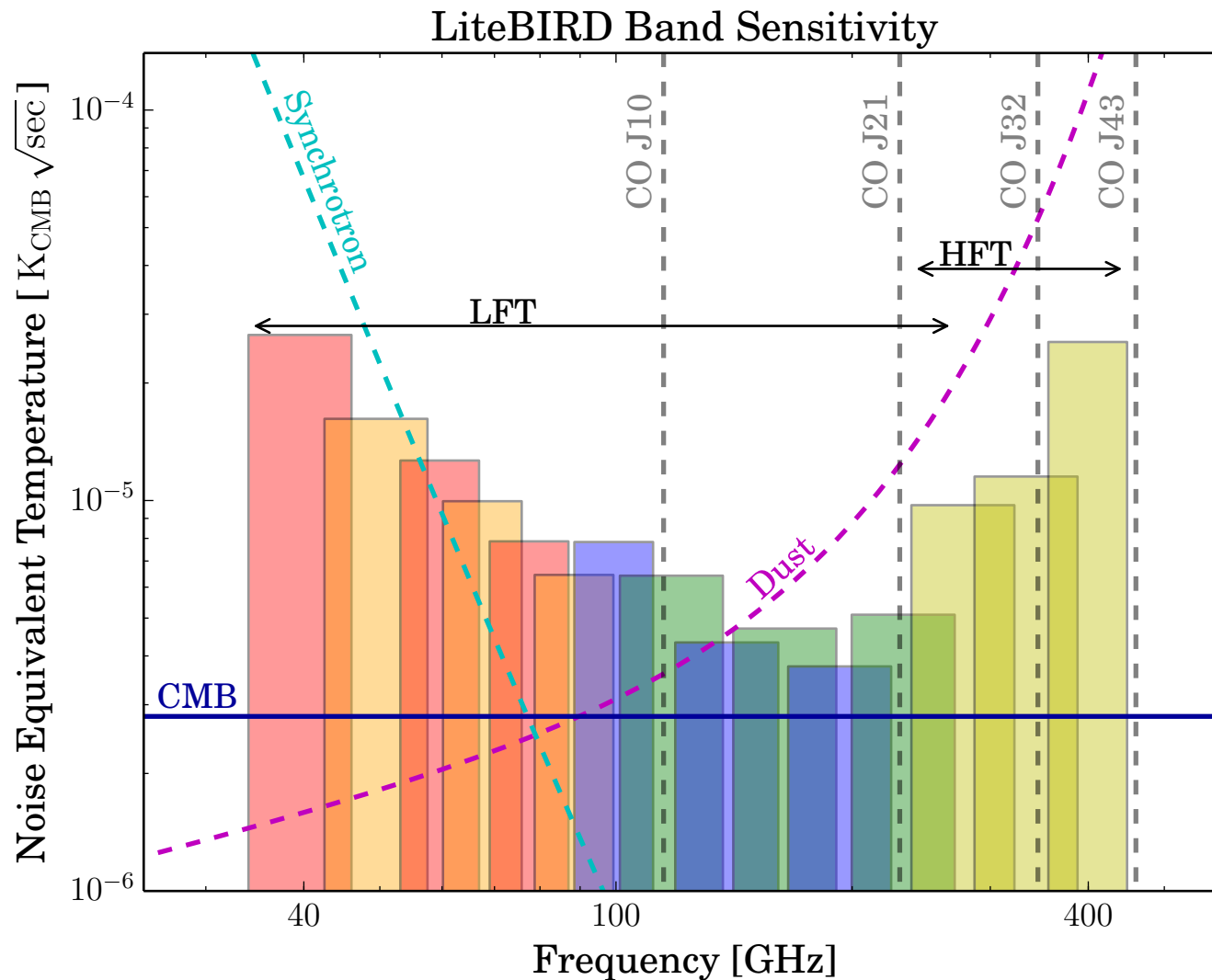
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 - Detection of **temperature anisotropies**
- WMAP (2001 – 2010)
 - 10 detectors, 5 frequency bands 30 – 100 GHz
 - Precise characterization of **temperature anisotropies**
 - Detection of **E-mode polarization**
- Planck (2009 – 2013)
 - 79 detectors, 9 frequency bands 30 – 900 GHz
 - Precise characterization of **E-mode polarization**



LiteBIRD: Precise Characterization of B-modes

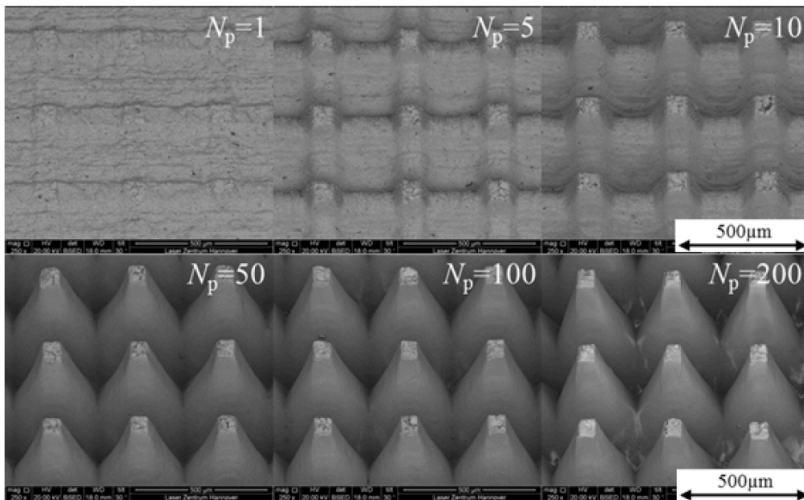
2276 detectors, 15 frequency bands 40 – 400 GHz



LiteBIRD HWP

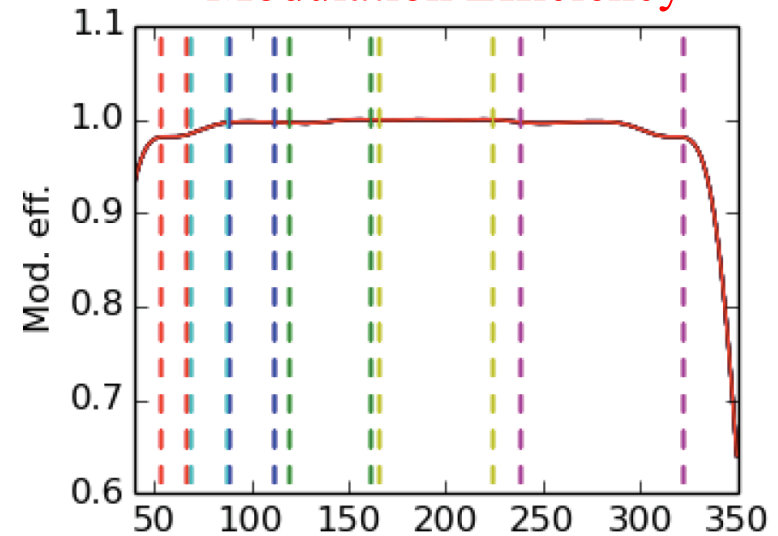
Broadband Performance

Anti-reflection Coating



Matsumura (2016)

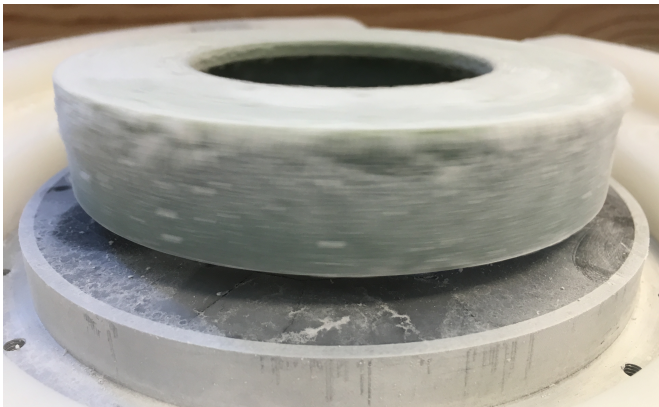
Modulation Efficiency



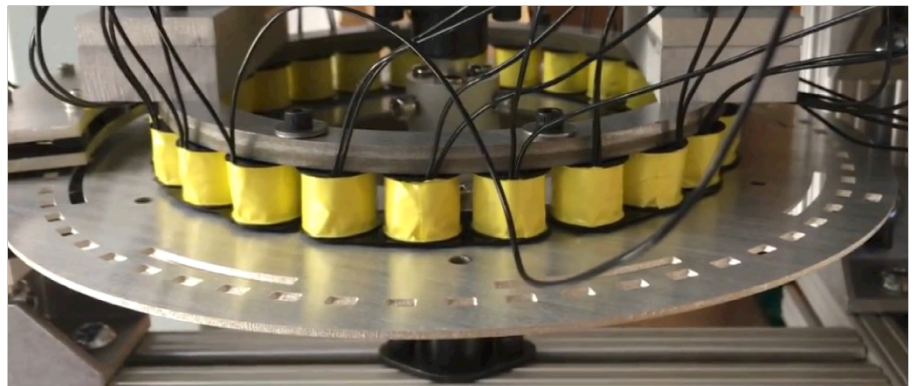
Matsumura (2014)

Very low frictional dissipation

Superconducting Bearing



Non-contact motors/stepped operation



The End