

The Atacama Cosmology Telescope

Mapping the CMB with high resolution

Introduction

- Historical overview of the study of the CMB through different experiments and their technology.
- Current CMB experiments: review current CMB experiments, including their scientific goals and technology.
- CMB experiments in Chile: why Chile?
- The Atacama Cosmology Telescope: general introduction.

Prediction

- The CMB was first predicted by R. Alpher and R. Herman in 1948, but was not taken seriously until the 60s



Ralph Alpher



George Gamow

They were impossible to measure at the time!

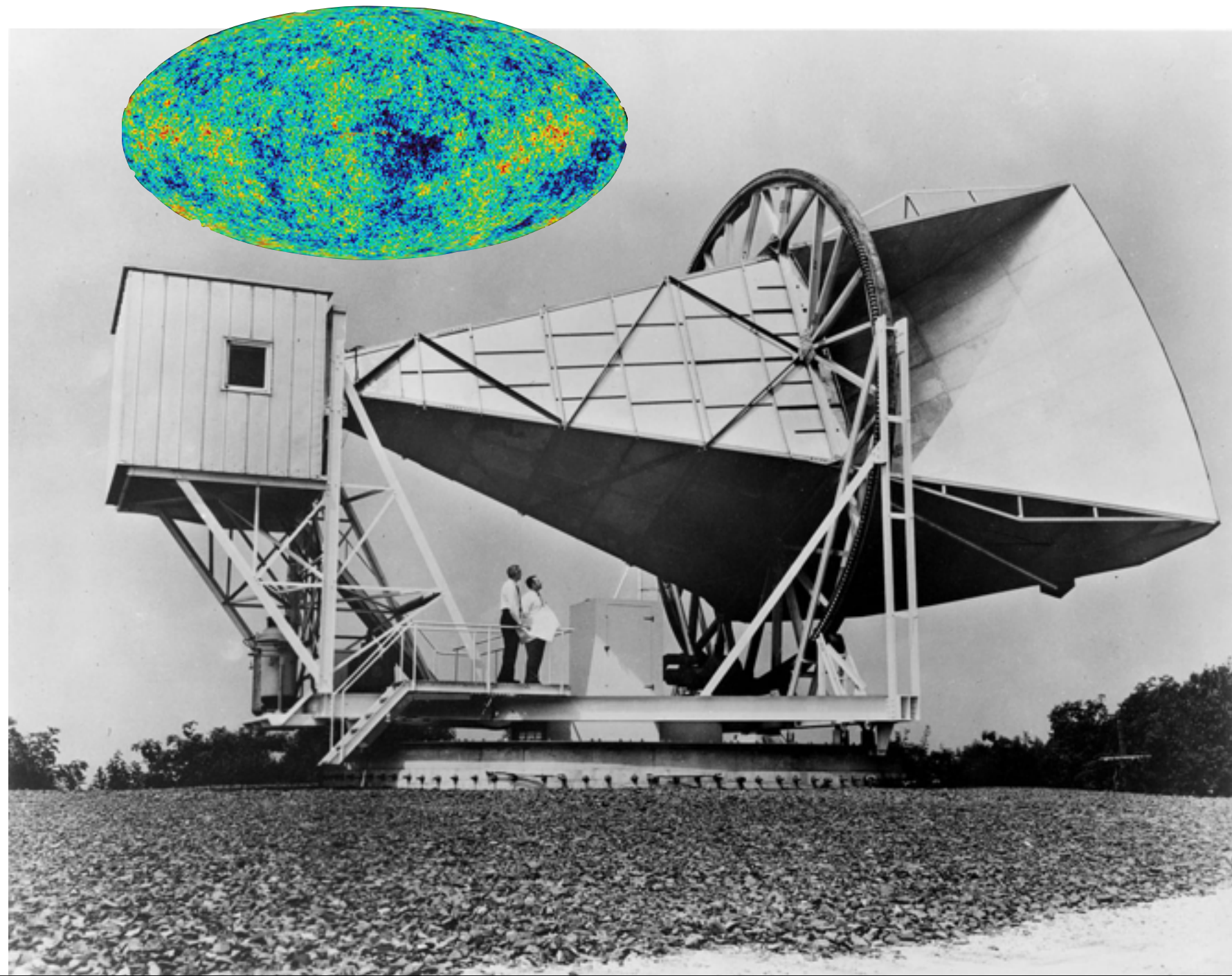
Discovery

- In 1964, D. Wilkinson and P. Roll (and R. Dicke) built a radiometer in Princeton University to try to detect the CMB, without success.



Discovery

- The same year, Penzias and Wilson serendipitously discovered the CMB while trying to understand an excess noise of their antenna at Bell Labs, in Holmdel, New Jersey.



Why P&W?

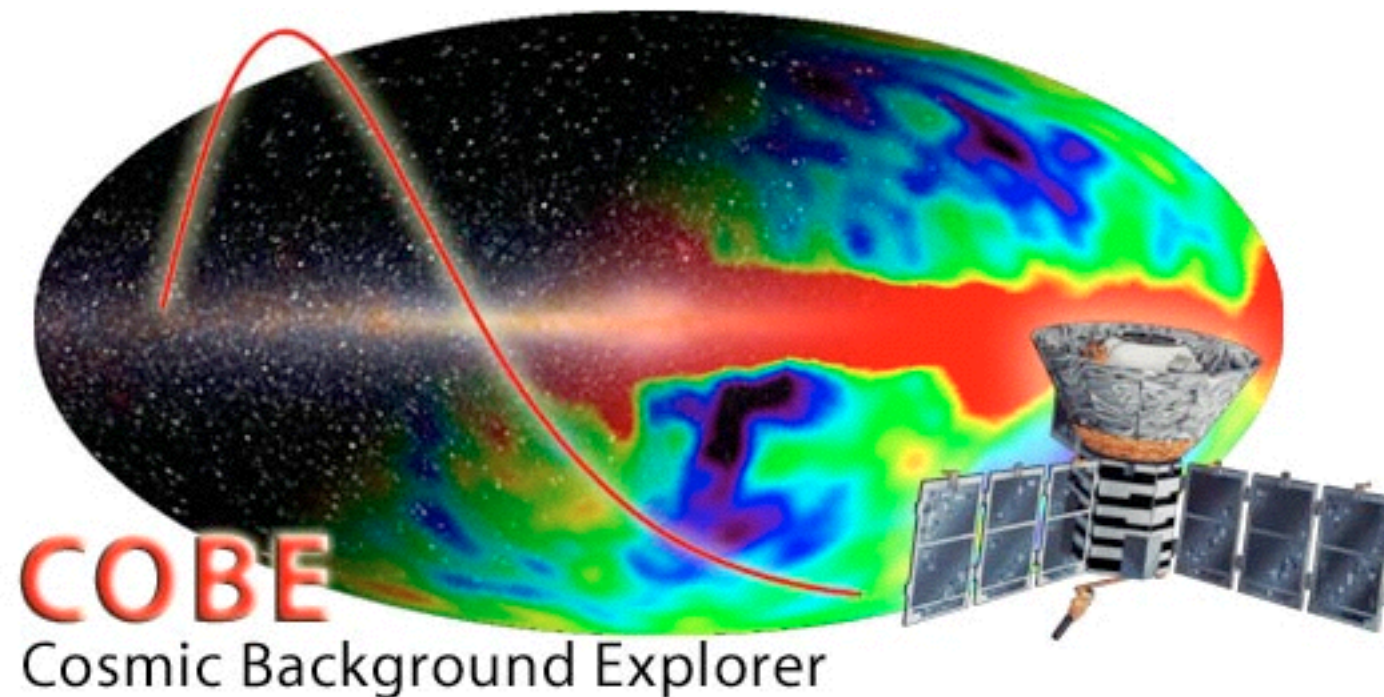
Technology!

Penzias and Wilson were using newly developed low noise solid state maser amplifiers that were 10 times less noisy than Dicke's.

And so Dicke said: “Boys, we’ve been scooped.”

Confirmation

The world had to wait almost 30 years!



1 satellite - 3 experiments:

- Differential Microwave Radiometer (DMR)
- Far-Infrared Spectrophotometer (FIRAS)
- Diffuse InfraRed Background Experiment DIRBE

Again the use of new detector technology, as well as new observation techniques was key in the achievement

- Silicon, GaAs FET and HEMT detectors.
- Differential measurement.
- Continuous scanning strategy.

Gold Race!

- After COBE there were a list of experiments trying to be the first to characterize the CMB fluctuations.

Cobra (1982 - 1990)

RELIKT-1 (1983 - 1984)

Tenerife (1984 - 2000)

BIMA (1986 - 2004)

ACME (1988-1996)

ARGO (1988 - 1993)

COBE (1989 - 1993)

FIRS (1989 - 1989)

ATCA (1991 - 1997)

MSAM (1992 - 1997)

Python (1992 - 1997)

Saskatoon (1993 - 1995)

CAT (1994 - 1997)

APACHE (1995-1996)

BAM (1995 - 1998)

MAXIMA (1995 - 1999)

QMAP (1996 - 1996)

SuZIE (1996 -)

BOOMERanG (1997 - 2003)

MAT (1997 - 1998)

COSMOSOMAS (1998 -)

ARCHEOPS (1999 - 2002)

Cosmological Gene (1999 -)

DASI (1999 - 2003)

BEAST (2000 -)

POLAR (2000 - 2000)

ARCADE (2001 -)

ACBAR (2001 -)

WMAP (2001 - 2010)

CAPMAP (2002 -)

AMiBA (2002 -)

CBI (2002 - 2008)

PIQUE (2002 - 2002)

TopHat (2002 -)

VSA (2002 - 2008)

KUPID (2003 -)

SZA (2004 - 2008)

AMI (2005 -)

APEX (2005 -)

QUaD (2005 - 2007)

BICEP (2006 - 2008)

SPT (2006 -)

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Bar-SPoRT (Future)

EBEX (Future)

MINT (Future)

MBI-B (Future)

CLASS (Future)

Qubic (Future)

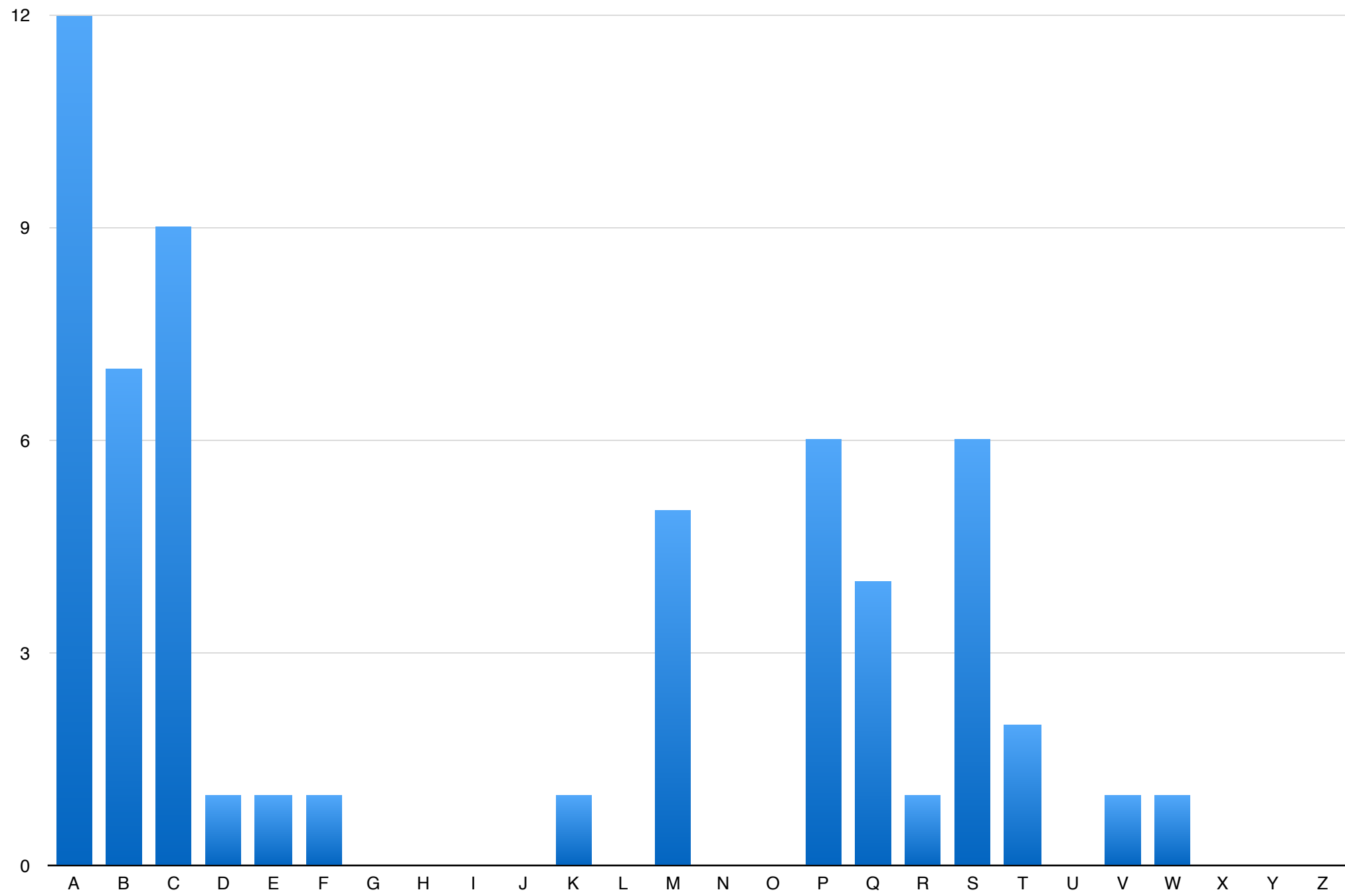
SPoRT (Future)

BRAIN (Never)

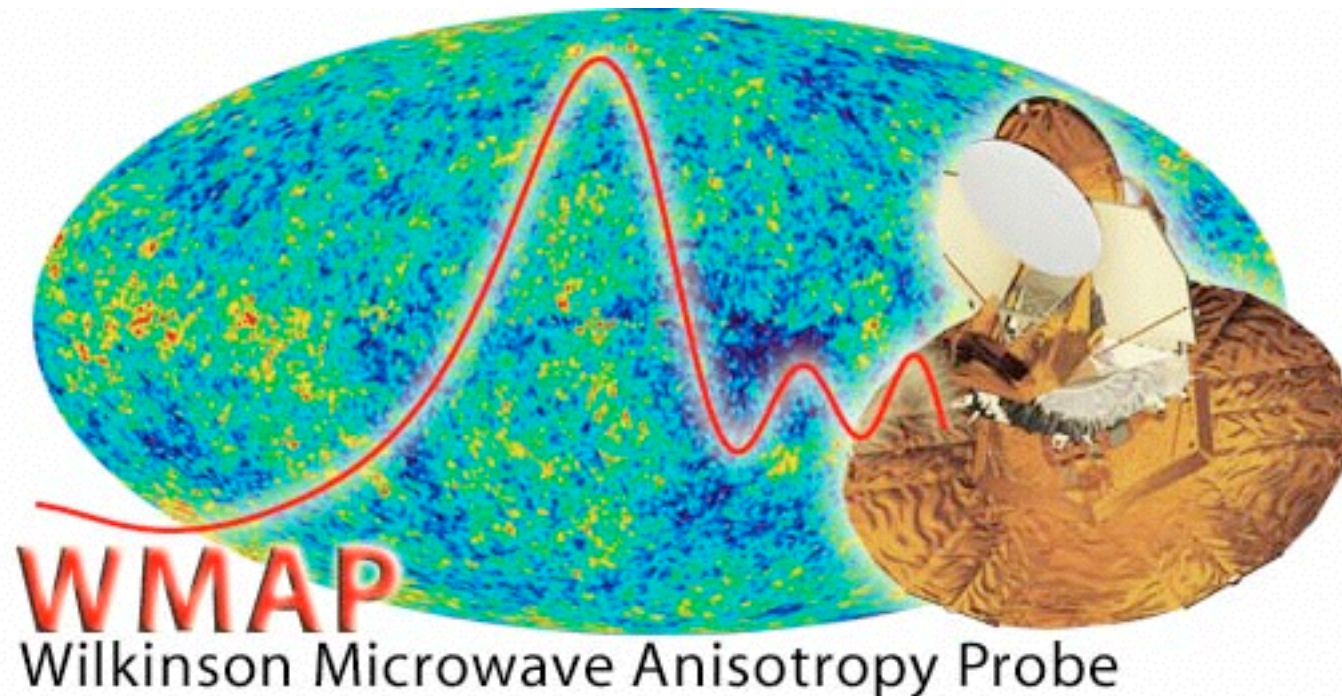
CLover (Never)

Polatron (Never)

■ Experiment Initial Letter



Next Jump: WMAP



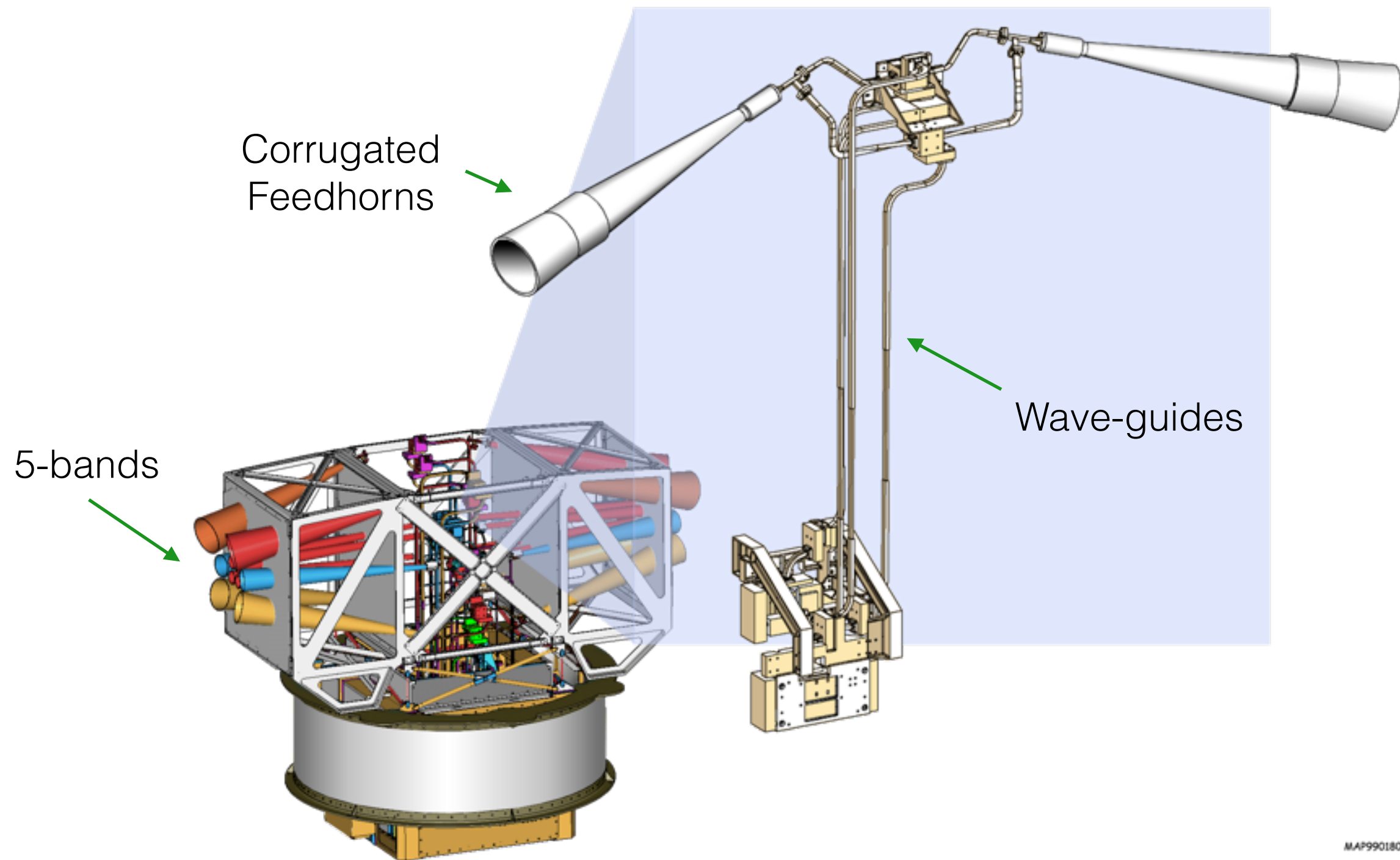
10 years after COBE the technology and techniques had evolved enough to allow for a high resolution mapper of the CMB.

- Low-noise HEMT detectors @90K.
- Polarization sensitive.
- Differential measurements (180 deg).

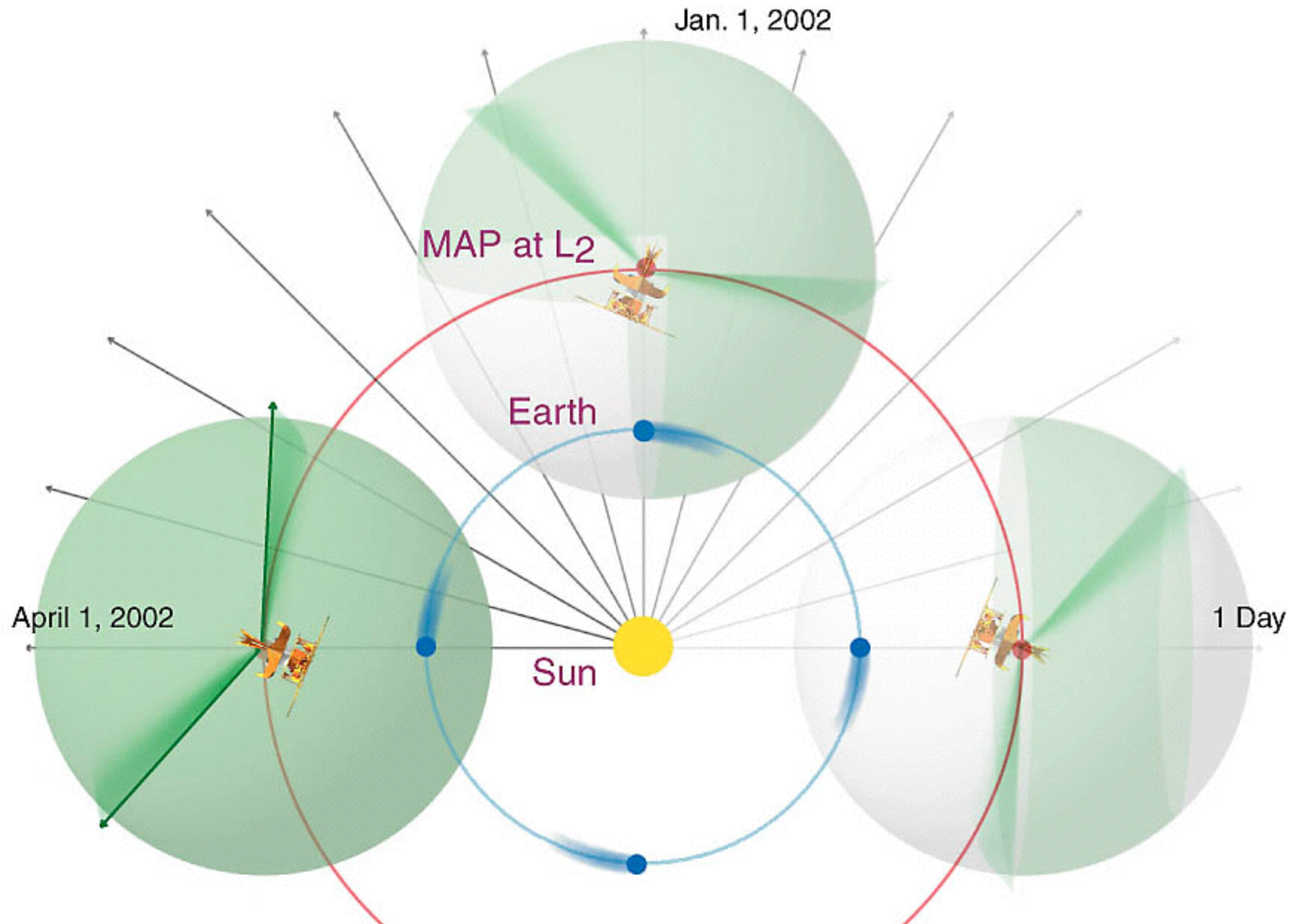
APPROXIMATE OBSERVATIONAL PROPERTIES BY BAND

Item	K Band	Ka Band	Q Band	V Band	W Band
Wavelength, λ (mm).....	13	9.1	7.3	4.9	3.2
Frequency, ν (GHz)	22.8	33.0	40.7	60.8	93.5
Ant./therm. conversion factor, $\Delta T/\Delta T_A$	1.014	1.029	1.044	1.100	1.251
Noise, σ_0 (mK), $\sigma = \sigma_0 N_{\text{obs}}^{-1/2}$	1.424	1.449	2.211	3.112	6.498
Beam width θ (deg FWHM)	0.82	0.62	0.49	0.33	0.21
Number of differencing assemblies	1	1	2	2	4
Number of radiometers.....	2	2	4	4	8
Number of channels.....	4	4	8	8	16

WMAP Receiver



WMAP Scan Strategy



WMAP Sky in 5 Wavelengths and CMB only

22 GHz

60 GHz

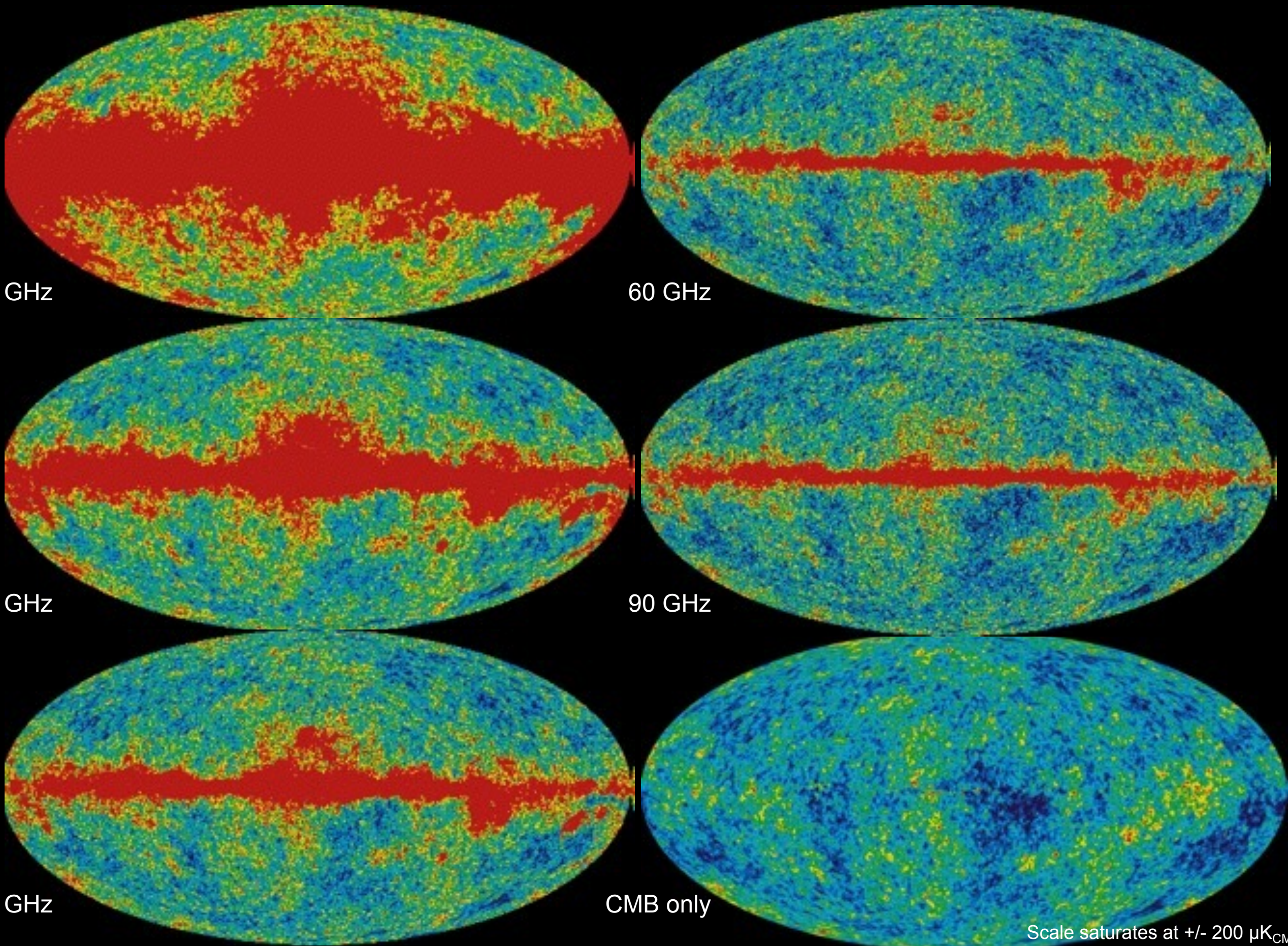
30 GHz

90 GHz

40 GHz

CMB only

Scale saturates at $\pm 200 \mu\text{K}_{\text{CMB}}$



WMAP: Final Power Spectrum

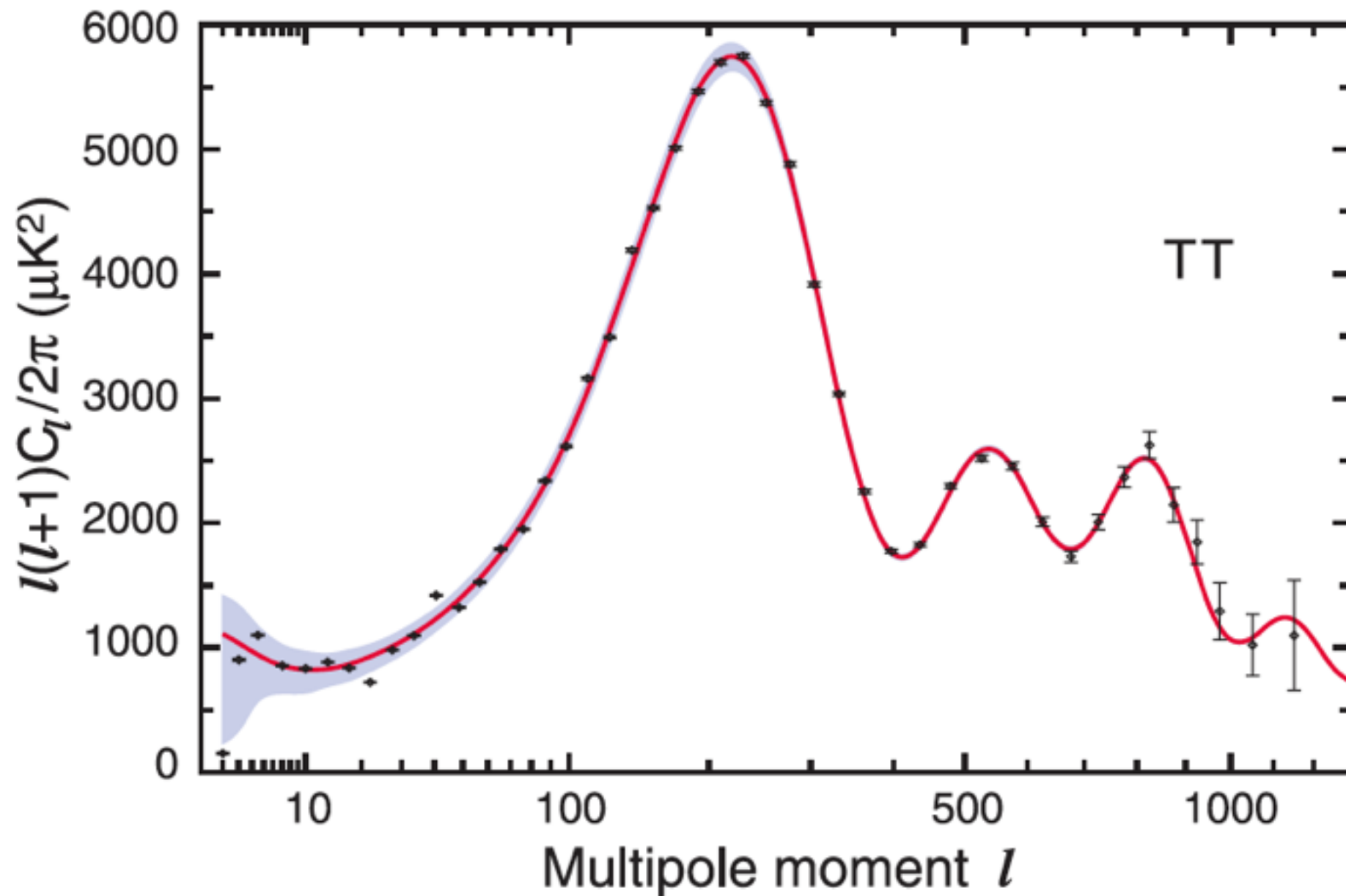
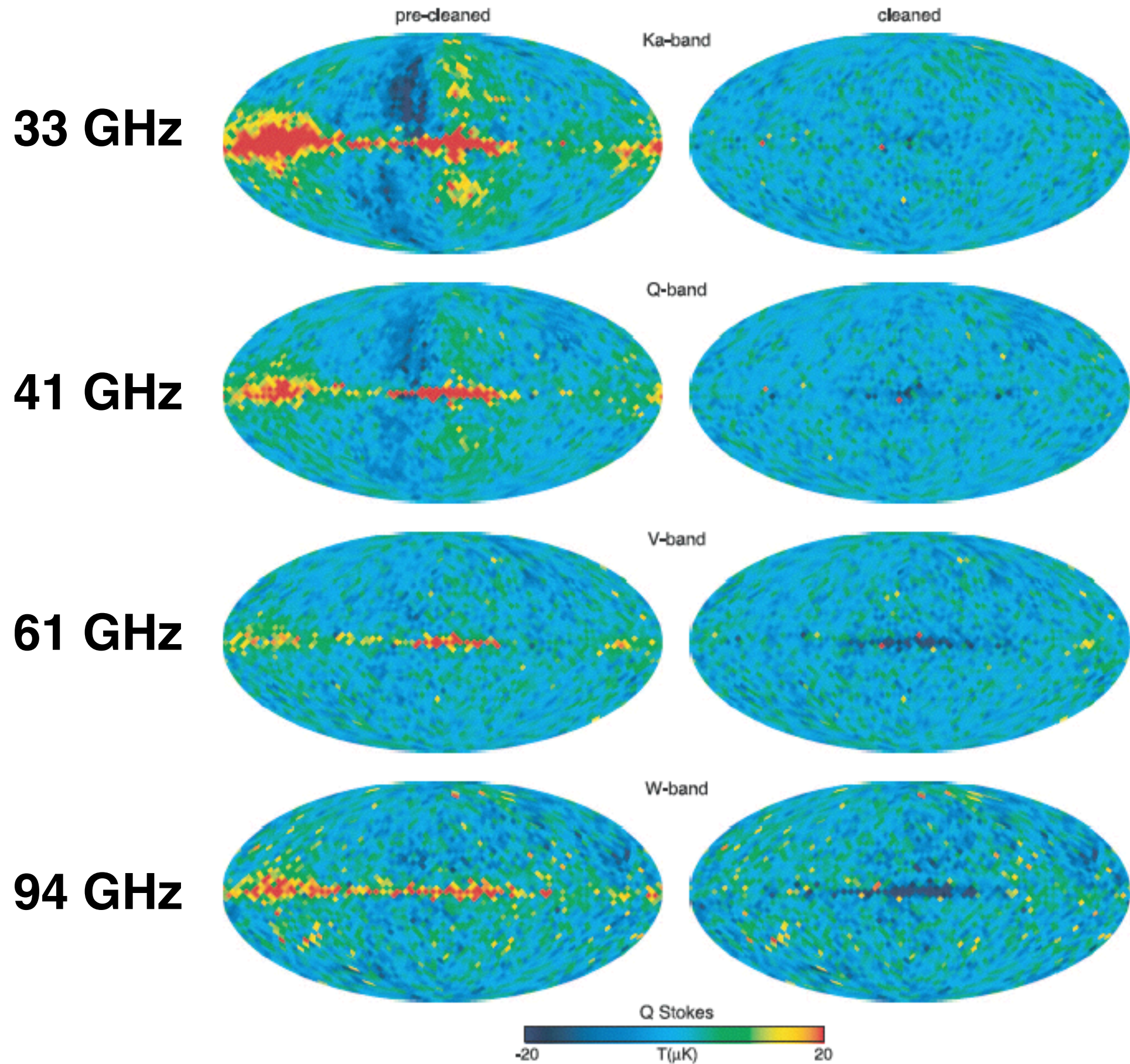


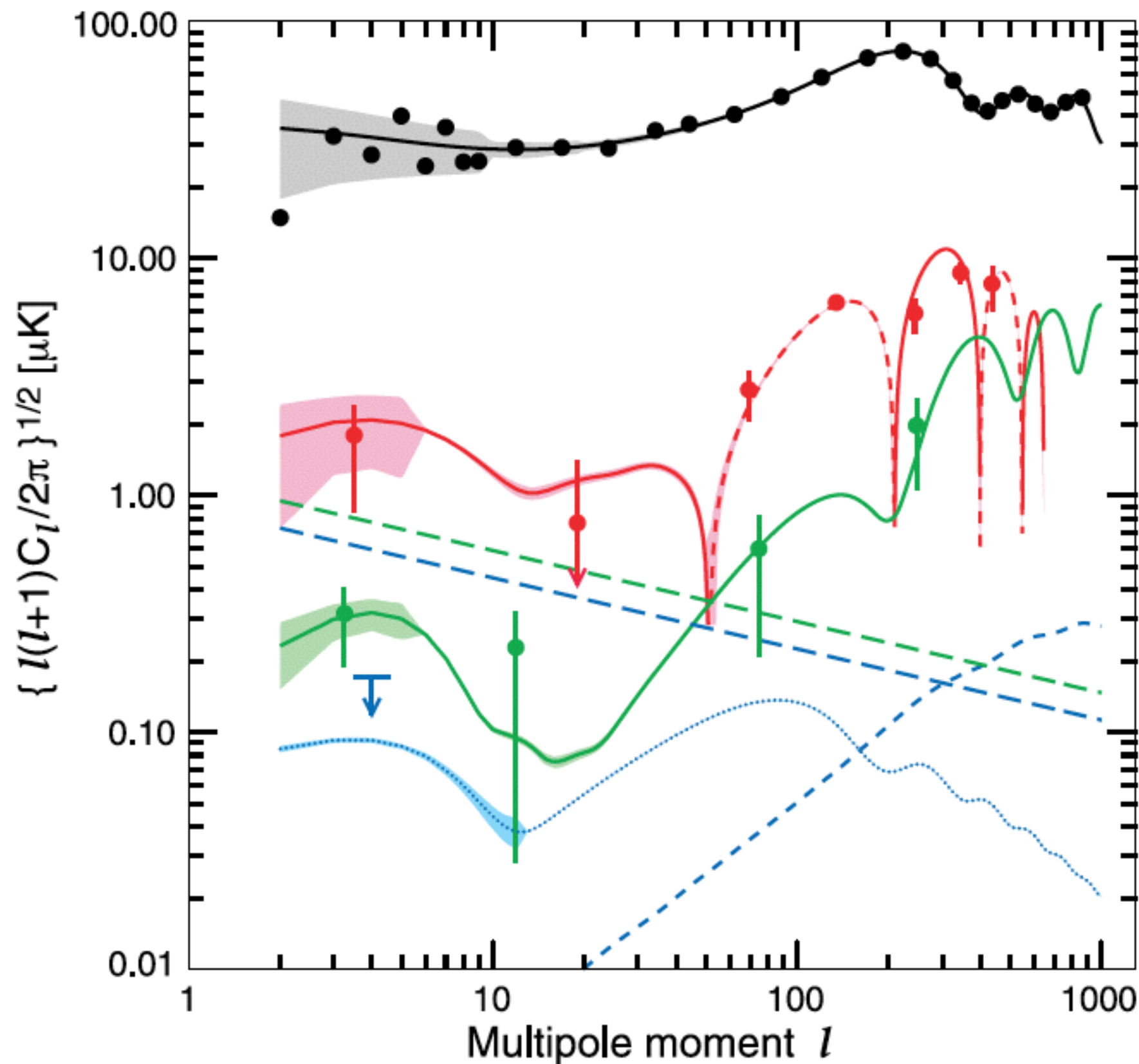
Fig. 32.— The nine-year *WMAP* TT angular power spectrum. The *WMAP* data are in black, with error bars, the best fit model is the red curve, and the smoothed binned cosmic variance curve is the shaded region. The first three acoustic peaks are well-determined.

WMAP Polarization

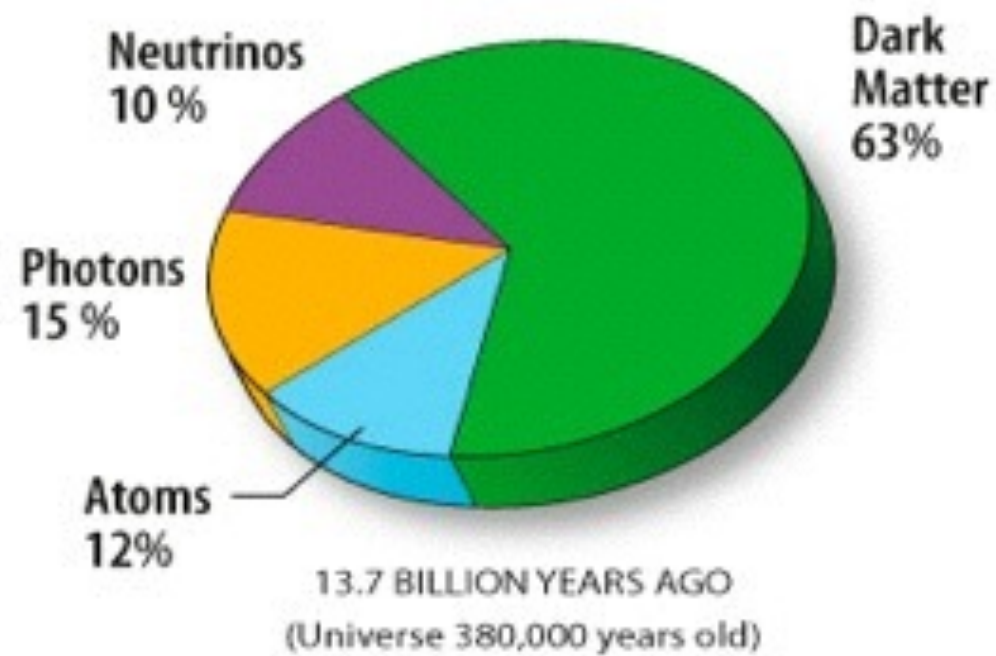
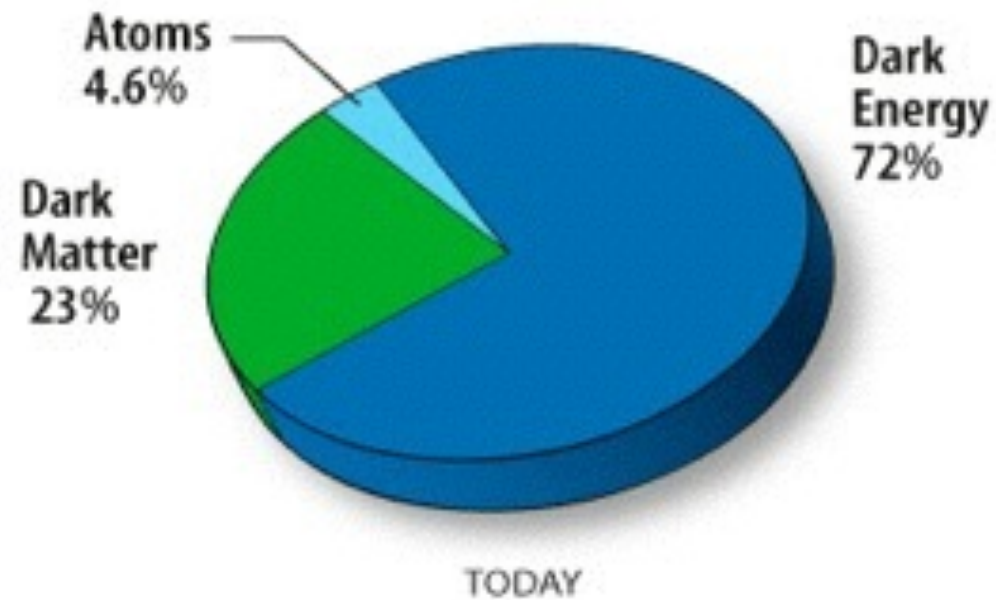
PAGE ET AL. 2007



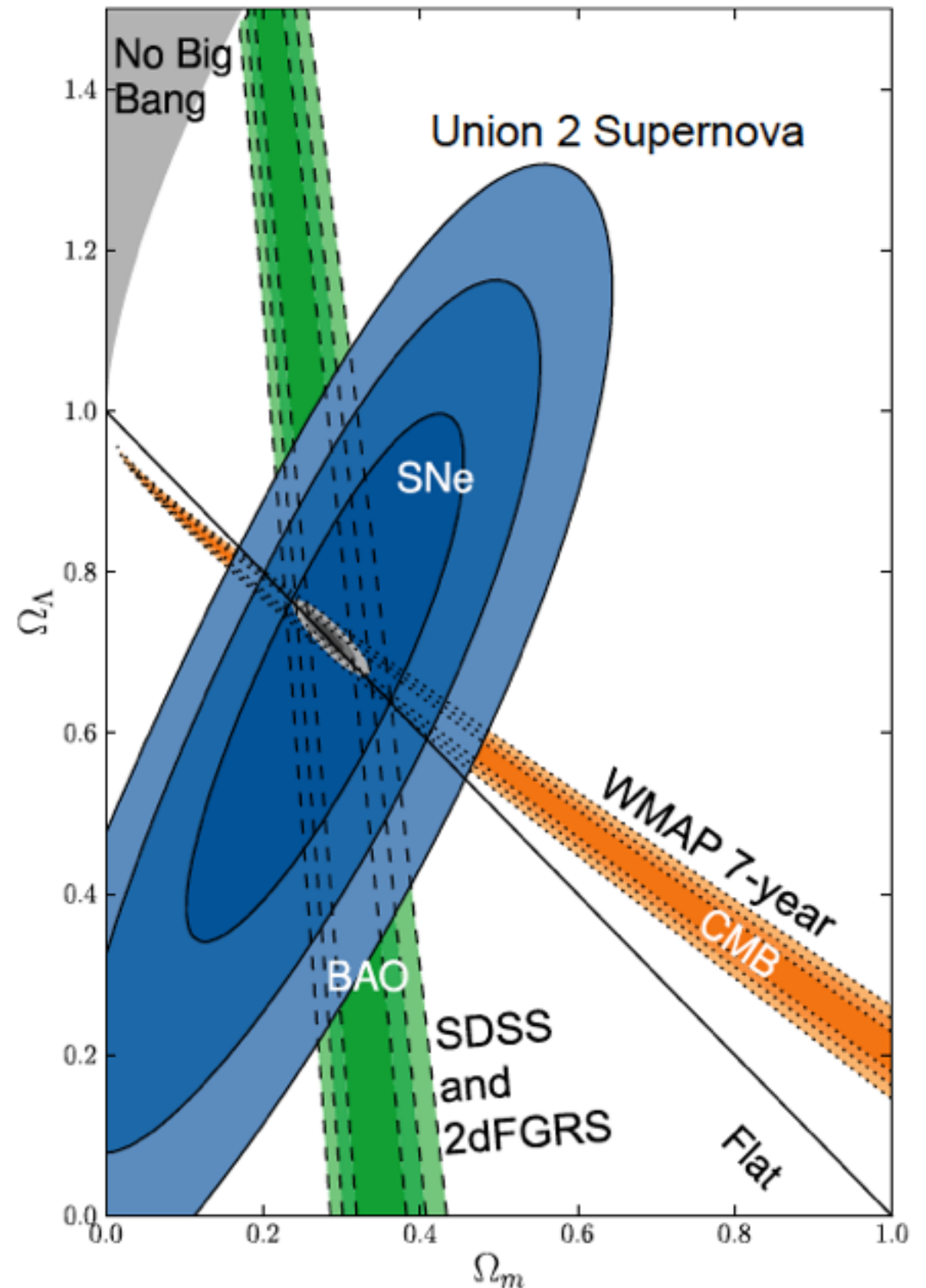
WMAP Polarization (2007)



Standard Cosmology

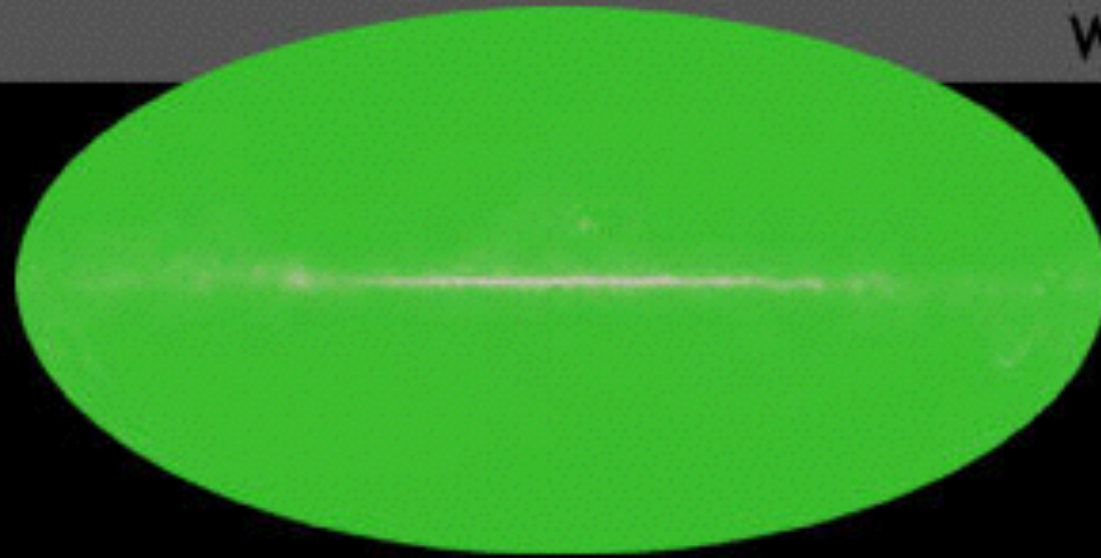
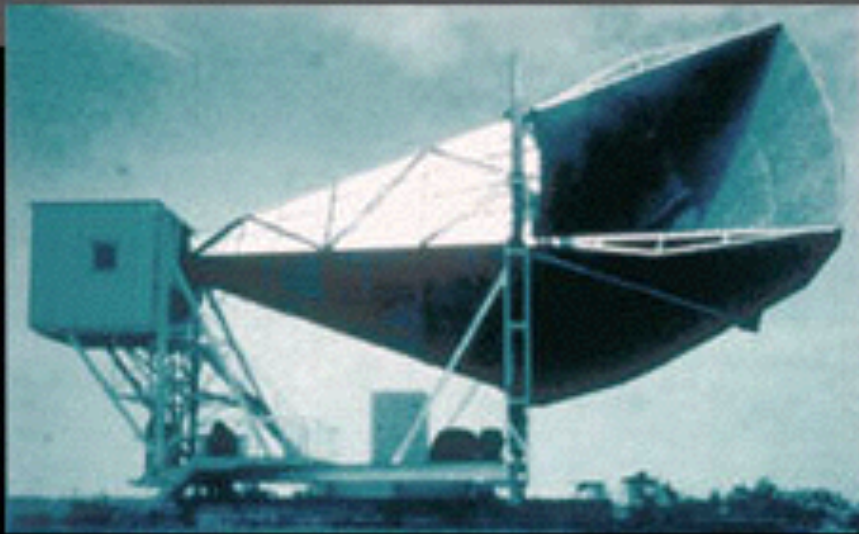


NASA / WMAP science team



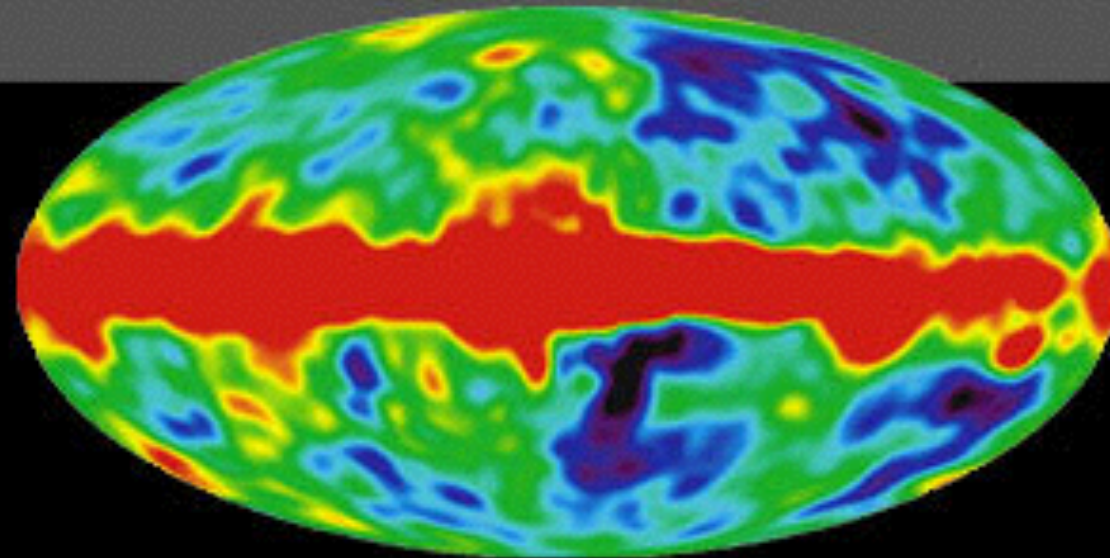
1965

Penzias and
Wilson



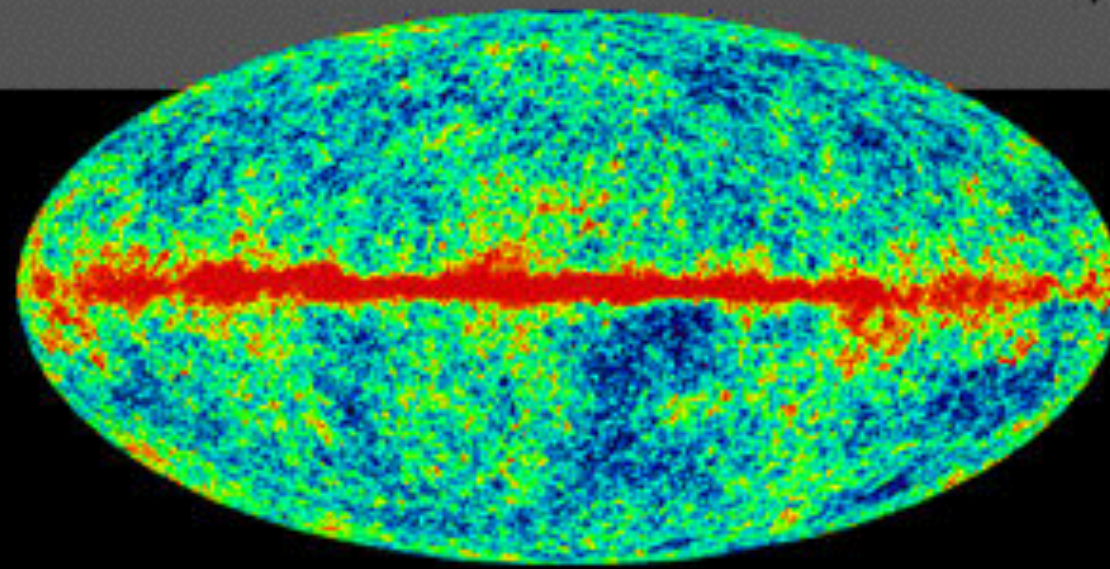
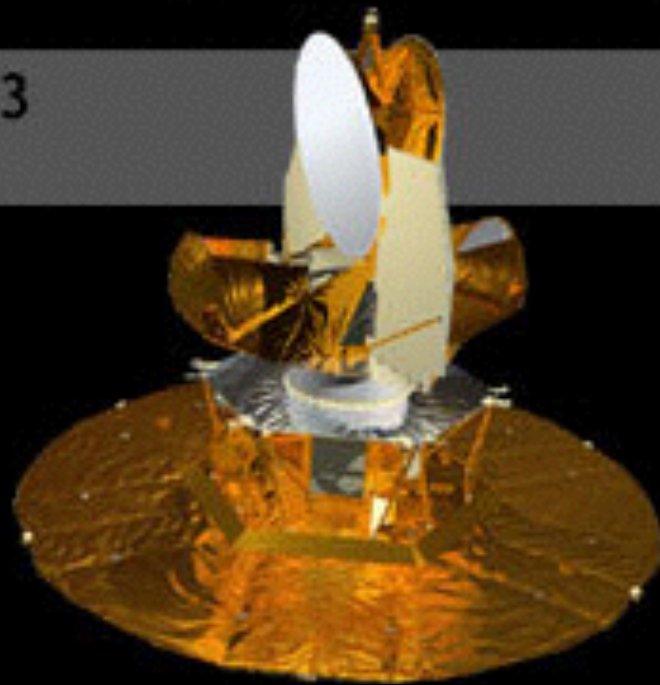
1992

COBE



2003

WMAP



Gold Race!

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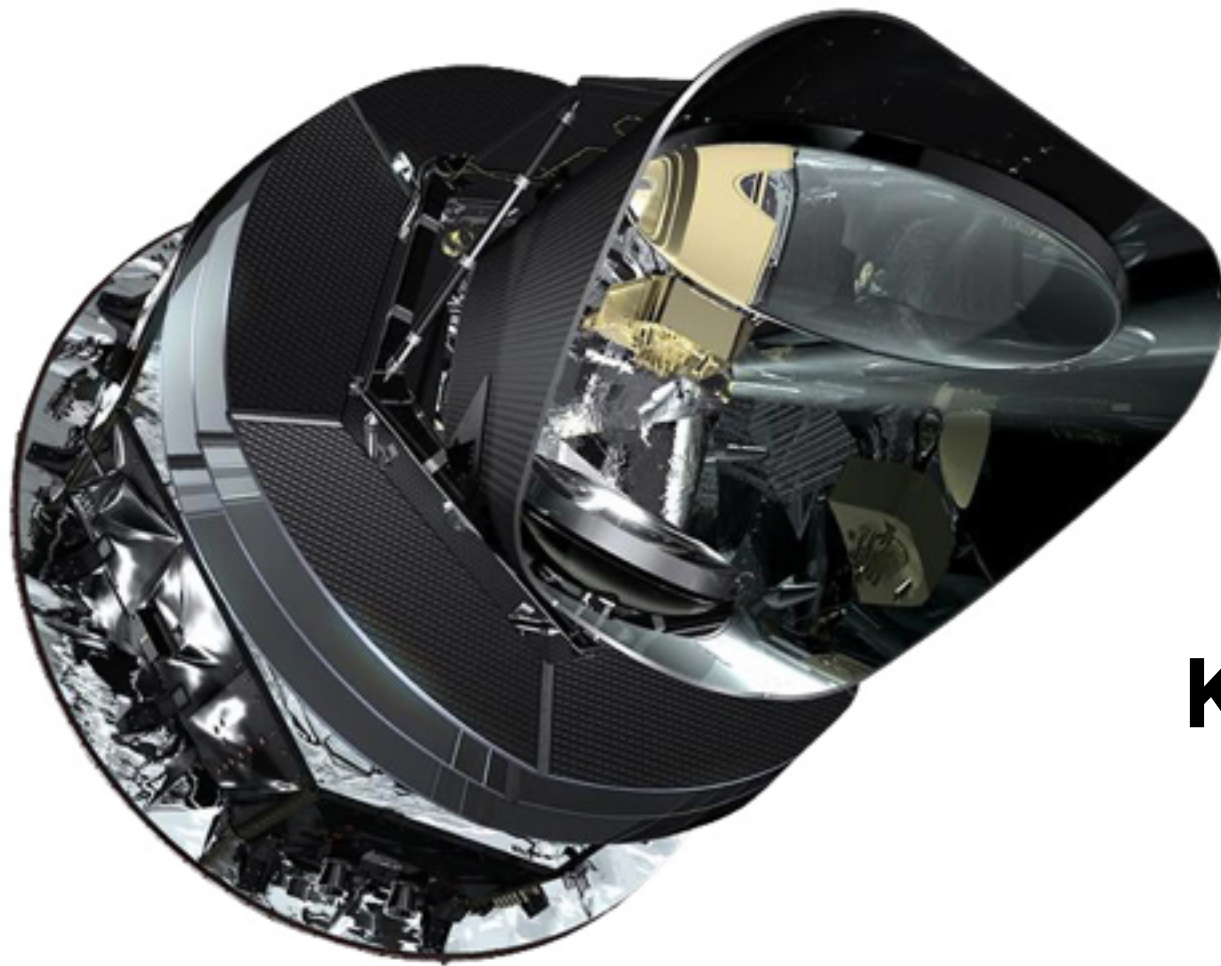
SPoRT (Future)

BRAIN (Never)

CLover (Never)

Polatron (Never)

PLANCK: The final hit



10 years after WMAP, PLANCK measured the whole sky with much finer resolution, completing the observable damping tail of the temperature power spectrum.

**25 more sensitive and
3 times higher
resolution than
WMAP!**

Key aspects:

- Use extremely low noise detectors: HEMT for low-frequency instrument (LFI) and Bolometers for the high frequency instrument (HFI).
- Exquisite control of the systematics.
- Large number of frequency bands for foreground subtraction.

PLANCK Instruments

Low-Frequency Instrument (LFI)

Frequency (GHz)	Bandwidth ($\Delta\nu/\nu$)	Resolution (arcmin)	Sensitivity (total intensity) $\Delta T/T$, 14 month observation	Sensitivity (polarization) $\Delta T/T$, 14 month observation
30	0.2	33	2.0	2.8
44	0.2	24	2.7	3.9
70	0.2	14	4.7	6.7

High-Frequency Instrument (HFI)

Frequency (GHz)	Bandwidth ($\Delta\nu/\nu$)	Resolution (arcmin)	Sensitivity (total intensity) $\Delta T/T$, 14 month observation	Sensitivity (polarization) $\Delta T/T$, 14 month observation
100	0.33	10	2.5	4.0
143	0.33	7.1	2.2	4.2
217	0.33	5.5	4.8	9.8
353	0.33	5.0	14.7	29.8
545	0.33	5.0	147	N/A
857	0.33	5.0	6700	N/A

THE Map

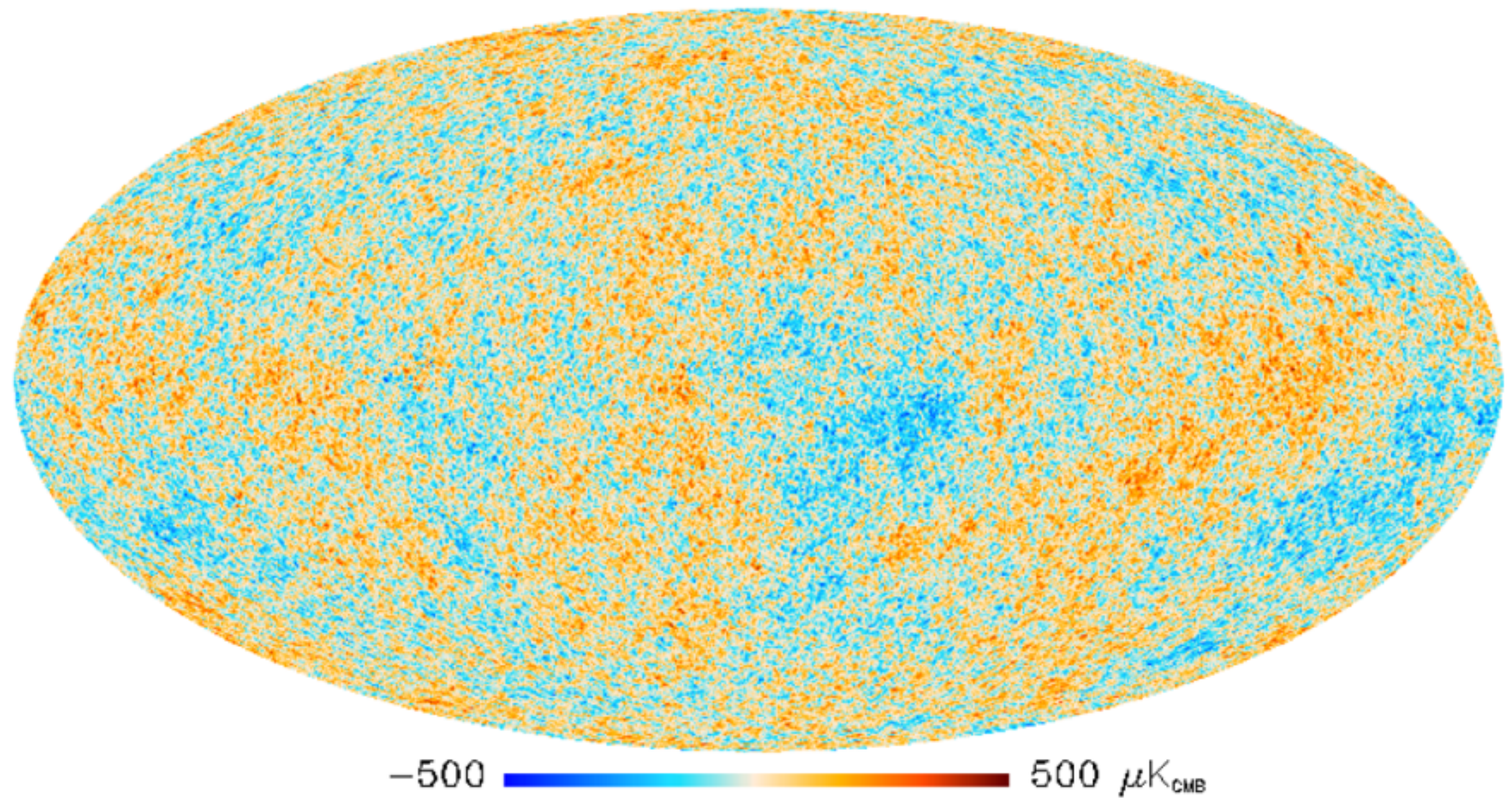
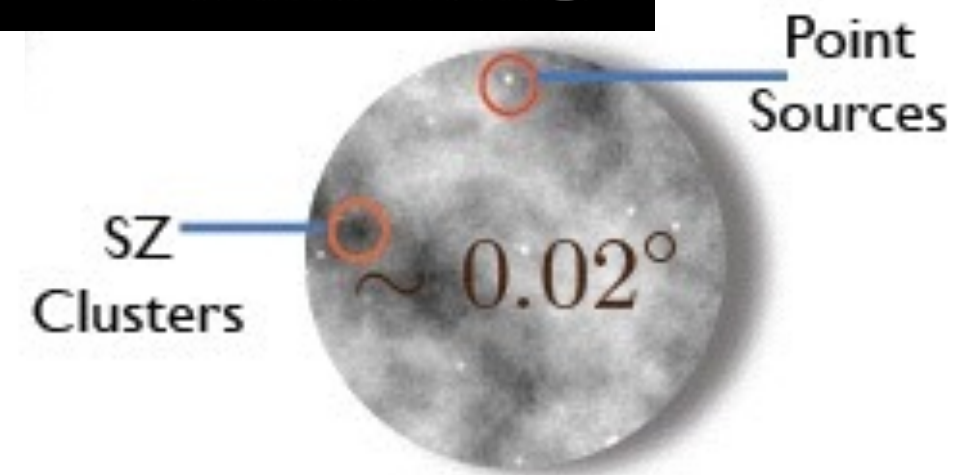
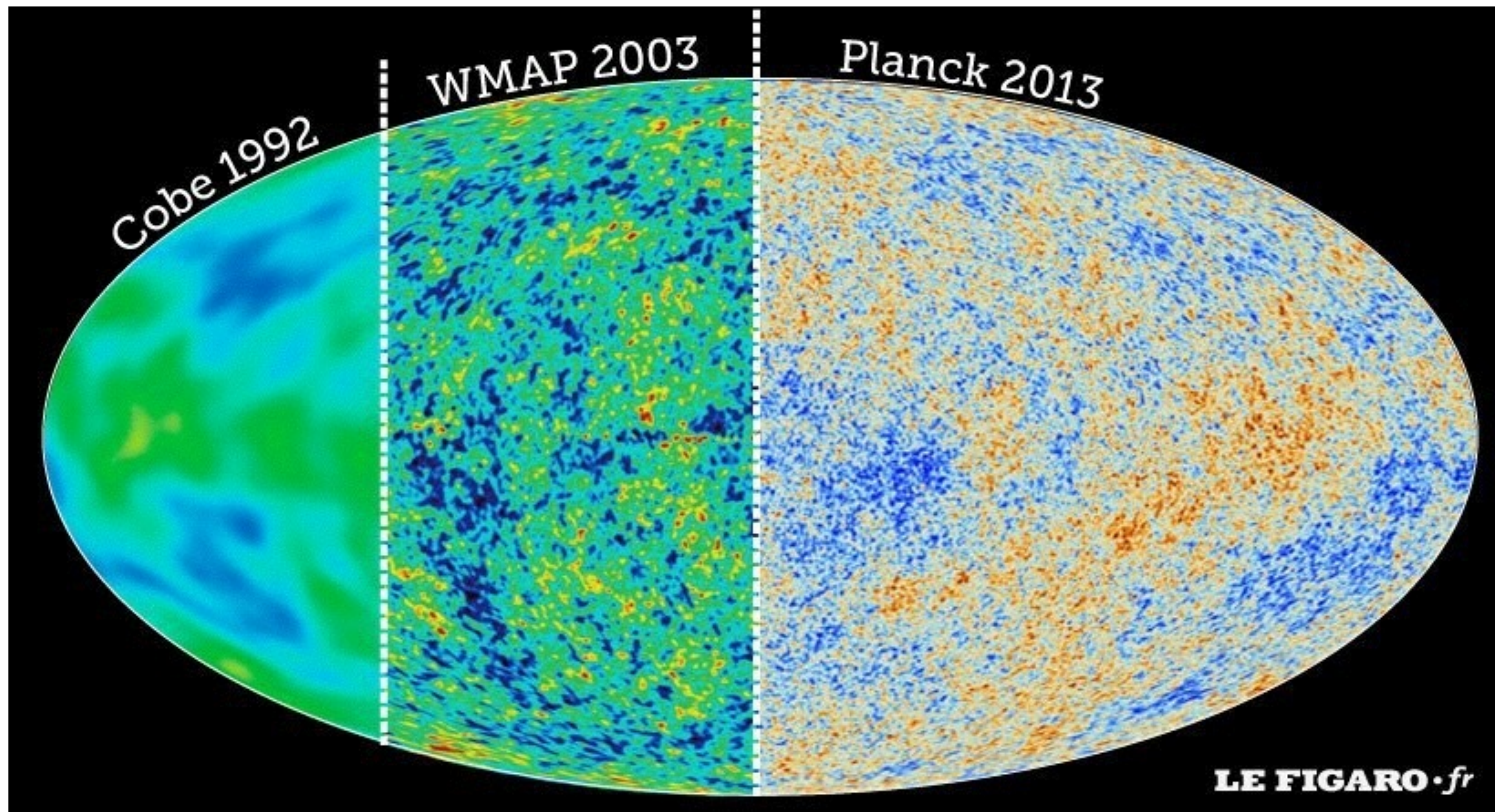
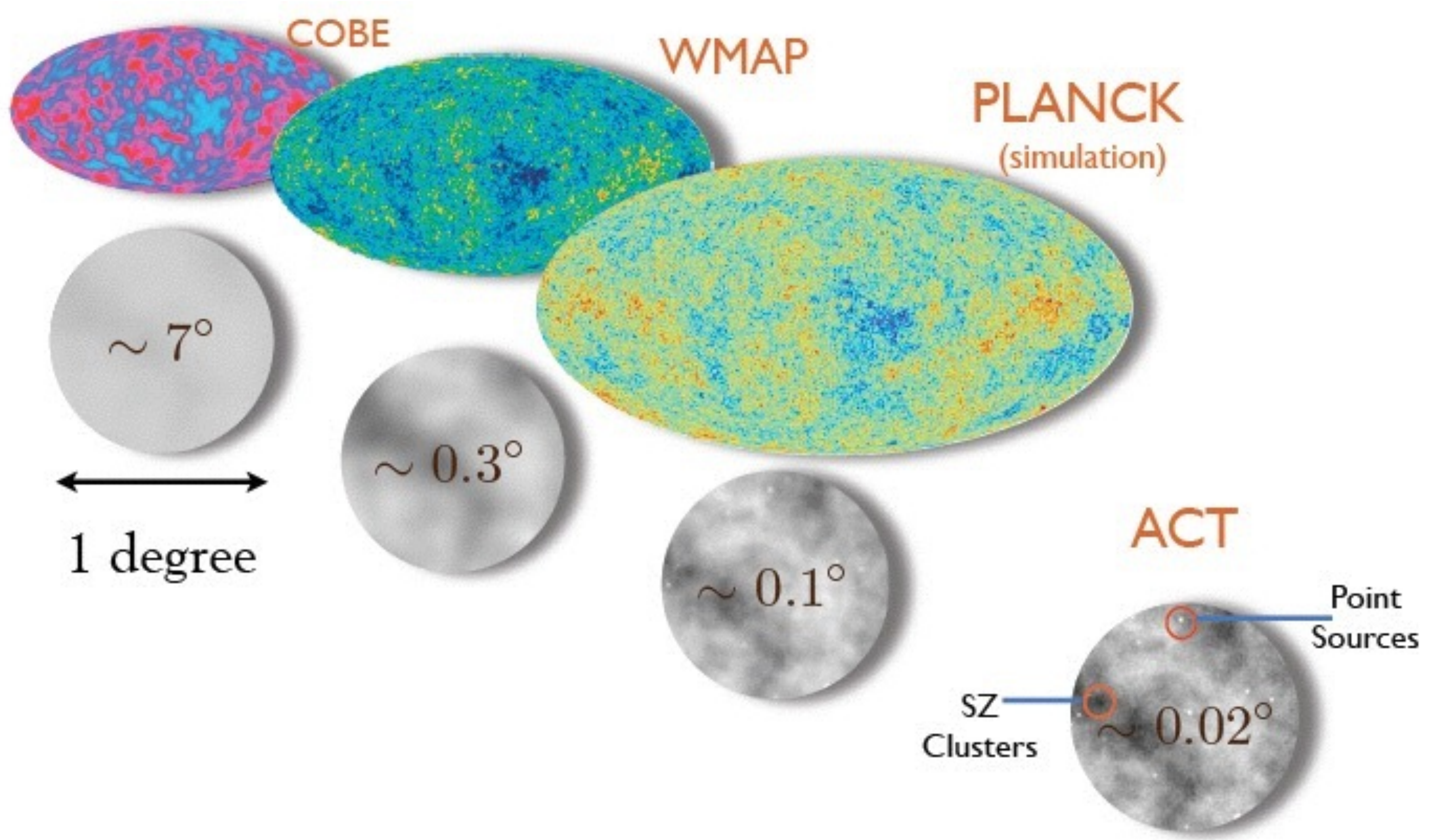


Fig. 14. The SMICA CMB map (with 3 % of the sky replaced by a constrained Gaussian realization).

CMB Measurements



CMB Measurements



What's left? A lot!!

High resolution (high-ell) temperature measurements:

- Detect foreground contribution to power spectrum, including SZ, CIB, CIB x SZ, kSZ, lensing, radio galaxies and dust.
- Blind search for galaxy clusters through their Sunyaev Zel'dovic (SZ) signature.
- Detect the kinetic SZ effect.
- Improve constraints on $dn_s/d\ln k$, N_{eff} , $\sum m_\nu$ and Y_p .
- Cross-correlate with other data sets.

High resolution polarization measurements:

- Measuring CMB lensing B-modes to constrain matter structure at $z \sim 2$.
- Constraining (or even measuring) the sum of the neutrino masses
- Improving the constraints on high-ell cosmological parameters, as the EE spectrum is less contaminated at small scales.

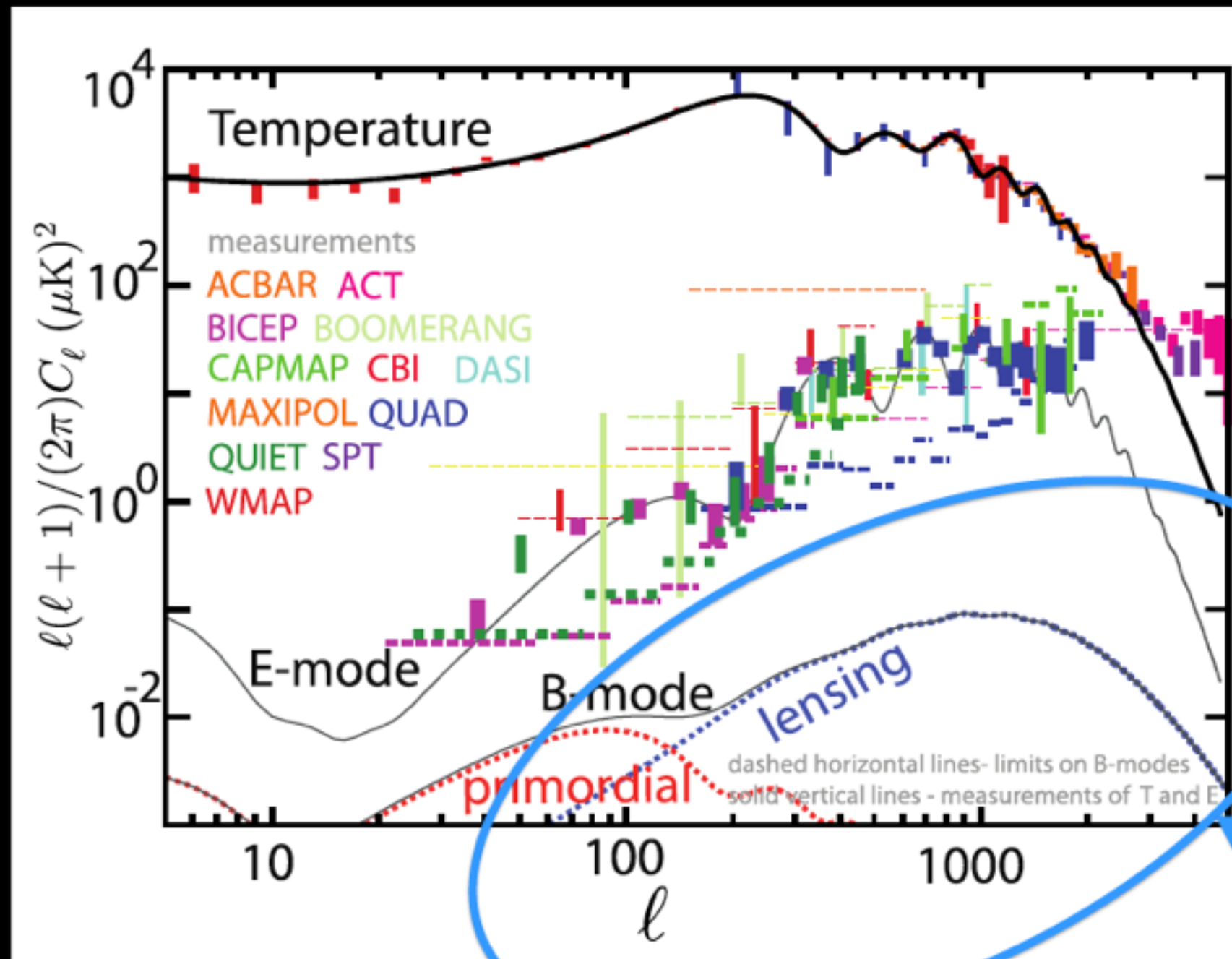
Low resolution polarization measurements:

- Detect B-mode polarization produced by primordial gravity waves (tensor to scalar ratio r).
- Reionization history and optical depth.

Current CMB Survey Research

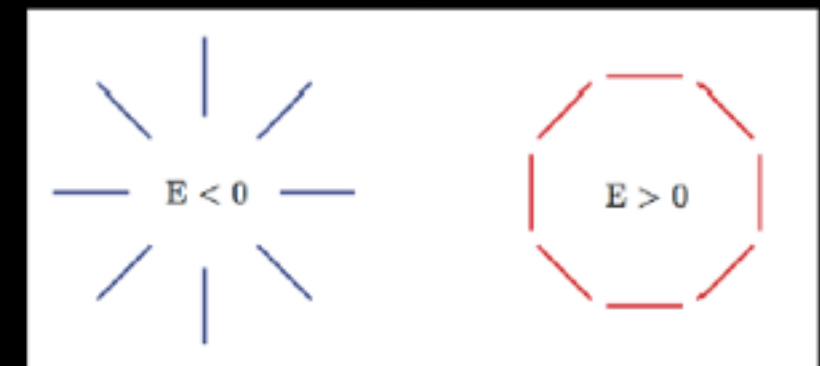
Temperature & Polarization Measurements

angular scale 10° 1° 0.1°



Polarization Anisotropies

Curl free 'E-modes'



Divergence free 'B-modes'



Not yet directly
detected

What's new for $l > 1000$?

Planck



ACT
(Chile)

ACTPol
(Chile)

2011

2012

2013

2014

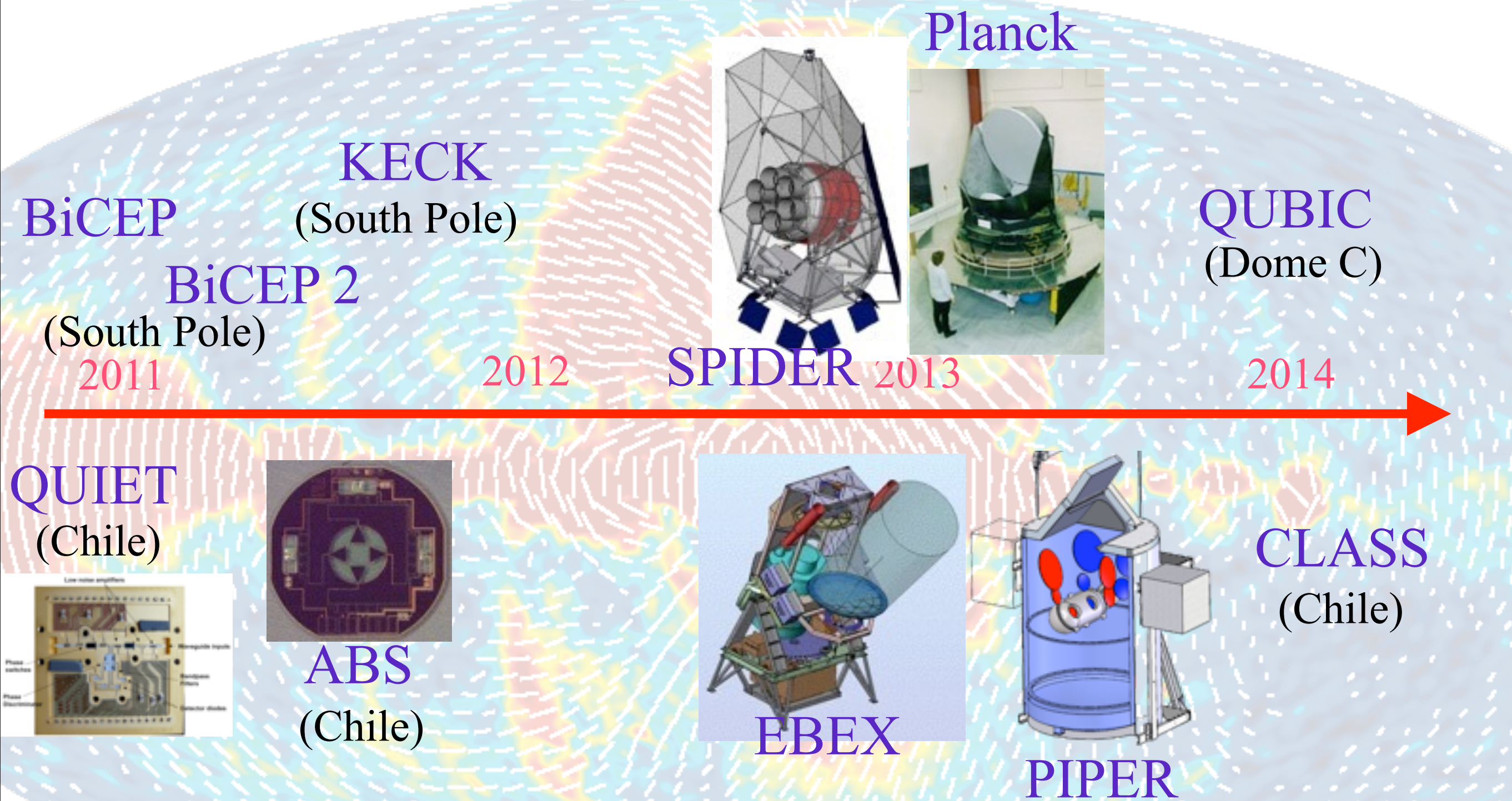
SPTPol
(South Pole)

Polar
(South Pole)

SPT
(South Pole)

HTT/Polarbear-I
(Chile)

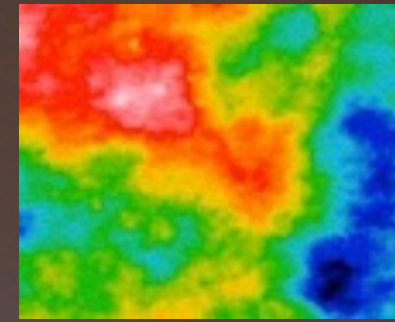
What's new in Polarization for $l < 200$?



ACT



Optical



Theory



X-ray

Since 2007

Parque Astronómico Atacama
CONICYT

Collaboration:

Princeton
NASA/GSFC
Columbia
Cape Town
Cardiff

PUC
NASA/JPL
Rudgers
Massachusetts
LLNL

UPENN
NIST
Toronto
Barcelona
INAOE

UBC
Oxford
Pittsburgh
KwaZulu-Natal
Haverford

Objectives

Science:

- CMB power spectrum
- Inflation
- Neutrino mass
- Ionization history
- Equation of state
- Growth of structure

Observations:

- 2000 deg² map at arcmin resolution.
- 145, 220 and 280 GHz
- 3x1000 TES@300mK (MBAC)
- CMB PS for $l > 1000$
- Clusters from SZ and kSZ
- Gravitational Lensing
- Optical and X-ray follow-ups

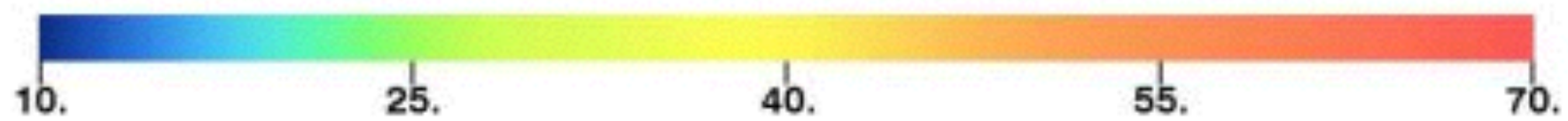
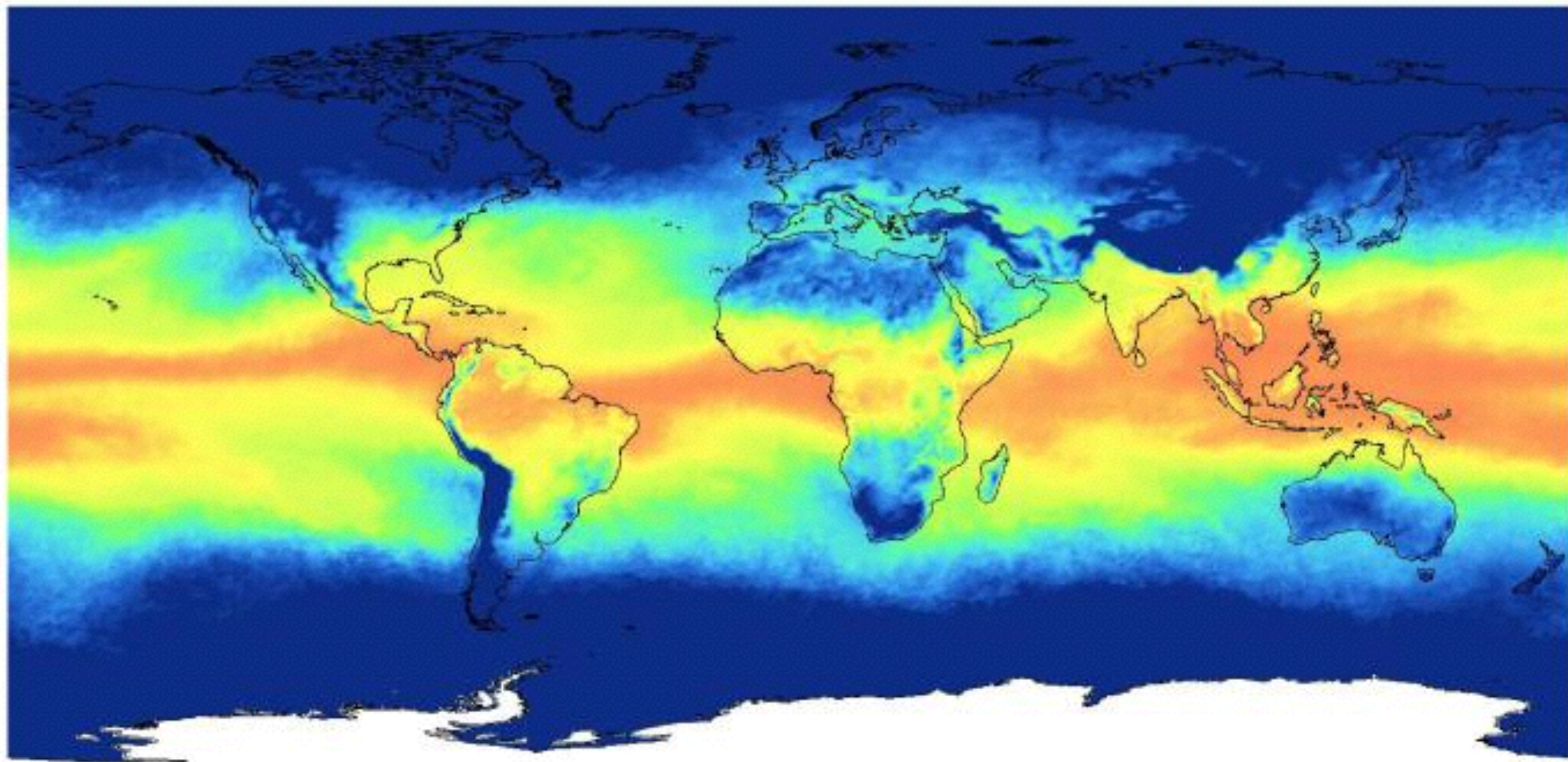
Why Chile?

Site Location

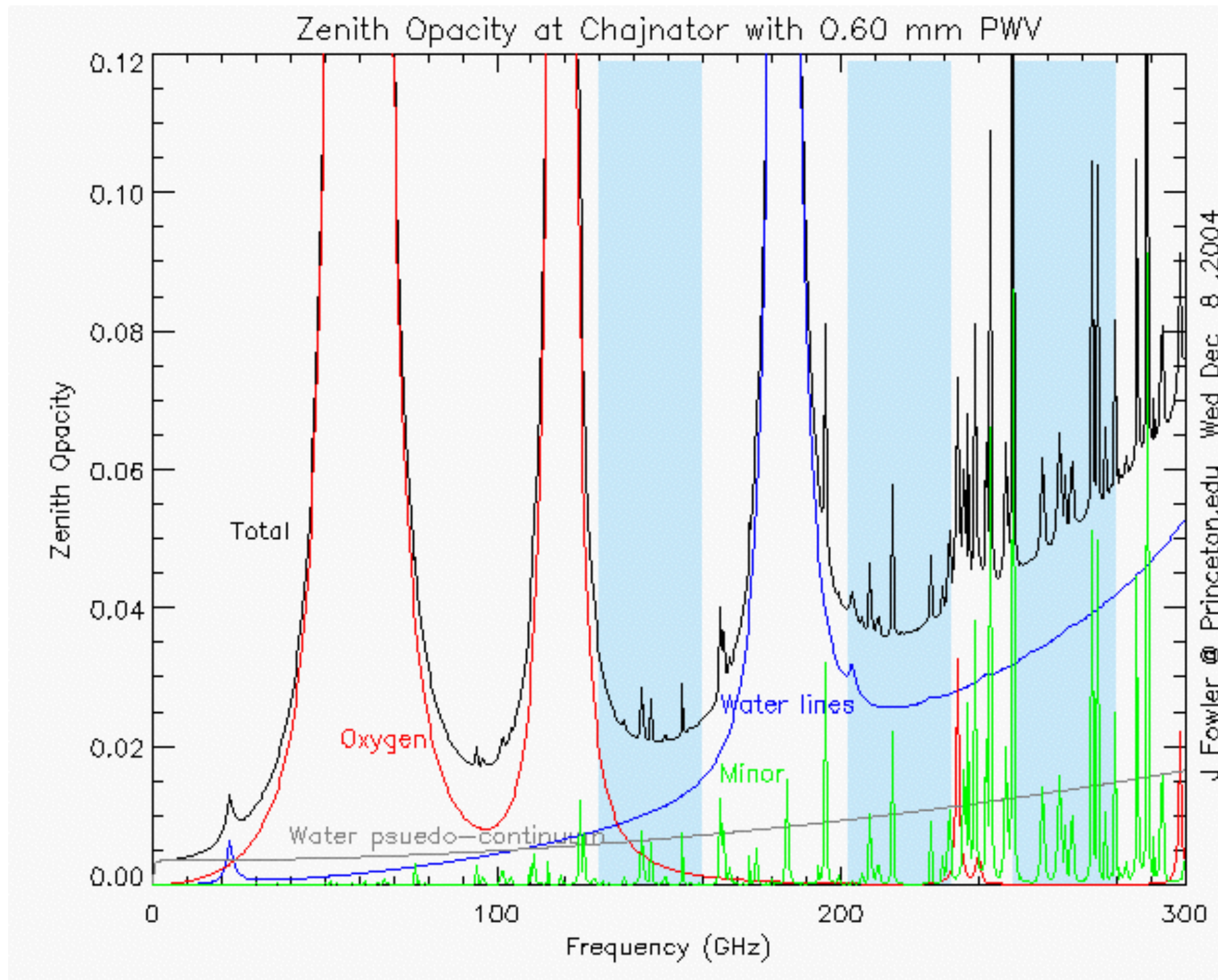


5200 meters near peak of Cerro Toco,
in the Atacama Desert in the Andes of
Northern Chile
23° south latitude.

AIRS TOTAL PRECIPITABLE WATER VAPOR (mm), May 2009

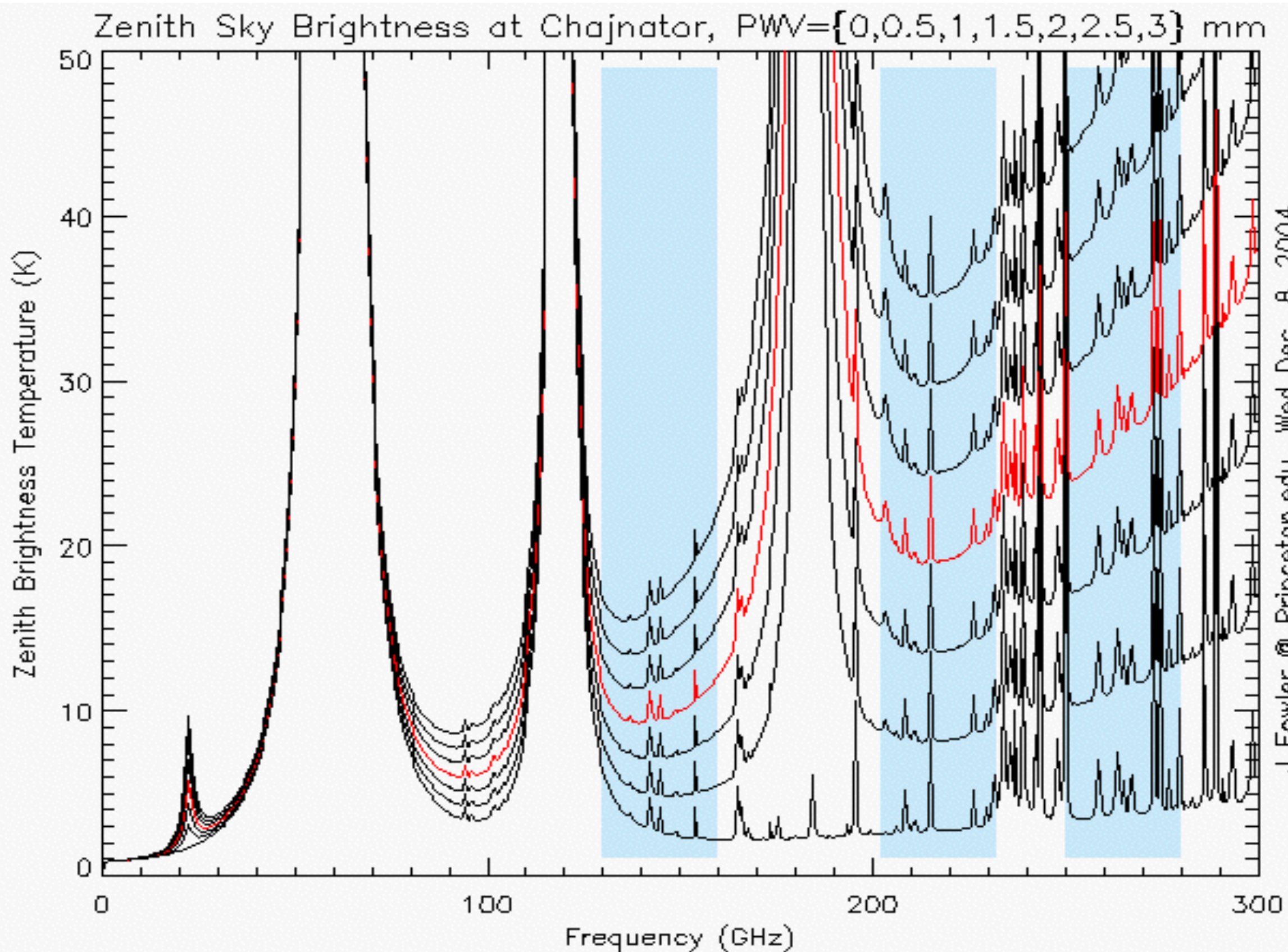


Atmosphere Emission

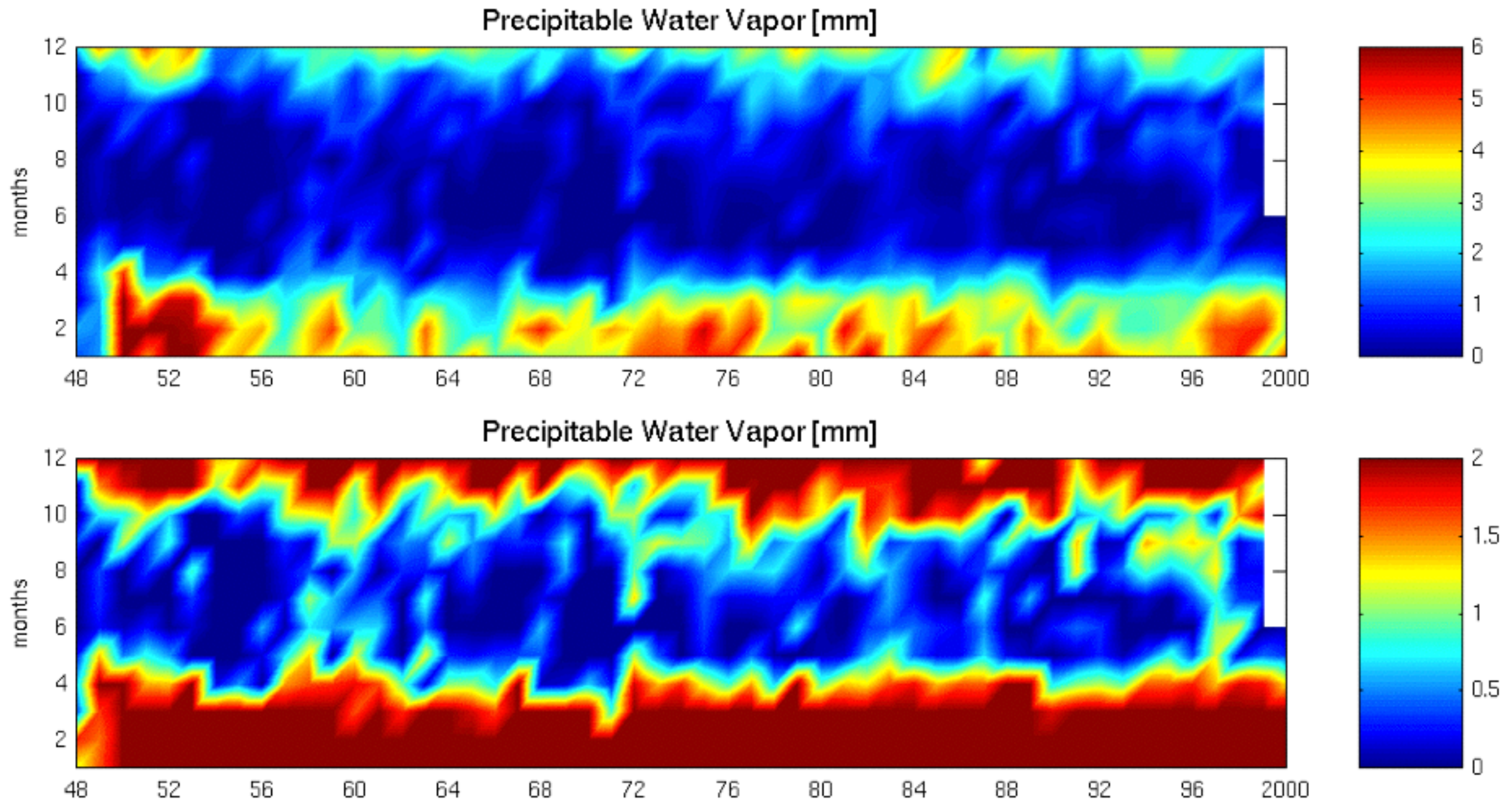


Water rotation lines dominate, also some oxygen at lowest frequency.

Atmosphere Emission



Historical PWV in Chajnantor

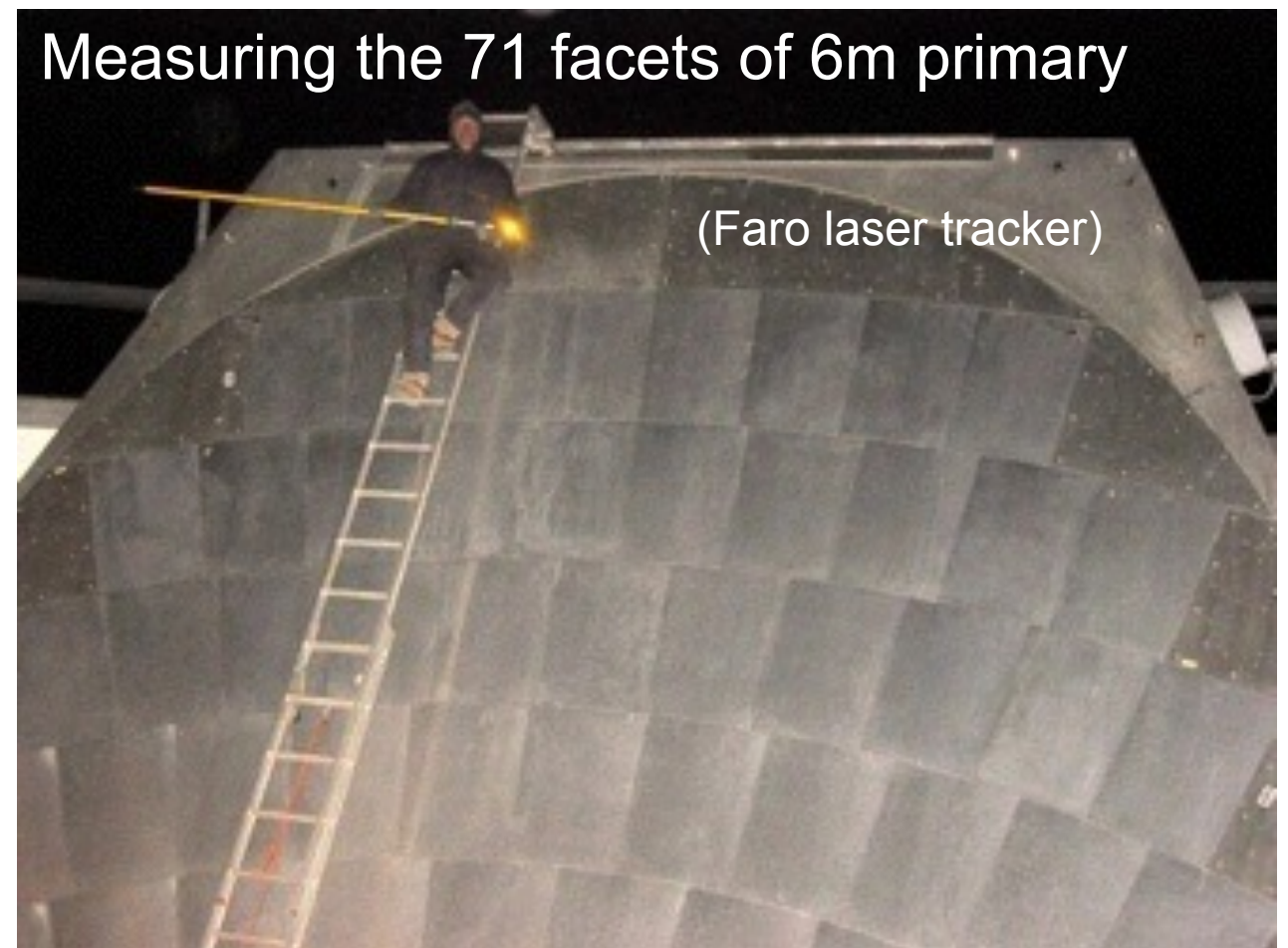
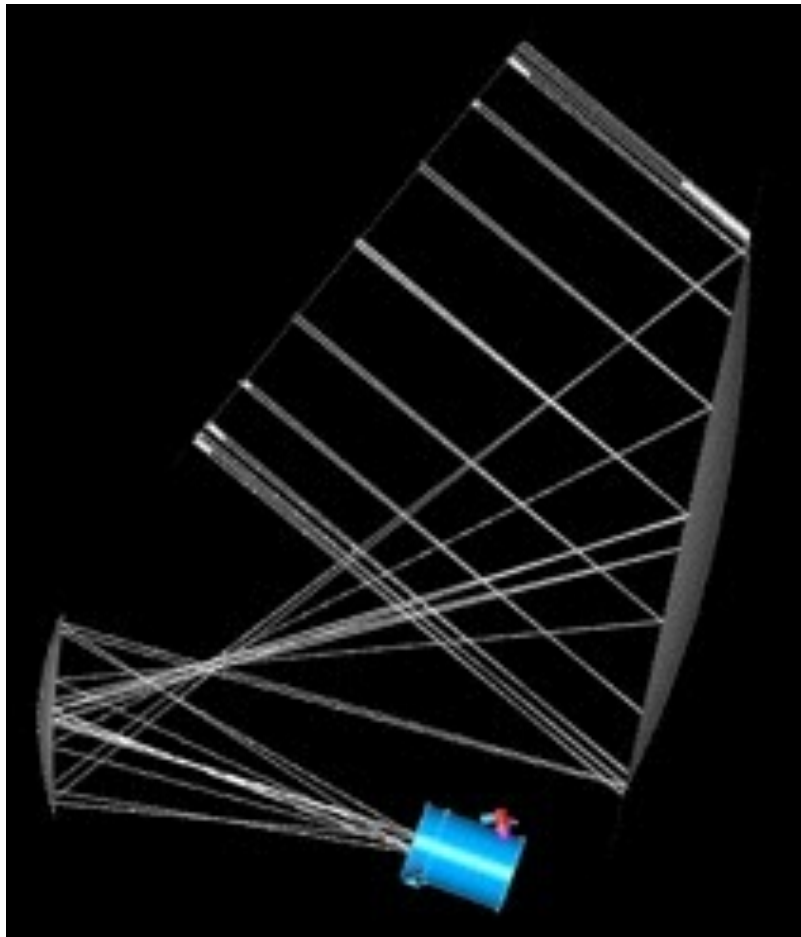


ACT: Telescope & Camera

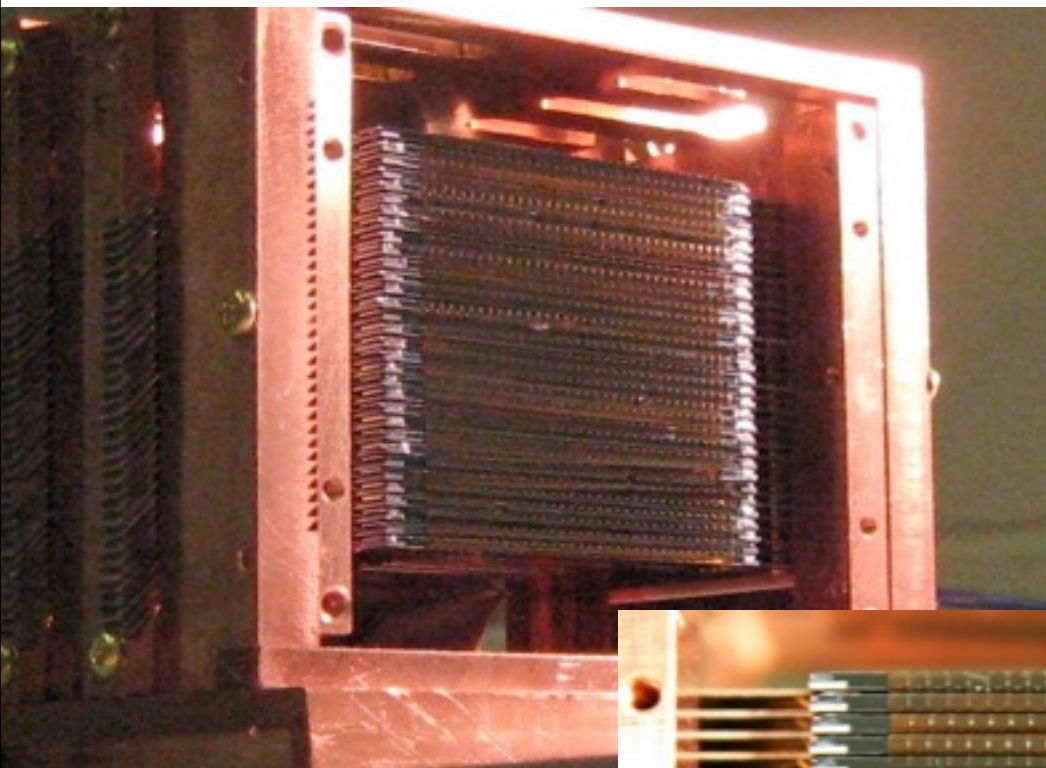
Some constraints:

- Diffraction-limited beams
- 25' fields of view (x3)
- Clear aperture
- 6-meter off-axis primary
- 2-meter secondary
- Fast / compact system
- 5" pointing accuracy

Roughly an aplanatic Gregorian.

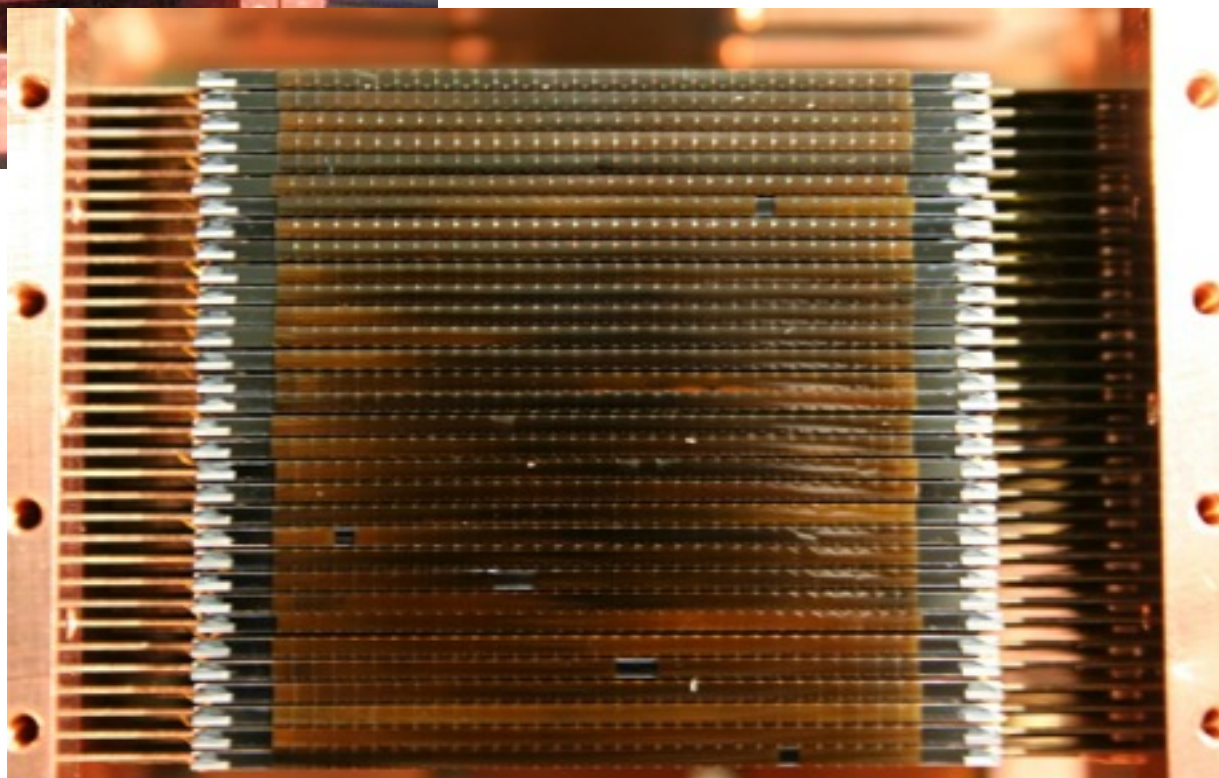


150 GHz

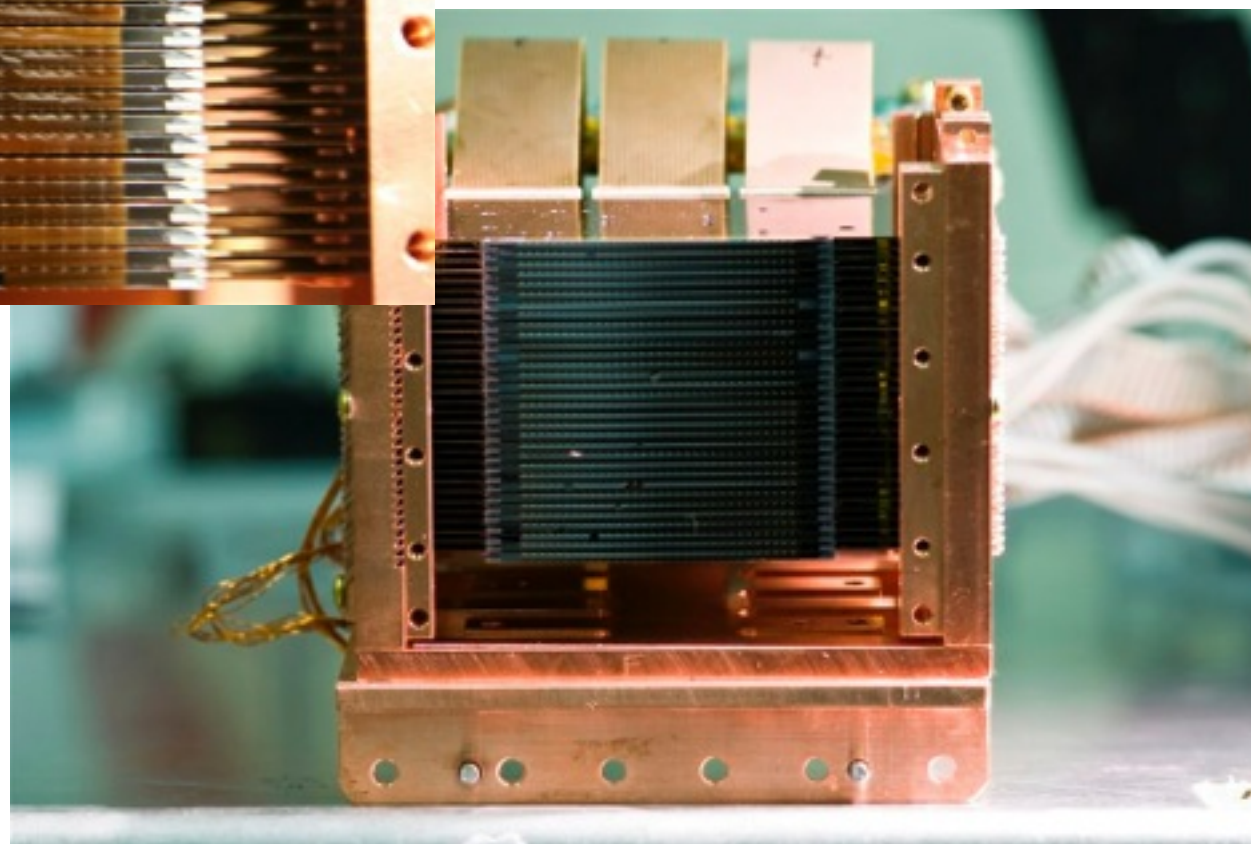


3x10²⁴ TES Bolometers

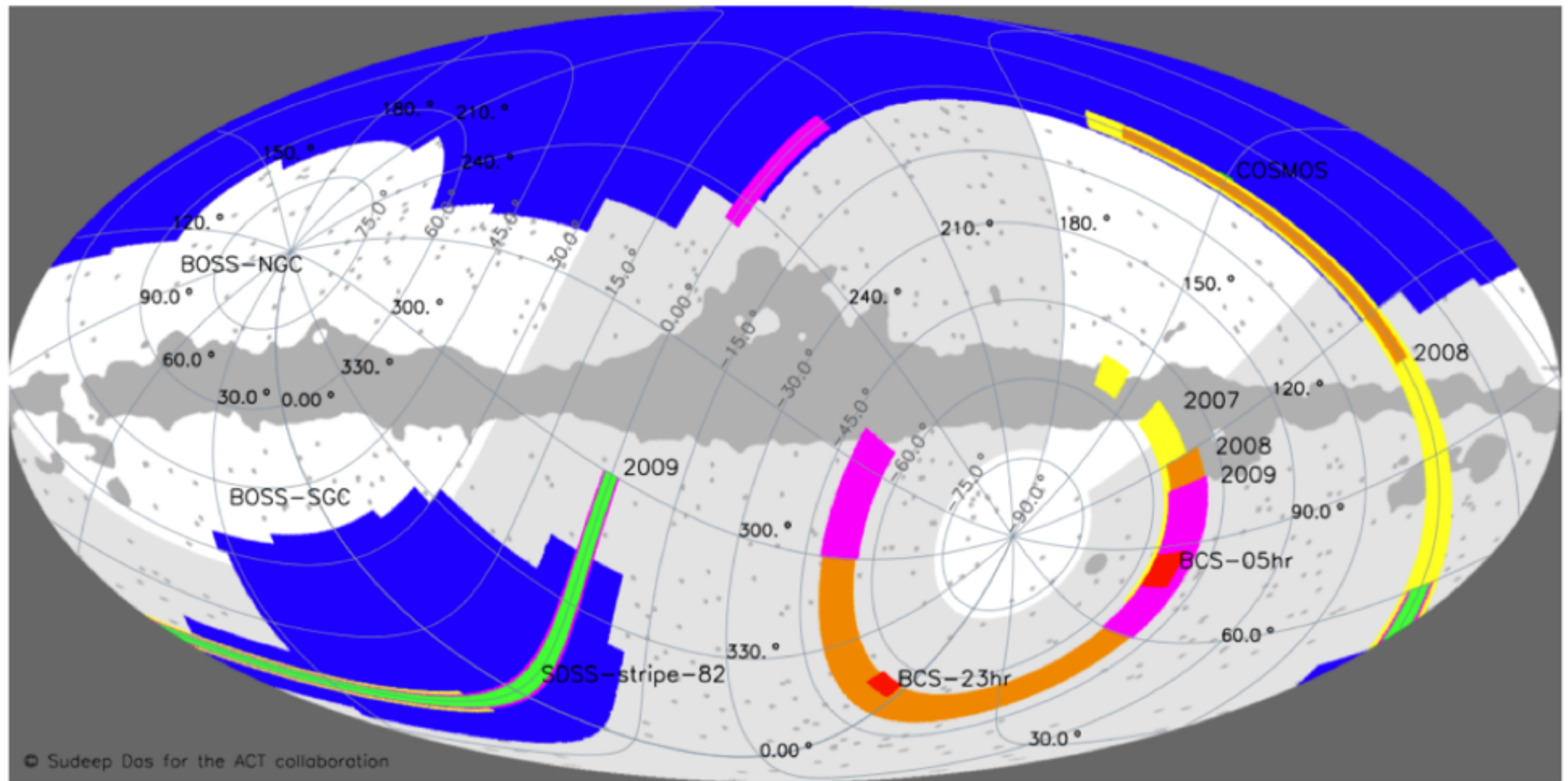
220 GHz



270 GHz



Results in this talk use full data from two frequencies (148+220 GHz).



2007

2009

Stripe 82

BCS

2008

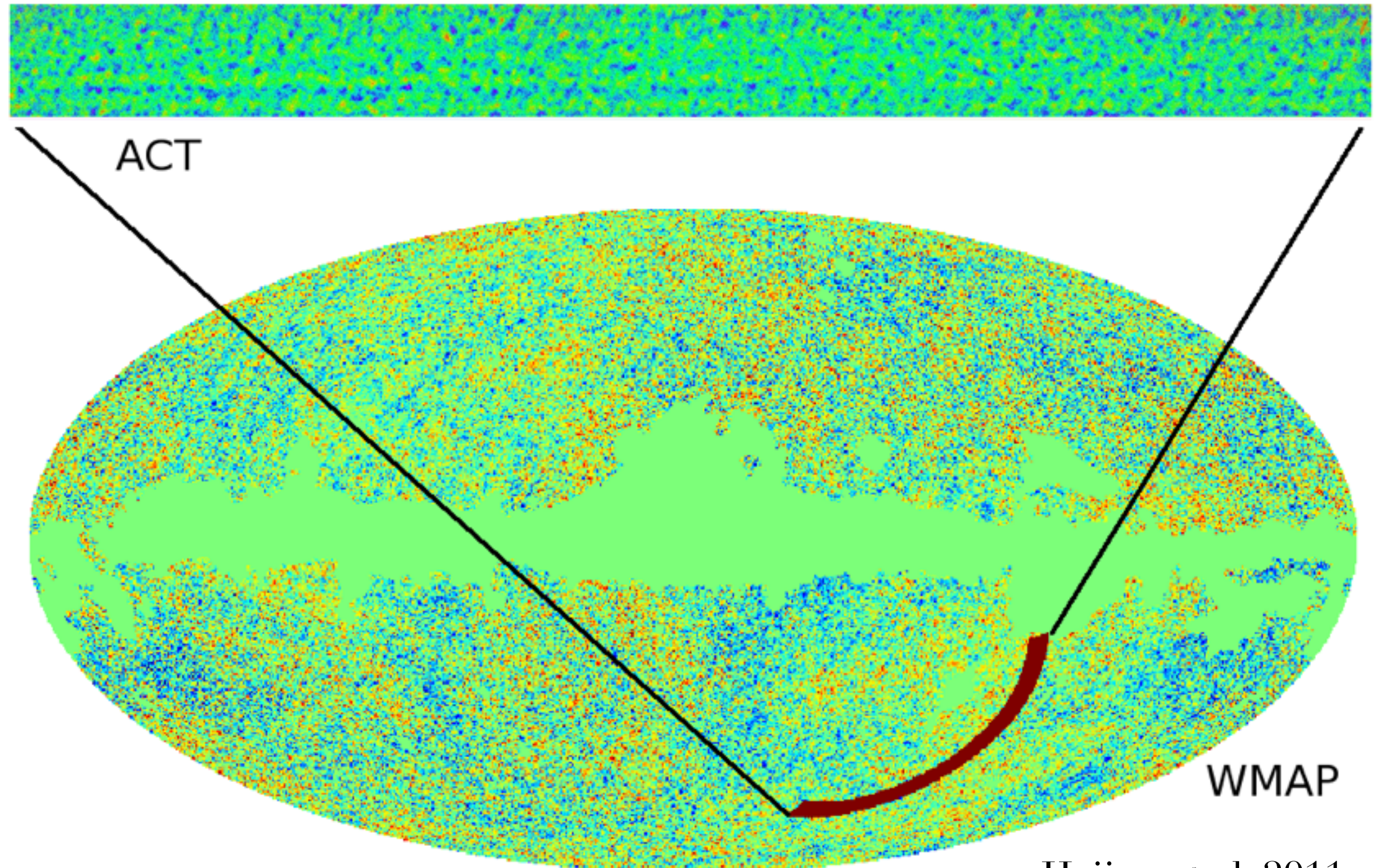
ACT Range

BOSS

Masked

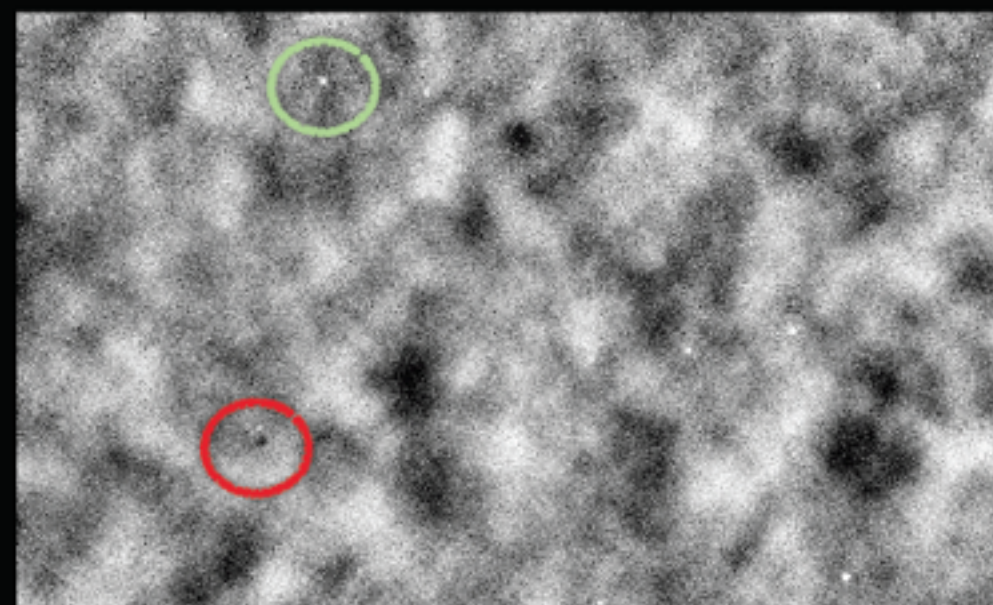
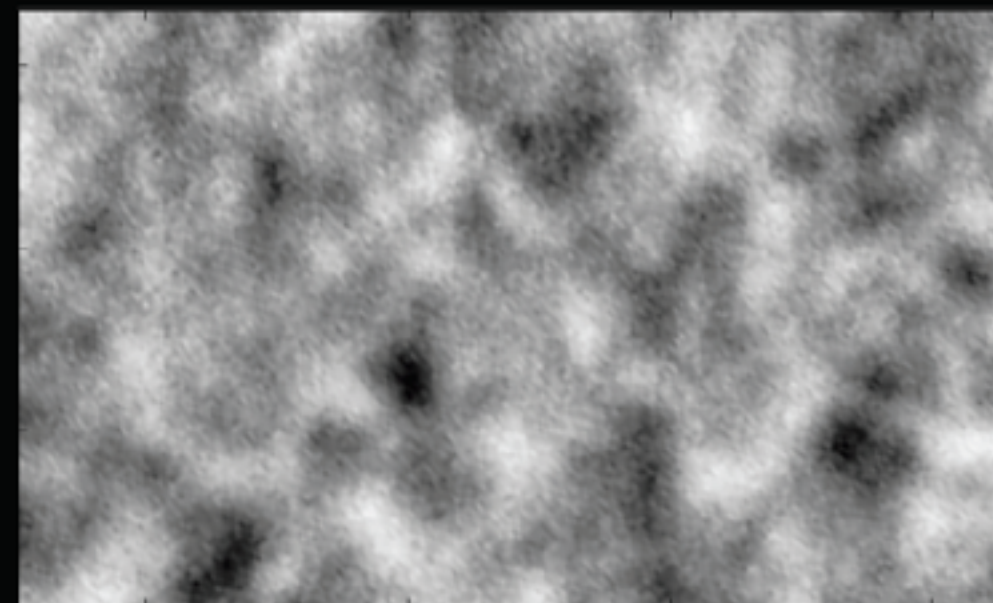
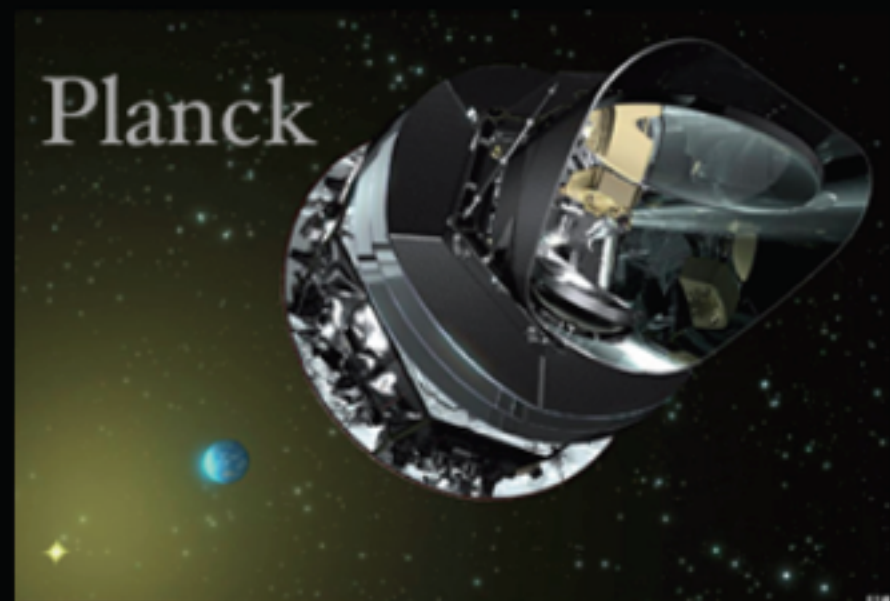
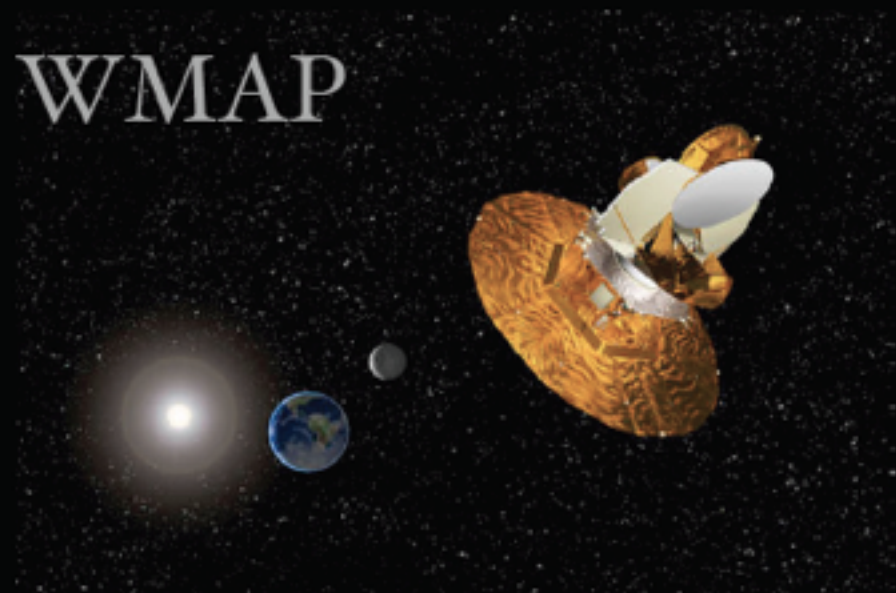
How ACT compares to WMAP

Hajian et al (2010)



Hajian et al. 2011

Some ACT Results



Amir Hajian for ACT

ACT (148GHz)



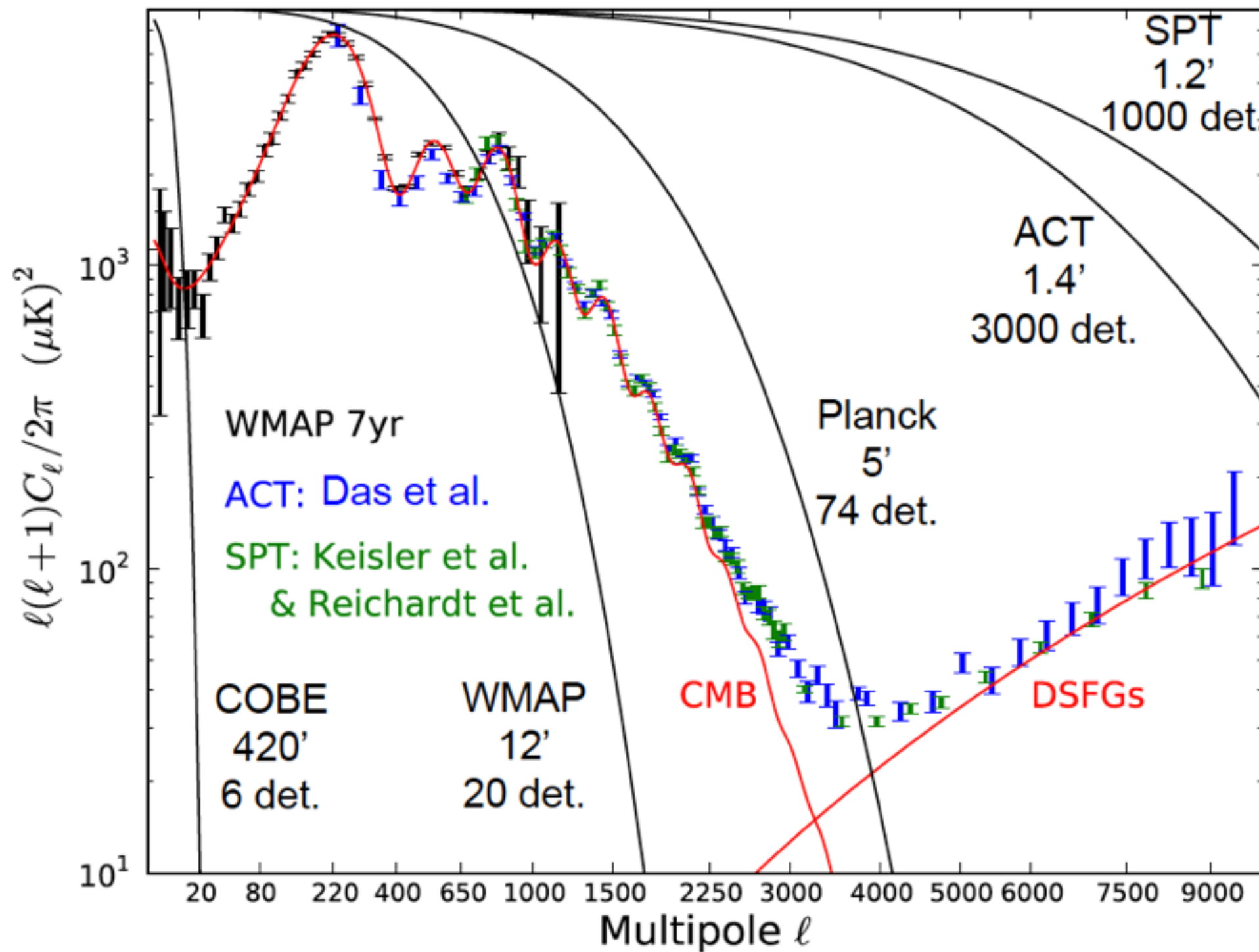
radio galaxy



SZ cluster

(C) Amir Hajian

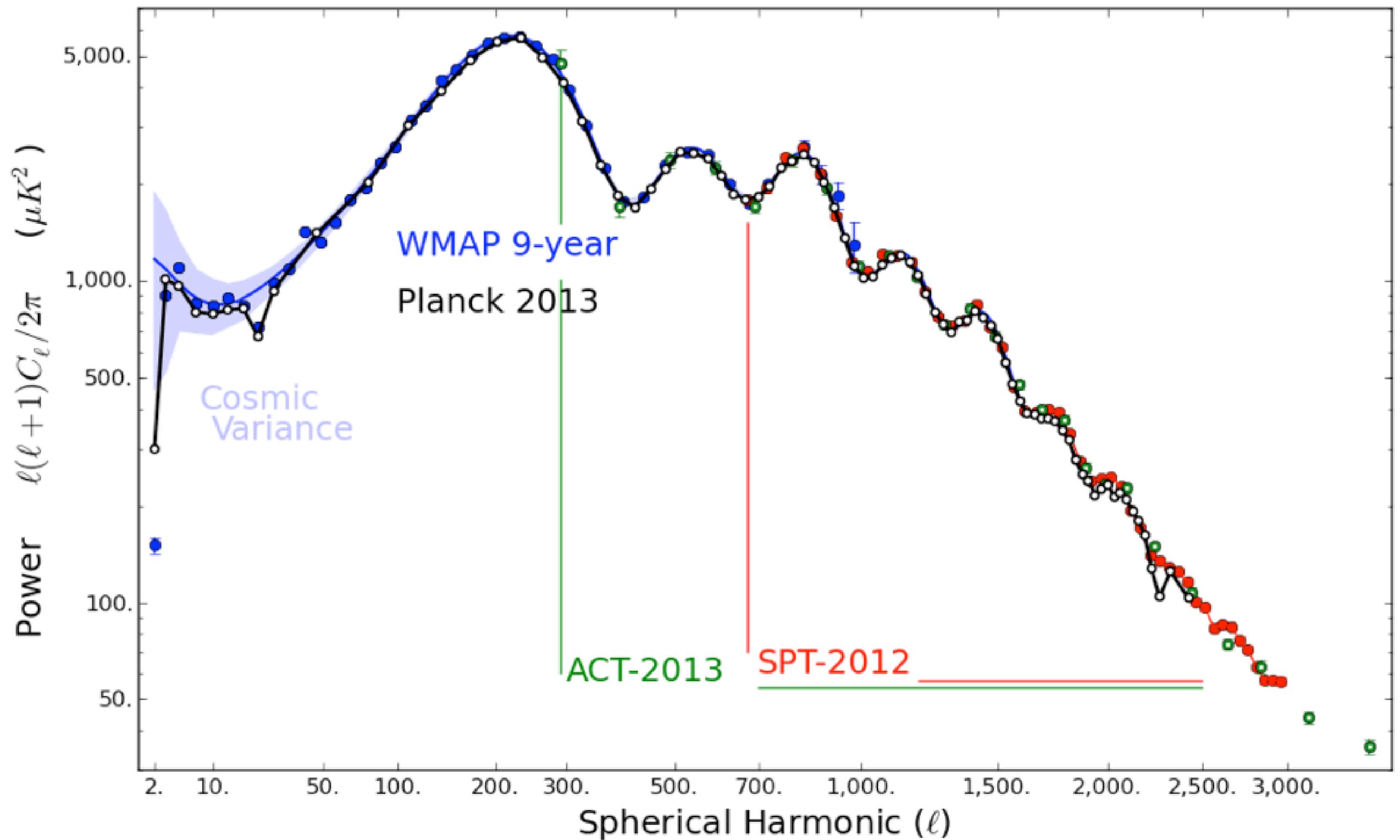
Small Angular Scale CMB Probes Additional Physics



$\ell < 3000$: Cosmological
Parameters

$\ell > 3000$: Secondary
Anisotropies

Current CMB Survey Results



The ACT components

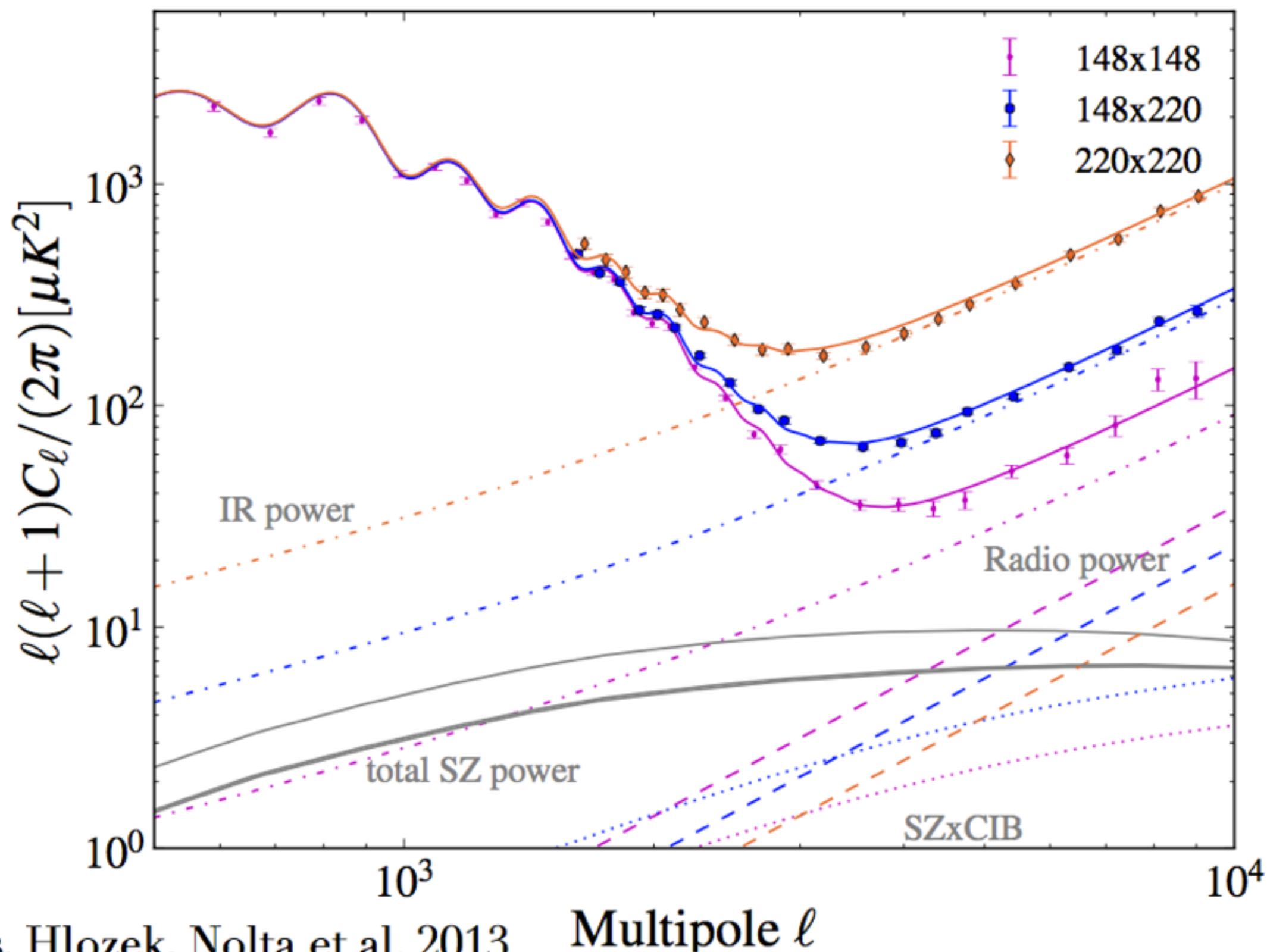


TABLE 5

EXTENDED MODEL PARAMETERS CONFIDENCE LIMITS FROM THE ACT DATA COMBINED WITH SEVEN-YEAR WMAP DATA, BAO AND H_0 MEASUREMENTS.

Parameter ^a		Λ CDM	Λ CDM + N_{eff}	Λ CDM + m_ν	Λ CDM r	Λ CDM + Ω_k
Primary Λ CDM	$100\Omega_b h^2$	2.225 ± 0.038	2.271 ± 0.046	2.259 ± 0.039	2.256 ± 0.040	2.261 ± 0.044
	$\Omega_c h^2$	0.116 ± 0.003	0.125 ± 0.008	0.115 ± 0.002	0.115 ± 0.003	0.114 ± 0.005
	$100\theta_A$	1.040 ± 0.002	1.038 ± 0.002	1.040 ± 0.002	1.040 ± 0.002	1.040 ± 0.002
	n_s	0.971 ± 0.009	0.982 ± 0.014	0.974 ± 0.010	0.972 ± 0.010	0.974 ± 0.011
	τ	0.090 ± 0.014	0.092 ± 0.015	0.091 ± 0.014	0.089 ± 0.014	0.092 ± 0.015
	$\log(10^{10}\Delta_{\mathcal{R}}^2)$	3.20 ± 0.03	3.19 ± 0.03	3.19 ± 0.03	3.19 ± 0.04	3.19 ± 0.04
Extended	N_{eff}		3.50 ± 0.42			
	Σm_ν (eV)			< 0.40		
	r				< 0.16	
	Ω_k					-0.0020 ± 0.0047
Derived	σ_8	0.83 ± 0.02	0.86 ± 0.03	0.79 ± 0.04	0.83 ± 0.02	0.83 ± 0.03
	Ω_Λ	0.71 ± 0.01	0.71 ± 0.01	0.71 ± 0.01	0.71 ± 0.01	0.72 ± 0.01
	Ω_m	0.29 ± 0.01	0.29 ± 0.01	0.29 ± 0.01	0.29 ± 0.01	0.29 ± 0.01
	H_0 (km s ⁻¹ Mpc ⁻¹)	69.3 ± 1.0	71.2 ± 2.0	68.8 ± 1.0	69.3 ± 1.0	69.0 ± 1.1
Secondary	a_{tSZ}	3.4 ± 1.4	3.4 ± 1.4	3.4 ± 1.4	3.4 ± 1.4	3.4 ± 1.5
	a_{kSZ}	< 8.3	< 8.8	< 8.5	< 8.2	< 8.5
	a_p	7.0 ± 0.5	7.0 ± 0.5	7.0 ± 0.5	7.1 ± 0.5	7.0 ± 0.6
	a_c	5.0 ± 1.0	4.8 ± 1.0	5.0 ± 1.0	5.0 ± 1.0	5.0 ± 1.0
	a_s	3.1 ± 0.4	3.0 ± 0.4	3.1 ± 0.4	3.1 ± 0.4	3.1 ± 0.4
	β_c	2.2 ± 0.1	2.2 ± 0.1	2.2 ± 0.1	2.2 ± 0.1	2.2 ± 0.1
	a_{ge}	0.9 ± 0.2	0.9 ± 0.2	0.9 ± 0.2	0.9 ± 0.2	0.9 ± 0.2
	a_{gs}	0.4 ± 0.2	0.4 ± 0.2	0.4 ± 0.2	0.4 ± 0.2	0.4 ± 0.2
Calibration	$y1s$	1.01 ± 0.01	1.01 ± 0.01	1.01 ± 0.01	1.01 ± 0.01	1.01 ± 0.01
	$y2s$	1.03 ± 0.02	1.03 ± 0.02	1.03 ± 0.02	1.03 ± 0.02	1.03 ± 0.02
	$y1e$	1.01 ± 0.01	1.01 ± 0.01	1.01 ± 0.01	1.01 ± 0.01	1.00 ± 0.01
	$y2e$	1.00 ± 0.02	1.00 ± 0.01	1.00 ± 0.01	1.00 ± 0.01	1.00 ± 0.01
$-2 \ln \mathcal{L}^b$		8153	8152	8153	8153	8152

Planck, ACT, SPT

Parameter	<i>Planck</i> +WP+highL		<i>WMAP</i> -7+SPT (S12)	
	Best fit	68% limit	Best fit	68% limits
$100\Omega_{\rm b}h^2$	2.207	2.207 ± 0.027	2.223	2.229 ± 0.037
$\Omega_{\rm c}h^2$	0.1203	0.1198 ± 0.0026	0.1097	0.1093 ± 0.0040
$10^9 A_{\rm s}$	2.211	2.198 ± 0.056	2.143	2.142 ± 0.061
$n_{\rm s}$	0.958	0.959 ± 0.007	0.963	0.962 ± 0.010
τ	0.093	0.091 ± 0.014	0.083	0.083 ± 0.014
$100\theta_{\ast}$	1.0415	1.0415 ± 0.0006	1.0425	1.0429 ± 0.0010
Ω_{Λ}	0.683	0.685 ± 0.017	0.747	0.750 ± 0.020
H_0	67.2	67.3 ± 1.2	72.3	72.5 ± 1.9

ACT+WMAP7

$100\Omega_{\rm b}h^2$	2.251 ± 0.047	σ_8	0.83 ± 0.03
$\Omega_{\rm c}h^2$	0.114 ± 0.005	Ω_{Λ}	0.72 ± 0.03
$100\theta_A$	1.040 ± 0.002	Ω_m	0.28 ± 0.03
$n_{\rm s}$	0.972 ± 0.012	H_0 (km s ⁻¹ Mpc ⁻¹)	70.0 ± 2.4
τ	0.091 ± 0.015		
$\log(10^{10}\Delta_{\mathcal{R}}^2)$	3.19 ± 0.04		

Atacama Cosmology Telescope

Exploring the Microwave Background Radiation



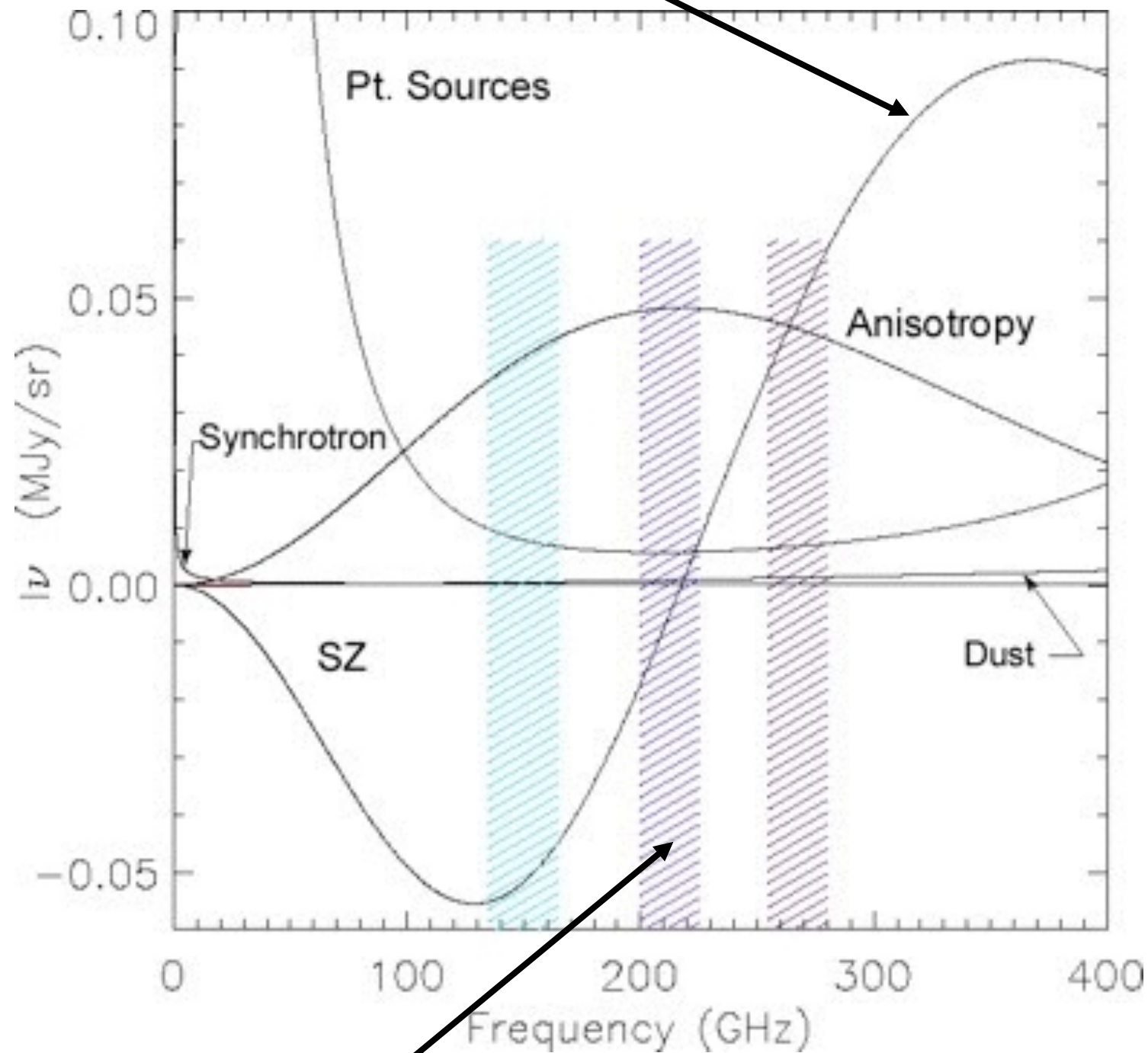
Rolando Dünner Planella

Pontificia Universidad Católica de Chile

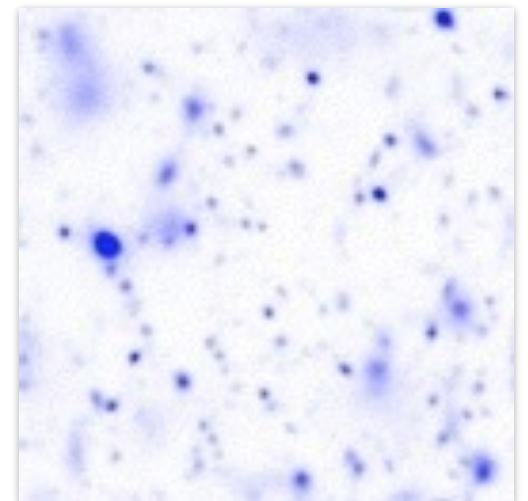
SZ Signature

Hot electron gas
imposes a unique
spectral signature

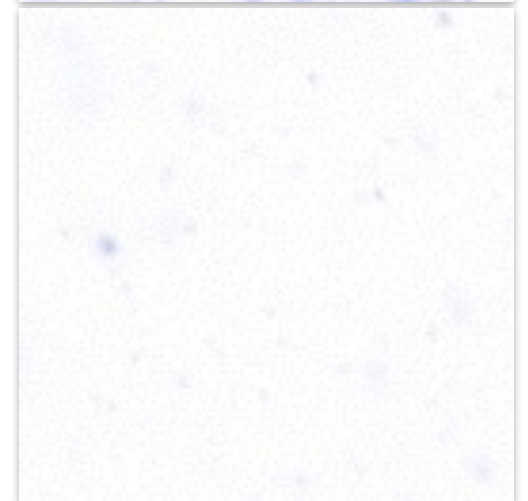
$$y = \int (k T_e / m c^2) n \sigma_T dl$$



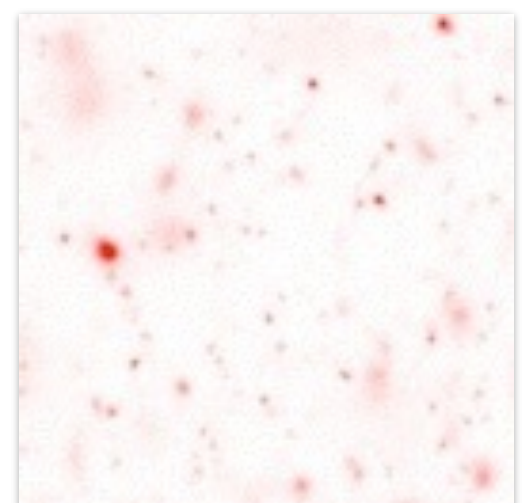
145 GHz
decrement



220 GHz
null



270 GHz
increment



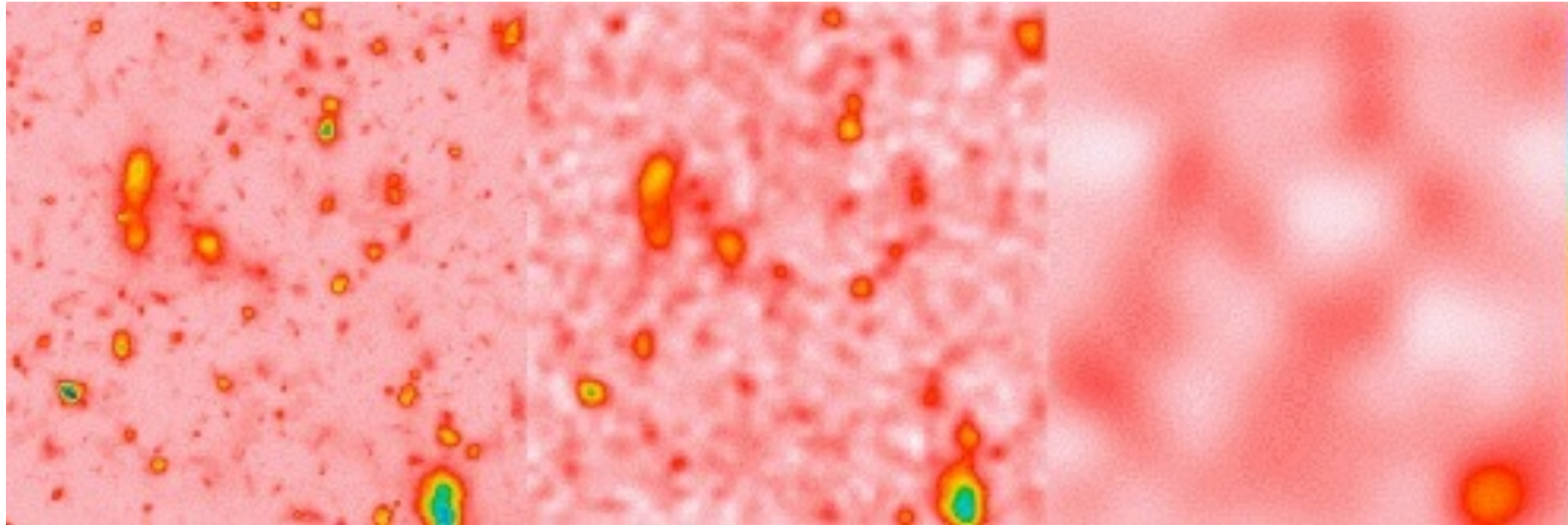
1.4° x 1.4°

NO SZ Contribution in Central Band

Arcminute Resolution mm-wave Observations

150 GHz

1.4°



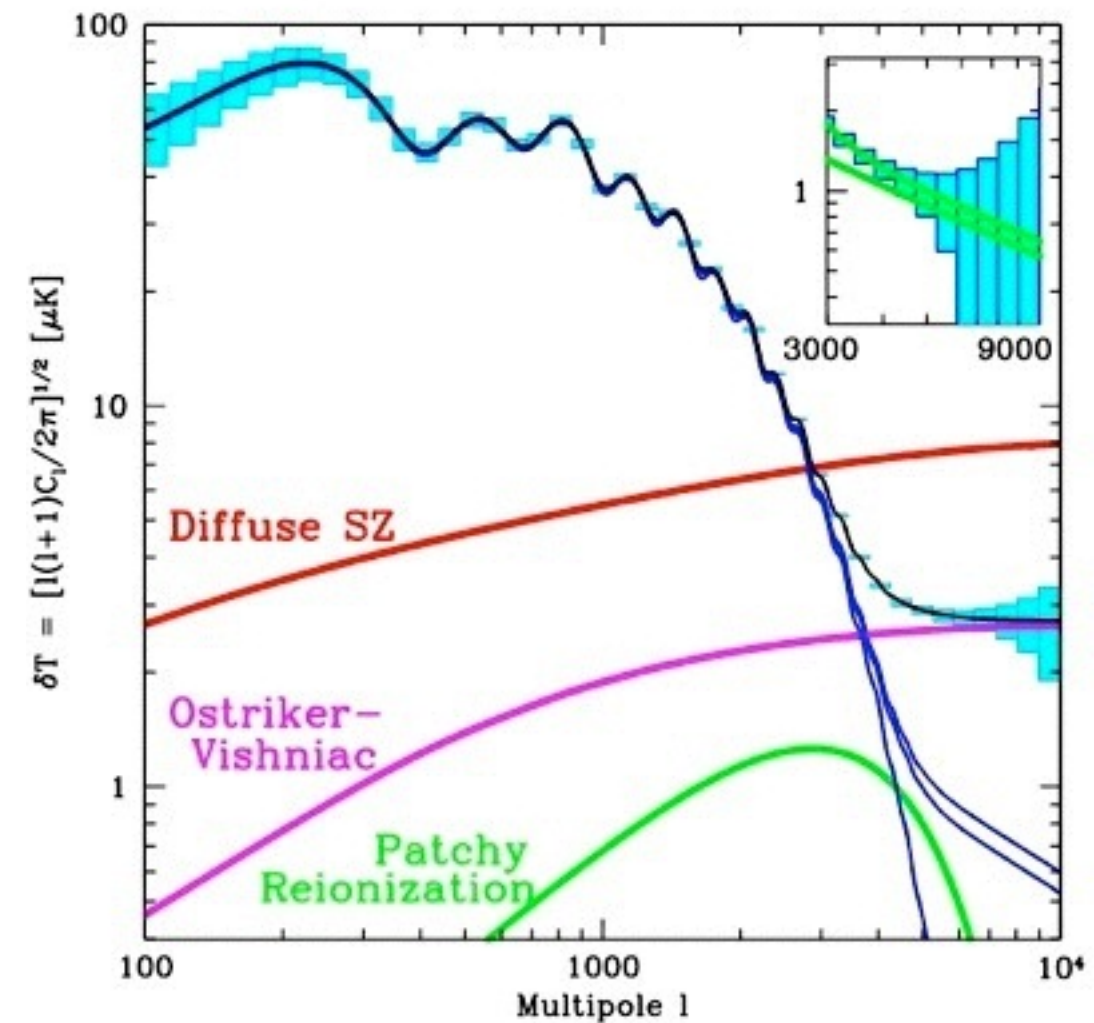
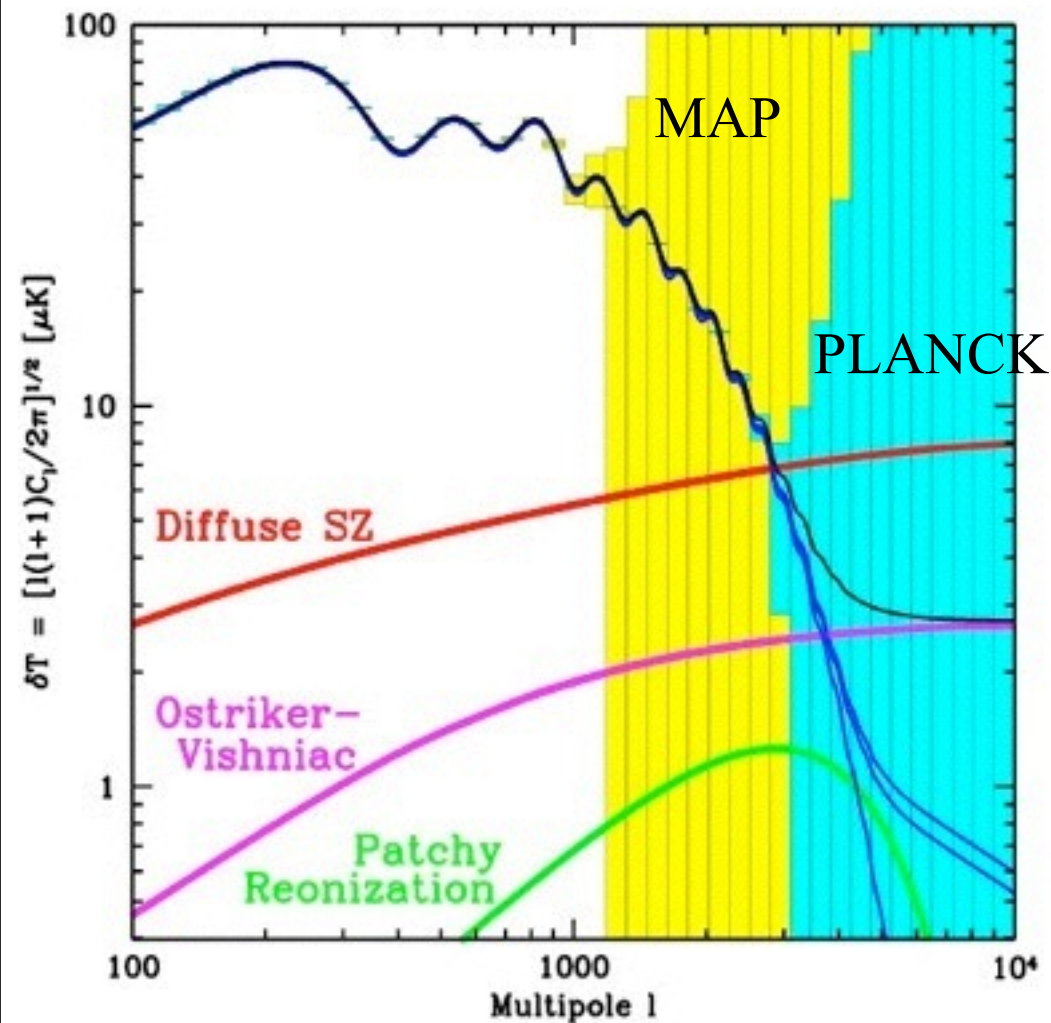
< 1% of
survey area

~2% of high
quality area

SZ Simulation

**MBAC on ACT 1.7'
beam w/ 2X noise**

PLANCK



Kinetic SZ/Ostriker-Vishniac (OV)

Amplitude of OV signal determines epoch of reionization.

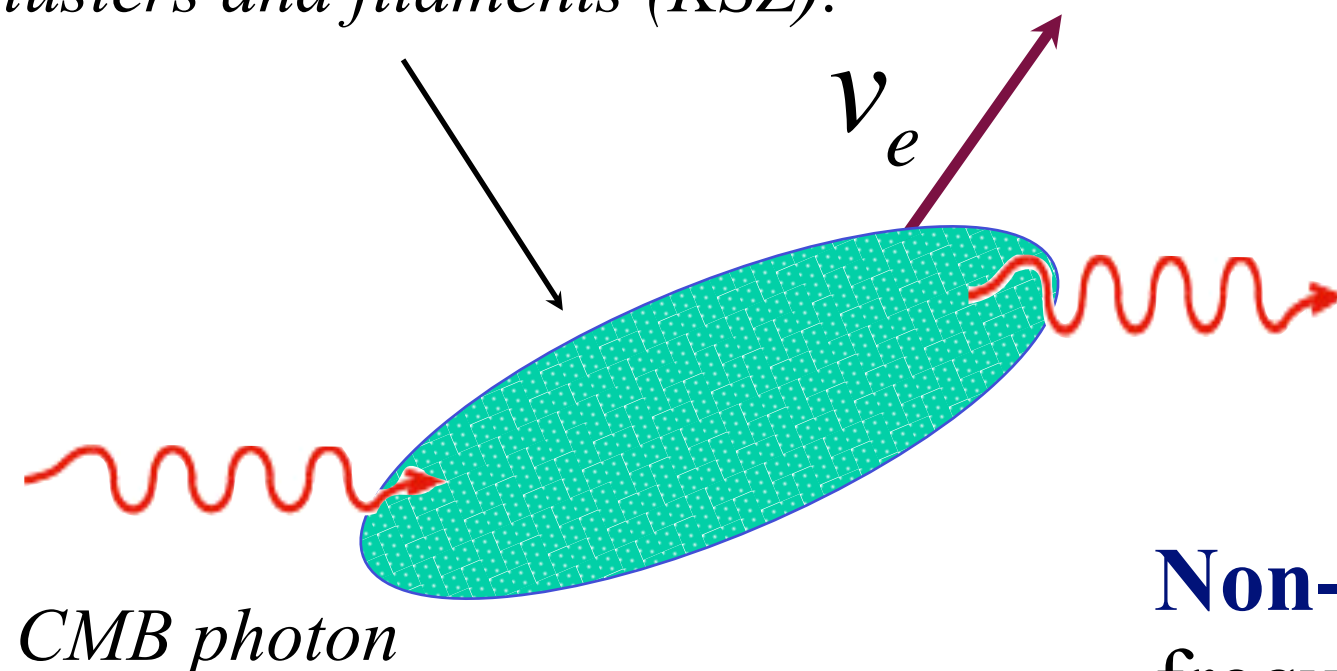
$$\delta T \propto \langle n_e^2 \rangle^{1/2} \langle v_e^2 \rangle^{1/2}$$

Bulk Velocity of hot electrons.

Bulk velocity of **HOT** electrons from ionization by the first stars (OV) or in clusters and filaments (KSZ).

OV power spectrum measures the density and velocity fluctuations at reionization.

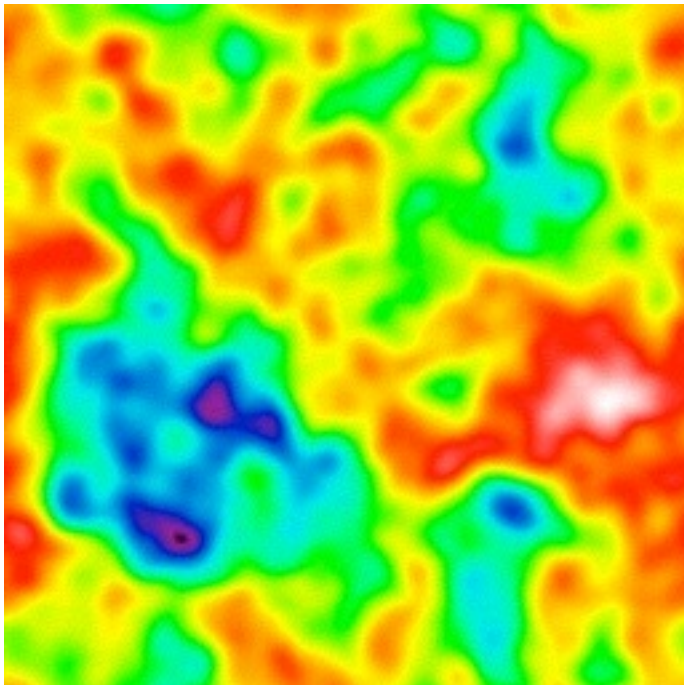
KSZ measures cluster bulk velocity field at low z .



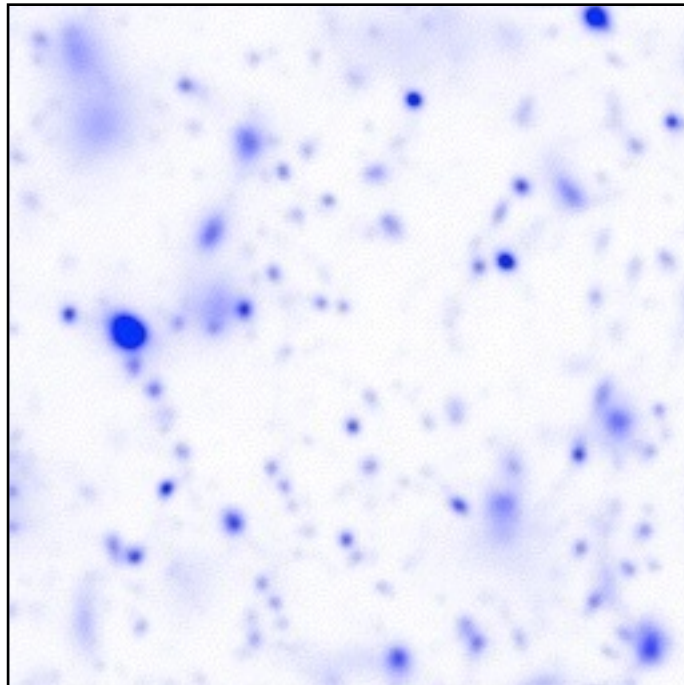
Non-Gaussian but with CMB frequency spectrum. Spatially distinguishable. Requires a high fidelity map.

145 GHz Maps

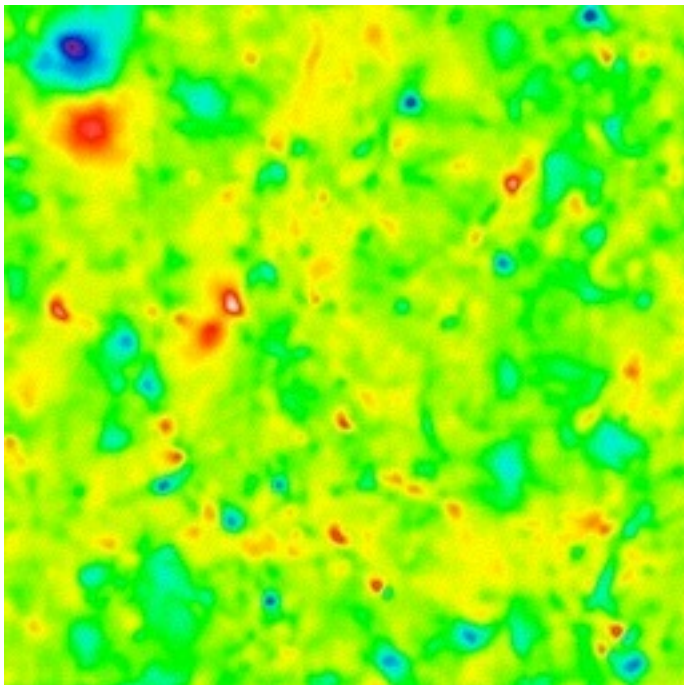
Map Components



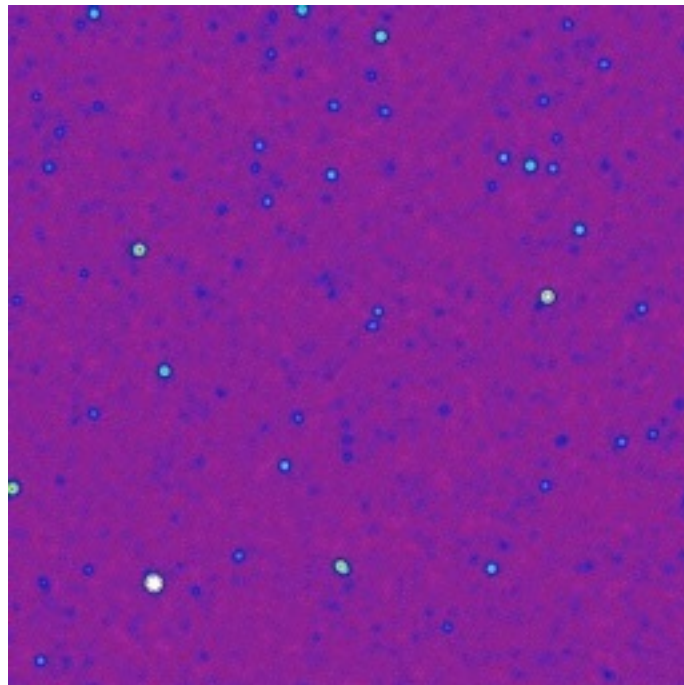
CMB



SZ

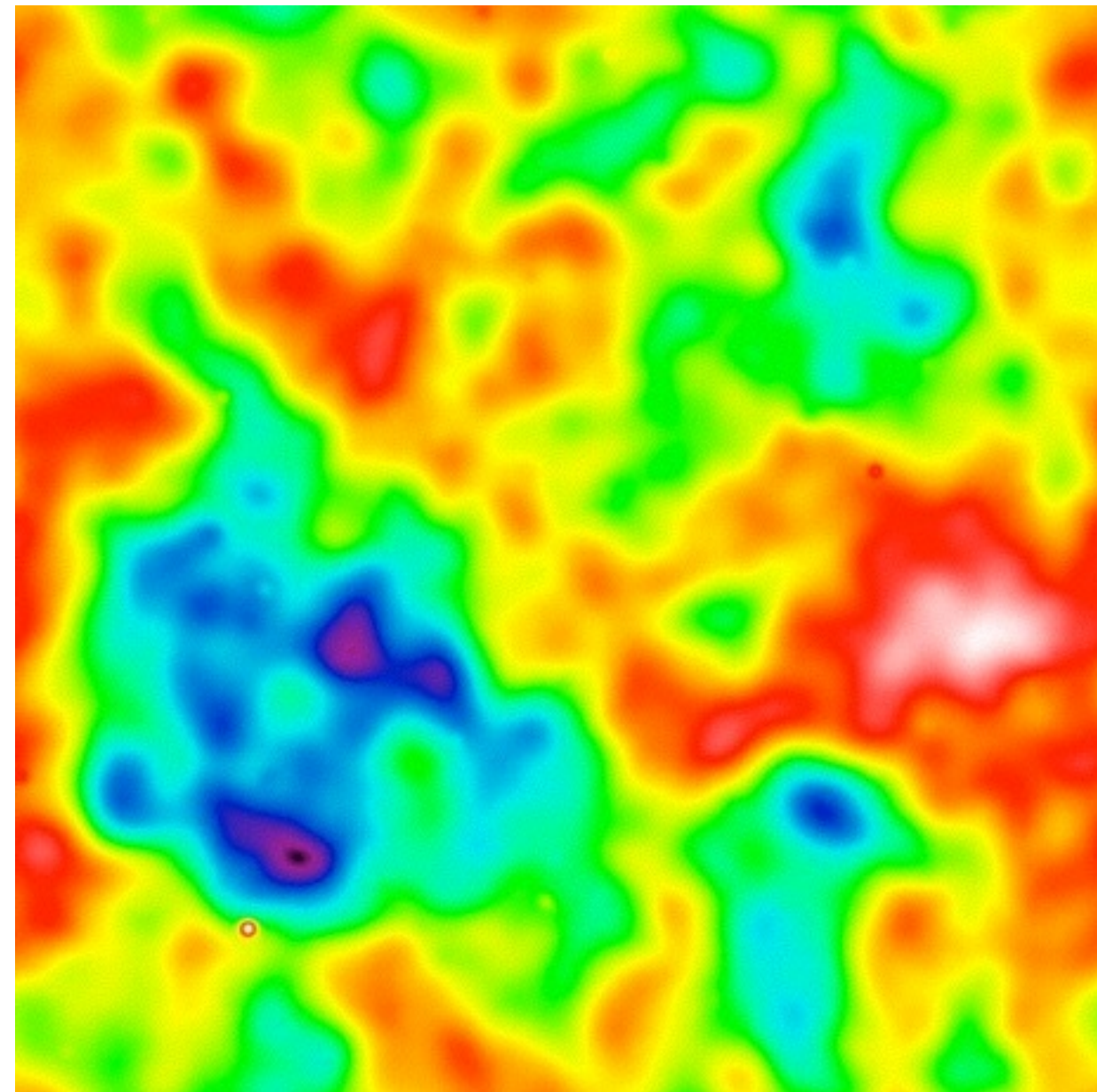


KSZ/OV



Point Sources

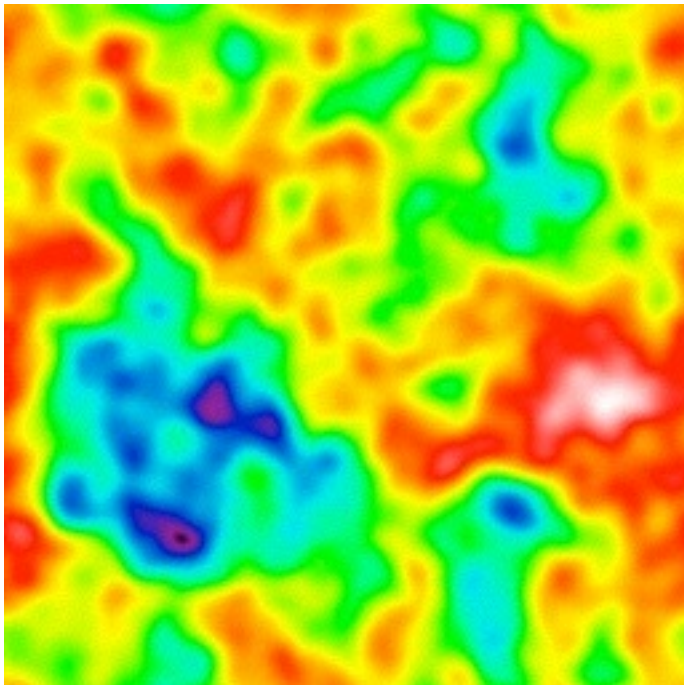
Components Summed to Scale



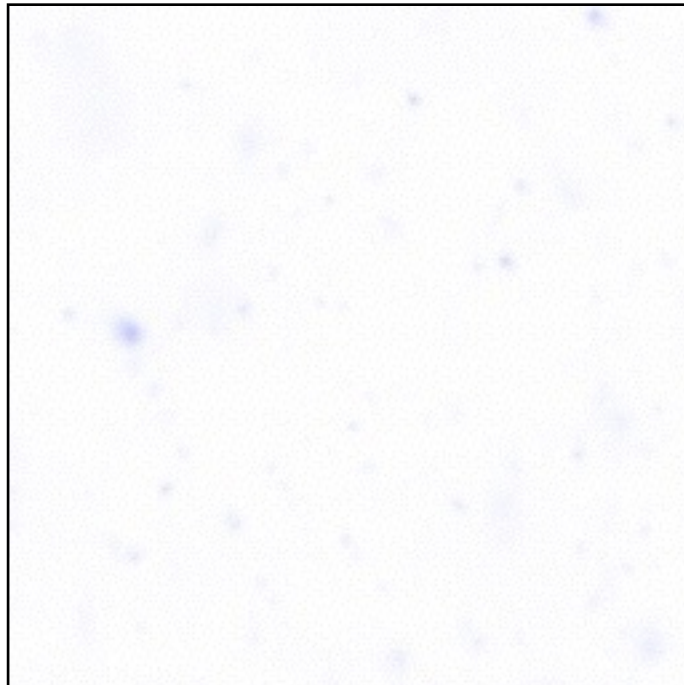
$1.4^\circ \times 1.4^\circ$

220 GHz Maps

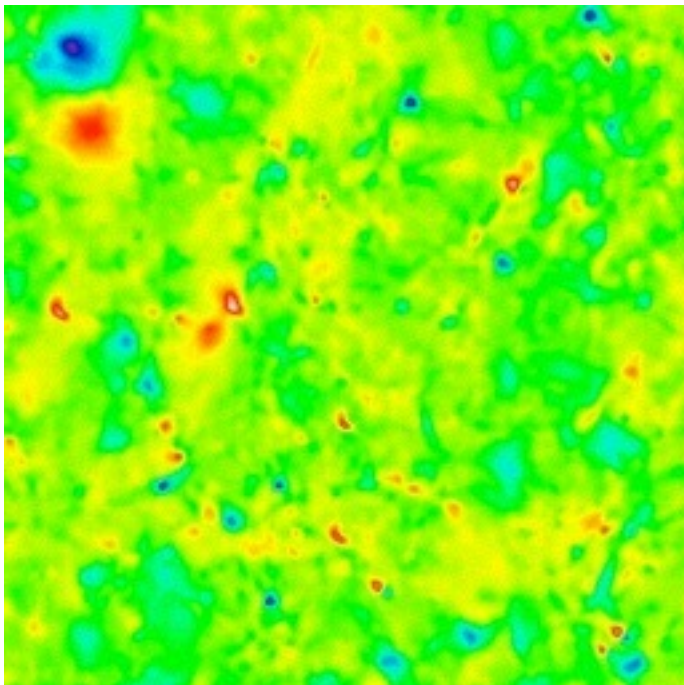
Map Components



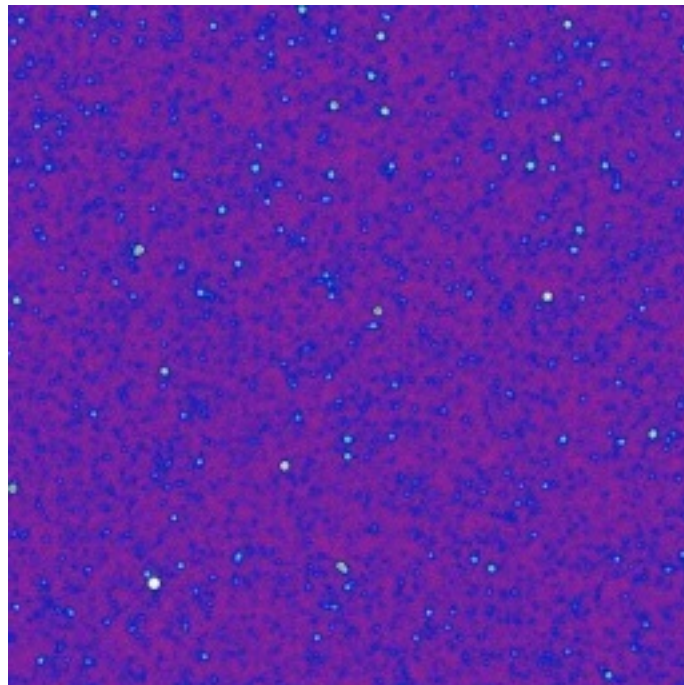
CMB



SZ

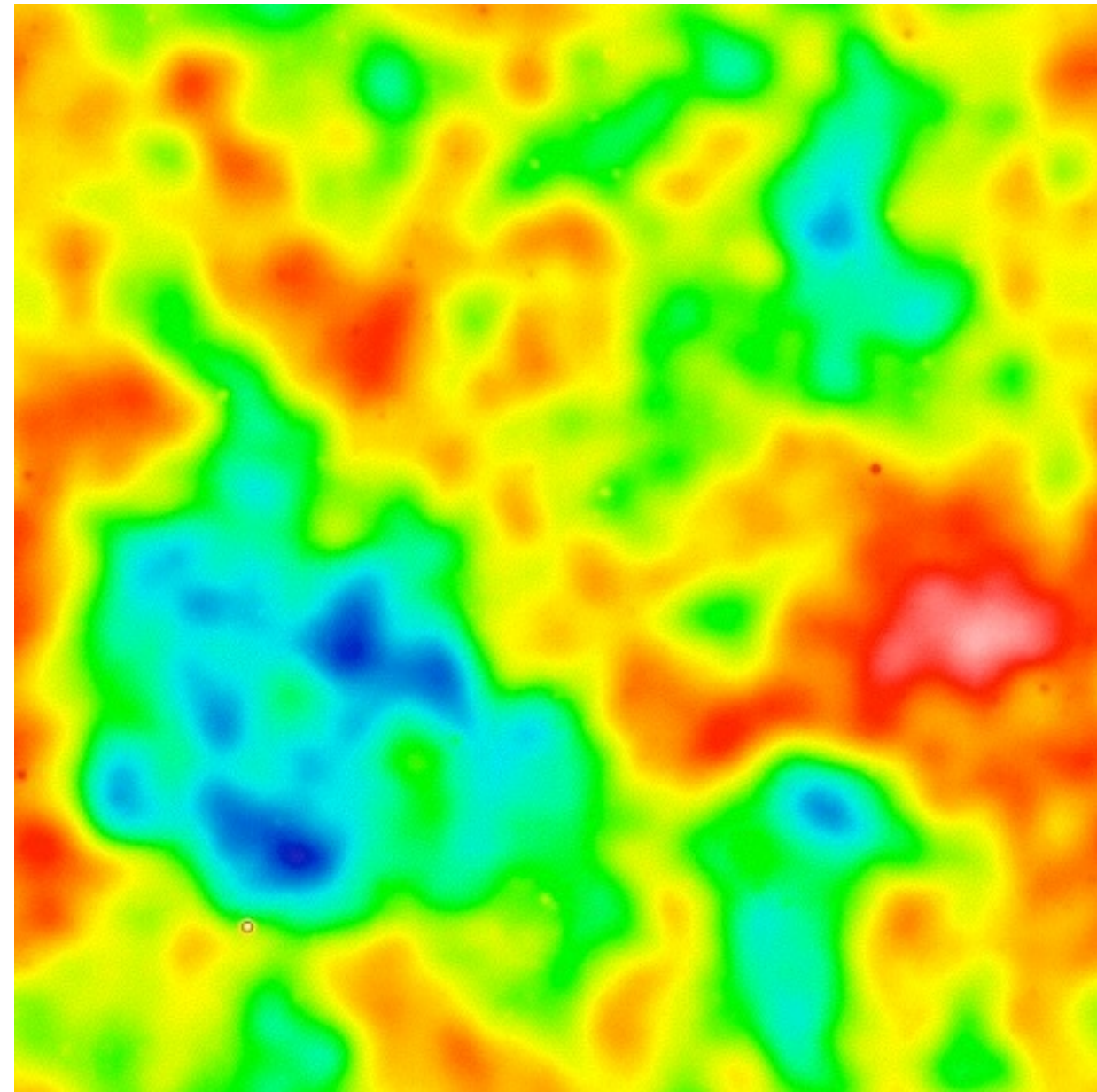


KSZ/OV



Point Sources

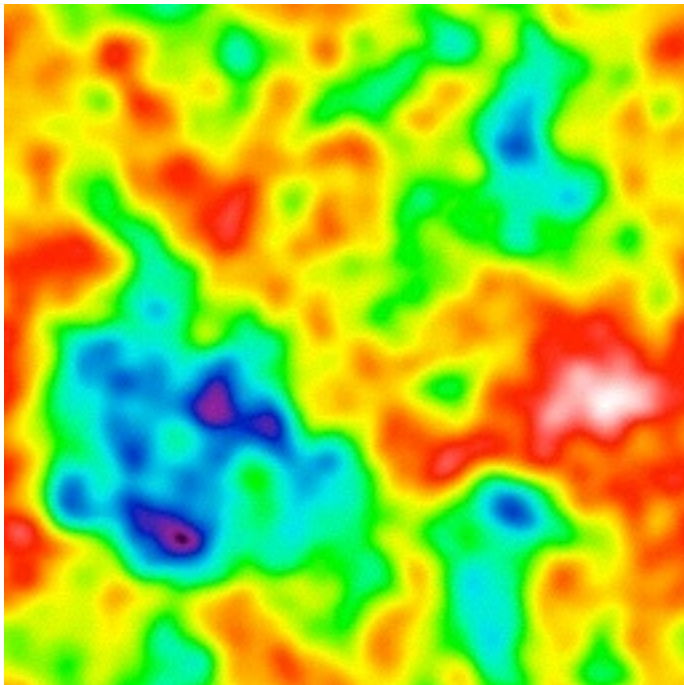
Components Summed to Scale



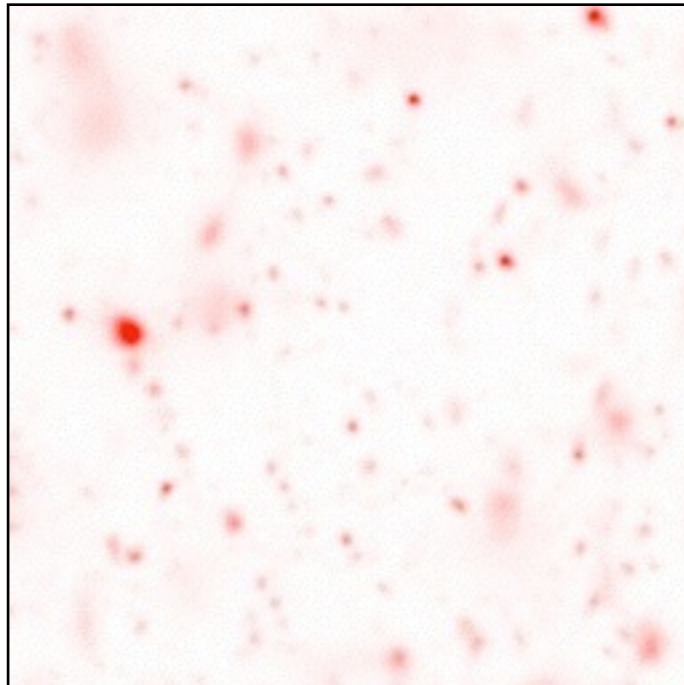
$1.4^\circ \times 1.4^\circ$

270 GHz Maps

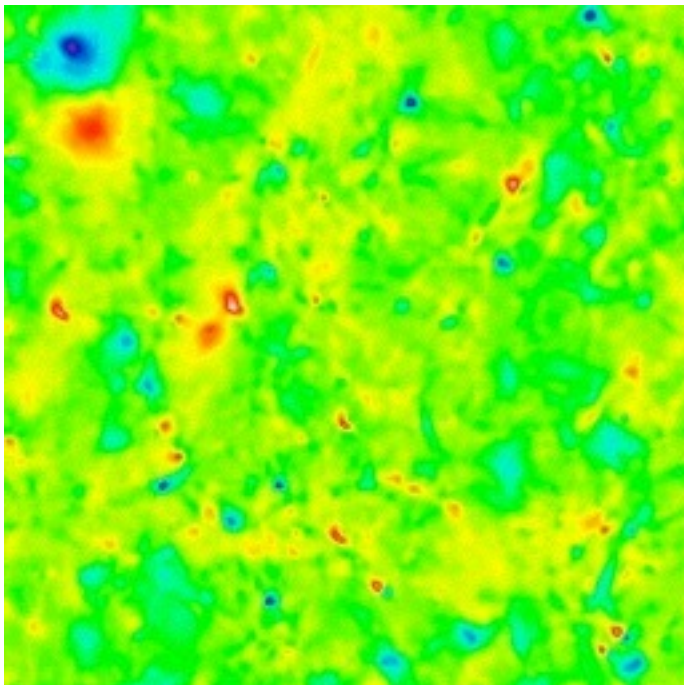
Map Components



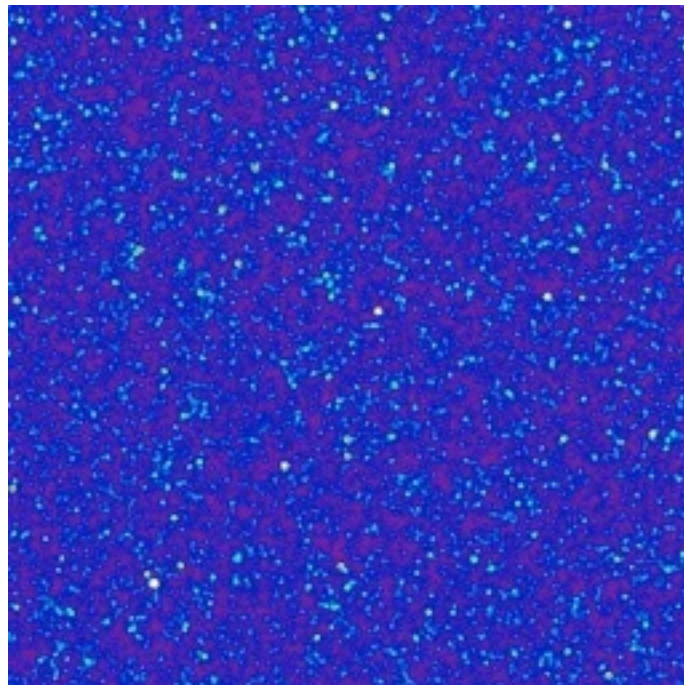
CMB



SZ

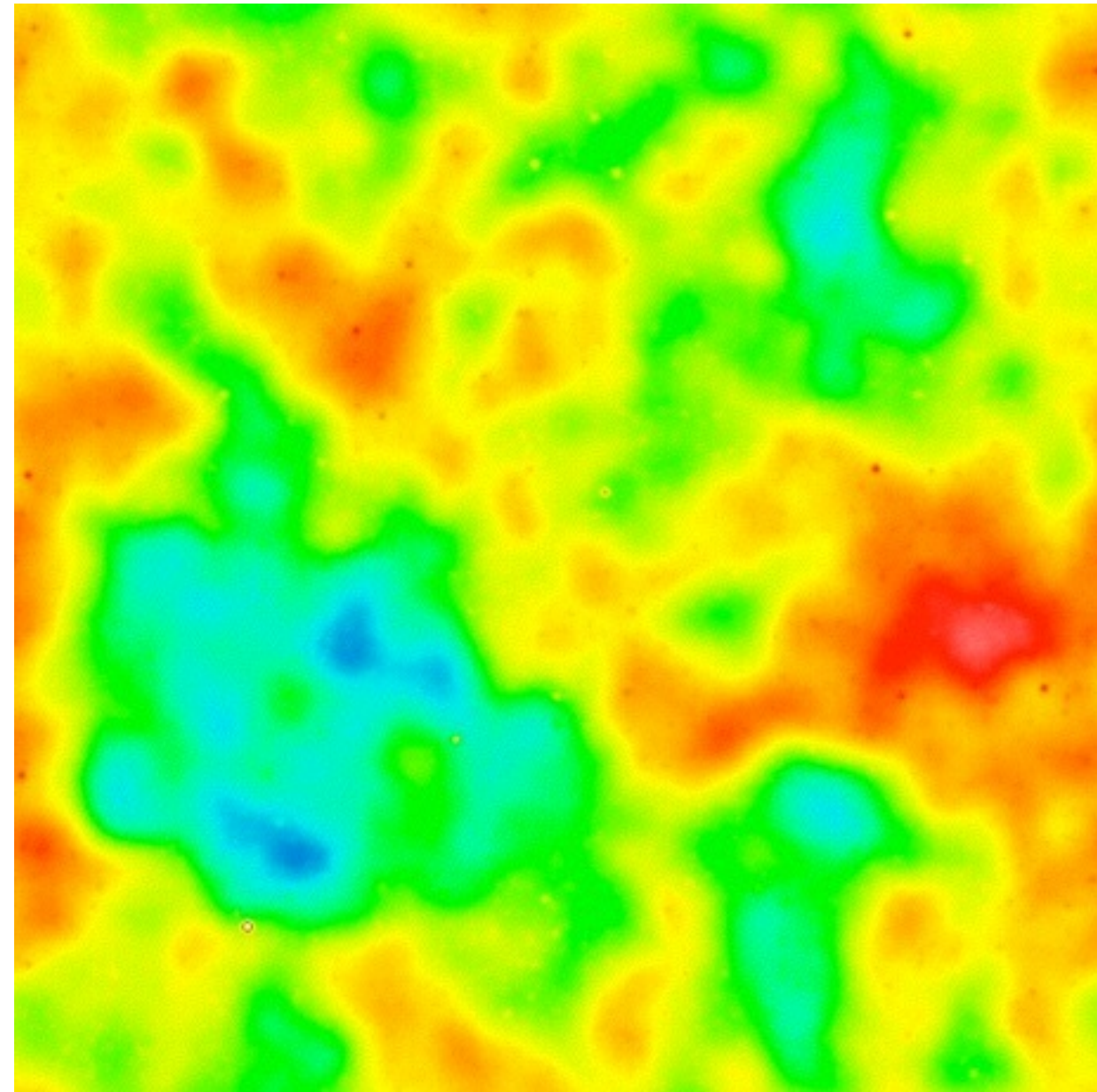


KSZ/OV



Point Sources

Components Summed to Scale



$1.4^\circ \times 1.4^\circ$

SZ Cluster Detection

Marriage et al. 2010

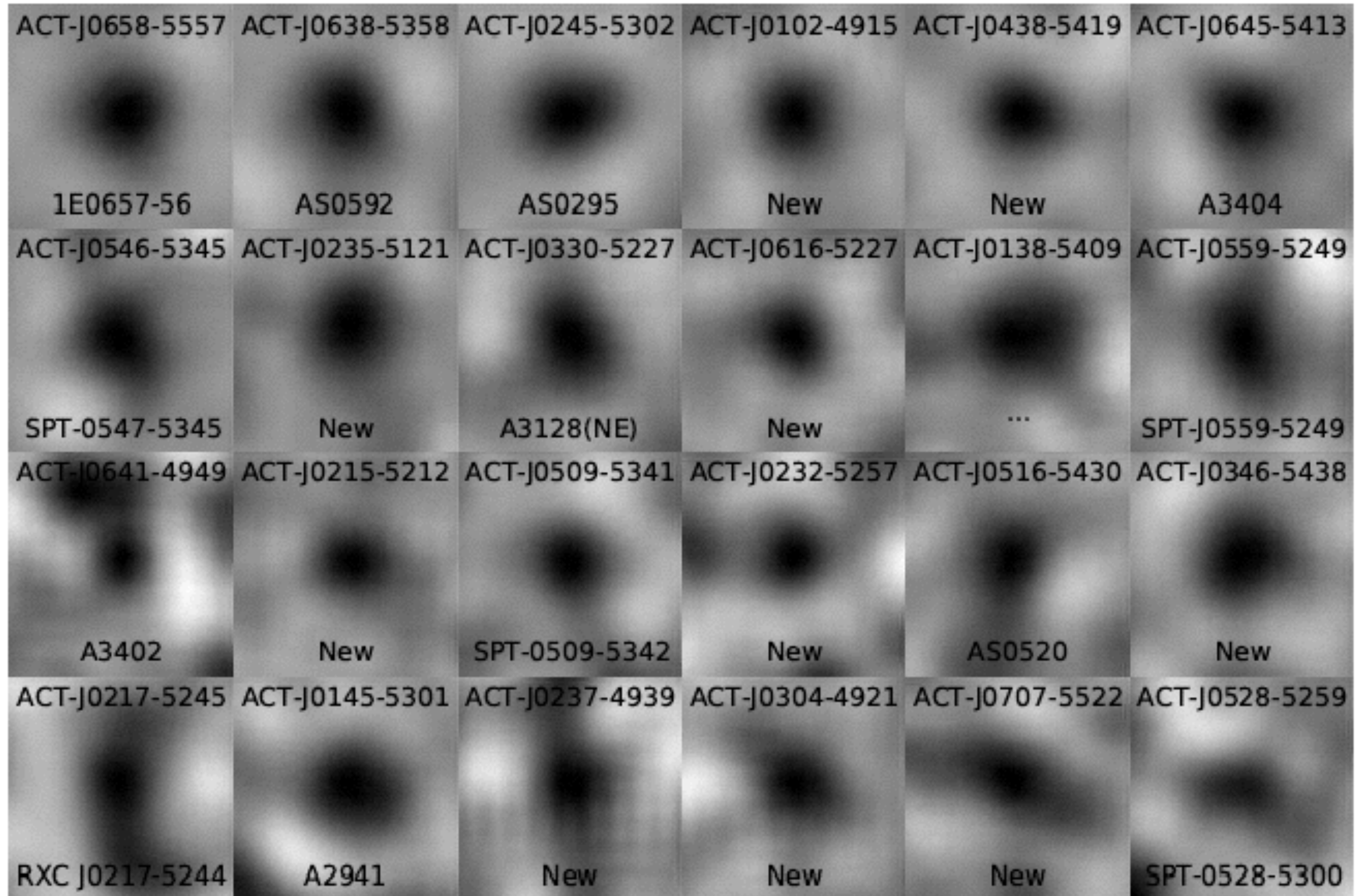
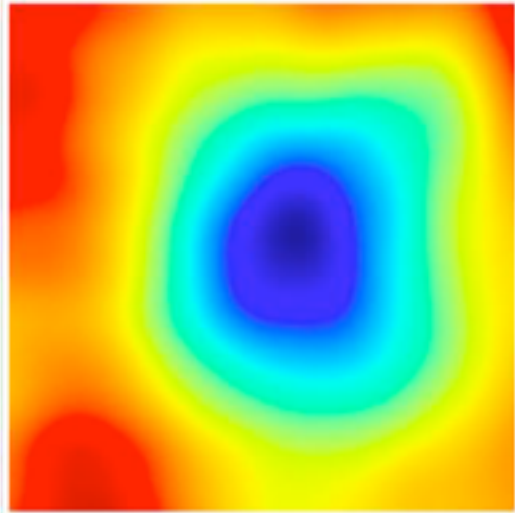
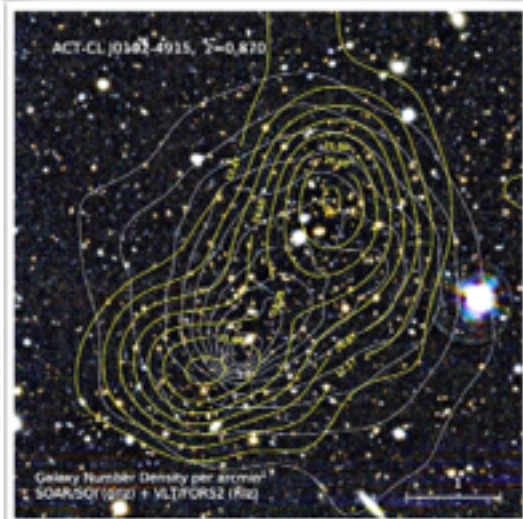


FIG. 3.— Temperature decrements. Each thumbnail is approximately 8' on a side. The grayscale of each thumbnail is symmetric about zero with a range set to the depth of the decrement. The ordering of the clusters is according to decreasing SNR from left to right and top to bottom.

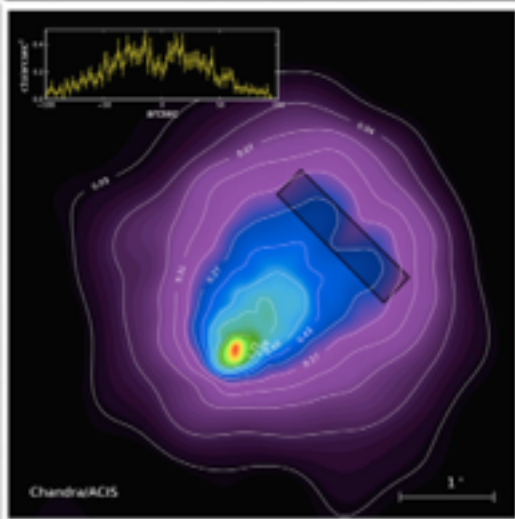
“El Gordo” ($z=0.87$)



SZ decrement



Optical

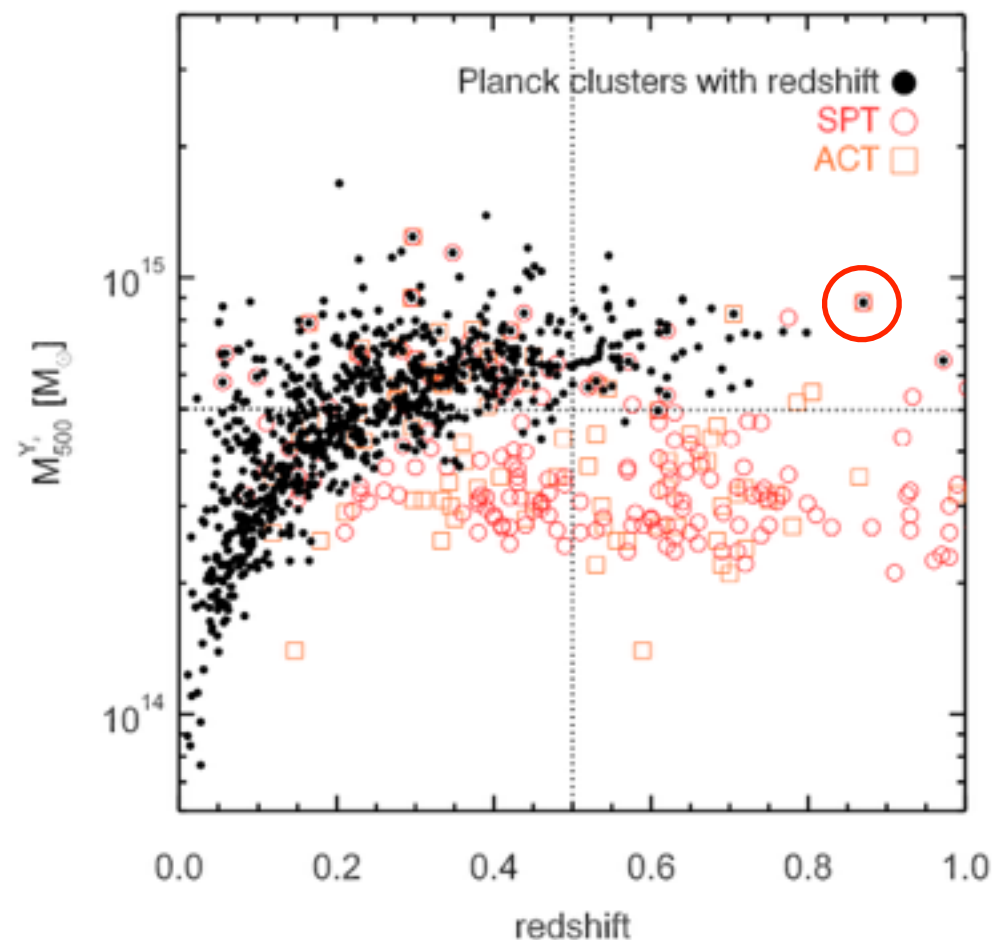


X-ray

- ACT detected - follow up by SOAR, VLT, Chandra and Spitzer
- Most massive and X-ray luminous cluster at $z > 0.6$
- Cluster merger 2:1 mass ratio, total mass:

$$M_{500} = (1.2 \pm 0.5) 10^{15} M_{\text{sun}}$$

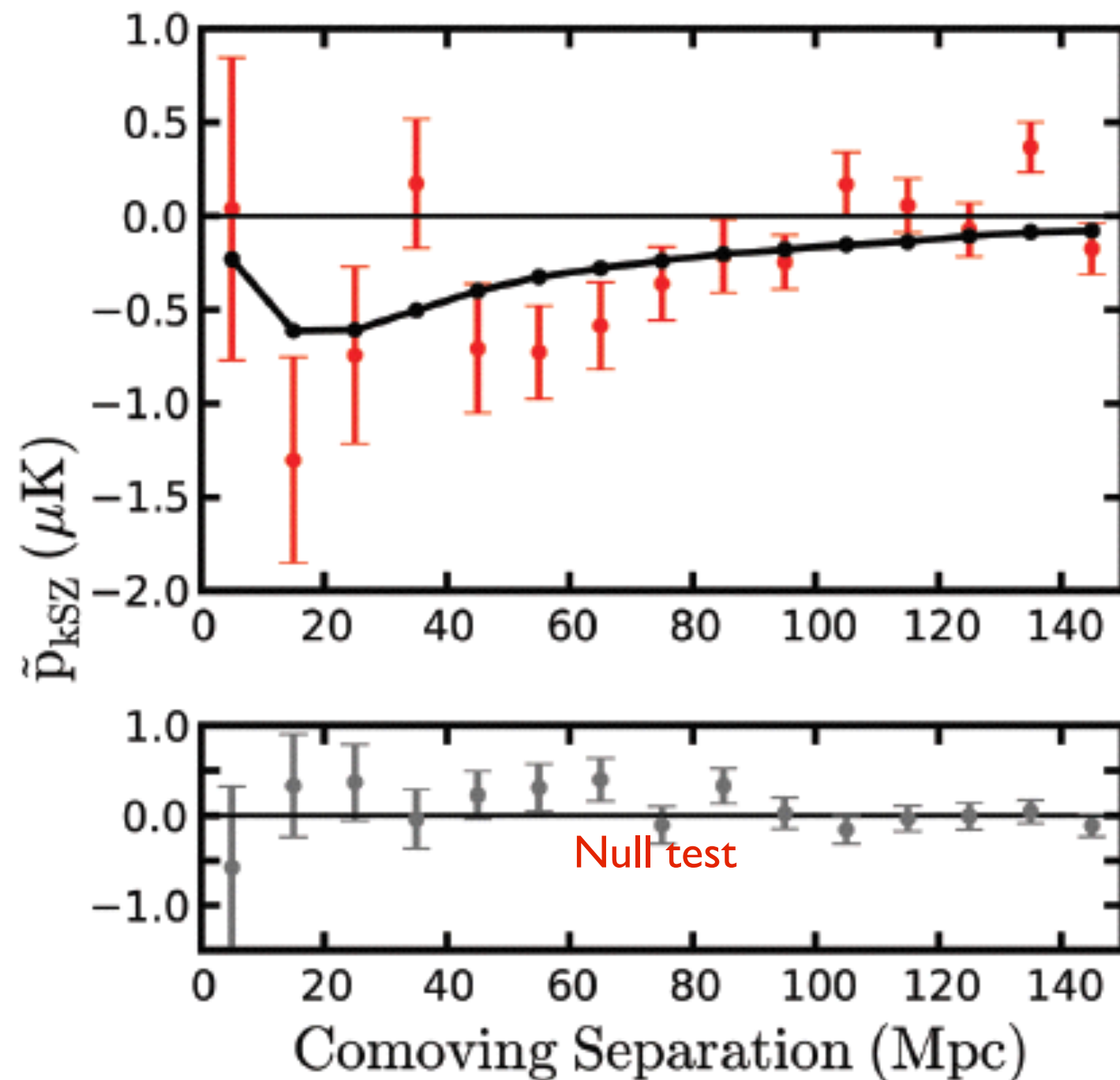
- Unlikely to find in ACT, but not in the whole sky.



PLANCK showed it to be consistent with LCDM

First kSZ Detection!

3.8 sigma detection



ACT's 148 GHz and 218 GHz maps, in combination to the location of 7500 most luminous galaxies from BOSS (cluster location proxies), were used to produce a statistical estimator for the cluster momentums as a function of their comoving separation.

Lensing of CMB detected at 4σ

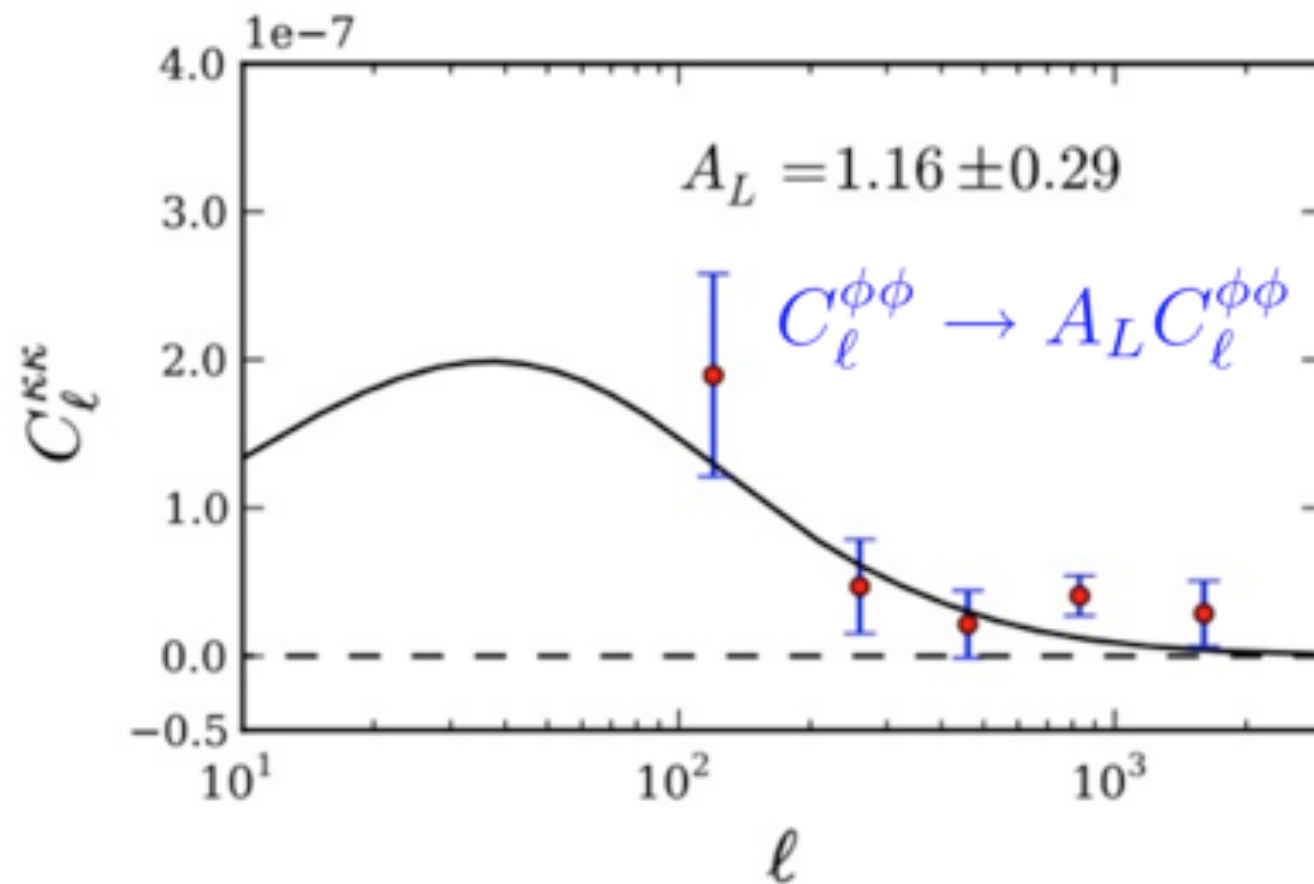
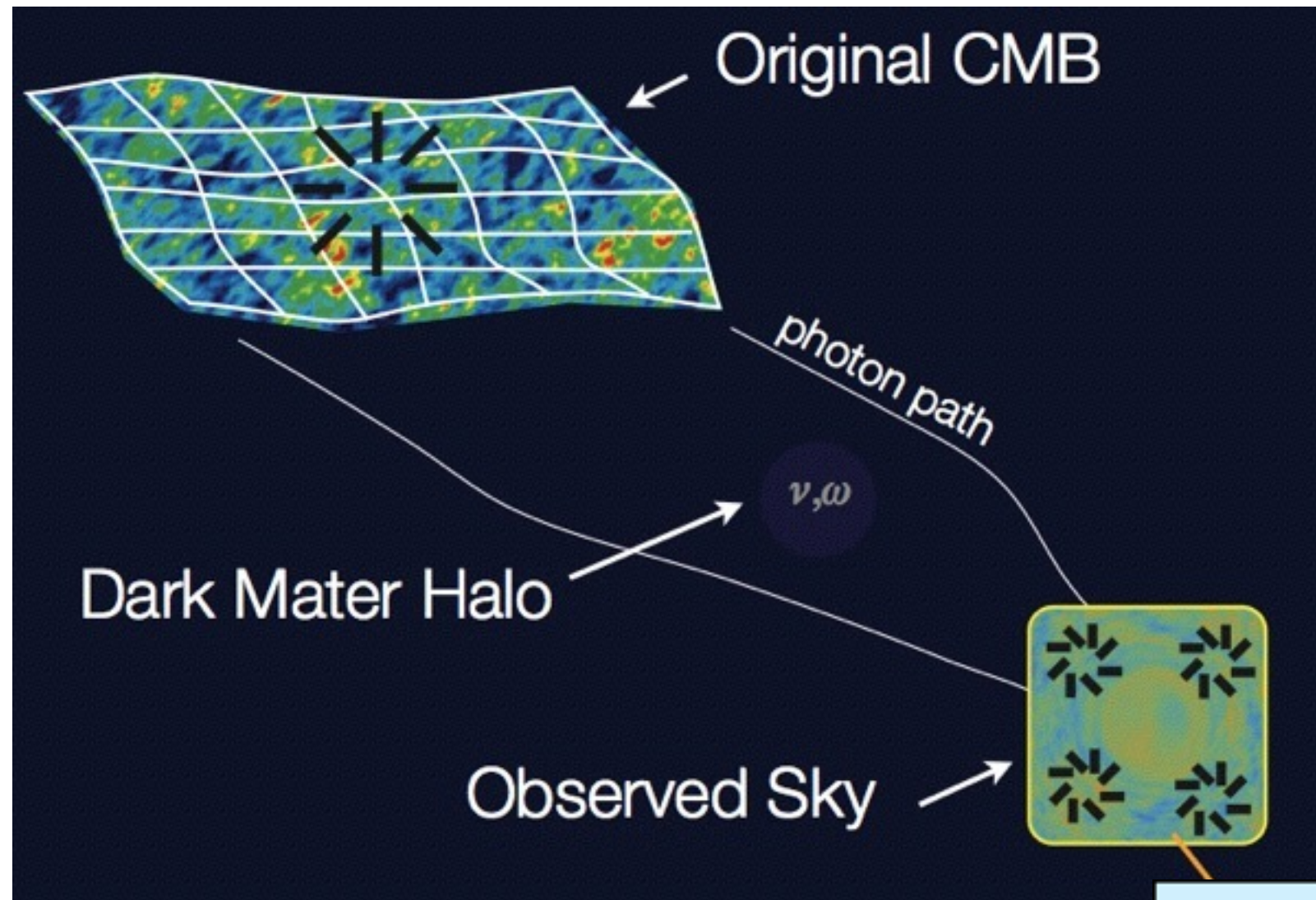


FIG. 2. Convergence power spectrum (red points) measured from ACT equatorial sky patches. The solid line is the power spectrum from the best-fit WMAP+ACT cosmological model with amplitude $A_L = 1$, which is consistent with the measured points. The error bars are from the Monte Carlo simulation results displayed in Fig. 1. The best-fit lensing power spectrum amplitude to our data is $A_L = 1.16 \pm 0.29$

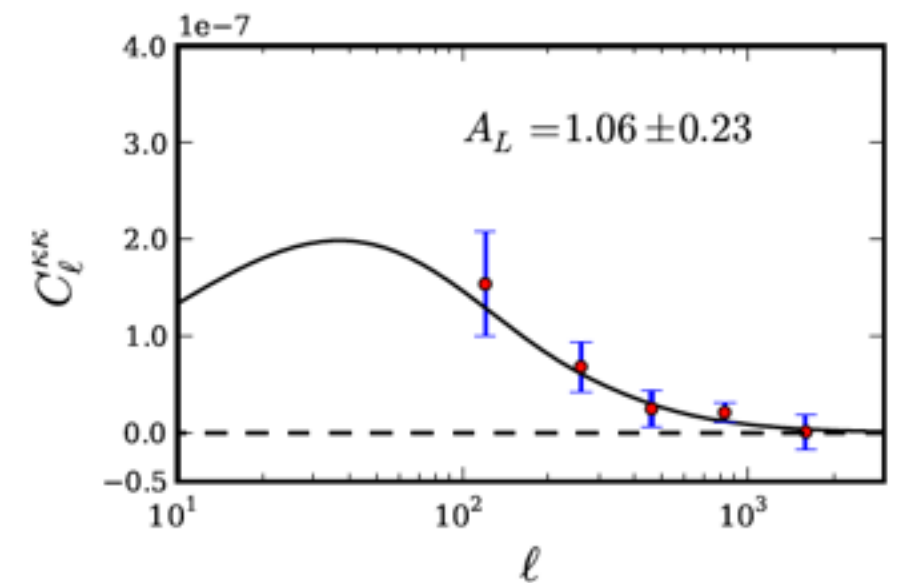
Based on Hu & Okamoto estimator plus phase randomization.

Detection is from 320 sq. degree of ACT equatorial data only.

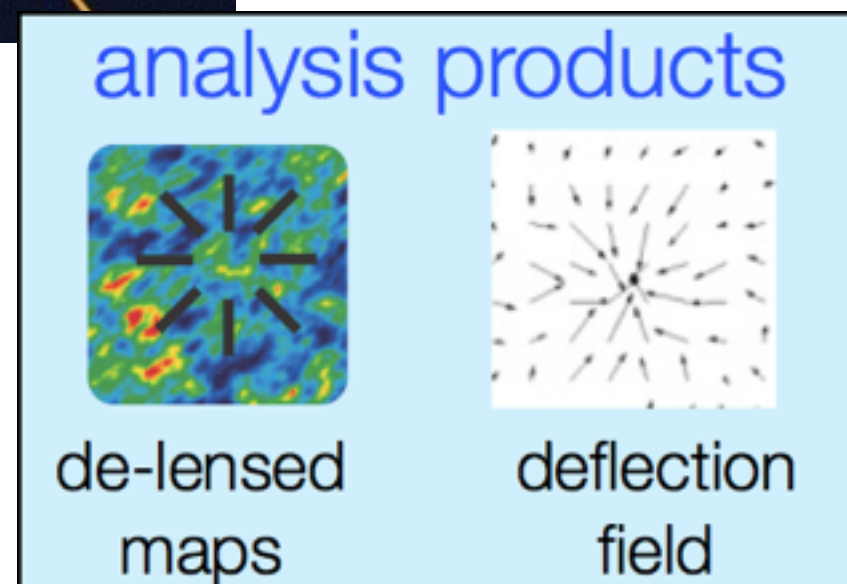
CMB lensing signal in polarization



The signal peaks
at $z \sim 2-4$



4-point function analysis
 $\Rightarrow$ Deflection field



ACTPol Collaboration: Official Logo Banner (Structural)

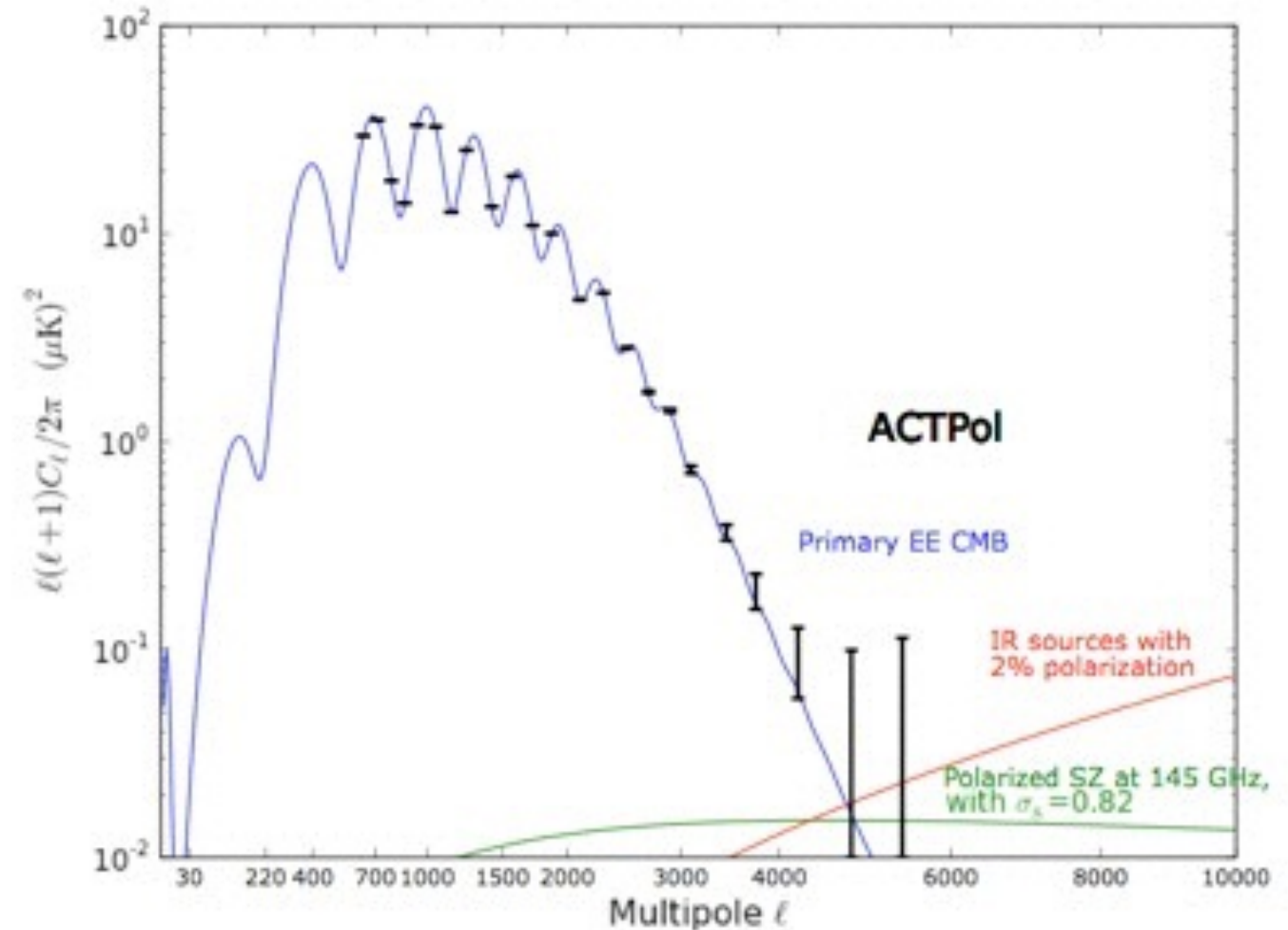
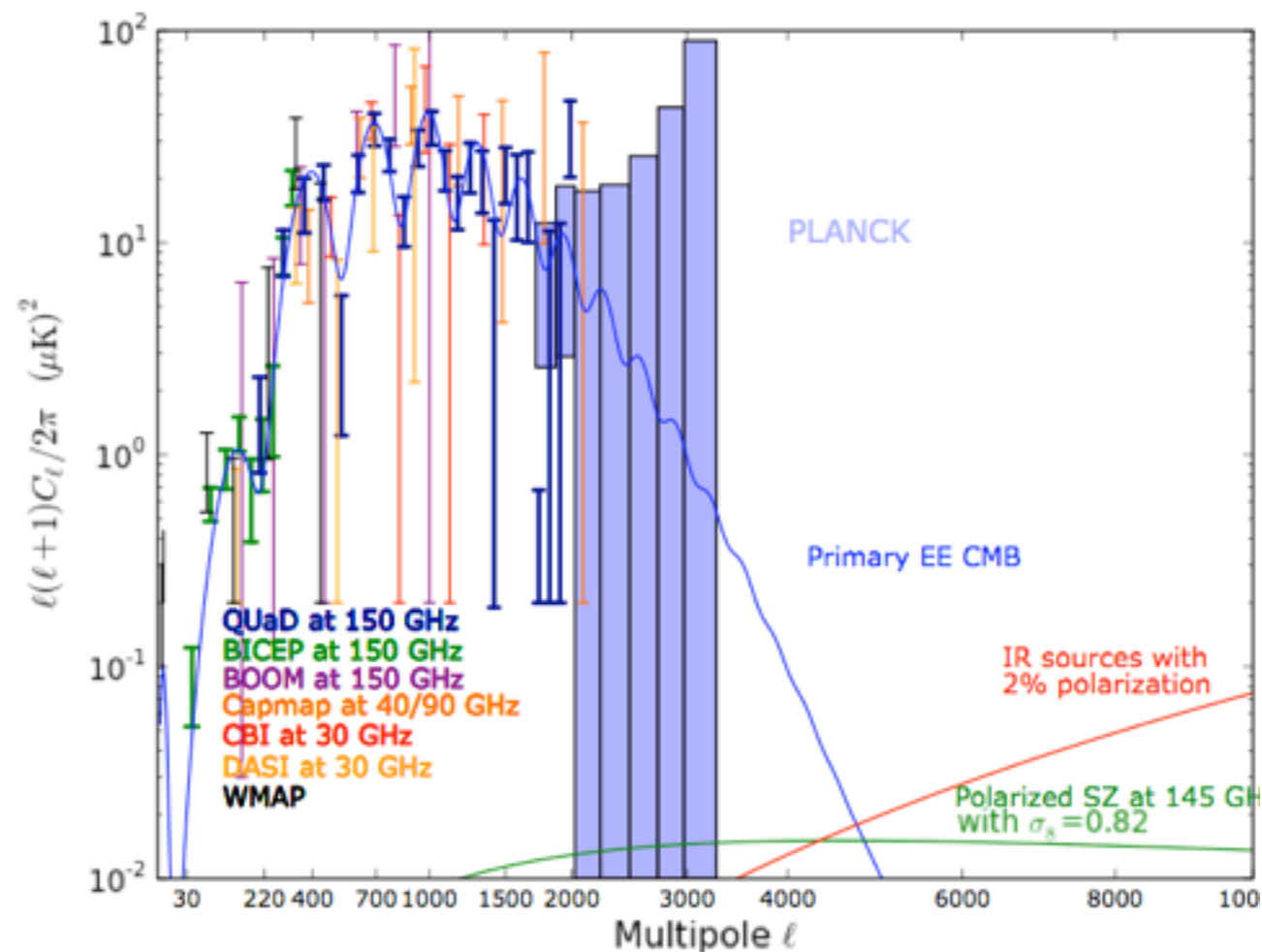


[From Left to Right]

- 1.) Pontificia Universidad Católica de Chile
- 2.) University of Oxford
- 3.) Stony Brook University
- 4.) West Chester University of Pennsylvania
- 5.) National Aeronautics and Space Administration Goddard Space Flight Center (NASA GSFC)
- 6.) University of British Columbia
- 7.) Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
- 8.) Carnegie Mellon University
- 9.) University of Pennsylvania
- 10.) Haverford College
- 11.) Institute for Advanced Study (IAS)
- 12.) National Institute of Standards and Technology (NIST)
- 13.) University of California, Berkeley
- 14.) Canadian Institute for Theoretical Astrophysics (CITA)
- 15.) Princeton University
- 16.) Cardiff University
- 17.) University of Michigan
- 18.) University of KwaZulu-Natal
- 19.) University of Miami
- 20.) University of Pittsburgh
- 21.) Academia Sinica
- 22.) Rutgers, The State University of New Jersey
- 23.) Cornell University
- 24.) The Johns Hopkins University

ACTPol

Planck: sensitive to $l=2000$ in polarization



Can look through foregrounds in EE at $l > 2000$ to get at n_s

Observe gravitational lensing through E-mode to B-mode conversion

What's next?

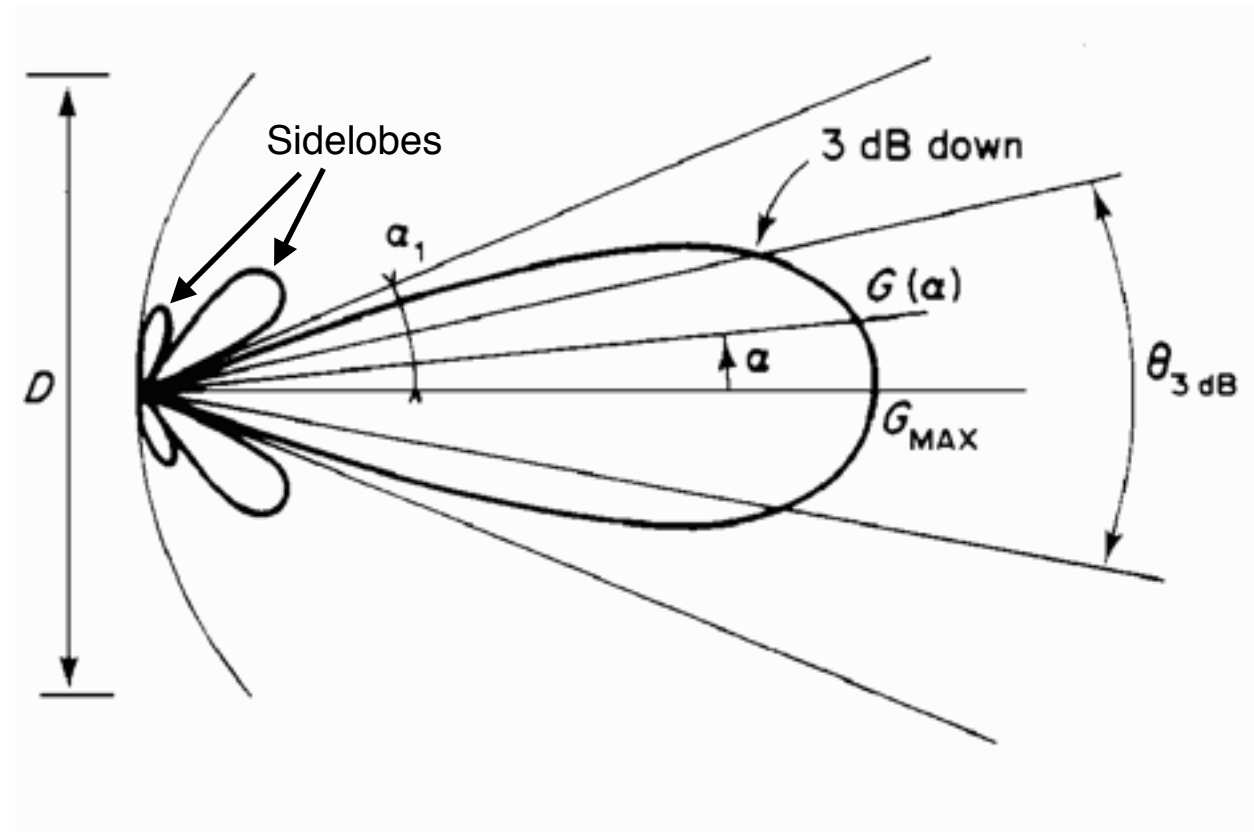
- Some antenna basics.
- Some detector (bolometer) basics.
- Some cryogenics basics.
- The MBAC design.
- A bit about the data acquisition system.
- Ready to observe!

Antenna Theory

Basics



- CMB telescopes can be classified as radio telescopes, so a bit of antenna theory is importante.
- At larger wavelengths telescopes suffer the effects of the undulatory nature of light, and so cannot be described solely by geometrical optics.
- The resolution is limited by diffraction, constraining the size of the telescope.
- For extended sources like the CMB, the collected power is independent on the size of the telescope!!



Normalized power

$$P_n(\theta, \phi) = \frac{1}{P_{max}} P(\theta, \phi)$$

Effective aperture

$$A_e = \frac{P_e}{|\langle S \rangle|} = \eta_A A_g$$

It can be shown that

$$A_e \Omega_A = \lambda^2$$

Directive gain

$$G(\theta, \phi) = \frac{4\pi P(\theta, \phi)}{\iint_{4\pi} P(\theta, \phi) d\Omega}$$

Beam Solid Angle

$$\Omega_A = \iint_{4\pi} P_n(\theta, \phi) d\Omega$$

Directivity

$$\mathcal{D} = G_{max} = 4\pi / \Omega_A$$

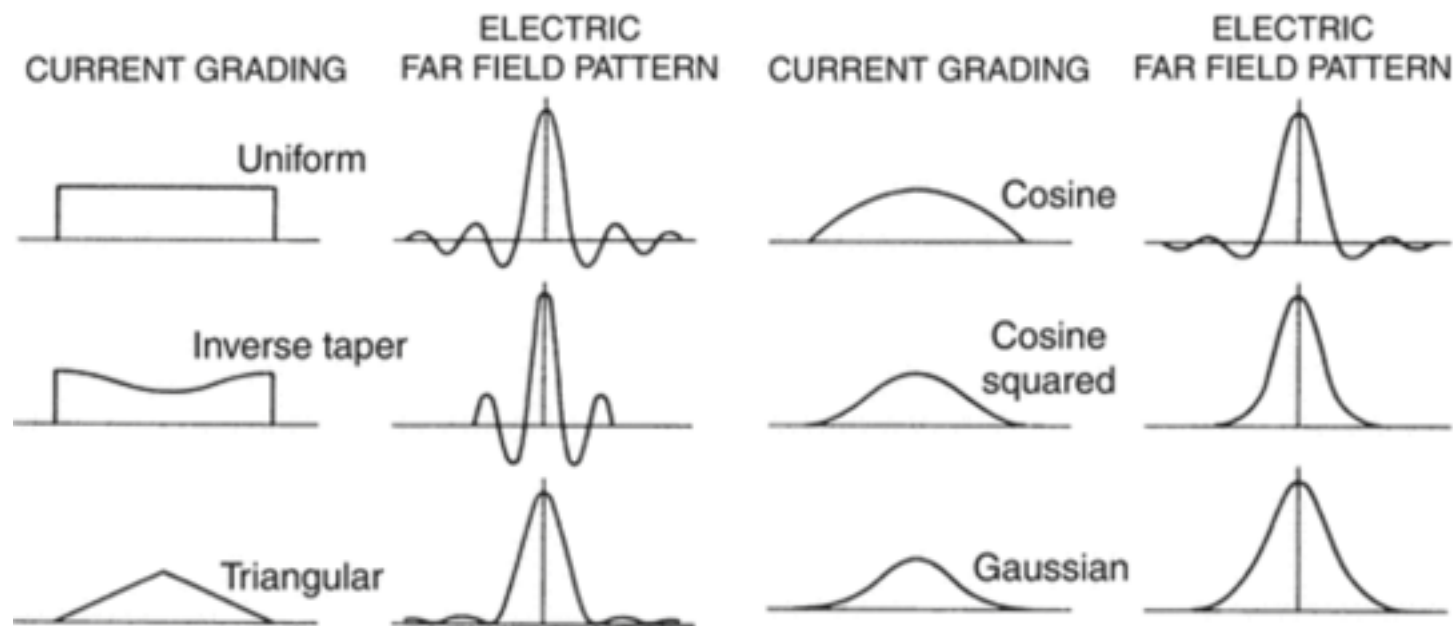
For an extended source $P = \int B_\nu dA d\nu d\Omega$

if the band is narrow... $P = B_\nu \Delta\nu A_e \Omega_A$

and for a thermal source in RJ limit

$$P = k T \Delta\nu \frac{A_e \Omega_A}{\lambda^2} = k T \Delta\nu$$

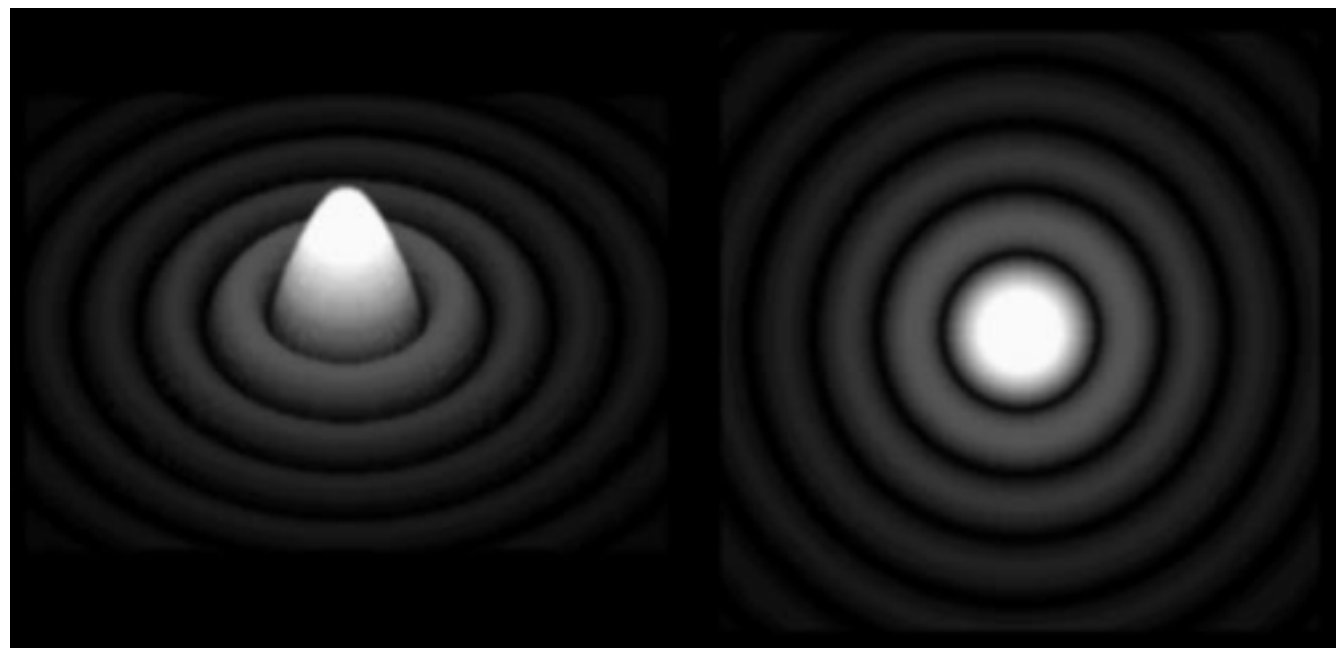
Antenna Pattern: is given by the integral of the currents in the aperture



For a filled circular aperture:

$$P(u) = \left[\frac{2J_1(\pi u D / \lambda)}{\pi u D / \lambda} \right]^2$$

with $u = \sin(\theta)$



So the resolution is given by

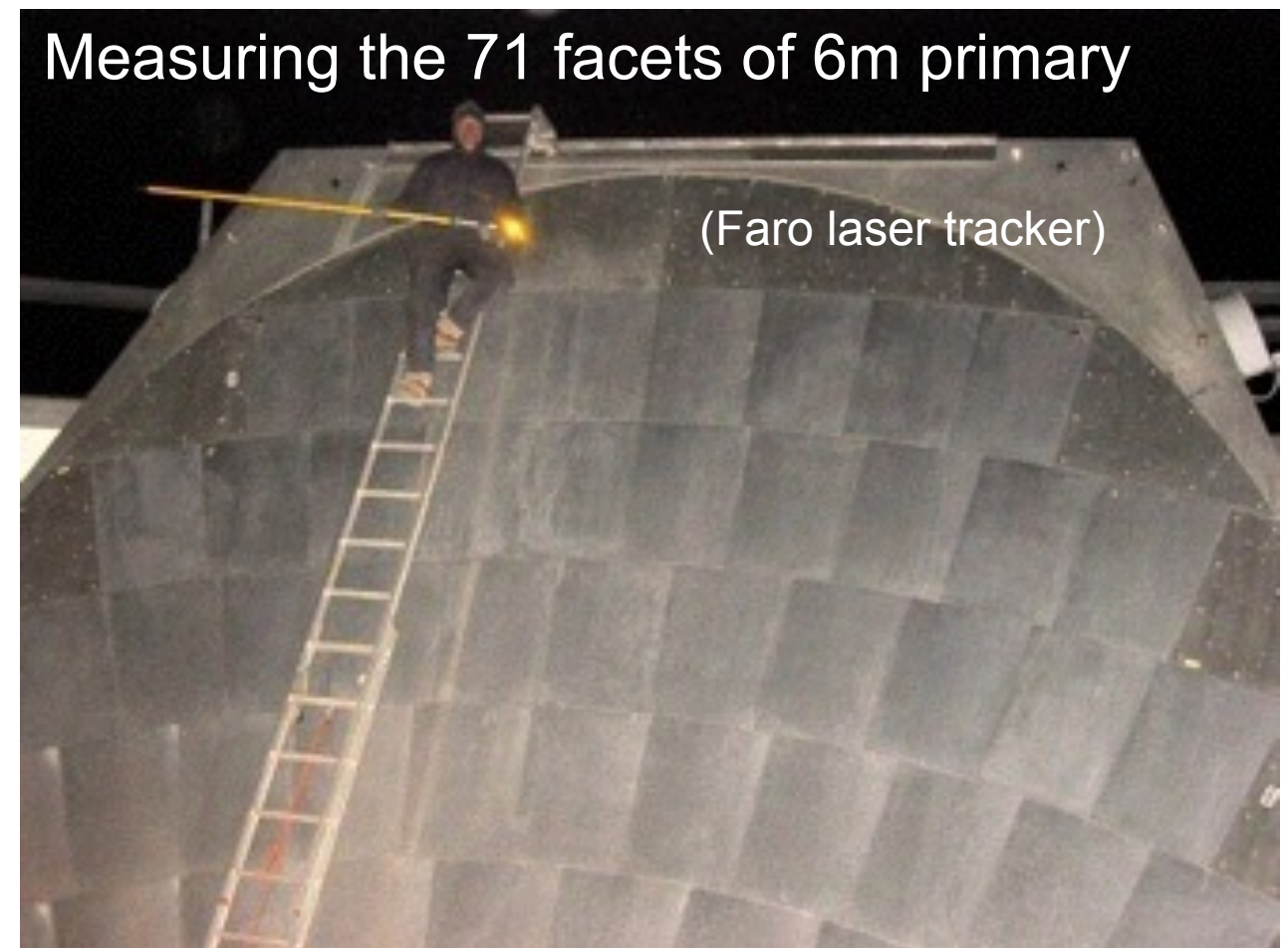
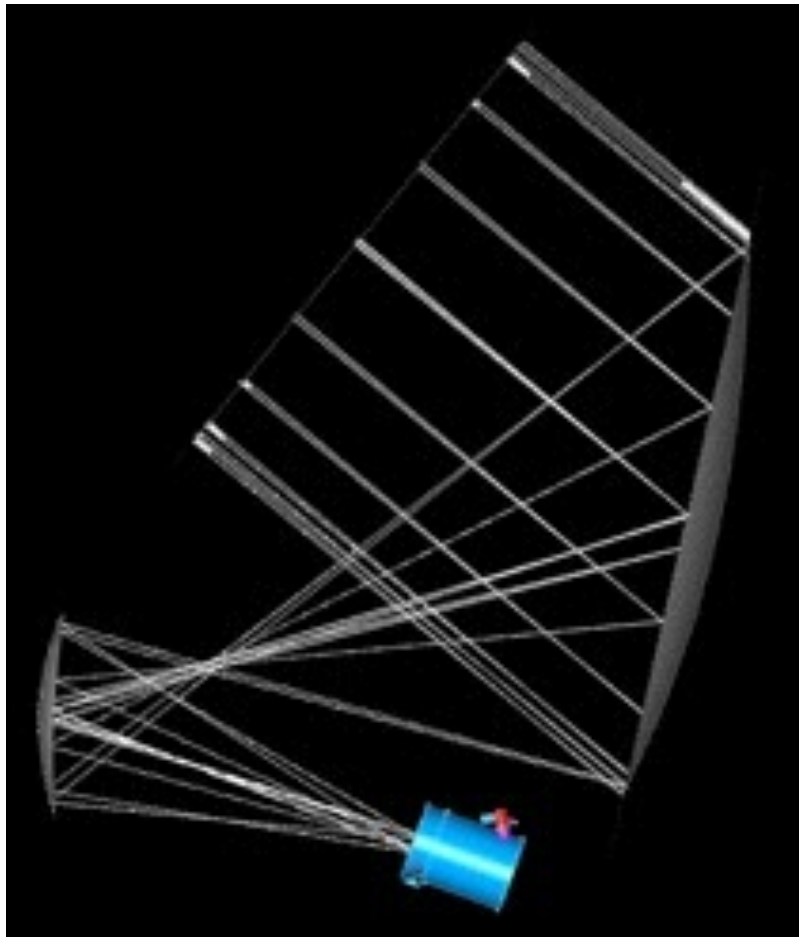
$$\text{FWHP} = 1.02 \frac{\lambda}{D} \text{ rad} \approx 58.4^\circ \frac{\lambda}{D}$$

ACT: Telescope & Camera

Some constraints:

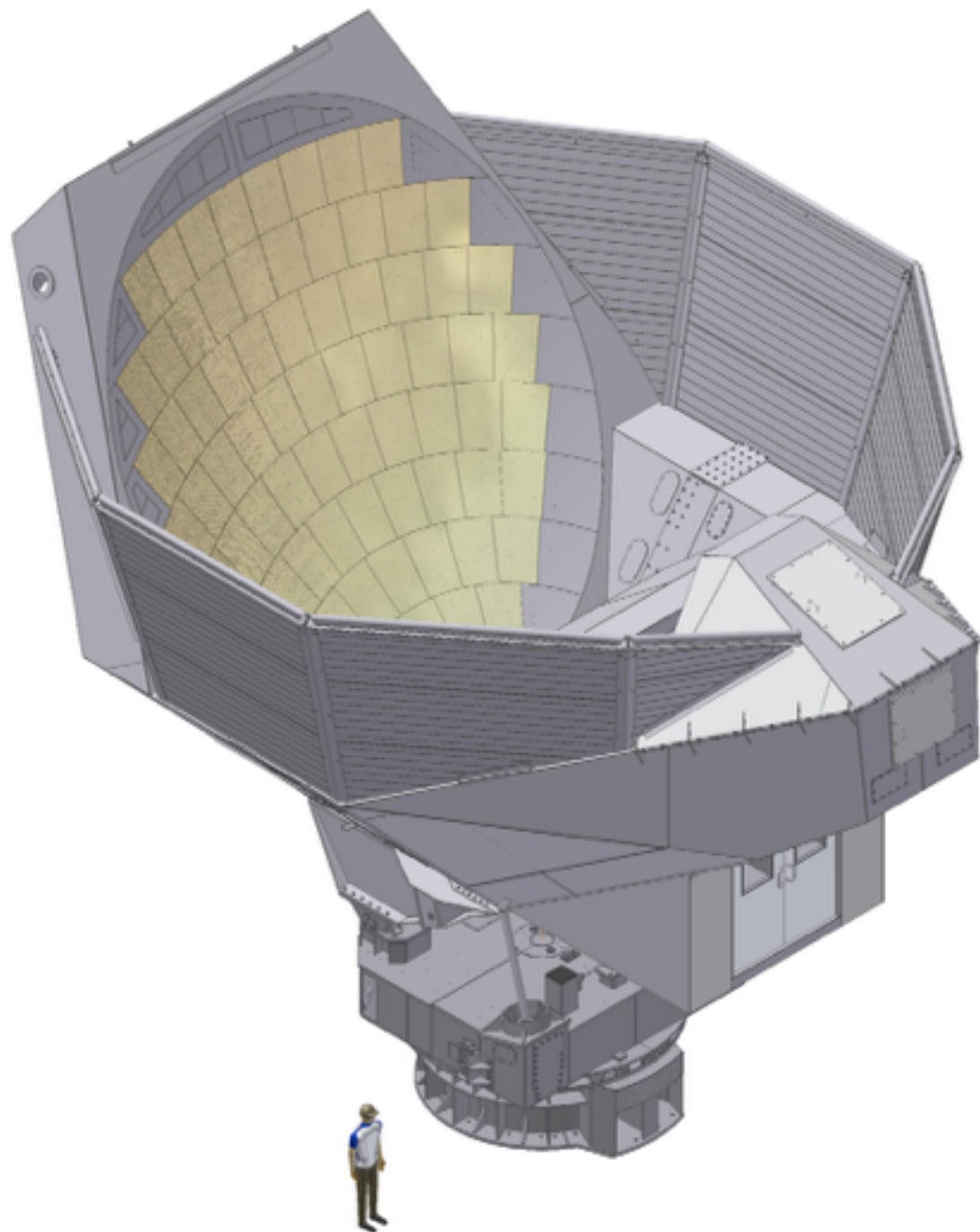
- Diffraction-limited beams
- 25' fields of view (x3)
- Clear aperture
- 6-meter off-axis primary
- 2-meter secondary
- Fast / compact system

Roughly an aplanatic Gregorian.



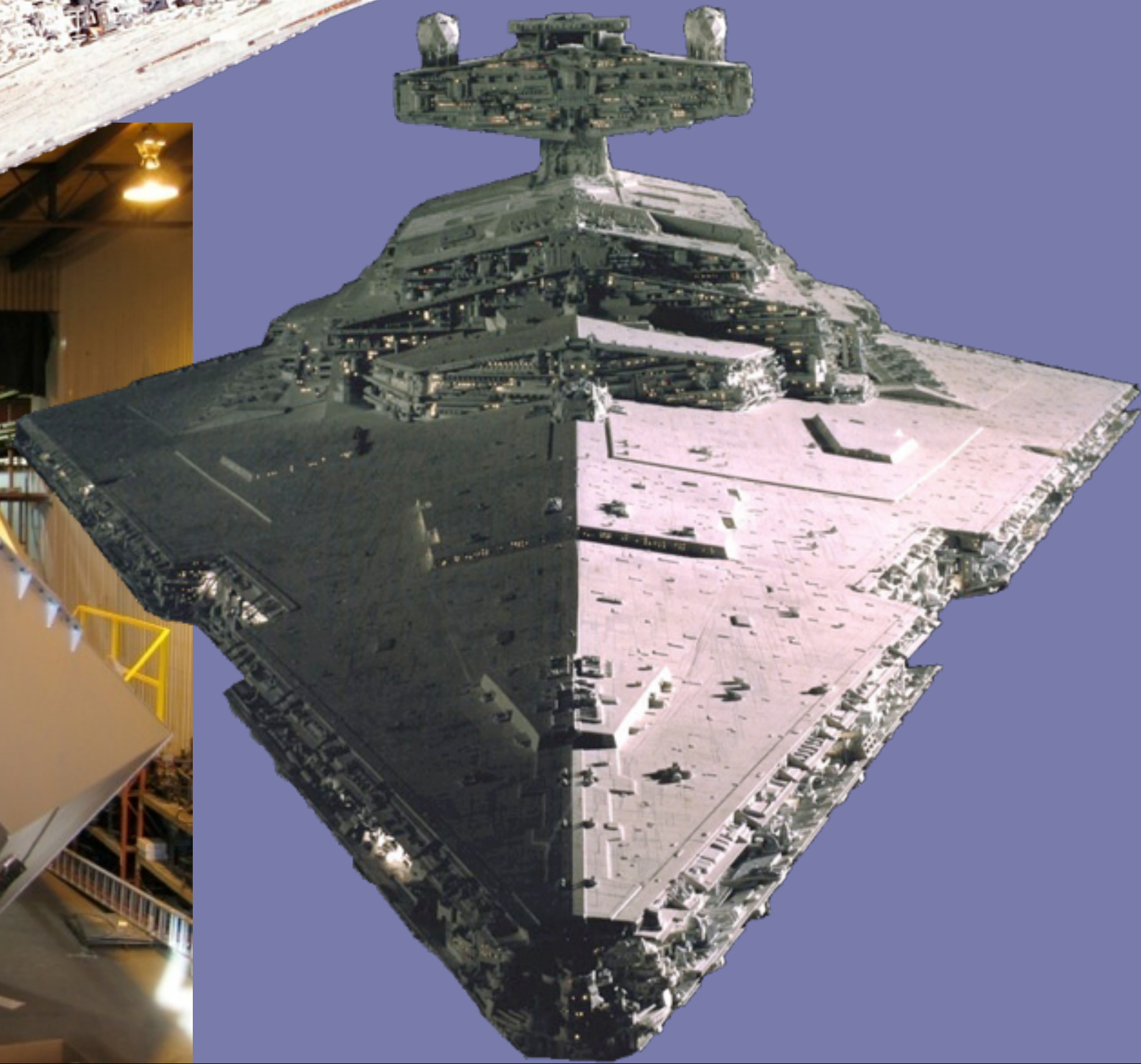
ACT - Atacama Cosmology Telescope

- 6 Meter Aperture
- Low Ground Pickup ($< 20\mu\text{K}$ dc)
- No Moving Optics
- Remote Controlled
- Flexible Focal Plane
- Near the ALMA Site



**Extreme control of
potential systematic
errors.**

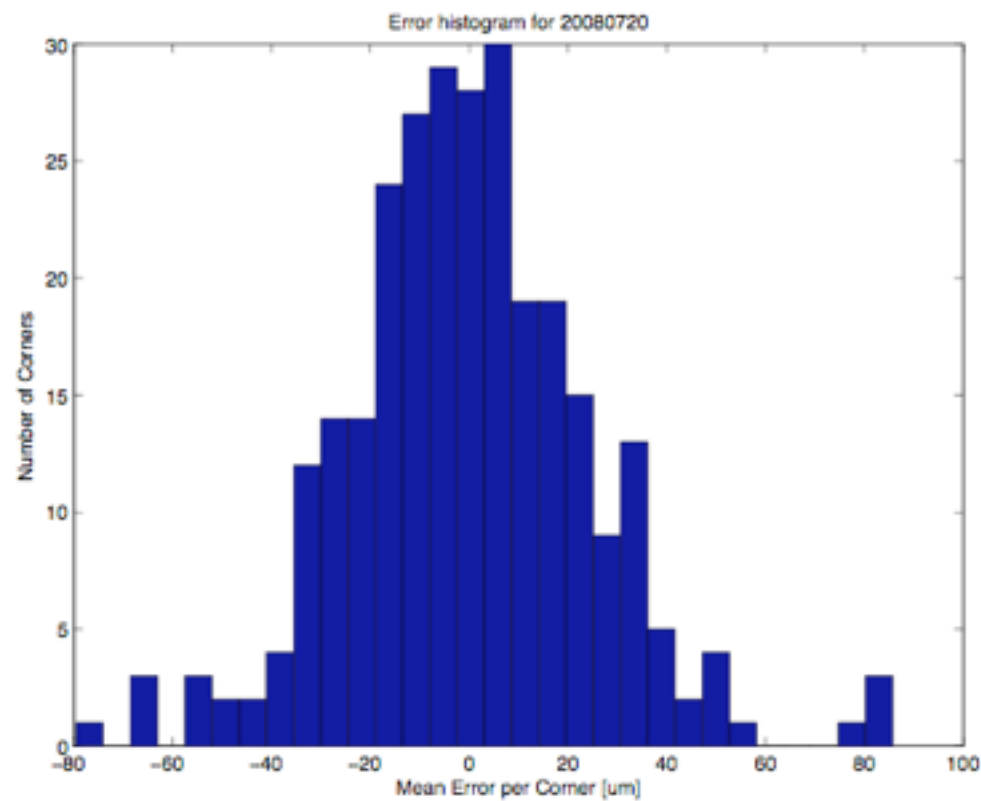
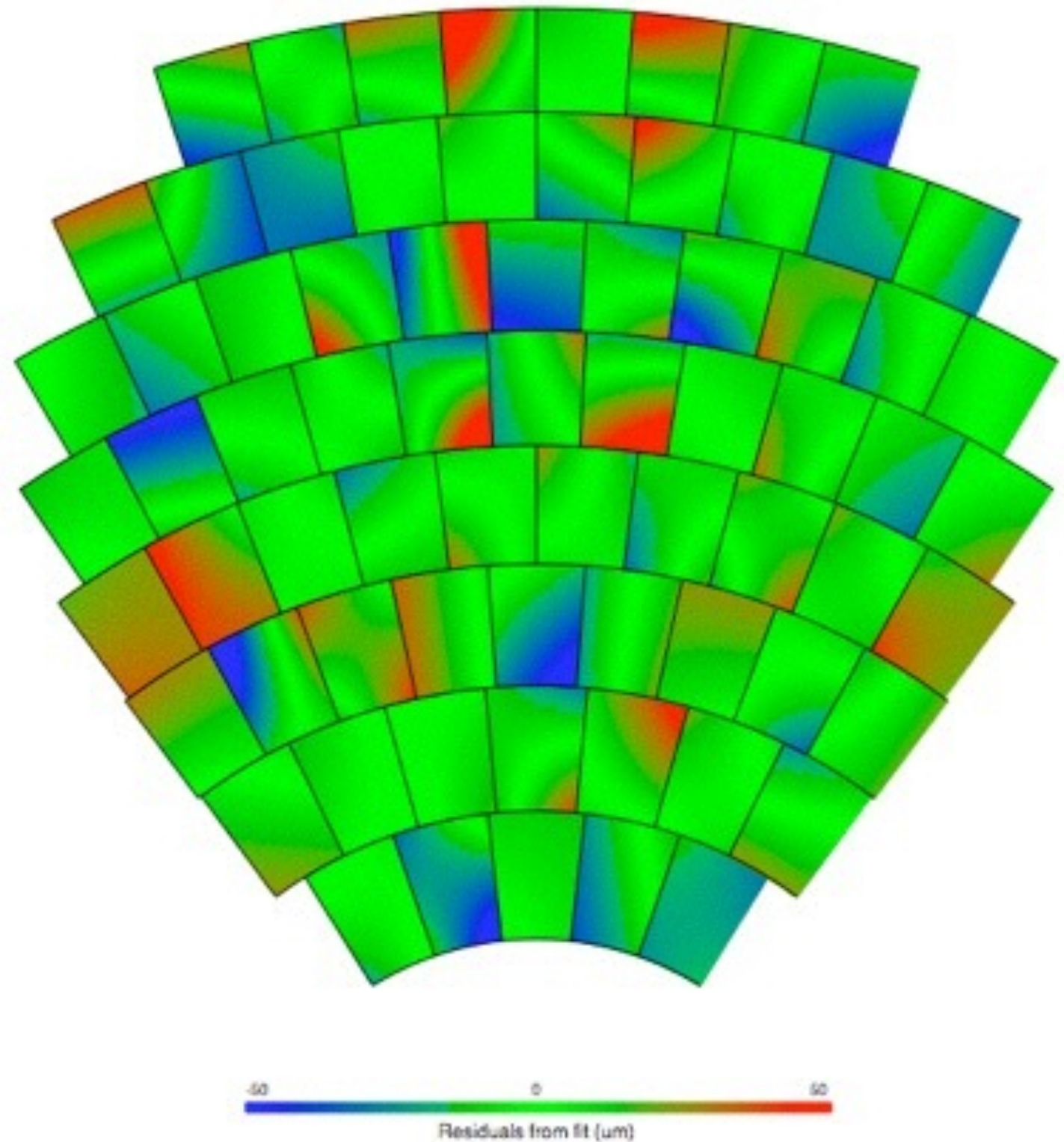
Design Inspiration



Primary Mirror Alignment

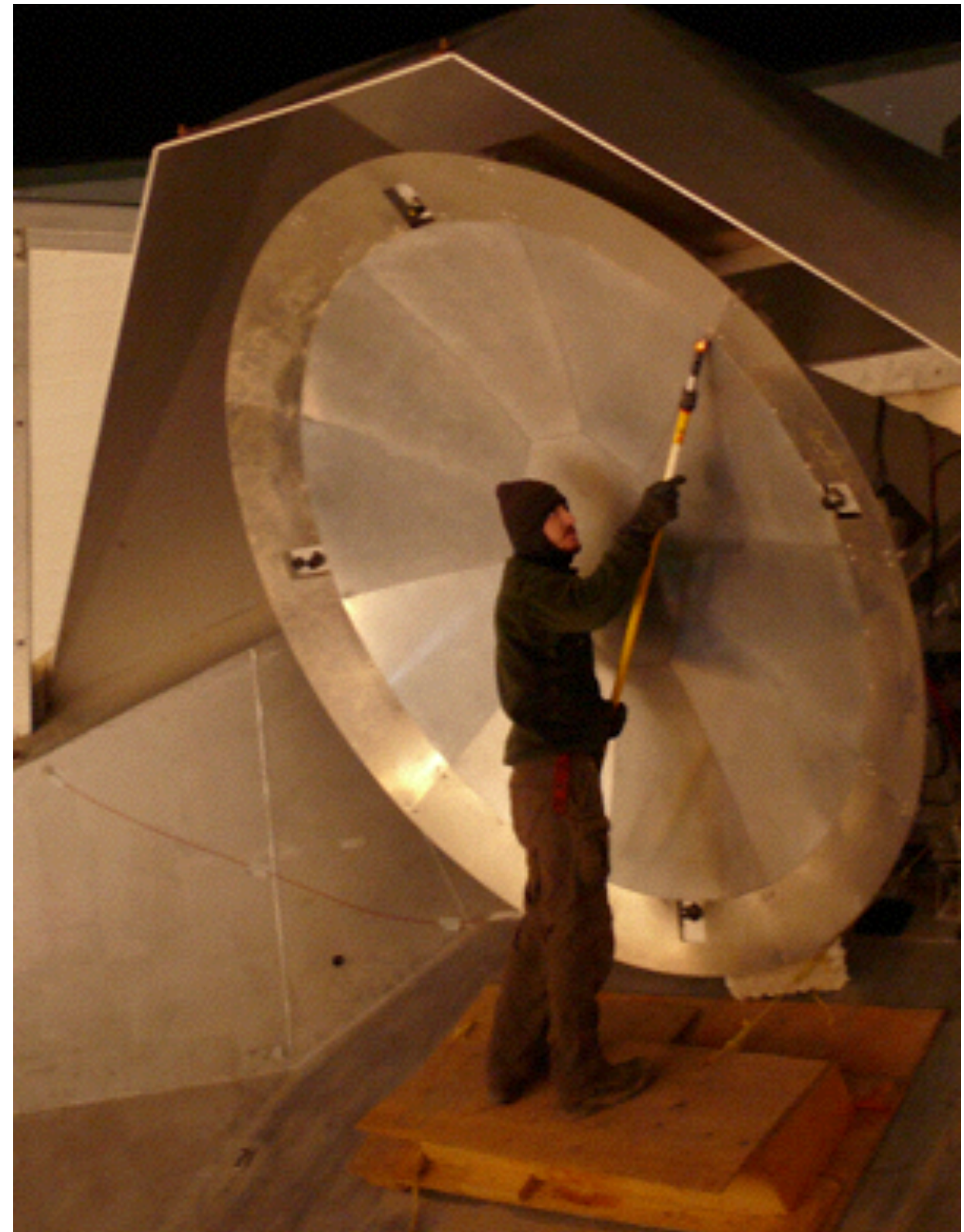
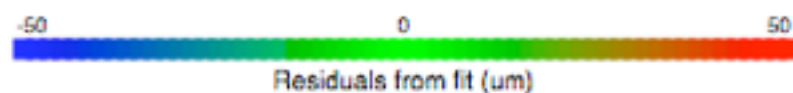
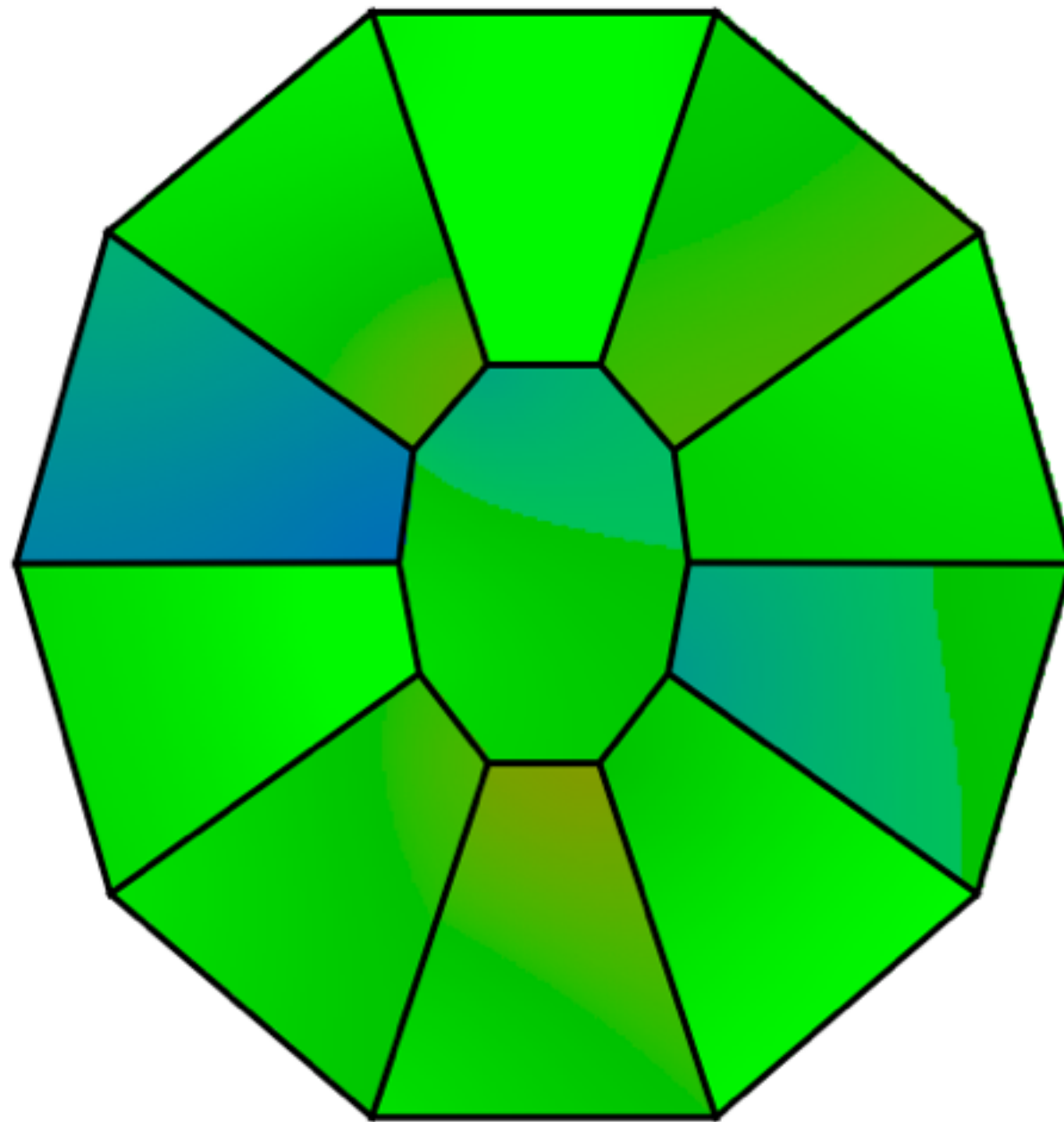


Results Summary			
Total Panels:	71	Date:	July 20, 2008
Residual RMS:	24.5545 μm		
Residual Sigma:	22.3085 μm		
Measurement Error:	13.6116 μm		



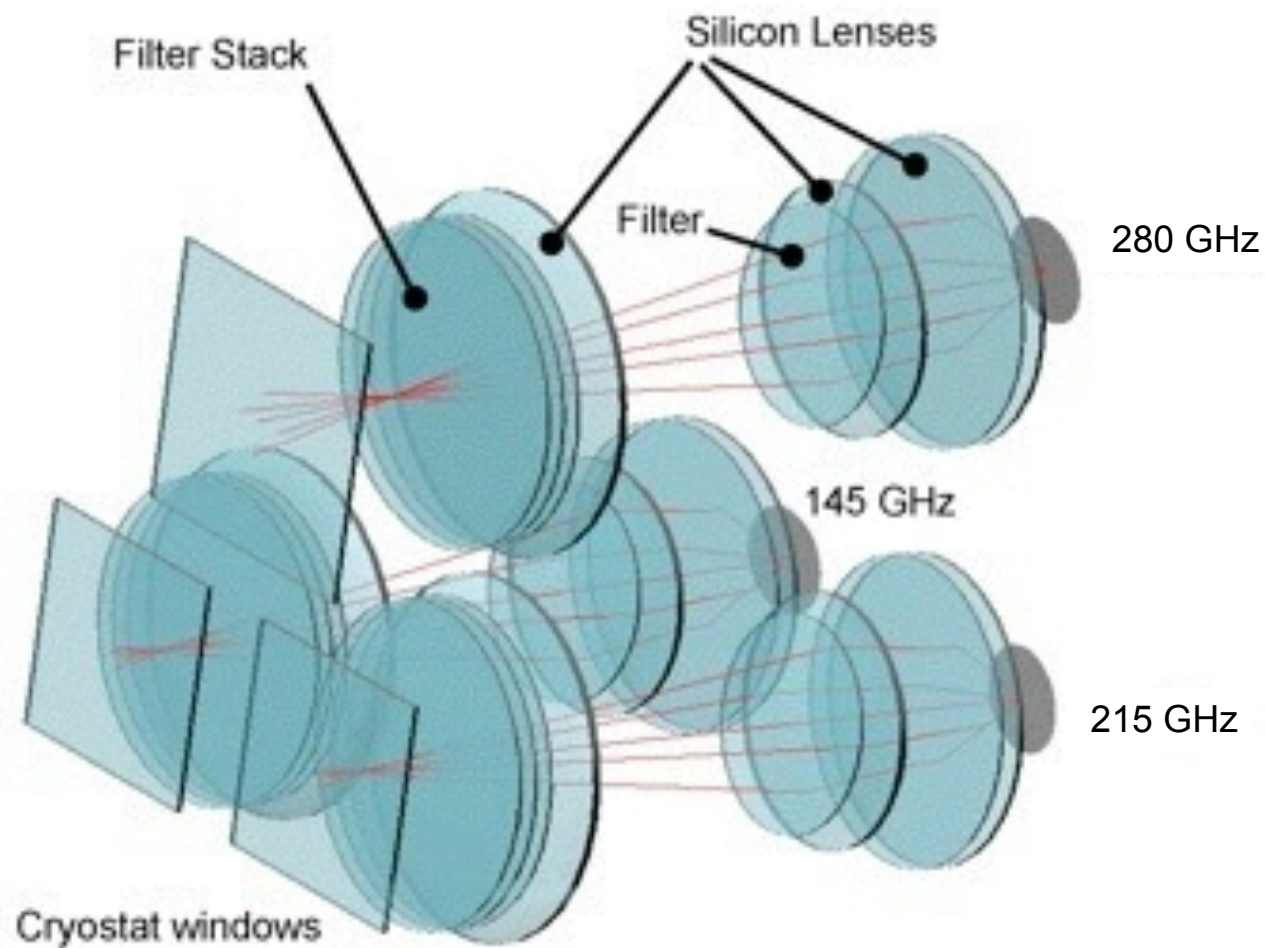
Secondary Mirror Alignment

Results Summary			
Total Panels:	11	Date:	July 19, 2008
Residual RMS:	11.7304 μm		
Residual Sigma:	14.3434 μm		
Measurement Error:	6.16172 μm		

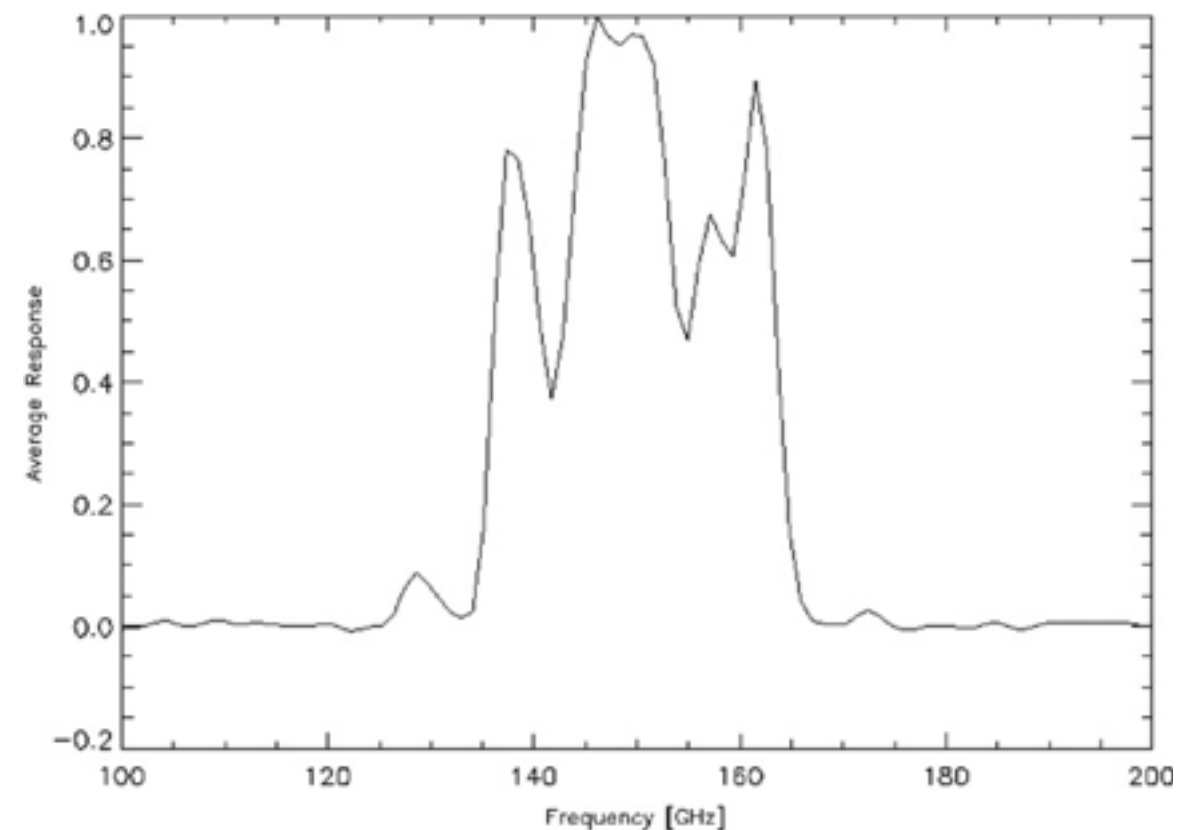
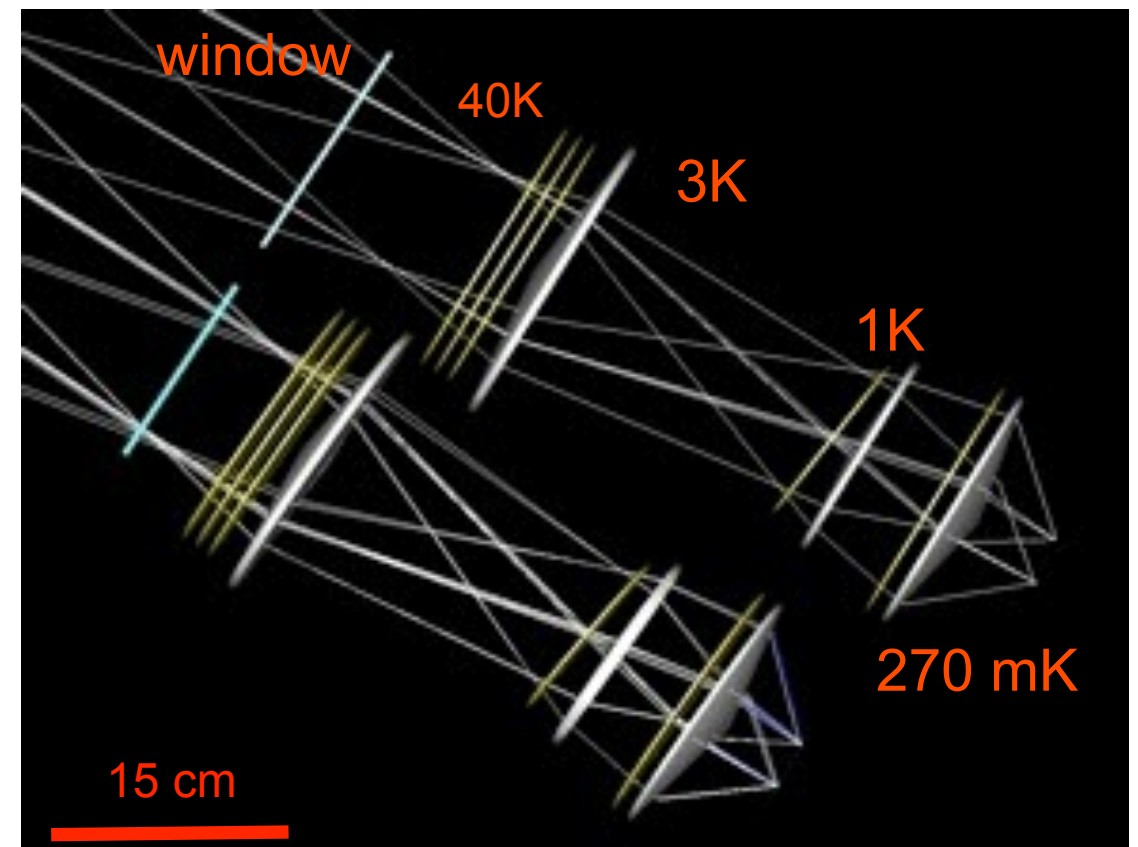


Cold Reimaging Optics and Filters

Cold silicon lenses to reimage sky



148, 215, & 280 GHz filters (Cardiff—Ade)



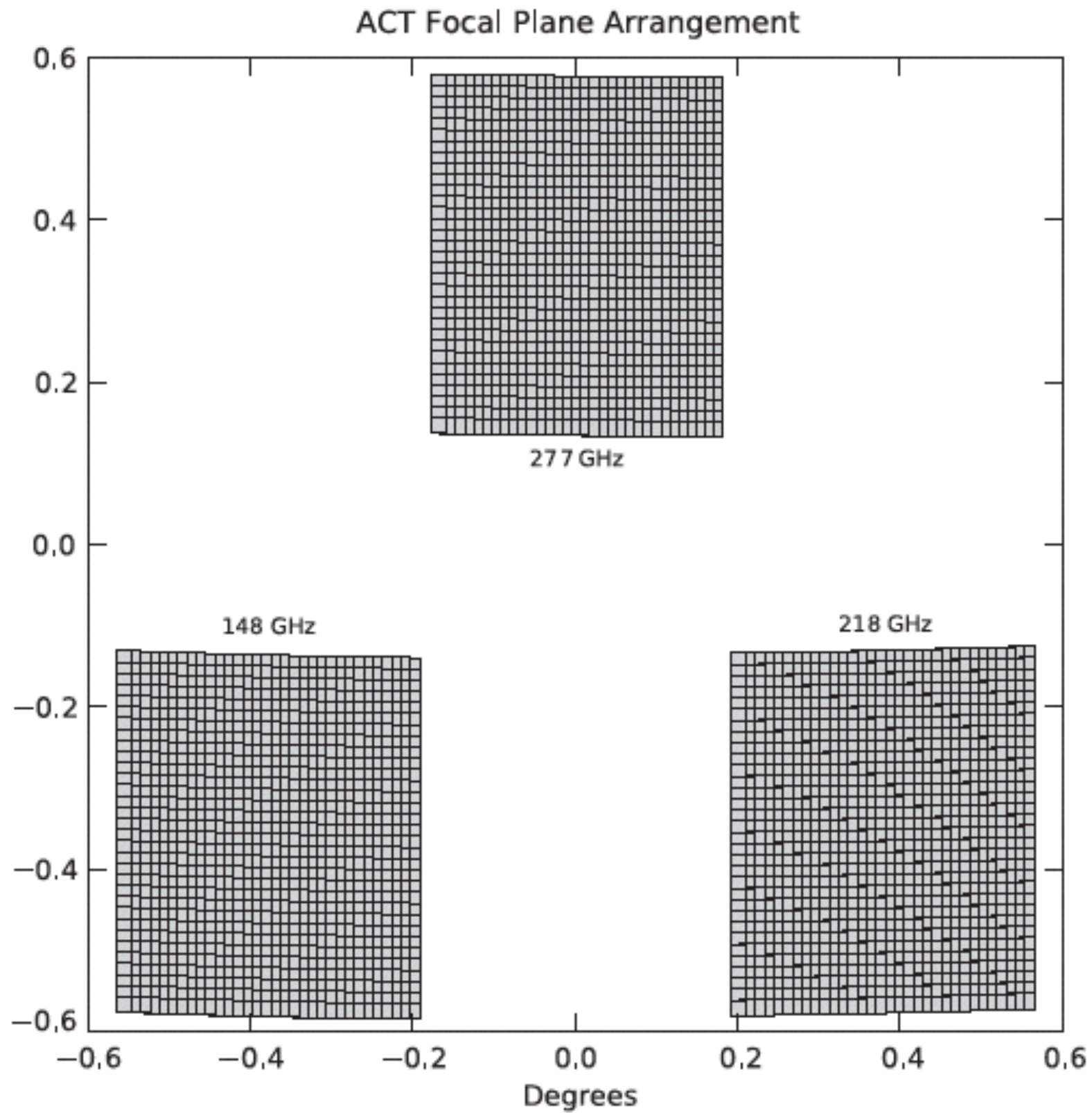


Figure 7. Idealized arrangement of the ACT detectors on the sky. This arrangement on the sky is the reverse of the view when looking into MBAC (Figure 5).

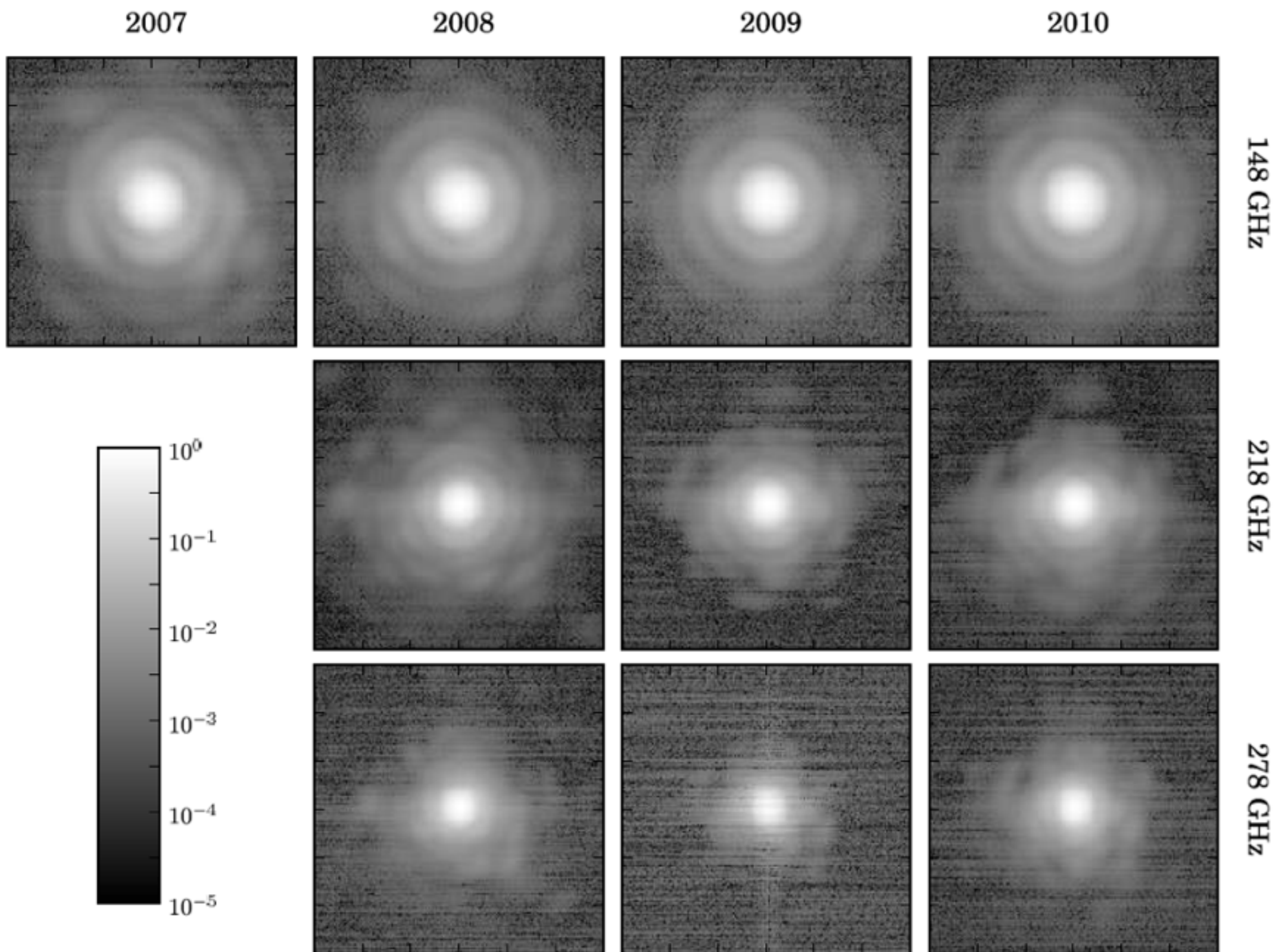
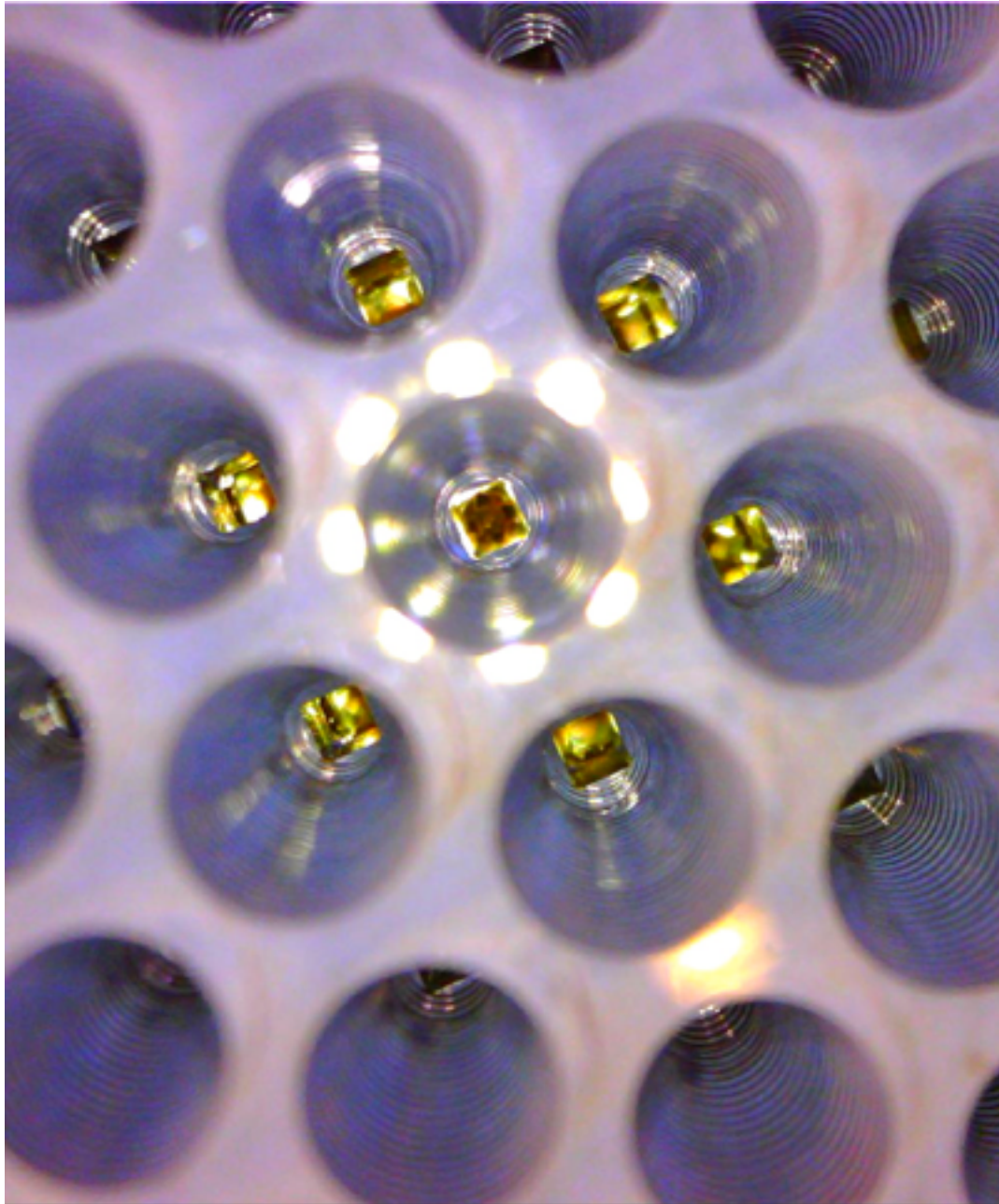


Figure 1. Beam maps for each season and array, formed from the average of selected Saturn maps. Gray scale is logarithmic. Each panel is 12' by 12'. Each contributing Saturn map incorporates all live detectors in the array. The well-resolved Airy rings indicates that the relative detector offsets are accurately known. The frequency labels correspond to the effective frequencies for CMB spectrum radiation (Swetz et al. 2011).

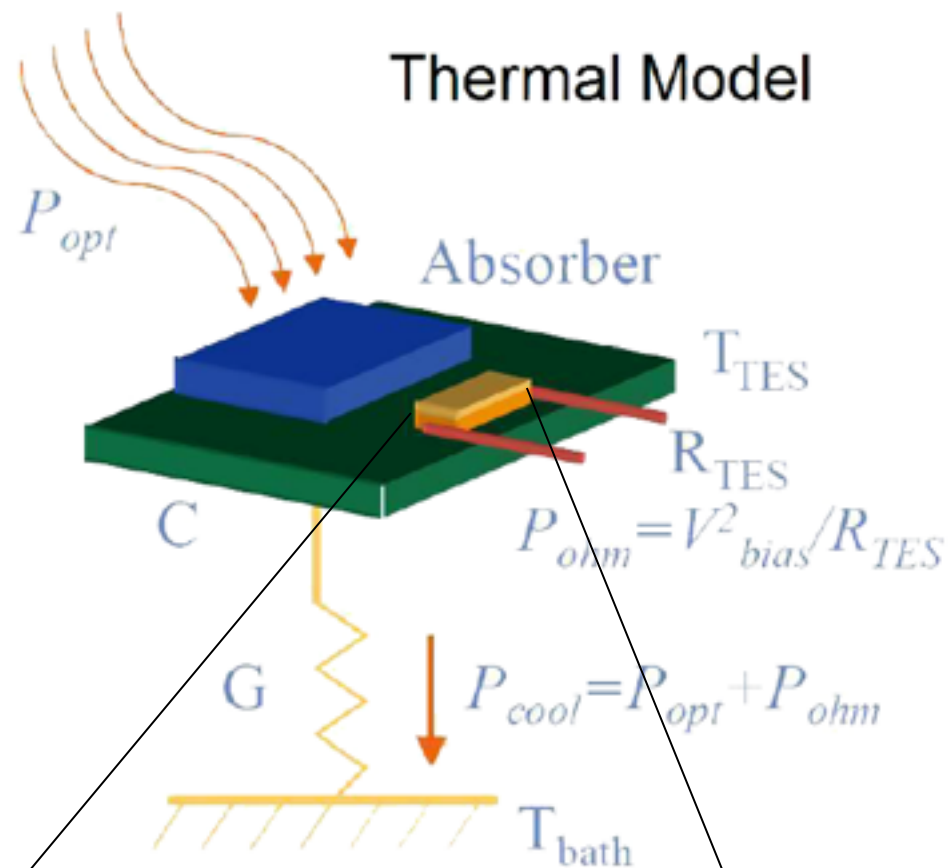
Bolometers



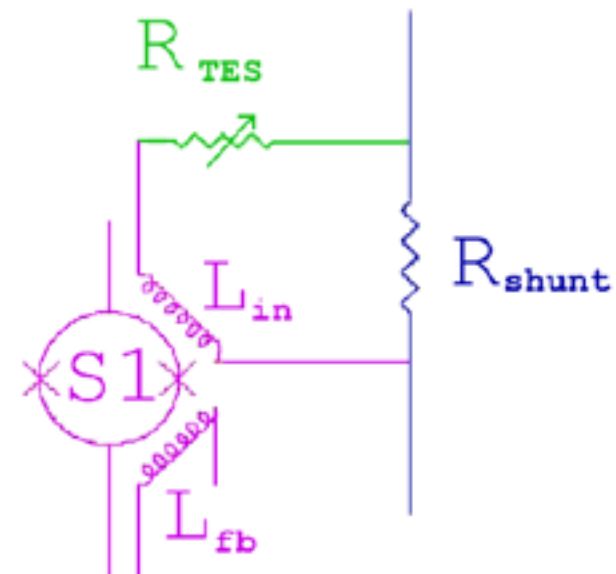
- Traditional heterodyne detectors are simple amplifiers that keep the phase of the incoming signal.
- Bolometers instead are power detectors, discarding the phase information but achieving a high sensitivity on the amplitude.
- Bolometers then can be used to measure signals in all frequency bands.
- They can be micro-fabricated and used to fill up the focal plane with an array of detectors.

Detectors

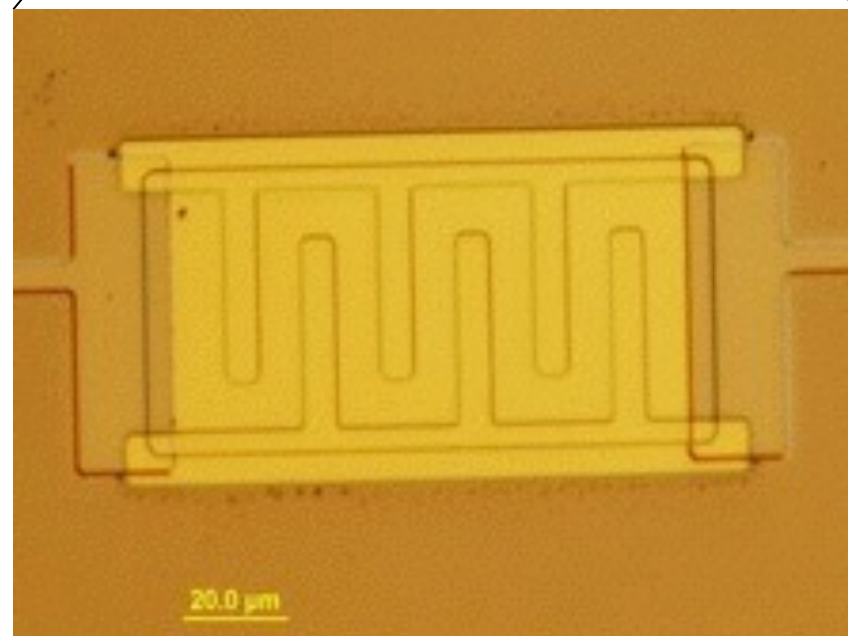
Thermal Model



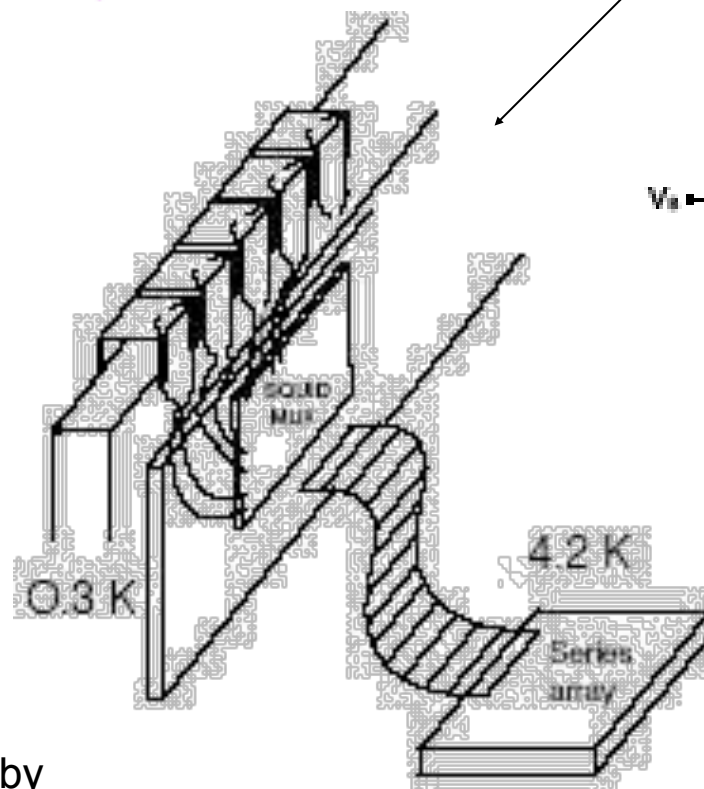
Electrical Model



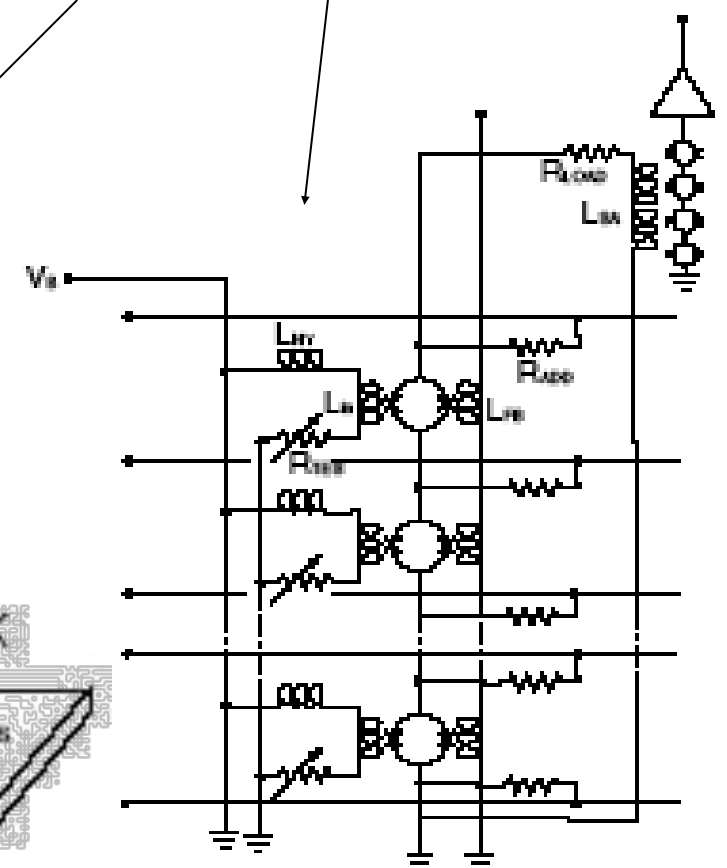
The SQUID multiplexing allows us to read 33 rows in series, while the 32 columns are read in parallel.



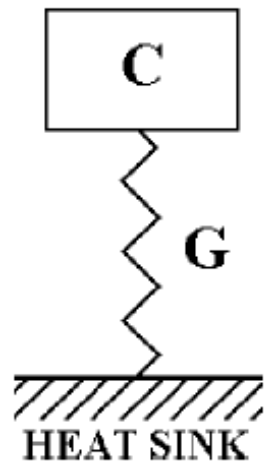
TES developed by NASA



SQUID Multiplexors developed by NIST



Detector models

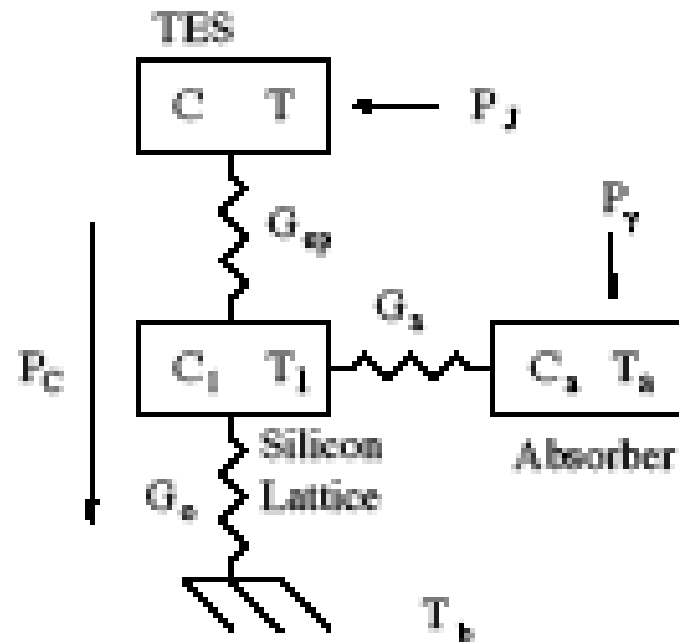


$$(j\omega C + G_{eff})\Delta T = W$$

$$G_{eff} = G + G_{ETF}$$

$$\frac{\Delta P}{\Delta T} = -G_{ETF} = G_{ETF0} \left(\frac{1 - j\omega\tau_{el2}}{1 + j\omega\tau_{el1}} \right)$$

$$G_{ETF0} = \frac{P_0\alpha}{T_0} \frac{R_0 - R_{sh}}{(1 + \beta)R_0 + R_{sh}}$$



$$L \frac{d(\Delta I)}{dt} = -((1 + \beta)R_0 + R_{sh})\Delta I - \frac{I_0 R_0 \alpha}{T_e} \Delta T_e - \Delta V_j - \Delta V_{sh}$$

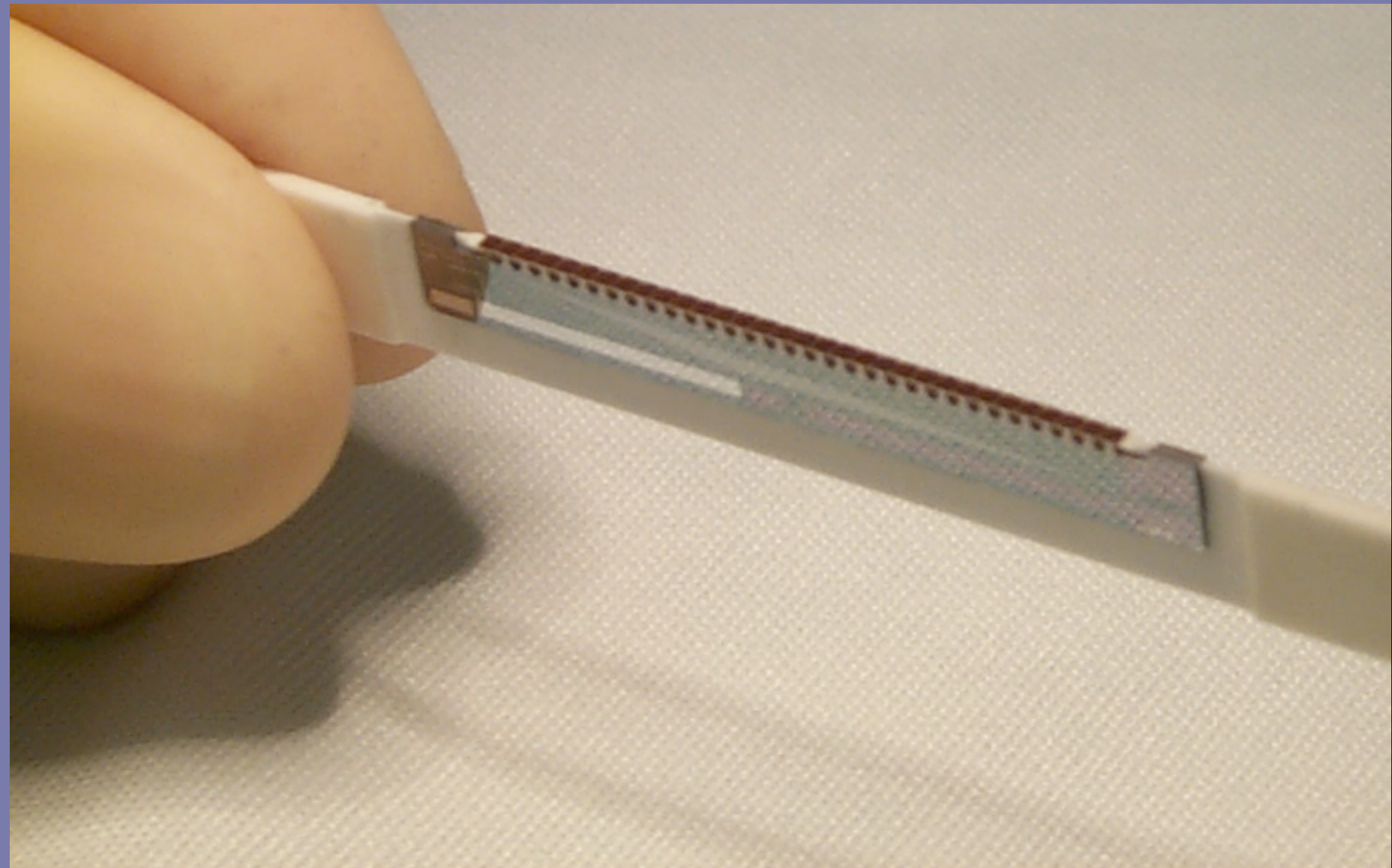
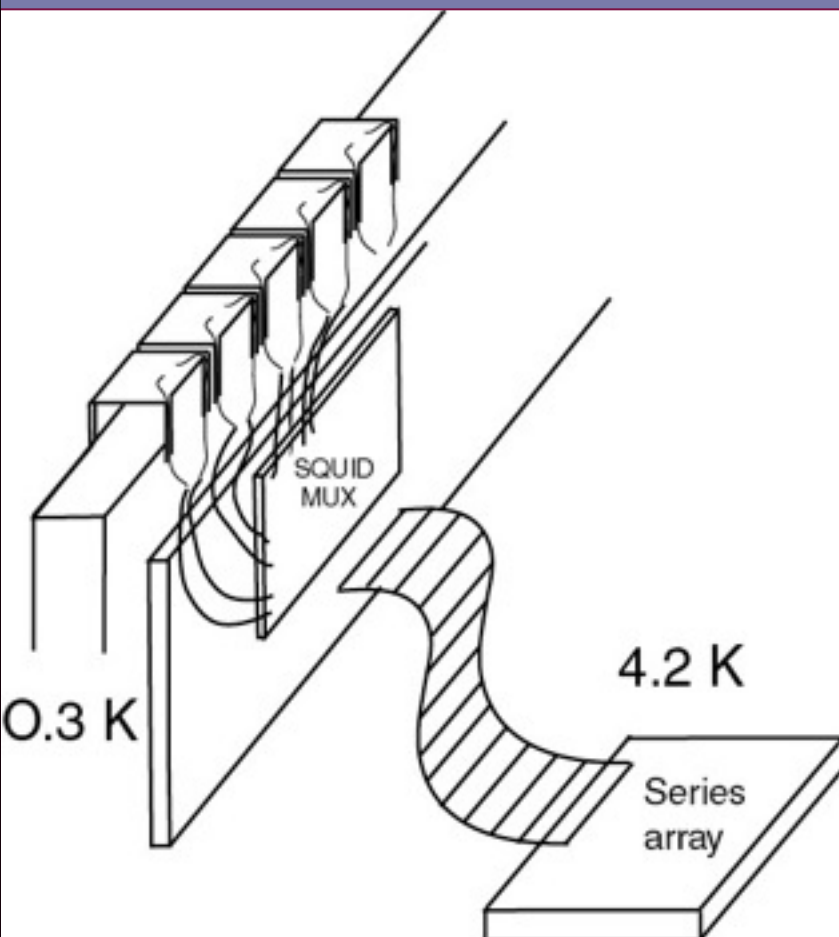
$$C_e \frac{d(\Delta T_e)}{dt} = (2 + \beta)I_0 R_0 \Delta I_0 + \left(\frac{I_0^2 R_0 \alpha}{T_e} - G_{el}(T_e) \right) \Delta T_e + G_{el}(T_l) \Delta T_l + I_0 \Delta V_j + \Delta P_{he} + \Delta P_{rl}$$

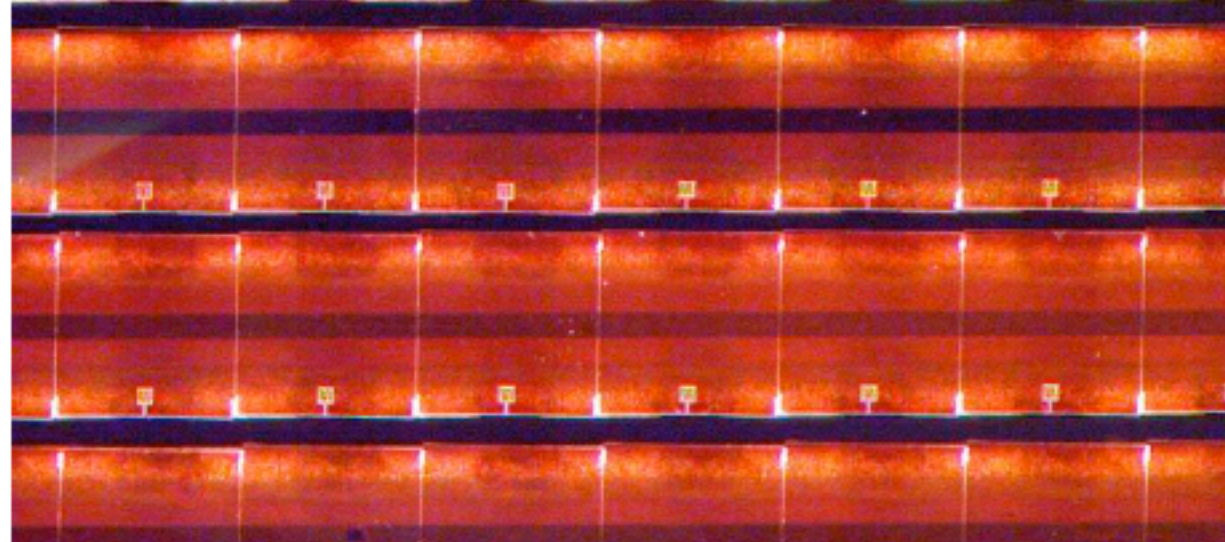
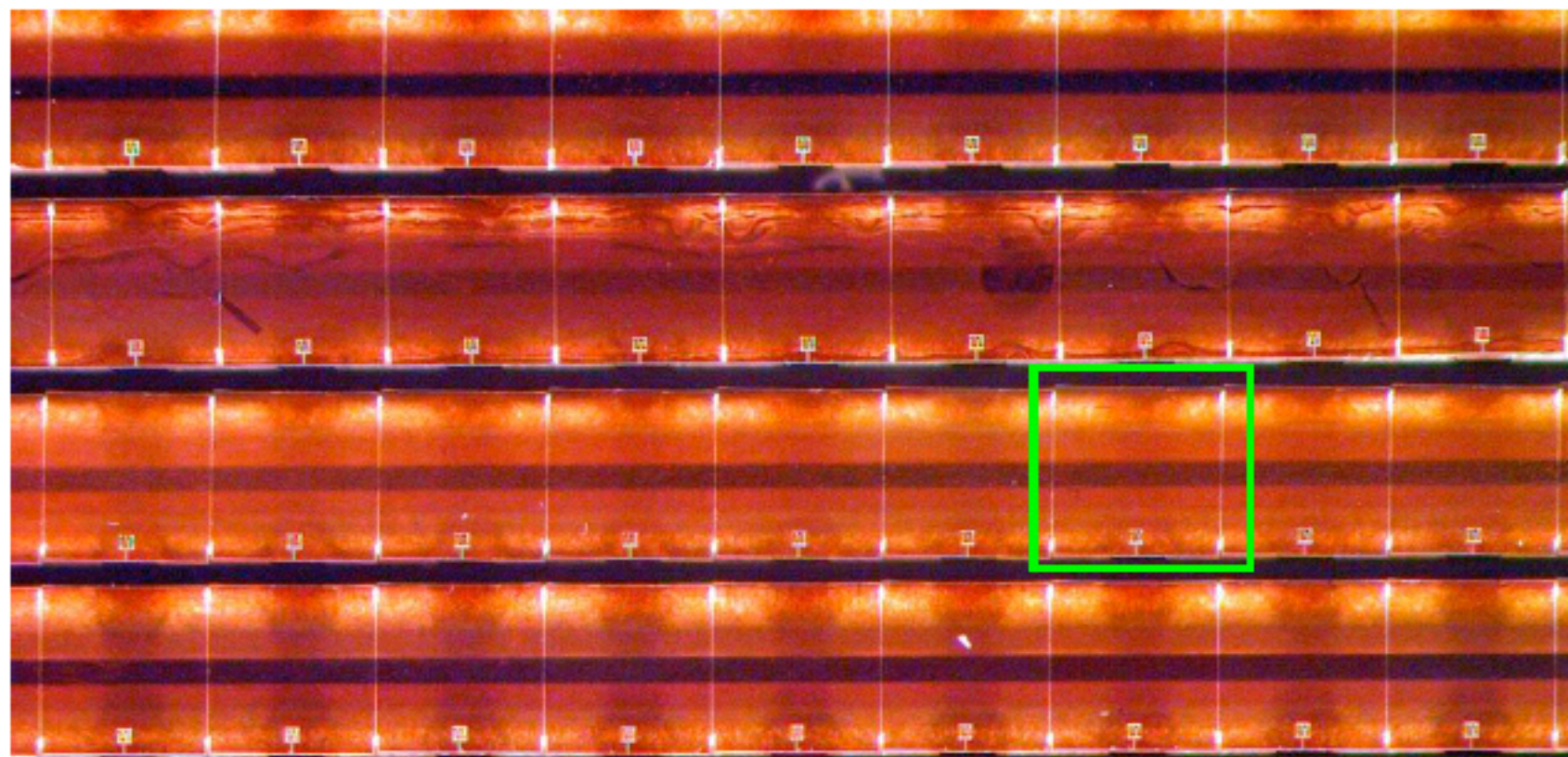
$$C_a \frac{d(\Delta T_a)}{dt} = -G_a \Delta T_a + G_a \Delta T_l + \Delta P_a + W$$

$$C_l \frac{d(\Delta T_l)}{dt} = G_{el}(T_e) \Delta T_e + G_a \Delta T_a - (G_l(T_l) + G_a + G_{el}(T_l)) \Delta T_l + \Delta P_{th} - \Delta P_a - \Delta P_{he}$$

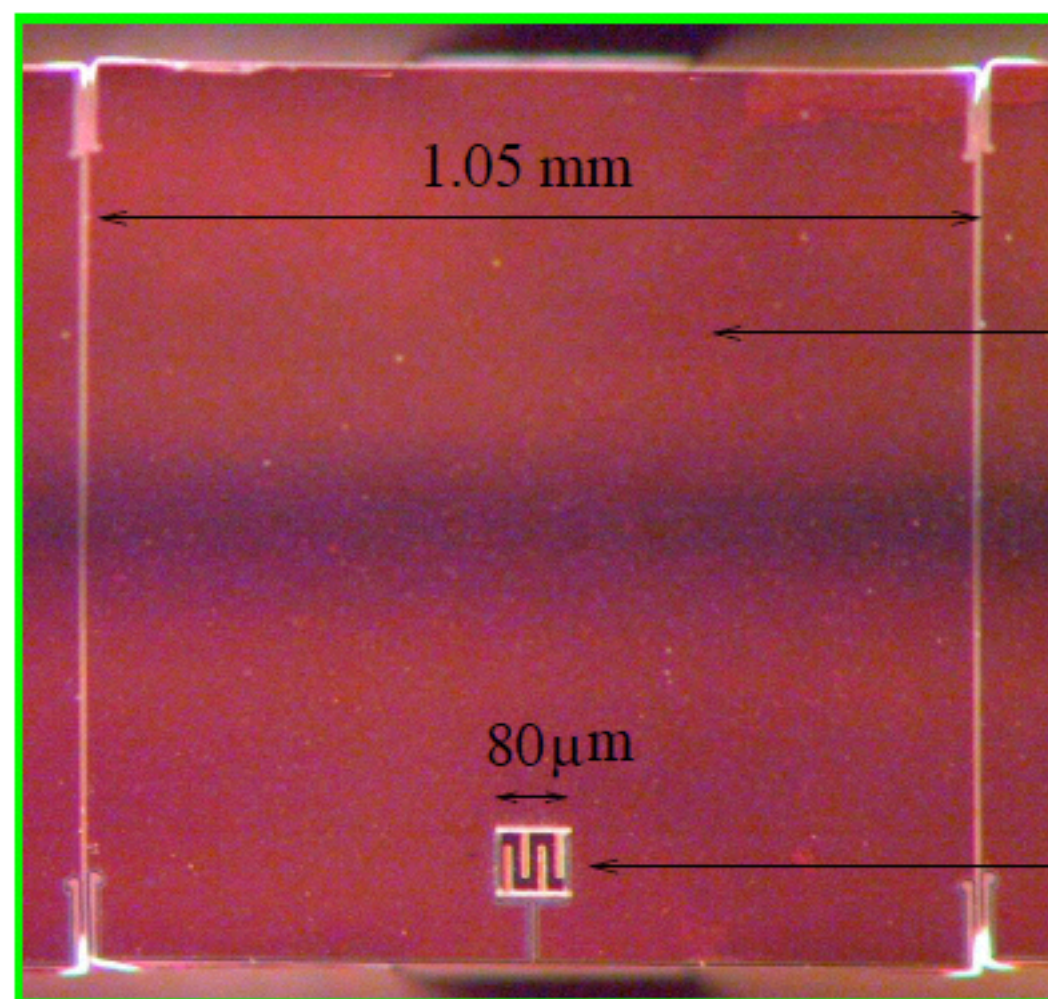
Revolutionary Detector Technology: CCD-like Arrays of Bolometers

- Pop-Up Detector (PUD): flat, monolithically fabricated array is folded to produce a detector where the wiring is behind the active area





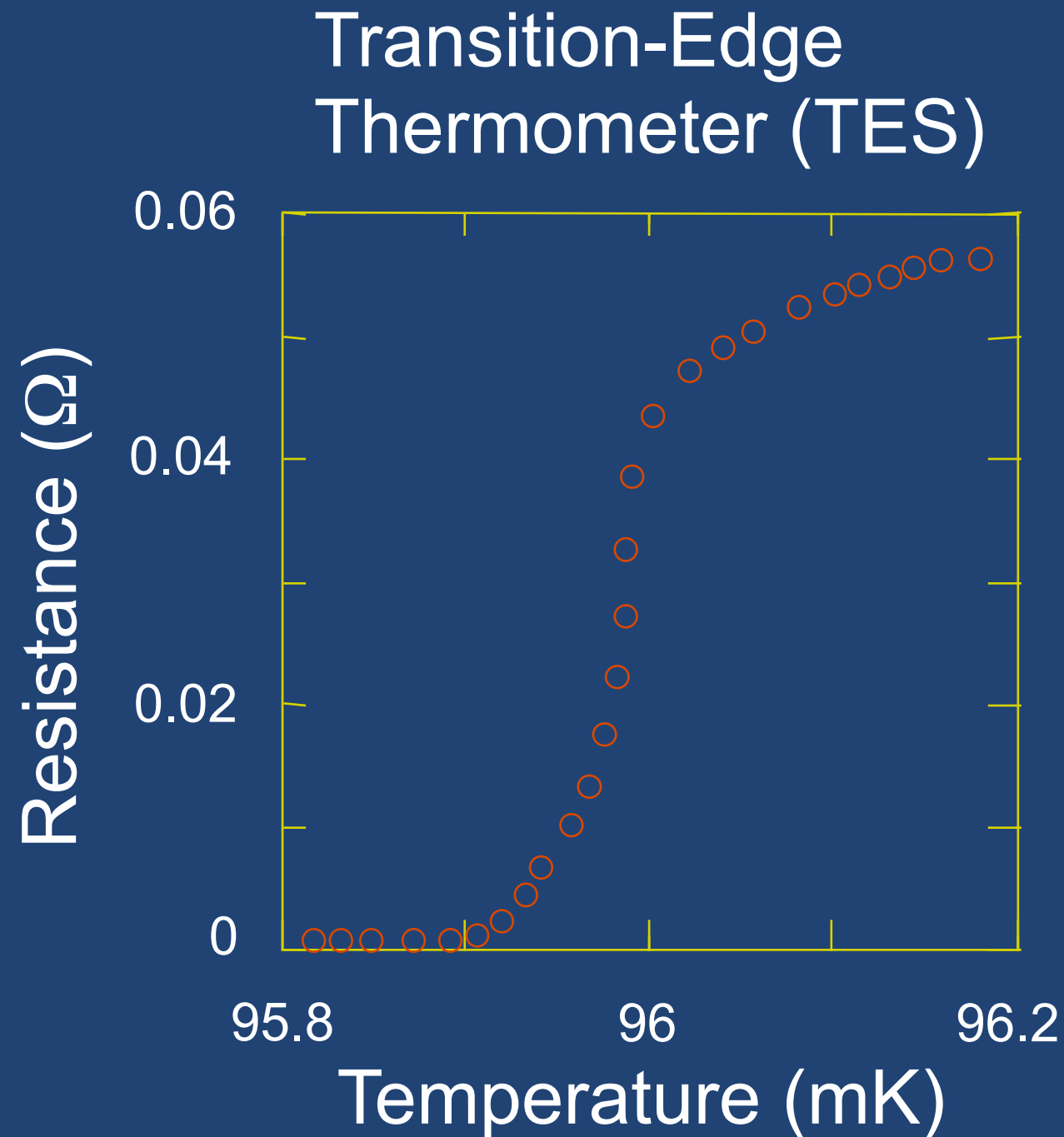
Single Pixel Detail



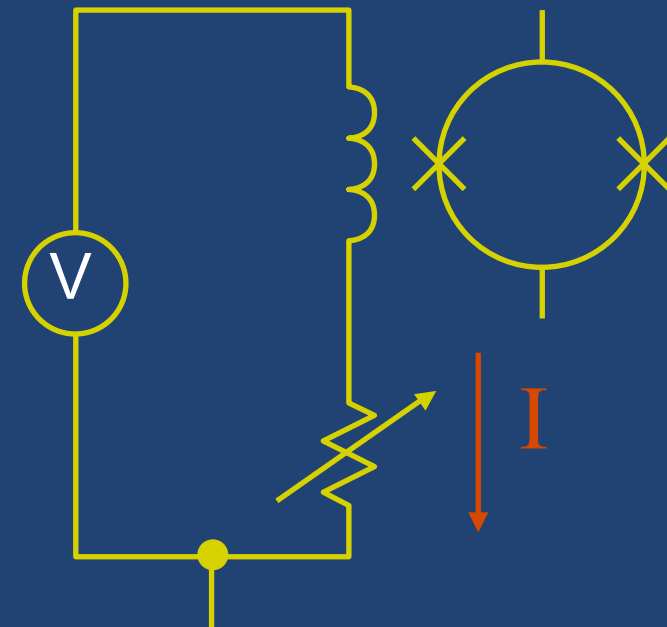
Absorber

TES

Superconducting Transition-Edge Thermometer



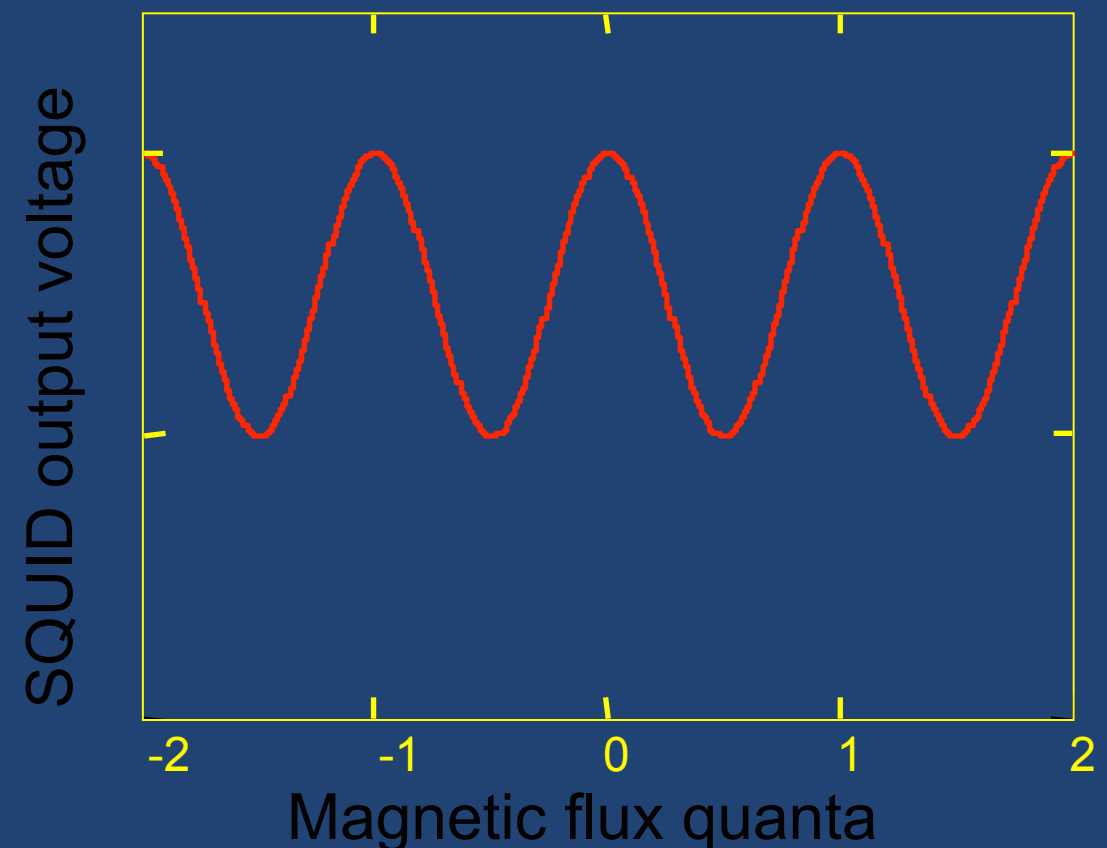
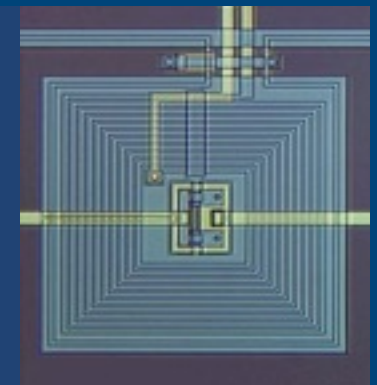
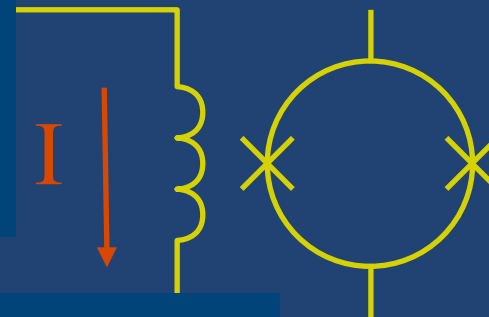
SQUID Current Amplifier



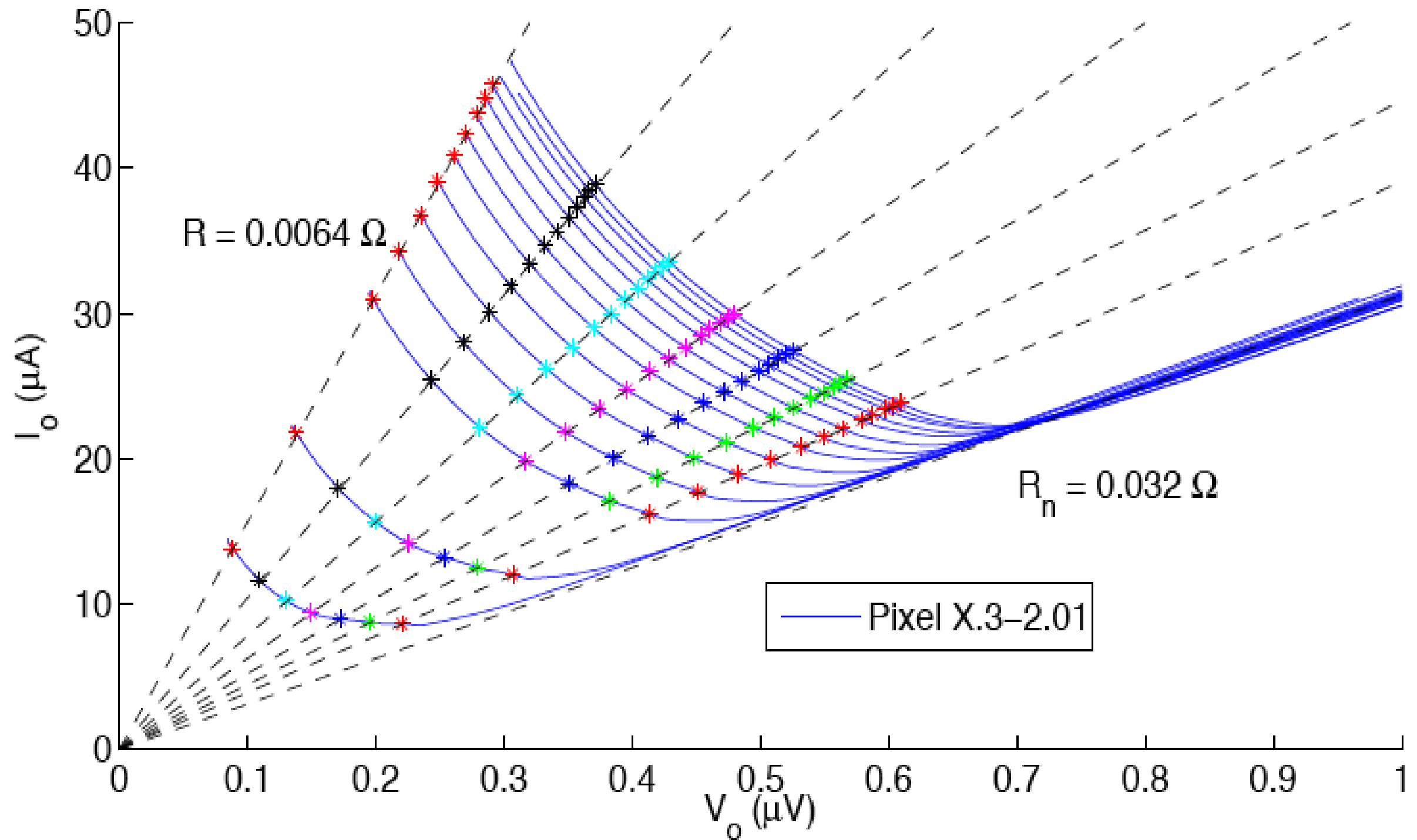
Transduces **heat** $\rightarrow$ **electrical signal**

SQUID Current Amplifier

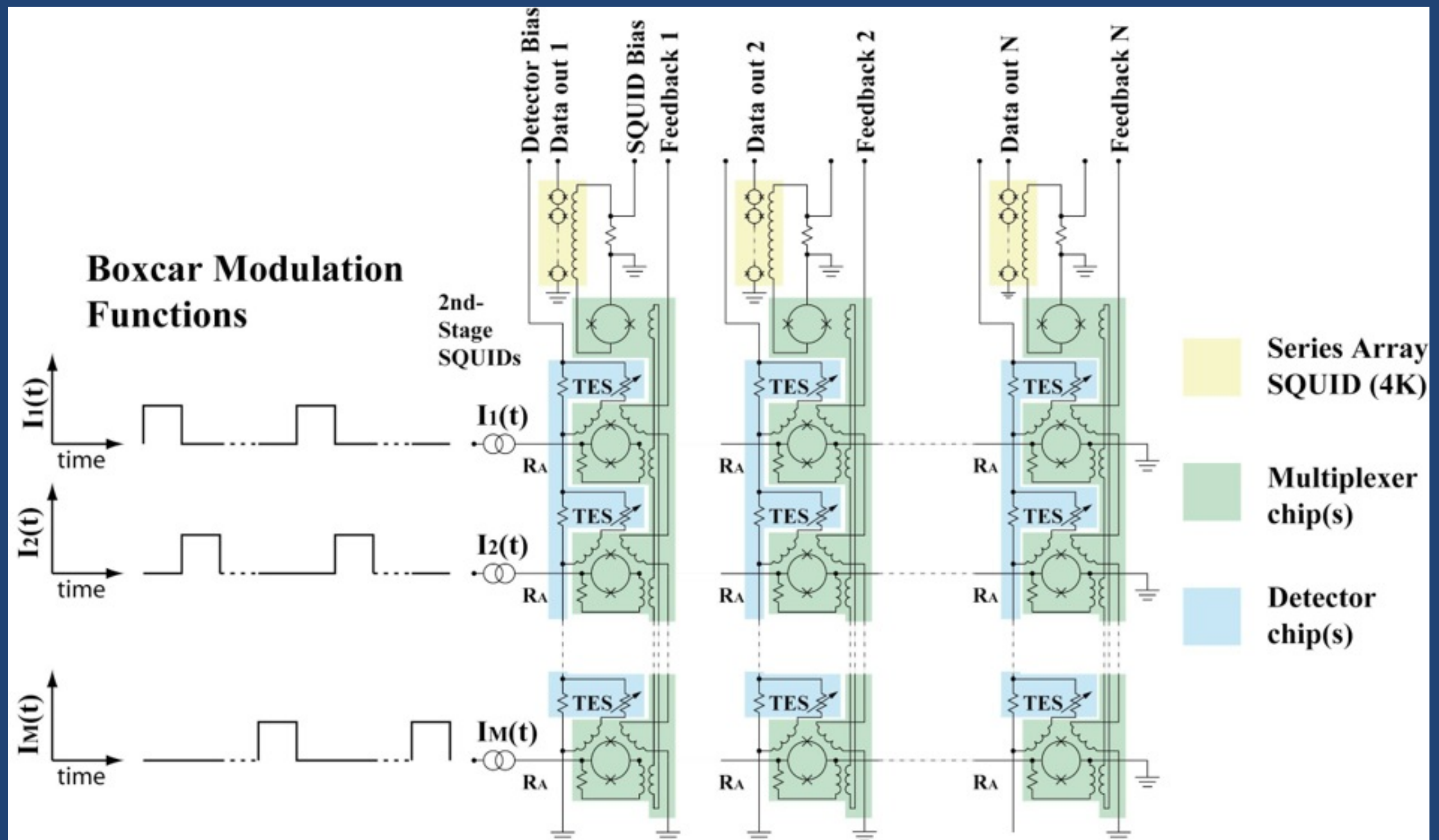
- Superconducting Quantum Interference Devices (SQUIDs)
- The most sensitive devices for the measurement of magnetic fields.
- Quantum interference between two Josephson tunnel junctions, analagous to a two-slit interferometer.
- Output voltage is a periodic function of the applied magnetic flux.



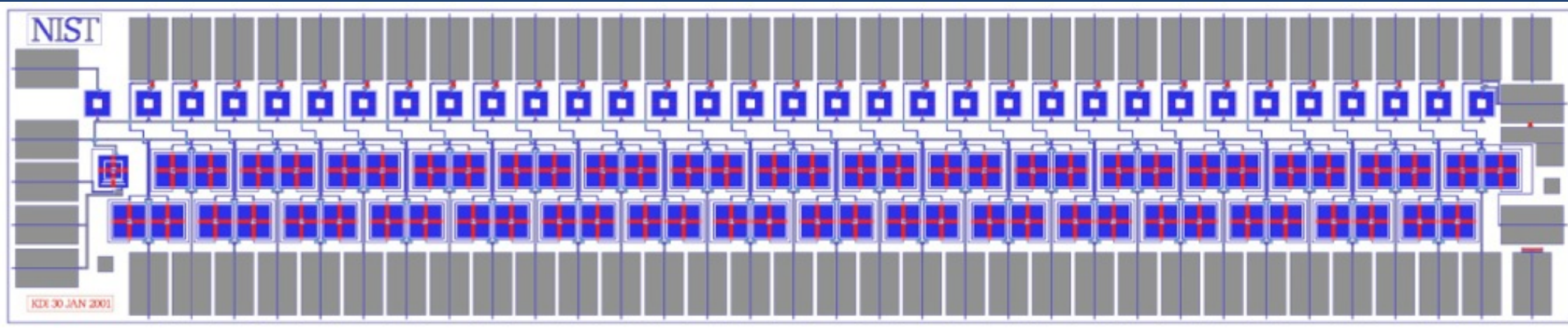
I-V Curves



Time-Division Multiplexer



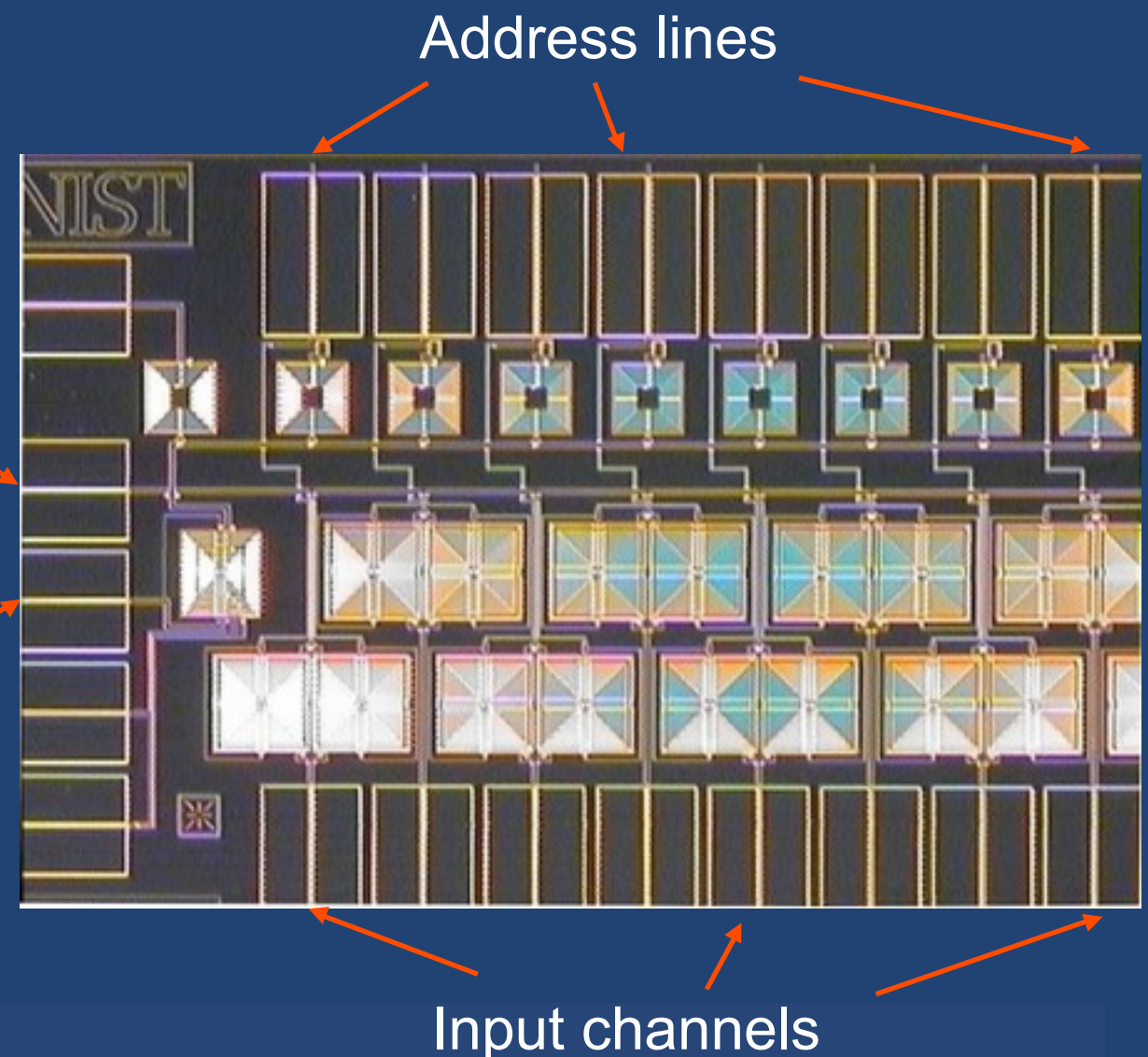
32-Channel MUX Chip

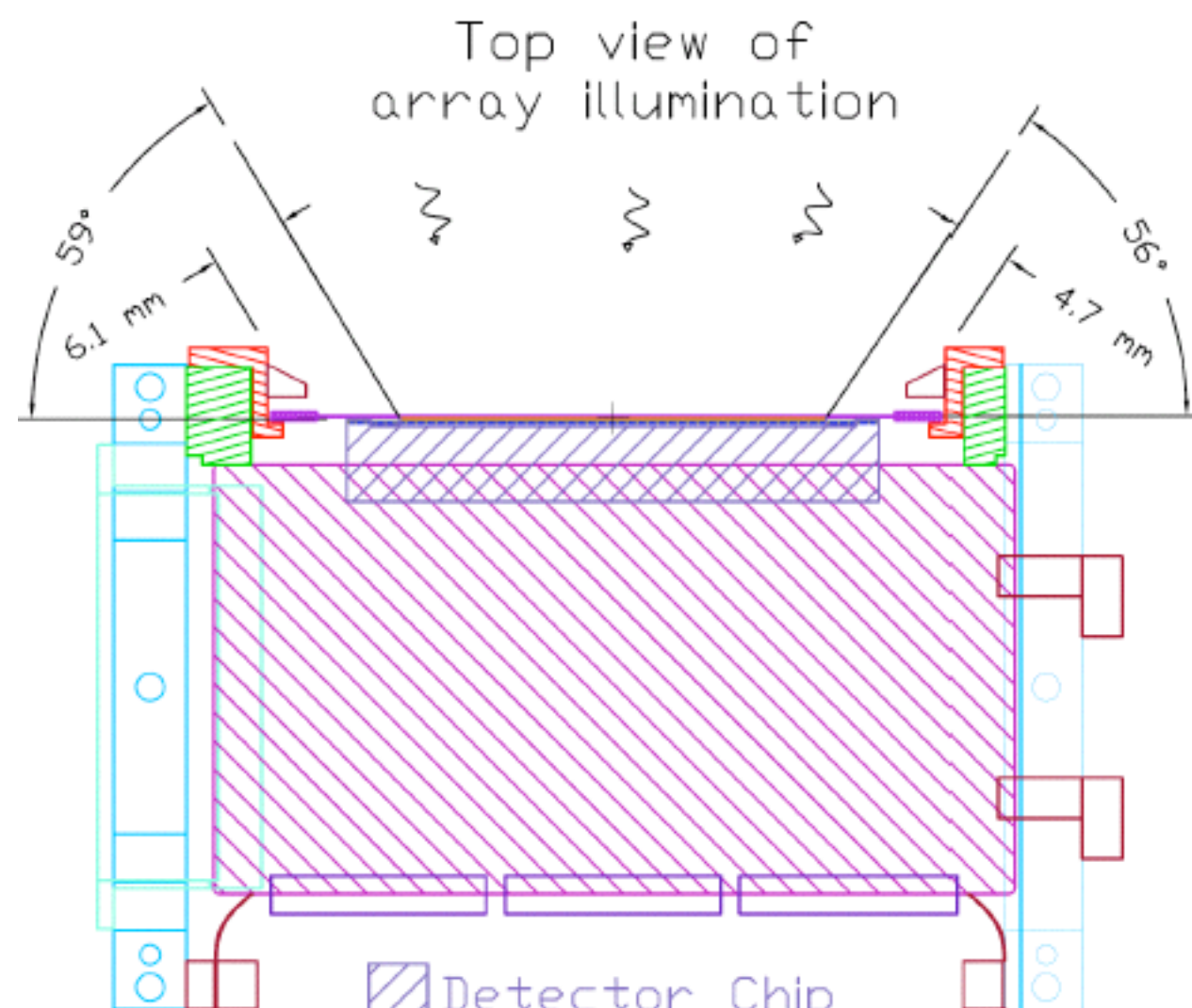


Multiplexes up to 32 channels in one column.

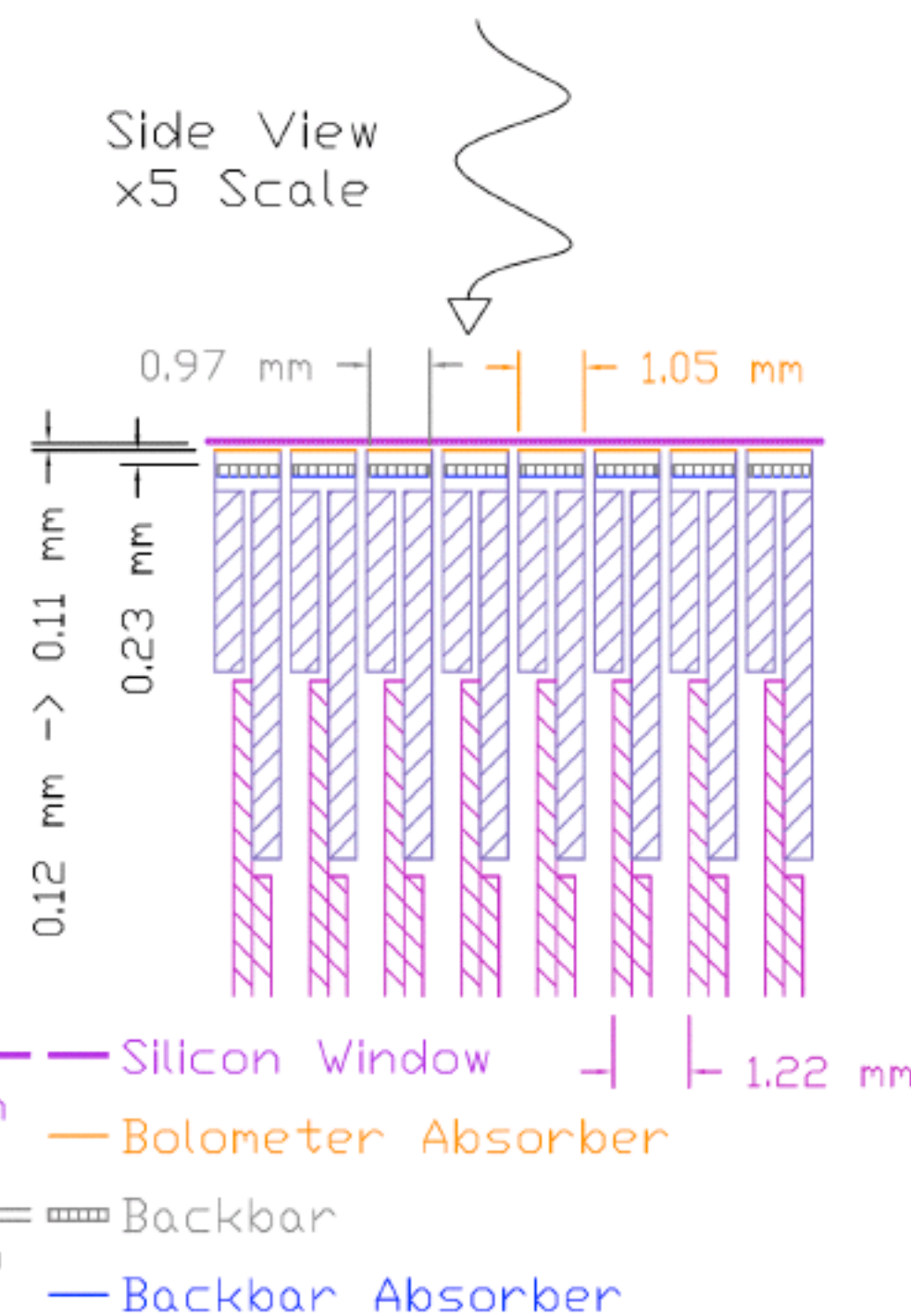
Column feedback

Column output

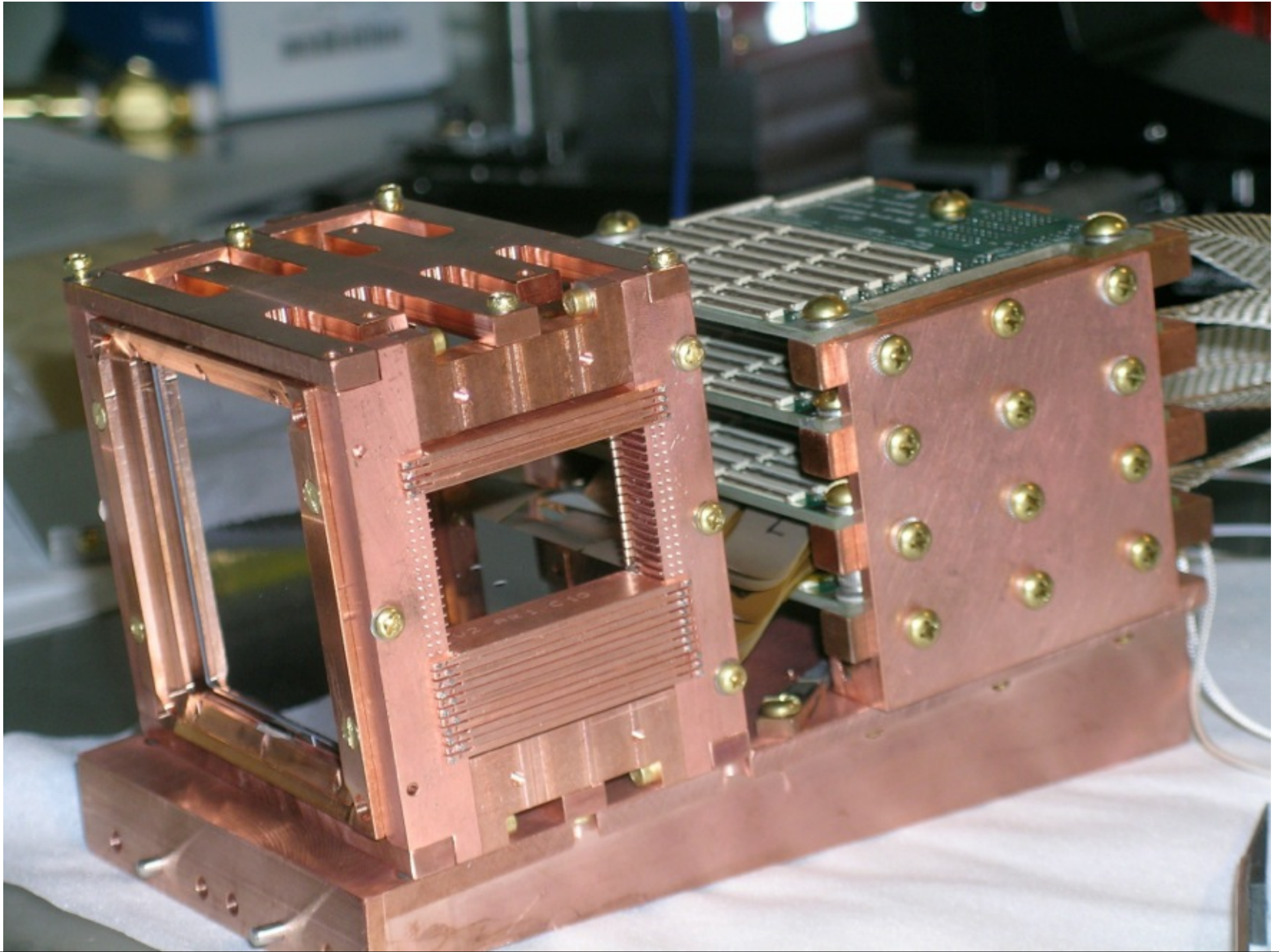




- Detector Chip
- Silicon Card
- Stop Blocks
- Window Holder
- Spring clamps



Anti-reflective Coating



MBAC

Liquid-Cryogen Free

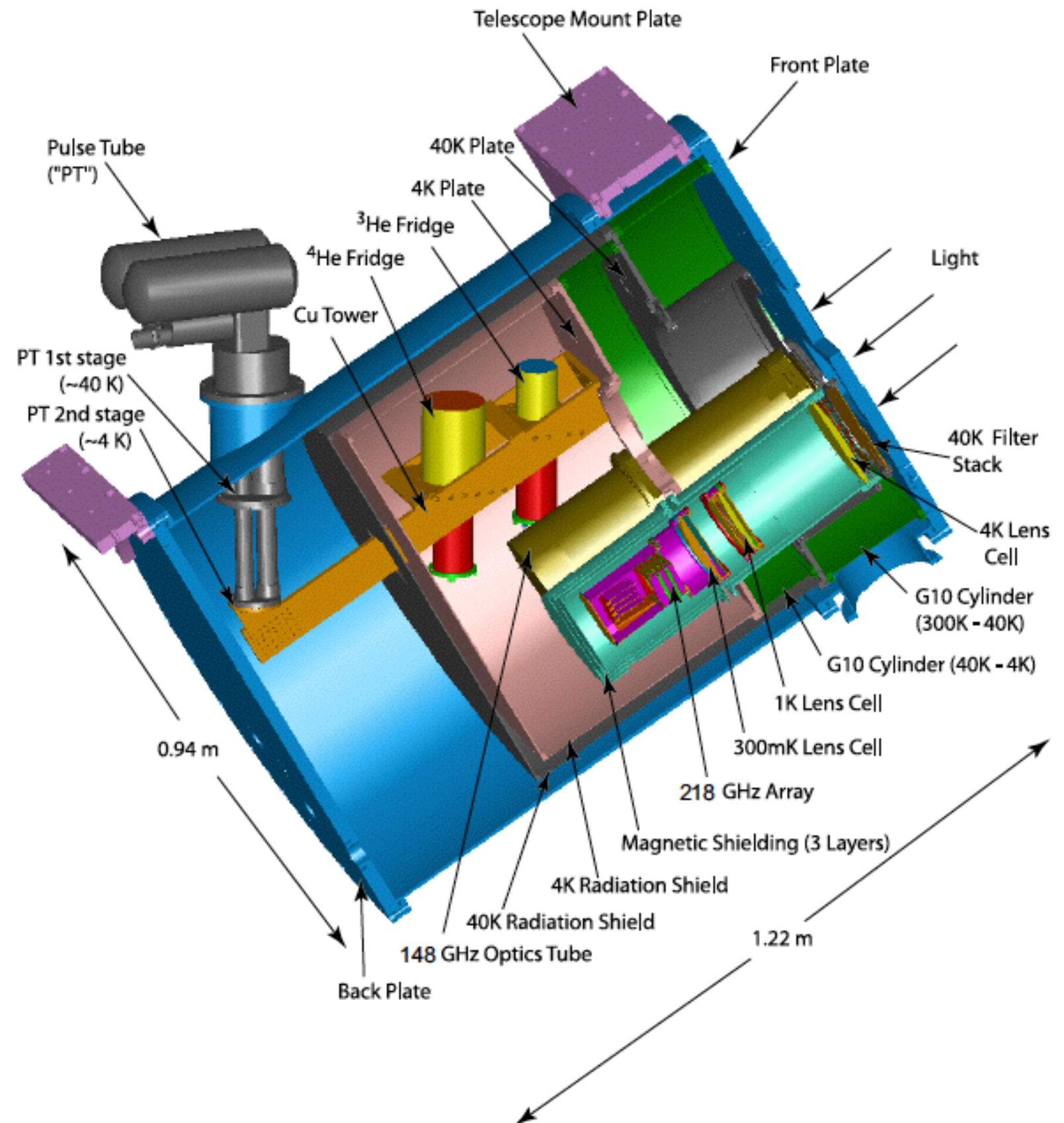
Pulse Tube Coolers

1st stage: 80W @ 45K
expected: 30W @ 40K

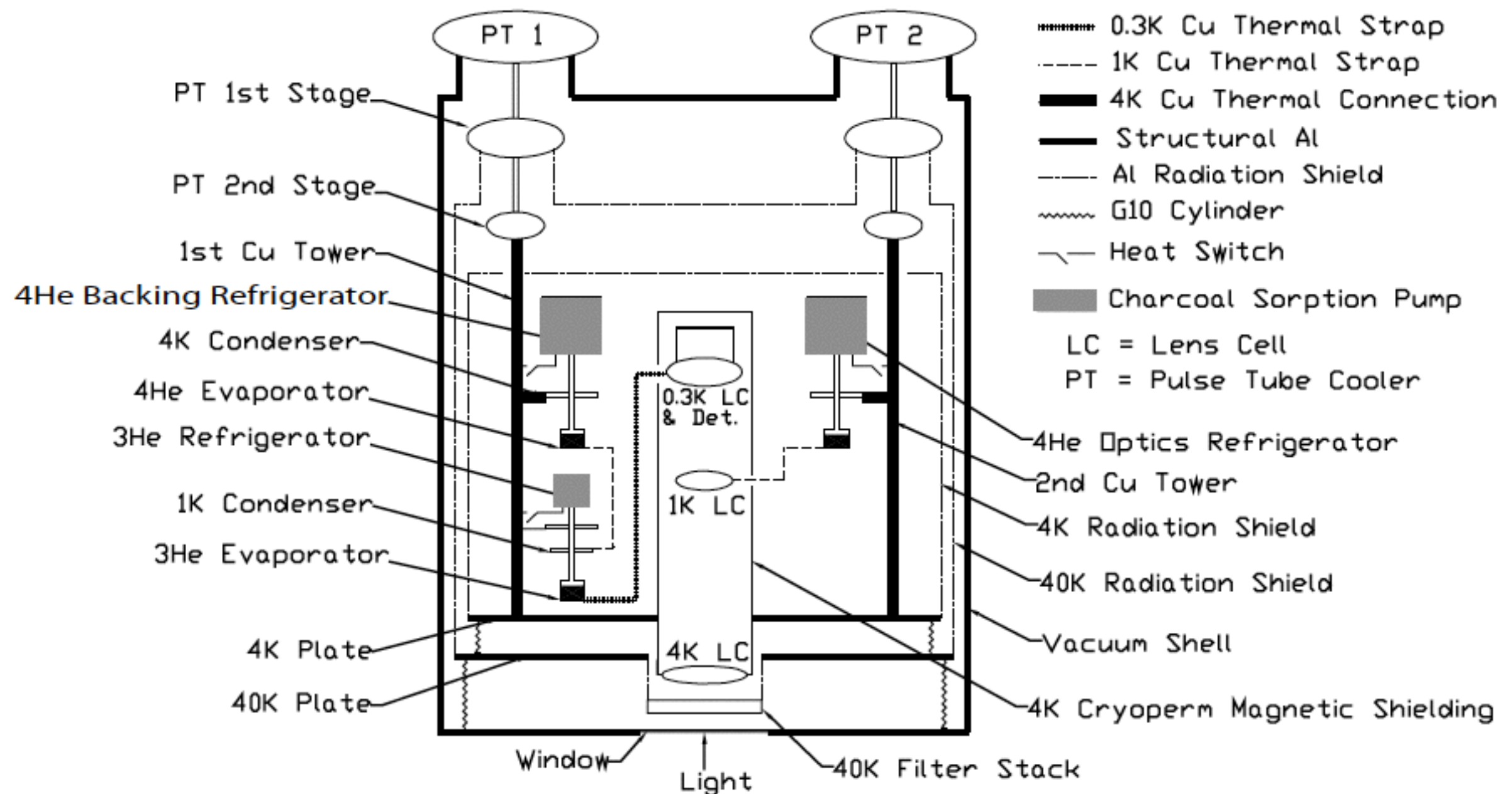
2nd stage: 2W @ 4.2K
expected: 0.2W @ 3K

Helium-4 and Helium-3
sorption Fridges

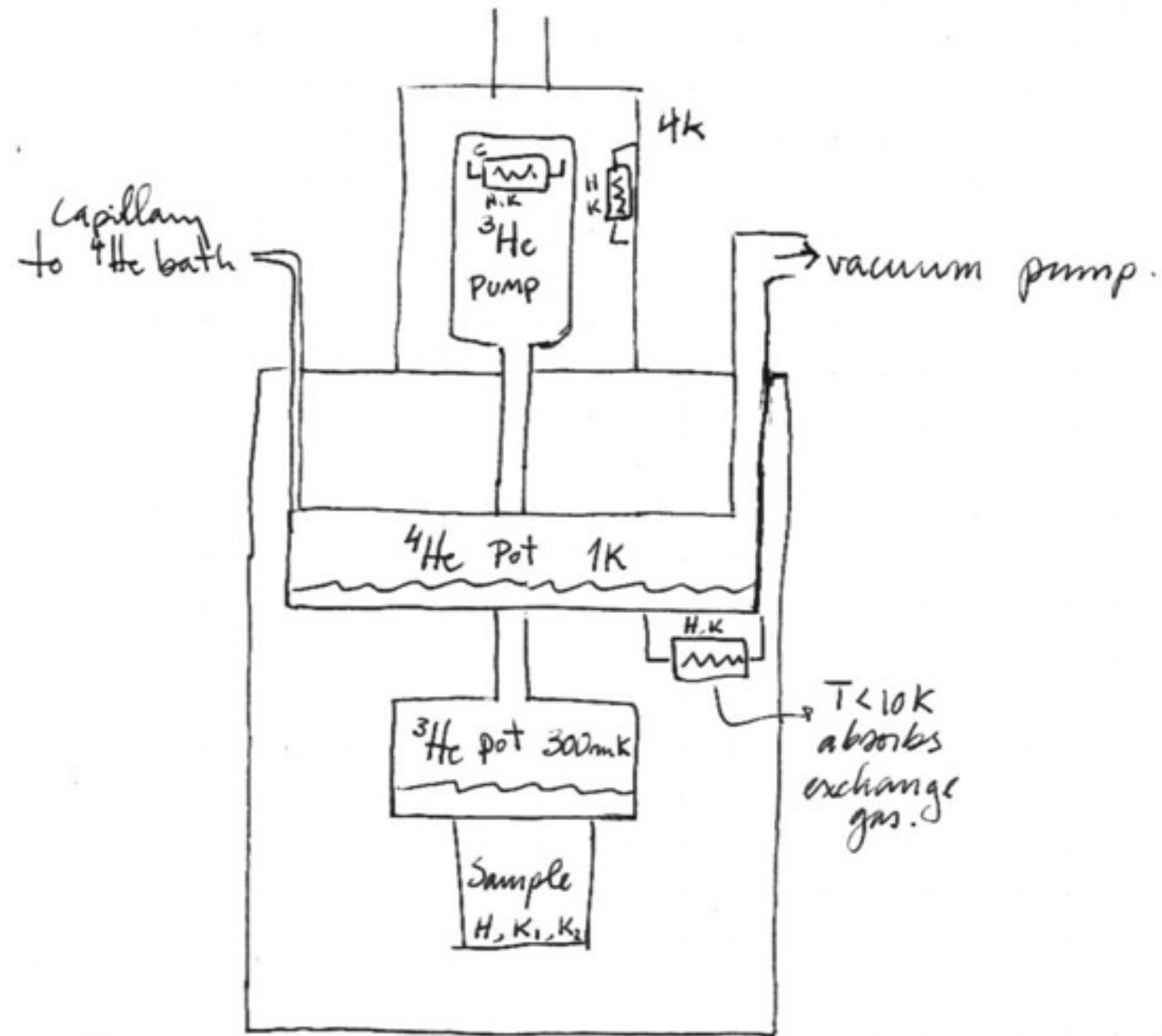
270 mK temp w/
17 hour hold time

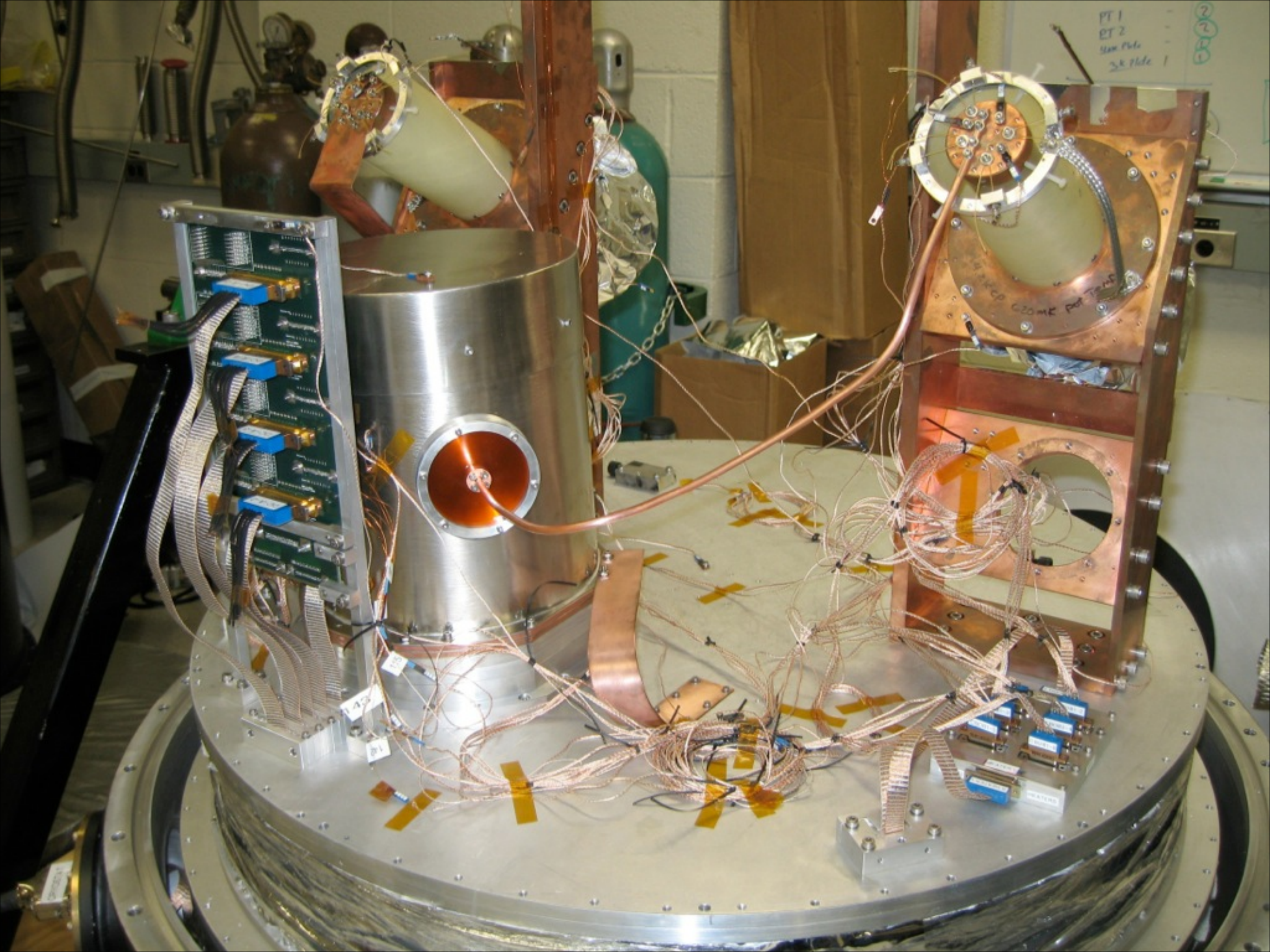


Cryogenics in MBAC



Sorption fridge



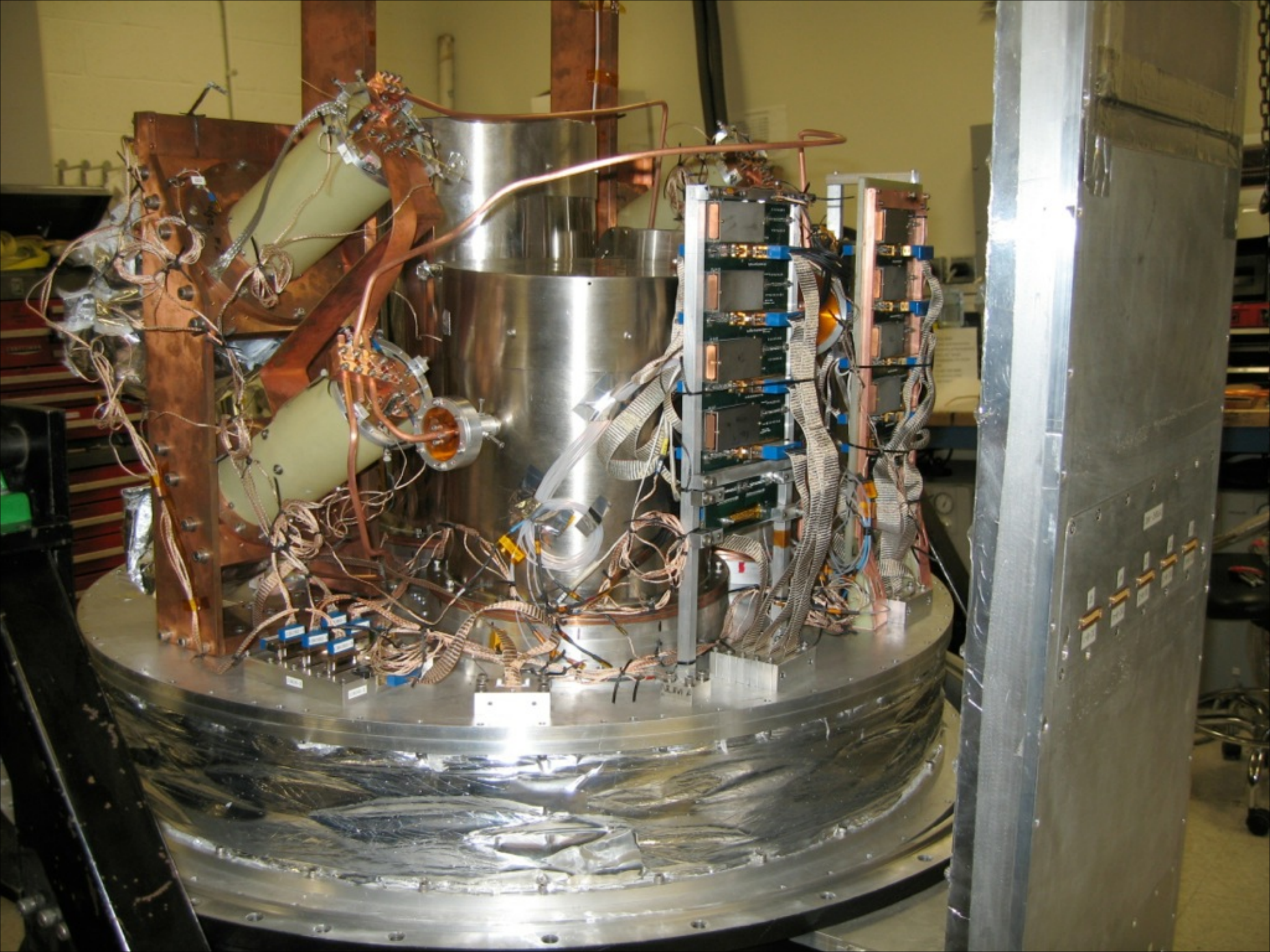


PT1 - 2
PT2 - 2
Main Plate - 1
Sub Plate - 1

620mK Pot Temp





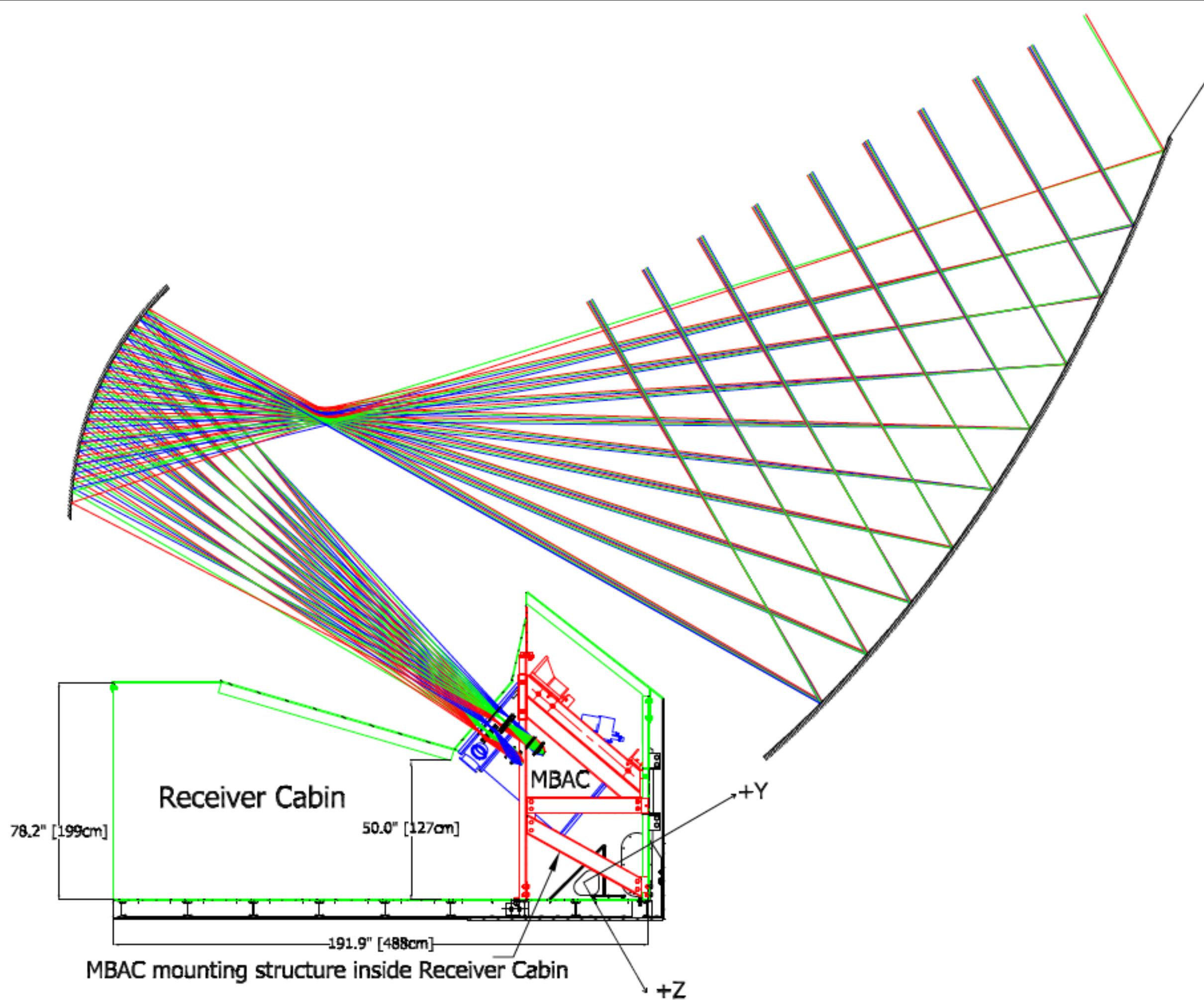


Ready Sir!

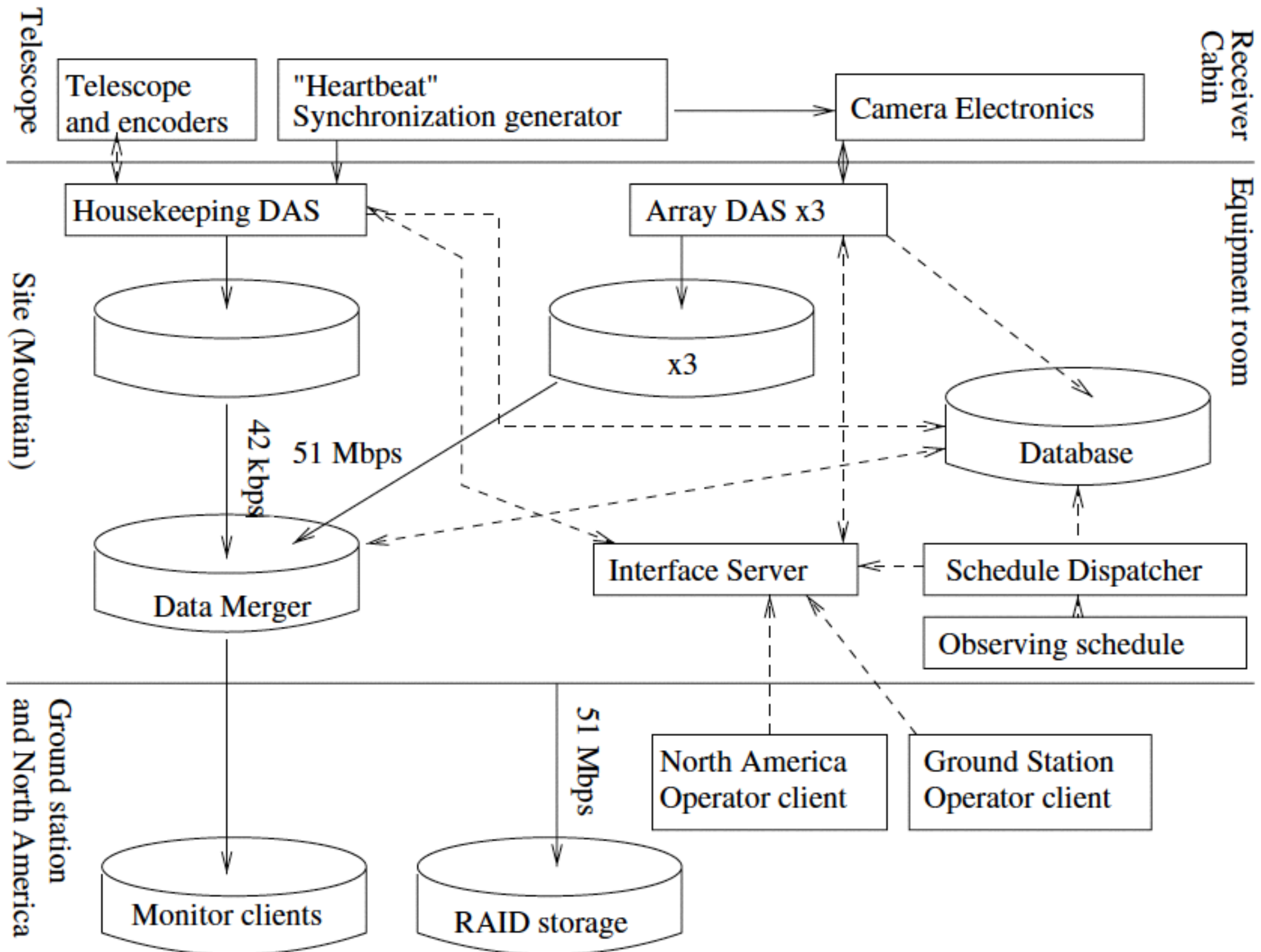
MBAC



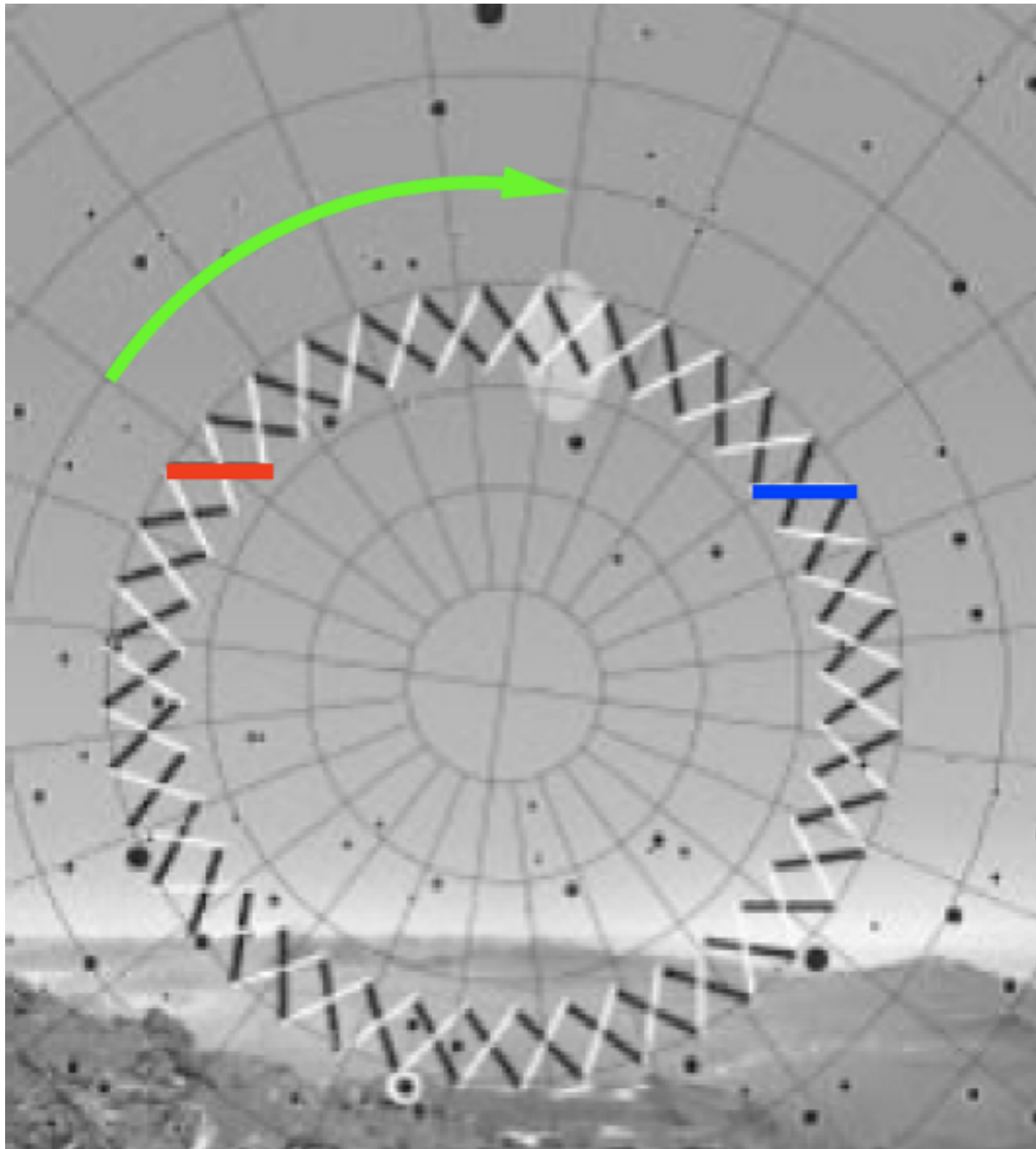




Housekeeping



Scan Strategy



- The measurements are done at single elevation to keep the air mass constant and minimize mechanical stresses on the system.
- This cross linking technique significantly reduces systematics, equalizing the noise modes in map space.
- The result are long map stripes on the sky.





ALL SET



And now we just need to
observe!



NOT SO FAST!







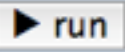
Observations



Observations

- The telescope observes during the fraction of the year with good weather (May - December)
- With MBAC only night time observations were done due to the recycling time of the cryogenics.
- With ACTpol we can observe non-stop.
- The telescope is controlled remotely, and only 2 operators are required at the site for maintenance.

HTML Scheduler

 run

sisyphus is idle

Script Queue

Pending

+

Running

Done

#944 Test Wide2	ok
#943 go_home	ok
#942 go_home	aborted
#941 conicyt_motion_3	ok
#940 go_home	ok
#939 conicyt_motion_2	ok

▼

Thu, 13 Mar 2014 16:24:07 GMT
Update time: 586 ms = 564 (network) + 22 (render)
mike@nolta.net

Housekeeping Monitor

ACTpol 2013		
Vital Stats		
C_Time	2014/03/13 12:25:19	
Dn_Heartbeat	No such field	
serialnum	78314350	
cpu_s	1394727919	
Enc_EI_Deg	59.99	
Enc_Az_Deg_Astro	180.01	
V_Limsw_Cov_Closed	No such field	
V_Limsw_Cov_Open	No such field	
Housekeeping		
T_Mot_Az_East	No such field	
T_Pan_R6_6	No such field	
T_Pan_R8_6	No such field	
T_Sec_1	No such field	
T_Sec_12	No such field	
T_Clin_Upper_Base	No such field	
V_Limsw_Cov_Open	No such field	
Act_Mir1	No such field	
Clin_X_Ped	No such field	
100mK Rxxs		
Tr1_100Mk_Cen_Twr	Outside LUT	
Tr1_Array_Pkg_Lid	0.0772 K	
Tr1_Arr_Pkg_Oppcf	Outside LUT	
Tr2_Arr_Pkg_At_Cf	Outside LUT	
40 K diodes		
Td_Pt_1st_Stage	295.16 K	
Td_40K_Heat_Strap	296.47 K	
Td_40K_Shield_Bk	296.67 K	
Td_40K_Cold_Plt	290.84 K	
Td_40K_Canopy_Plt	296.19 K	
Td_40K_Lpe_Filter	291.92 K	
3K/1K Rxxs		
Tr2_Lens_1	Outside LUT	
Tr1_1K_Cen_Twr	Outside LUT	
Tr1_1K_Shield_Lid	Outside LUT	
Tr1_Lower_Sa_Susp	Outside LUT	
Tr1_Sa_Hex_Pcb	Outside LUT	
Tr2_Lens_3	Outside LUT	
Tr2_Lens_2	Outside LUT	
Tr2_Lyot_Stop	Outside LUT	
3K diodes		
Td_Pt_2nd_Stage	294.69 K	
Td_3K_Cu_Rod_Bk	295.32 K	
Td_3K_Shield_Bk	290.14 K	
Td_3K_Cu_Rod_Fnt	289.59 K	
Td_3K_Cold_Plt	294.88 K	
Td_3K_Mce_Htsink	293.61 K	
Td_Cryoperm_Lid	295.23 K	
Td_3K_Lpe_Filter	294.46 K	

Computer Monitor

ACT Site Computer Status Thu Mar 13 12:26:03 2014

Basic computer status

Host	Site	Time	Uptime	Users	Load	Disk	NTP	Kernel	OS
bors	Toco	12:25:59	2 days, 3:14	4	1.52, 1.18, 0.96	ok	bors: 0.005 +- 0.009	2.6.32-45-generic-pae	Ubuntu 10.04.3 LTS
mce1	Toco		Unreachable						
mce2	Toco	12:26:00	2 days, 3:14	2	0.14, 0.29, 0.30	ok	bors: -0.544 +- 0.258	3.2.14-bigphys	Ubuntu 12.04.2 LTS
lancelot	adobe	12:26:00	5 days, 3:24	0	0.00, 0.04, 0.04	ok	bors: -0.363 +- 0.196	2.6.32-46-generic-pae	Ubuntu 10.04.4 LTS
raid	adobe	12:26:00	5 days, 4:28	0	0.00, 0.09, 0.11	ok	bors: 0.229 +- 0.429	3.5.0-36-generic	Ubuntu 12.04.2 LTS
galahad	adobe		Unreachable						

Table Notes: "Disk" notes any warnings about full disk (see detailed table, below). "NTP" notes the clock offset and jitter in milliseconds for the bors server, or if bors isn't available, for the best server (the one with the lowest jitter). For computers on Toco, it's a warning condition not to reach bors. Expect offsets well below 100 ms.

Important daemons

Host	Stopped	Daemons running
bors	colossusd, amcp	bede
mce2	none	colossusd
raid	colossusd	

Resource Use

CPU load

Host	CPUs	CPU State	#1	#2	#3	#4	#5
bors	0		amcp (17.7%)	events/0 (9.2%)	firefox (1.0%)	Xorg (0.2%)	beam.smp (0.1%)
mce2	0		kst2 (5.1%)	compiz (2.9%)	Xorg (1.6%)	psensor (1.0%)	unity-panel-ser (0.3%)
lancelot	0		ntop (0.2%)	apache2 (0.1%)	python (0.1%)	adefile (0.1%)	mysqld (0.0%)
raid	0		python (5.0%)	kworker/0:2 (0.0%)	irqbalance (0.0%)	ksoftirqd/1 (0.0%)	rsyslogd (0.0%)

Red=sys, orange=IRQ service, gold=user, cyan=nice user, green=waiting on IO, gray=idle.

Top 5 CPU processes are sorted by percentage of CPU time they have occupied since they started.

Memory (resident set size)

Host	Mem (kB)	Top 5 memory users	#1	#2	#3	#4	#5
bors	3095292		firefox (5.6%)	amcp (3.4%)	Xorg (1.3%)	kst (0.9%)	nautilus (0.9%)
mce2	8060936		mysqld (6.7%)	kst2 (3.8%)	compiz (2.8%)	update-manager (1.2%)	Xorg (0.6%)
lancelot	993668		named (3.7%)	ntop (2.5%)	mysqld (1.4%)	apache2 (0.9%)	apache2 (0.9%)
raid	8177692		zenity (0.2%)	Xorg (0.1%)	python (0.0%)	NetworkManager (0.0%)	whoopsie (0.0%)

Weather Status



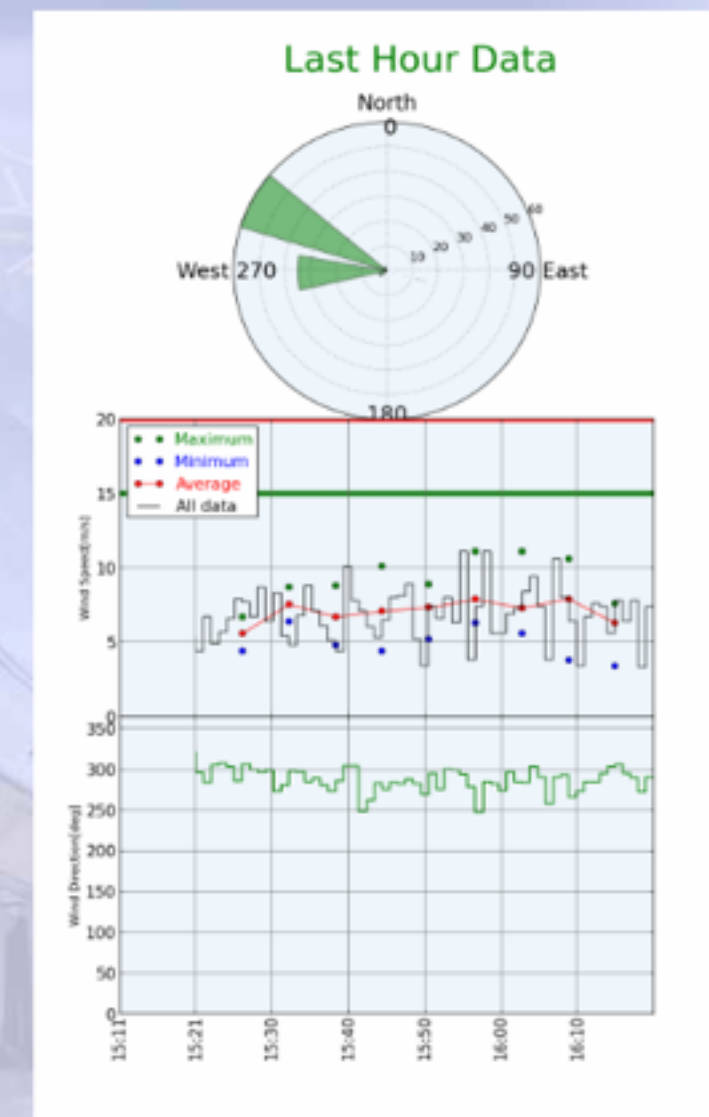
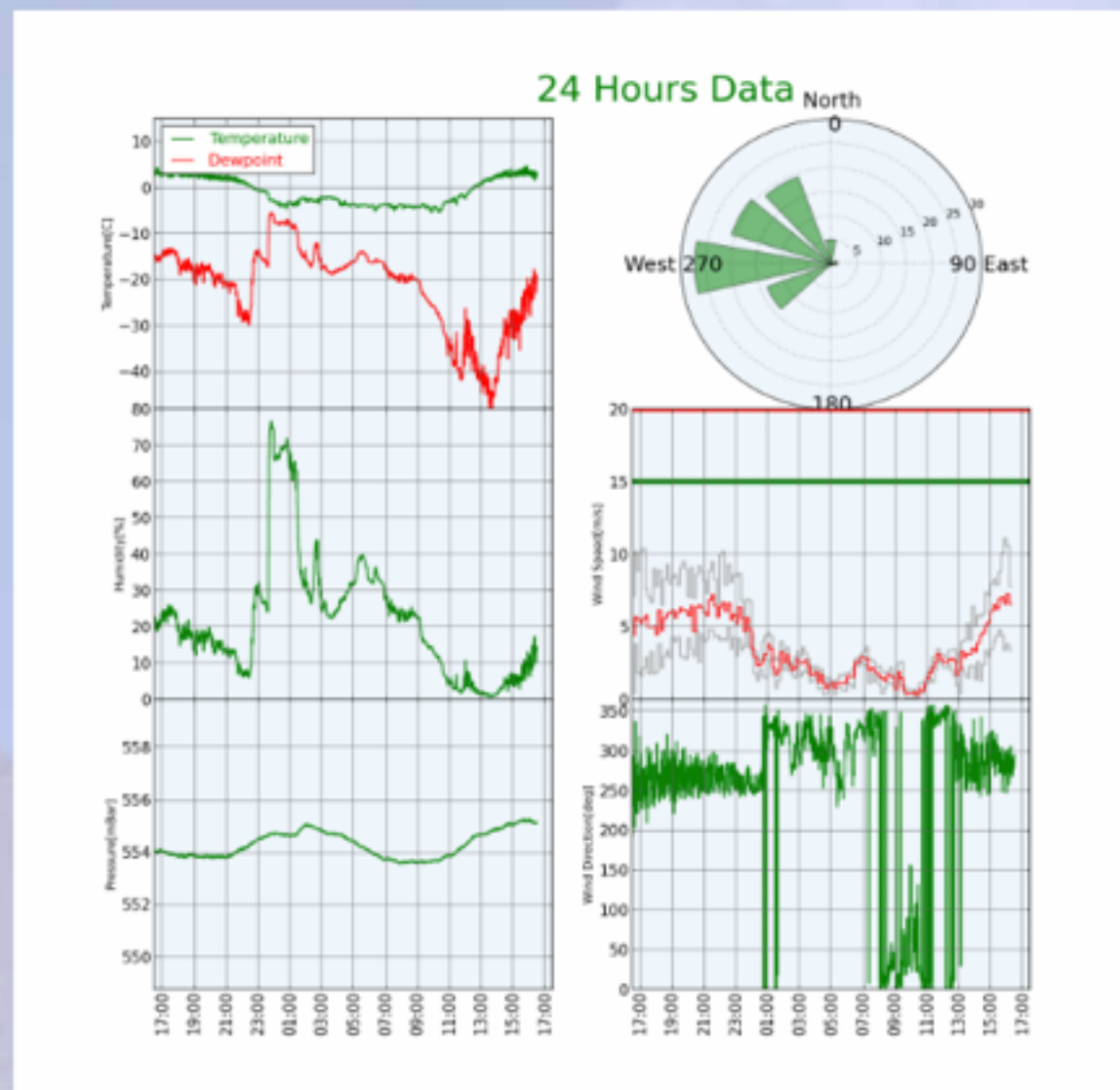
Atacama Pathfinder EXperiment APEX
Weather monitor

Max-Planck-Institut
für
Radioastronomie



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[Home](#) > [Weather monitor](#)



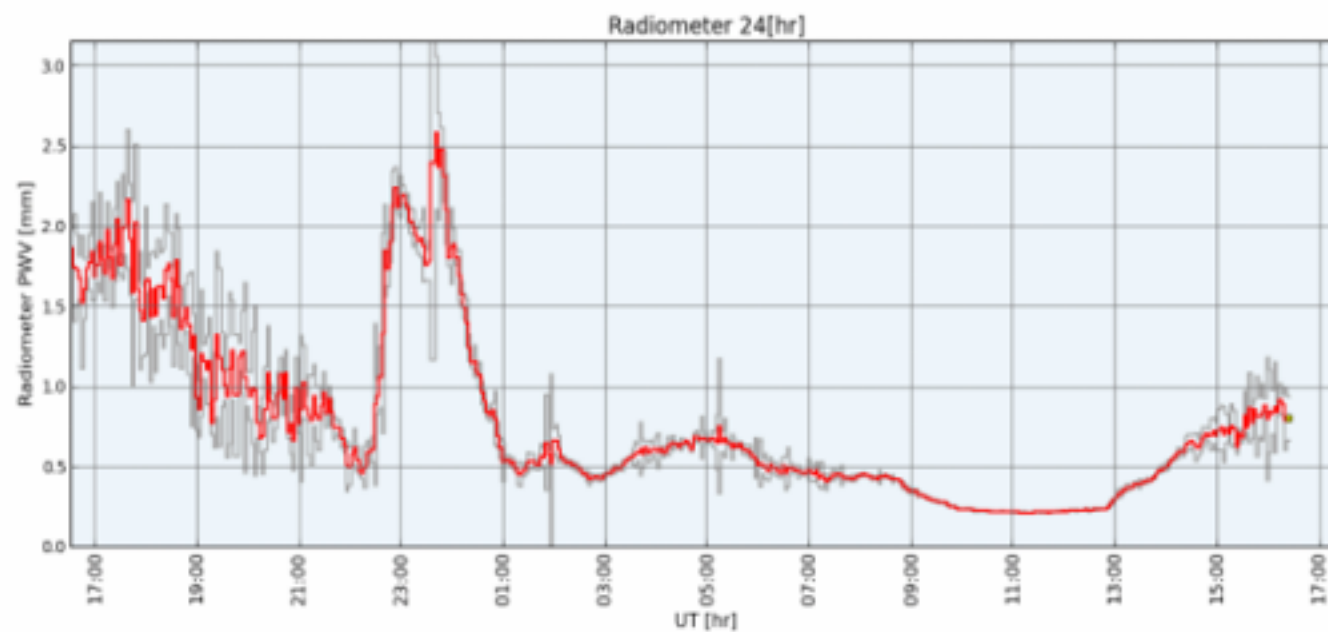
Radiometer Plots

☐ Last 30 days ☐ Last 7 days ☒ Last 24 hours

PWV Status

Radiometer Plots

☐ Last 30 days ☐ Last 7 days ☒ Last 24 hours



Current Data

Radiometer	[mm] :	0.89
Temperature	[C] :	2.85
Dewpoint	[C] :	-17.9
Humidity	[%] :	16.95
Pressure	[hPa] :	555.12
Wind Speed	[m/s] :	7.4
Wind Direction[deg]	:	291.0
Wind Chill	[C] :	-10.17
Last update	:	Thu Mar 13 16:20:00 2014

DATA REDUCTION

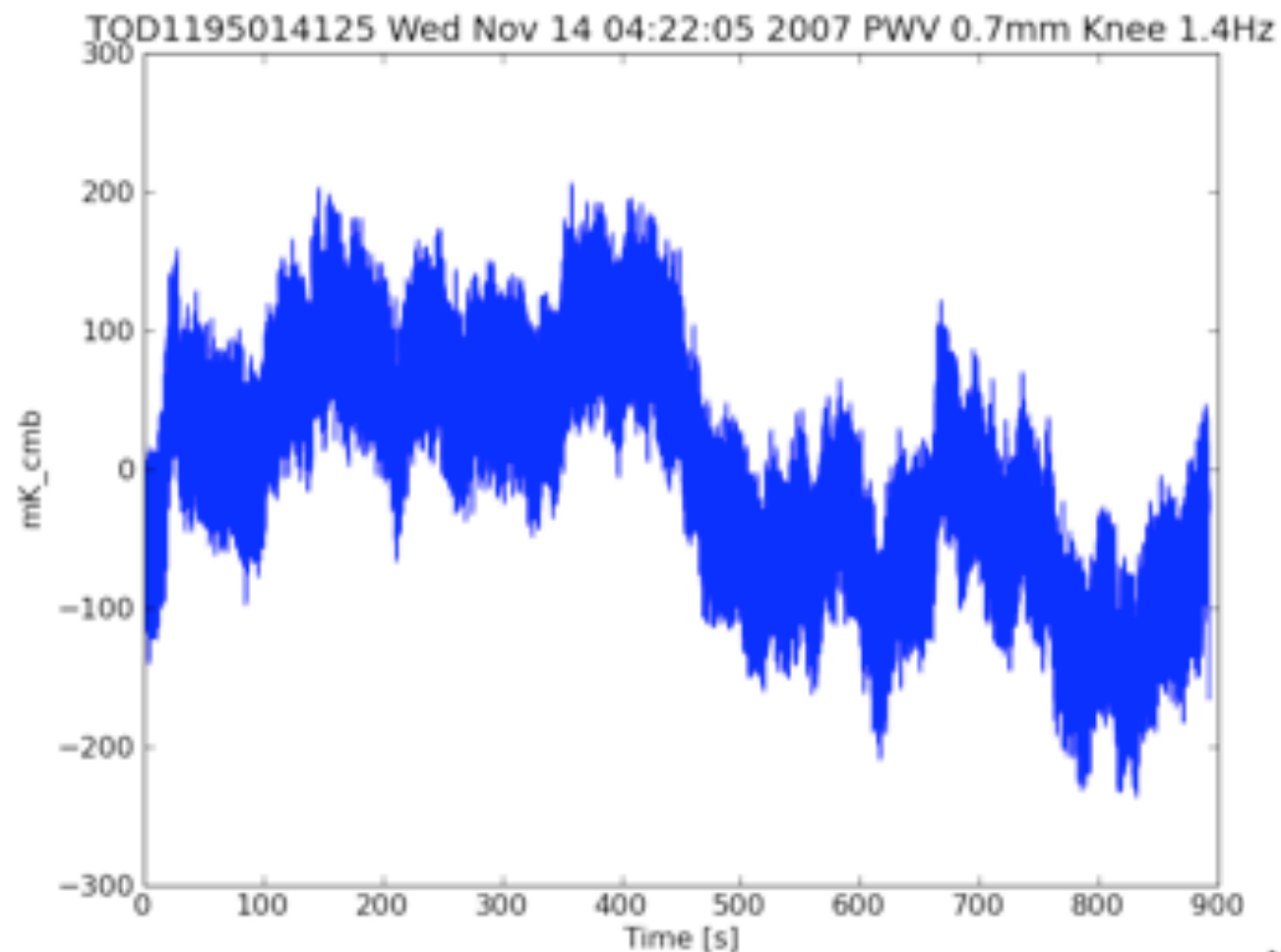
From Data to Maps



Time Ordered Data (TOD)

- Each detector is sampled at 400 Hz, producing a TOD.
- Each sample is given a time stamp, used to relate them to the pointing information.
- You are left with $1000 \times 3 \times 400$ samples, 32 bits each, meaning 4.8 MB/s or 17 GB/h of data.
- The data is stored in disk waiting to be processed into maps.

TOD



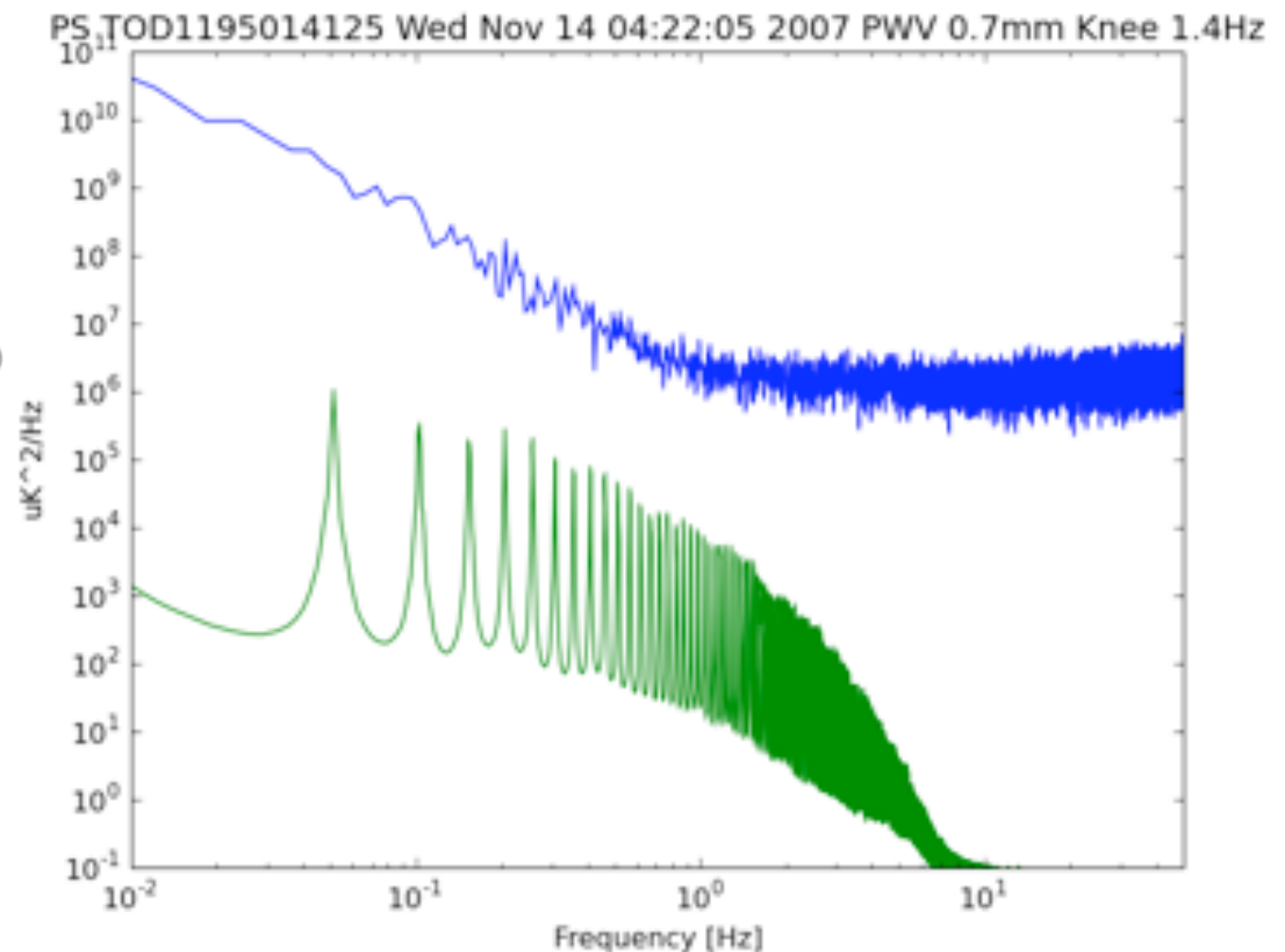
The power spectrum is dominated by $1/f$ noise that equilibrates with the white detector noise at around 1Hz. This noise is caused mainly by the atmosphere drift.

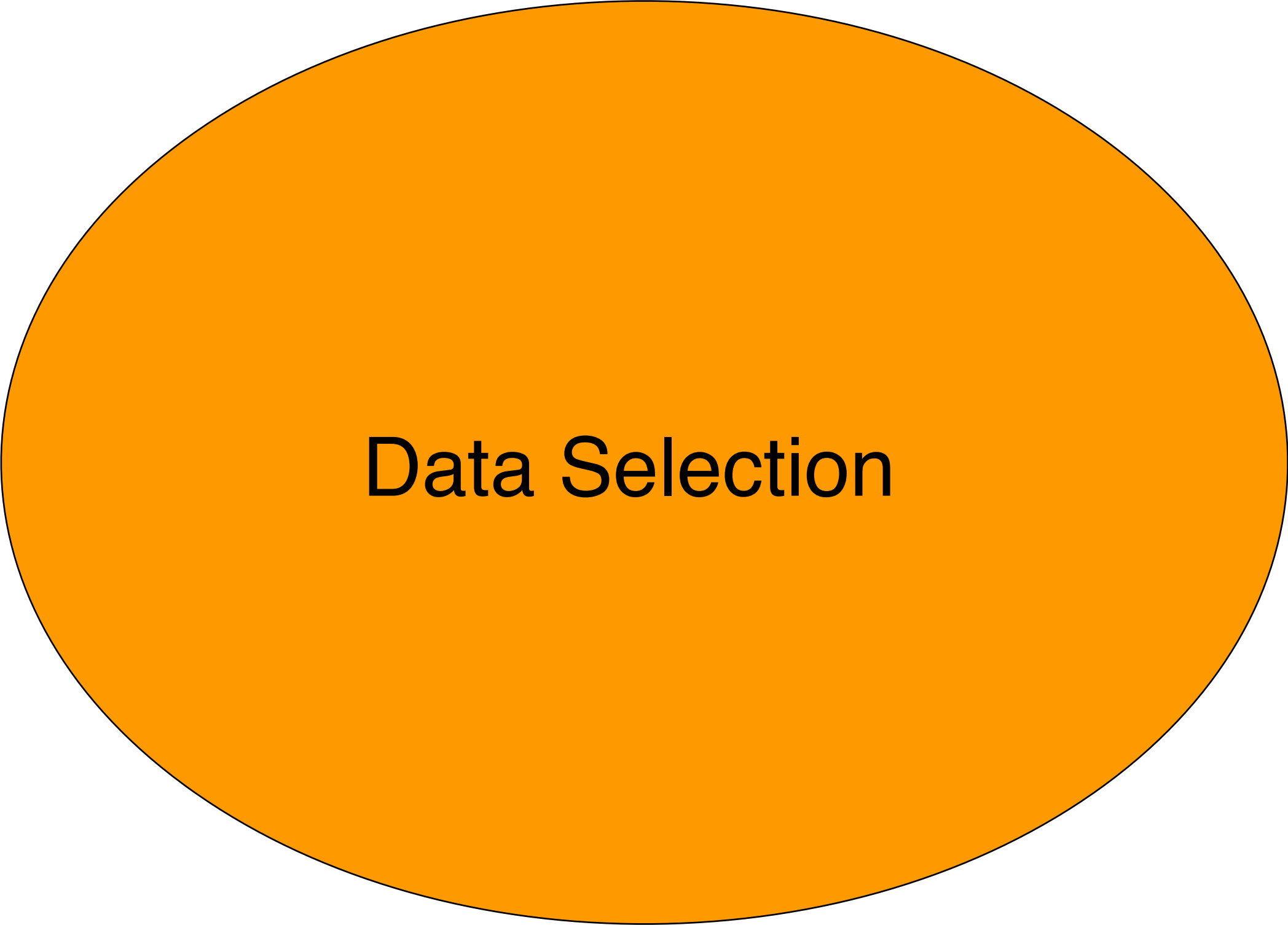
The CMB concentrates its power in the same region with the atmosphere noise. The frequency range with better signal to noise ranges from 1 to 8Hz.

The data is retrieved continuously from the camera as a long vector or “Time Ordered Data” (TOD).

19GB of data per hour!

The main drift seen in the TOD is caused by changes in loading from the atmosphere.





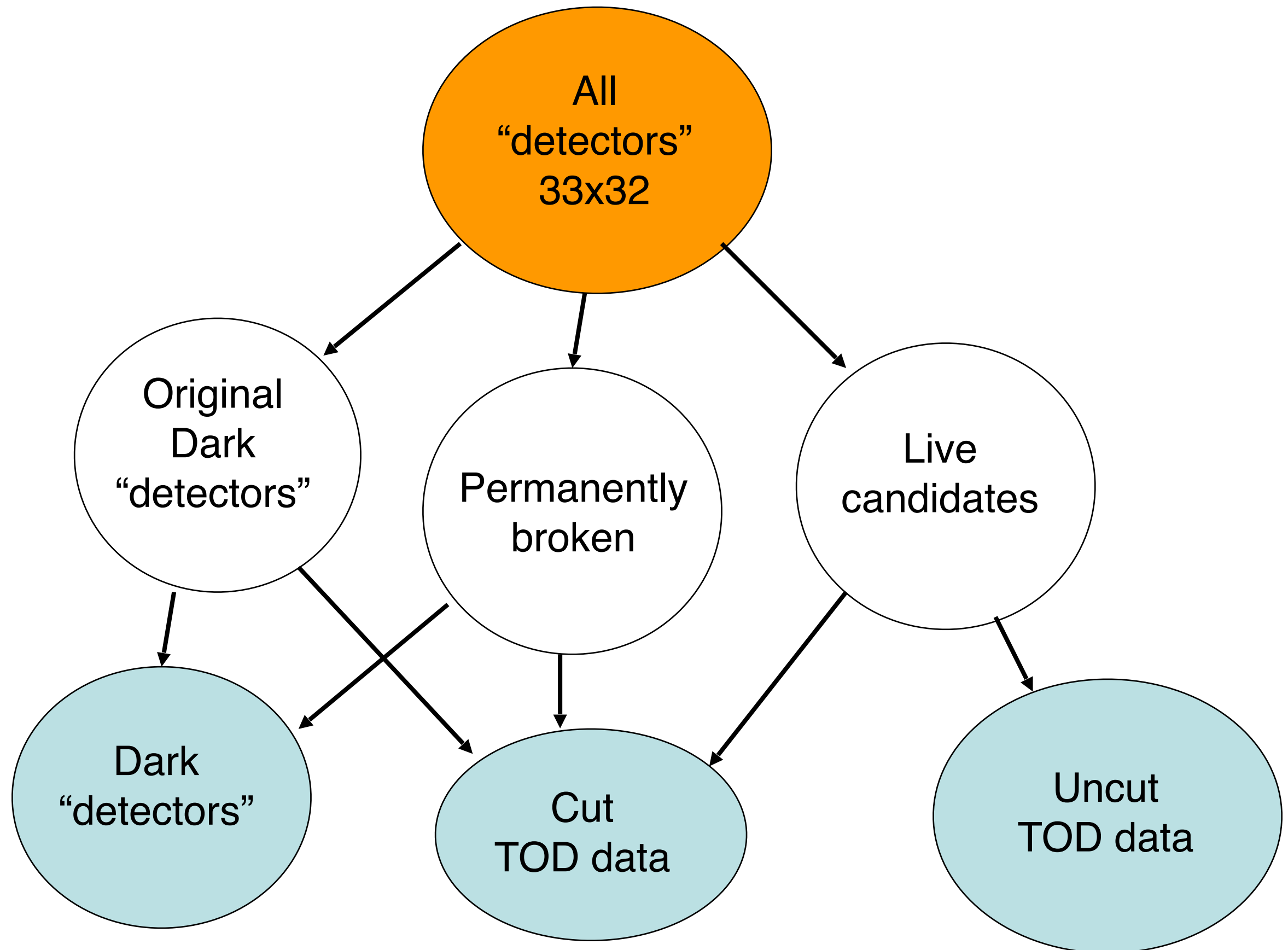
Data Selection

Data Selection

- Not all data is useful for making maps.
- Some detectors are permanently broken.
- Eventual pathologies in the data can make a fraction of a TOD unusable.
- A careful but efficient analysis is required to determine the usable fraction of the data.
- Given that data files store 15 min long TODs, that becomes the standard test length for pathologies and cuts.
- Some times shorter cuts are preferable, in which case the scan period is used, or even shorter periods depending on the kind of pathology.
- The number of effective detectors is defined as the sum over all detectors of the fraction of uncut time.

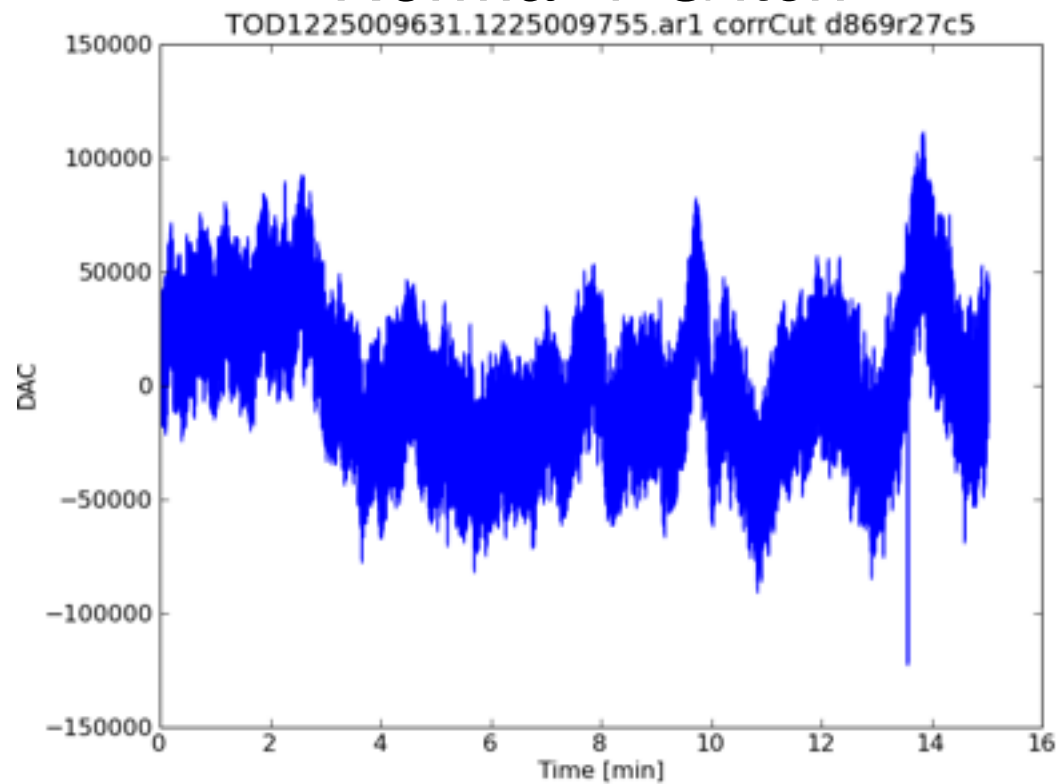
$$N_{eff} = \sum_{i=1}^N \frac{T_{i,uncut}}{T_{total}}$$

“Kinds” of detectors

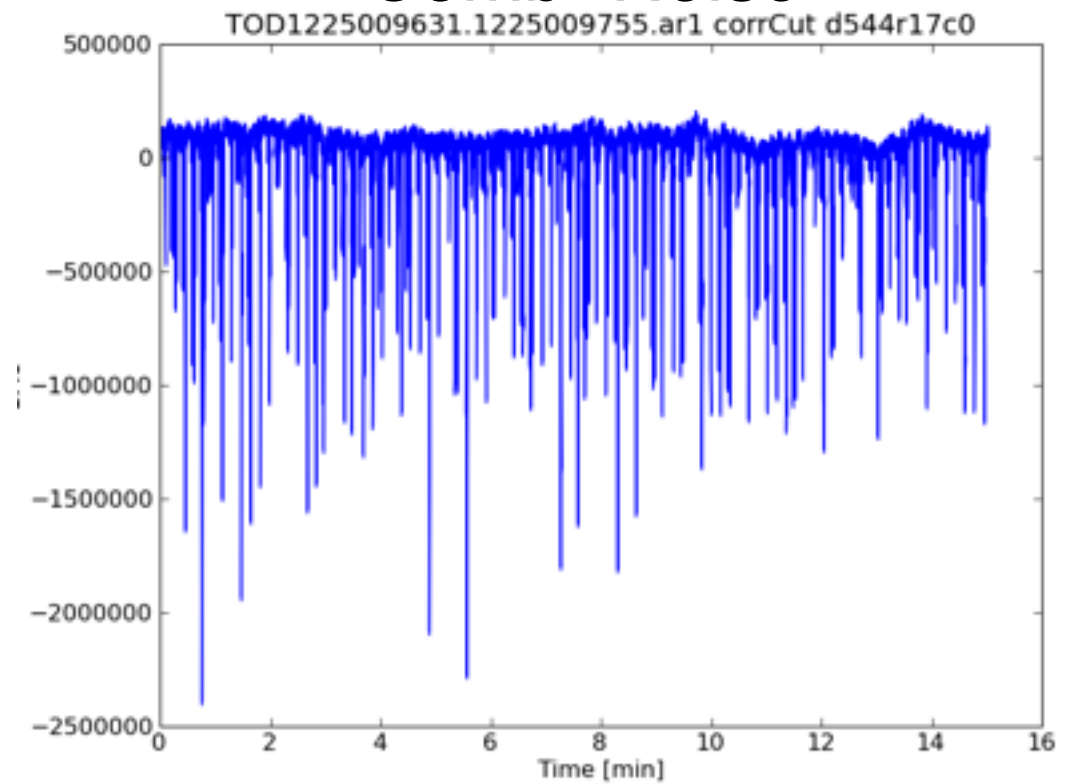


Pathologies Examples

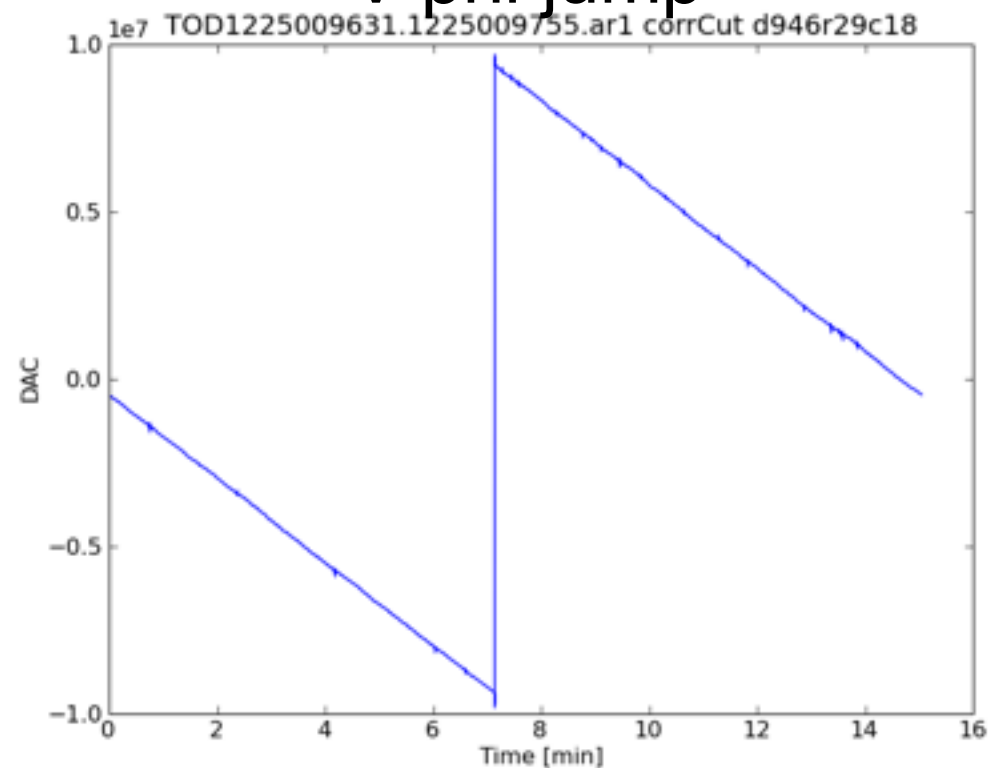
Normal + Glitch



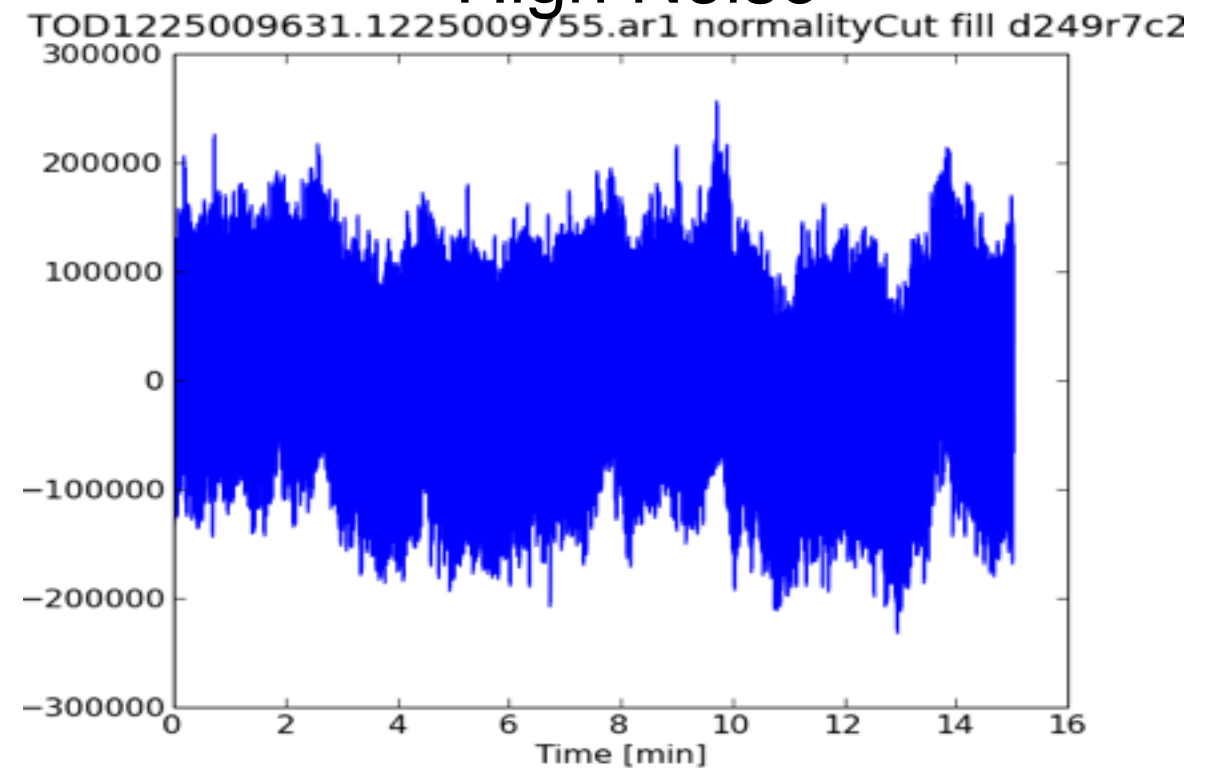
“Comb” Noise



V-phi jump



High Noise



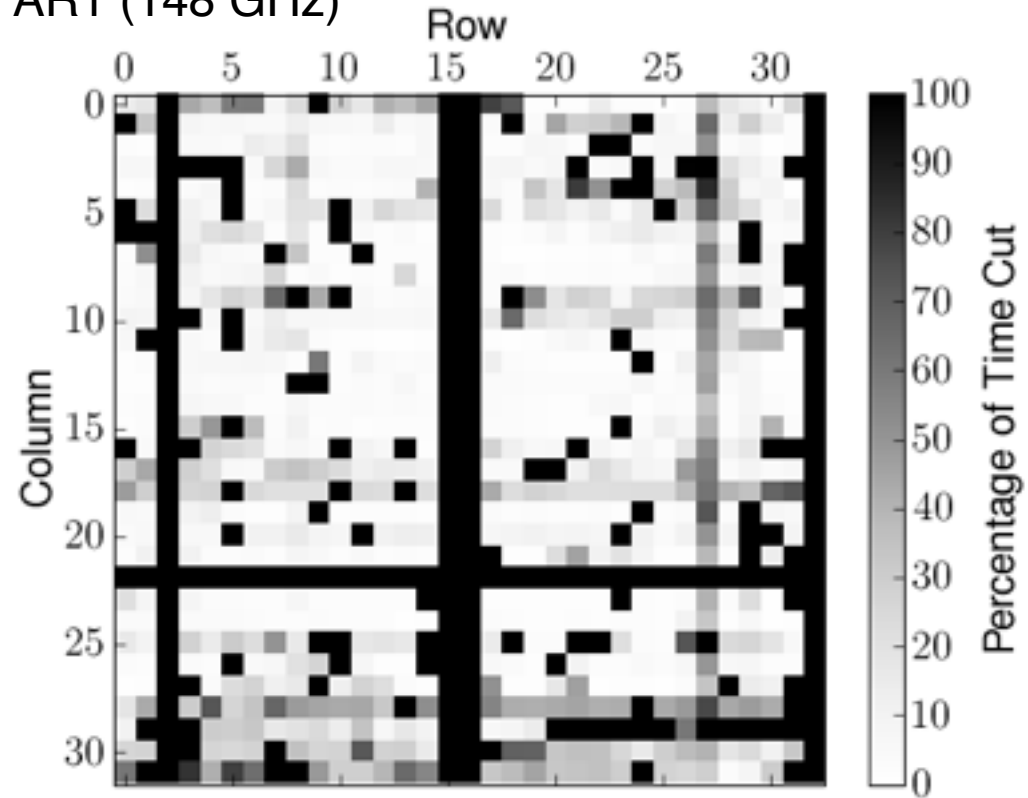
Detector Cuts Results

	148 GHz	218 GHz	277 GHz
<i>Detector classification</i>			
Live Candidates	800	959	685
Dark Candidates	128	62	55
Broken Detectors	128	35	316
Total	1024	1024	1024
<i>Cuts by criterion applied to live detectors</i>			
Drift Error	102.9	78.9	82.8
Norm	2.1	5.4	102.8
RMS	31.1	29.3	41.0
Skewness	0.6	0.9	0.5
Kurtosis	0.2	0.4	1.8
Slow	5.3	2.9	38.9
Glitches	5.0	4.9	25.0
Calibration	0.7	0.4	0.0
<i>Effective detectors</i>			
	652.1	835.9	392.3

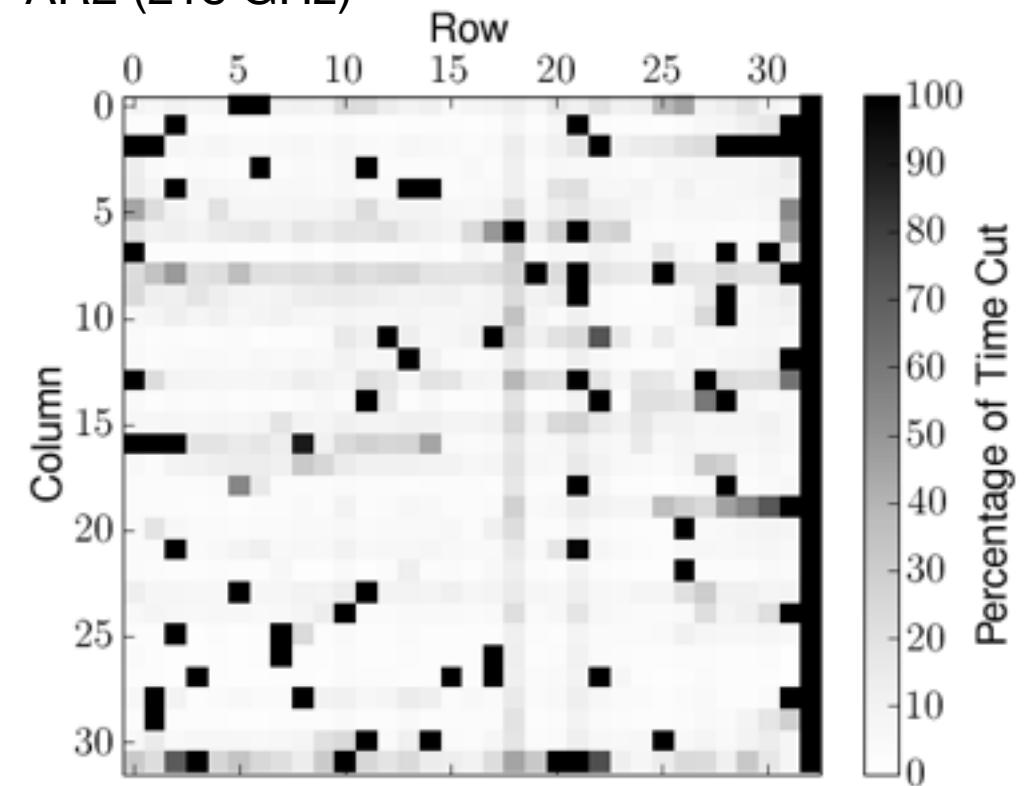
$$N_{eff} = \sum_{i=1}^N \frac{T_{i,uncut}}{T_{total}}$$

Detector Stability

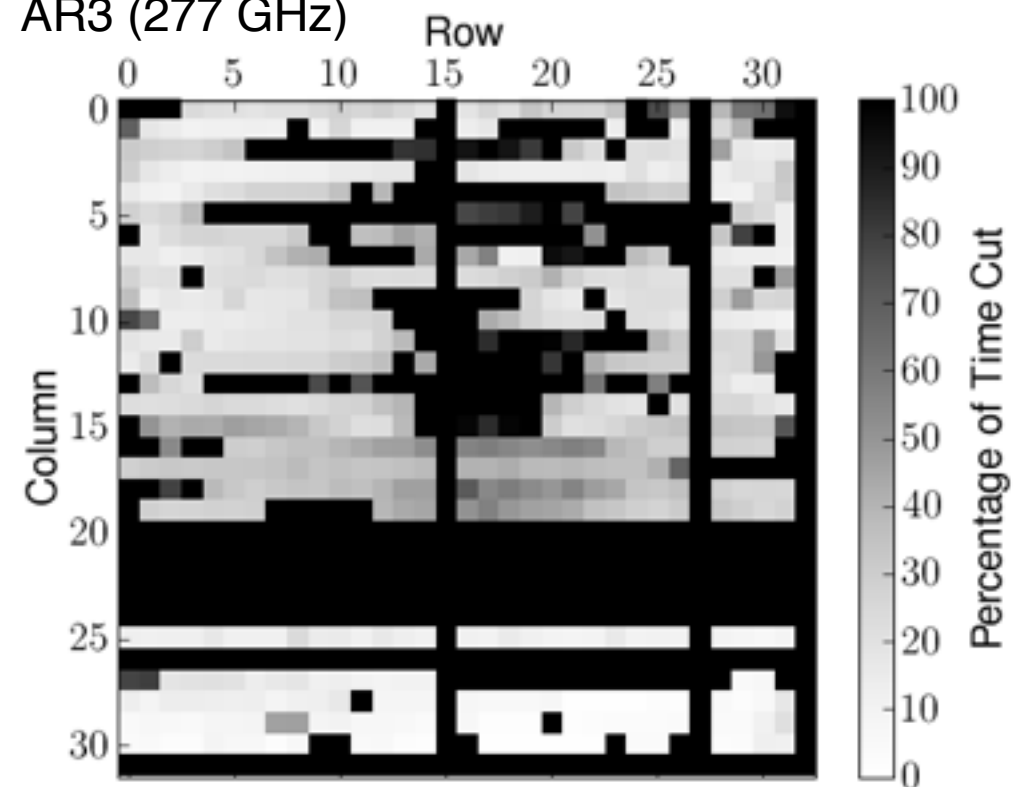
AR1 (148 GHz)



AR2 (218 GHz)



AR3 (277 GHz)

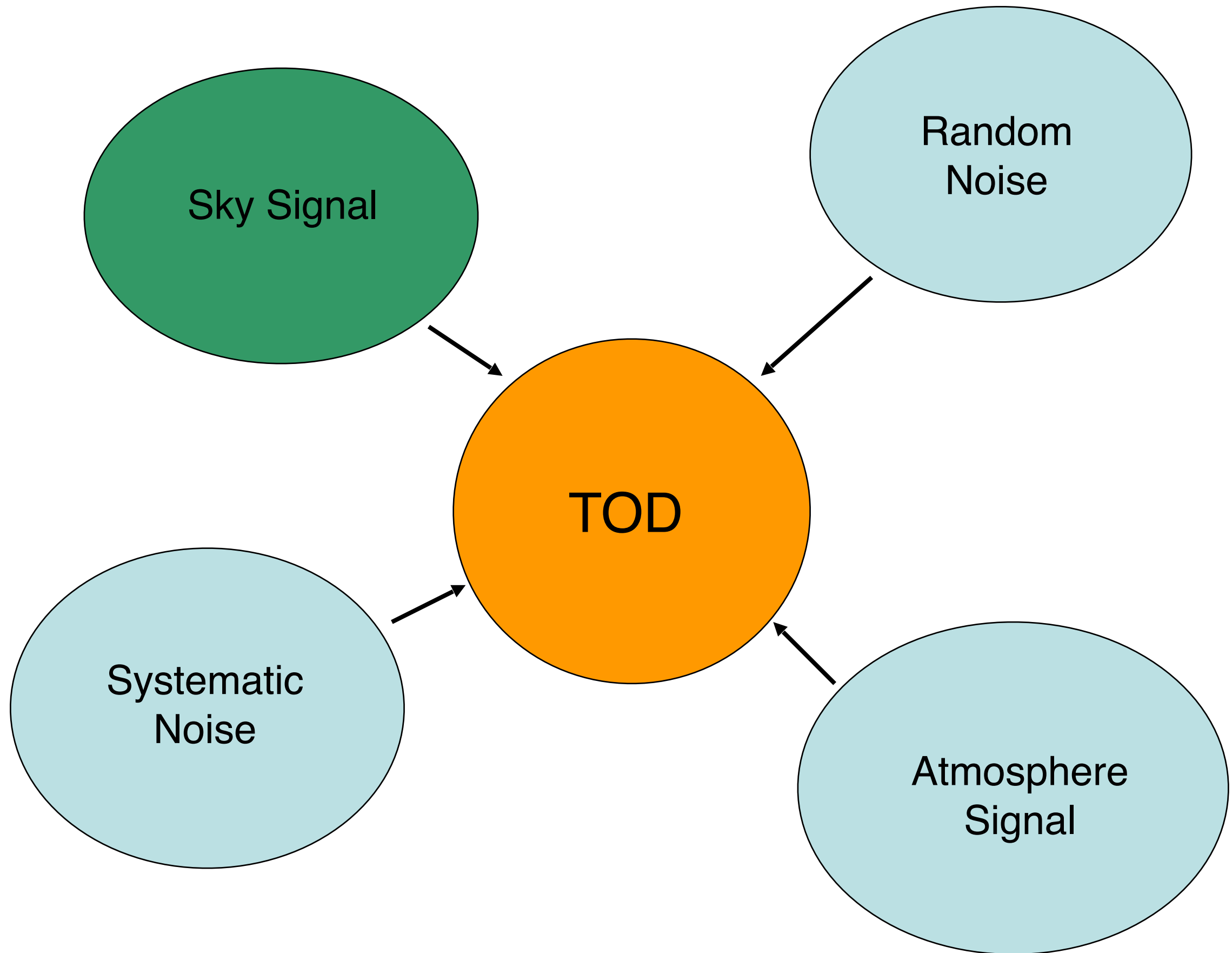


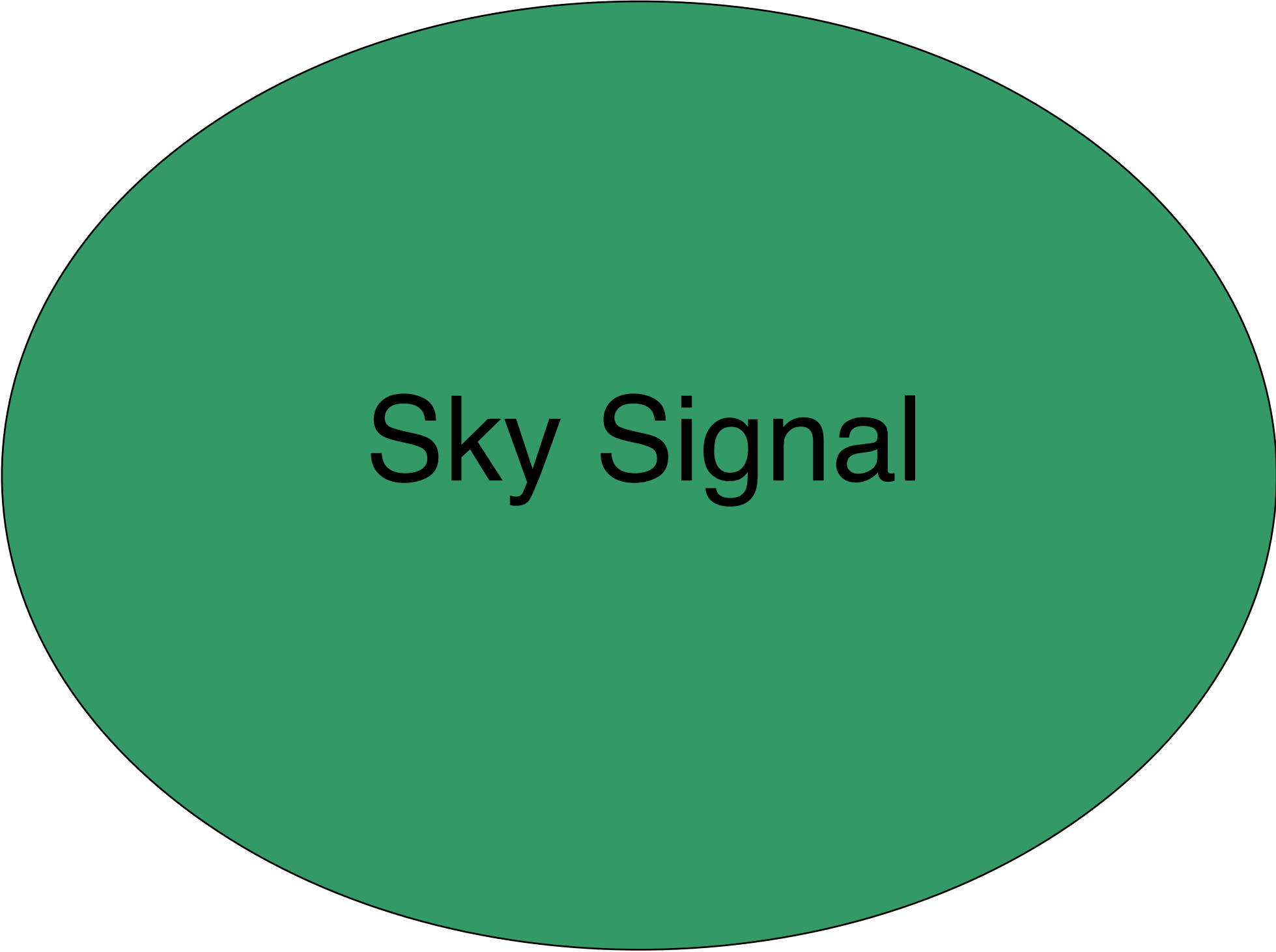
Data-files Selection

- Data files with less than 500 effective detectors in AR1 and AR2, and less than 150 effective detectors in AR3 are not used (12%, 12% and 16.7% of the observed hours respectively).
- Data files obtained while the PWV was higher than 3.0 mm for AR1, 2.0 mm for AR2 and 1.75 mm for AR3 were not used (nearly 4% of the data).

Year	148 GHz 2007	148 GHz 2008	218 GHz 2008	277 GHz 2008
Calendar	960 h	3264 h	3264 h	3264 h
Total Obs.	427 h	1423 h	1423 h	1437 h
Total Survey	348 h	1194 h	1191 h	1217 h
Low Effective Detectors	39 h	146 h	147 h	203 h
High PWV conditions	34 h	41 h	59 h	38 h
Uncut Survey	275 h	1007 h	985 h	976 h

Data Characterization





Sky Signal

Sky Signal (CMB)

- The CMB anisotropies on the celestial sphere can be decomposed in spherical harmonics, such that

$$a_{lm} = \int Y_{lm}^* \Delta T(\theta, \phi) d\Omega \quad \langle a_{lm} a_{l'm'}^* \rangle = C_l \delta_{ll'} \delta_{mm'}$$

- For a small patch on the sky, the multipole number $l \gg 1$ can be approximated by the wave number $k = 2\pi/\lambda_{sky}$.
- The multipole number is related to the TOD frequency as $l \approx \frac{2\pi}{\dot{\theta}} f_{TOD}$

ℓ	Season 2007	Season 2008
200	0.35 Hz	0.53 Hz
530	0.94 Hz	1.40 Hz
800	1.41 Hz	2.12 Hz
3000	5.30 Hz	7.95 Hz

Sky Signal (CMB)

- The CMB radiation has a blackbody spectrum of temperature 2.725 ± 0.002 K, meaning

$$I_\nu = \frac{2h\nu^3 / c^2}{e^{h\nu / kT} - 1}$$

- Temperature anisotropies of the CMB are 10^5 times smaller than that.
- In the Rayleigh-Jeans limit $I_\nu = \frac{2kT\nu^2}{c^2} = \frac{2kT}{\lambda^2}$
- Small changes in CMB temperature can be expressed in terms of a Rayleigh-Jeans equivalent as

$$\Delta T_{RJ} = \frac{x^2 e^x}{(e^x - 1)^2} \Delta T_{CMB}$$

where $x = h\nu / kT$

Sky Signal (Point Sources)

- Sources with angular size smaller than the beam size are considered point sources.
- The power absorbed from a point source with RJ temperature T_{RJ} and solid angle Ω_s is

$$P_{ps} = 2\varepsilon k T_{RJ} \frac{\Omega_s}{\Omega_A} \Delta\nu$$

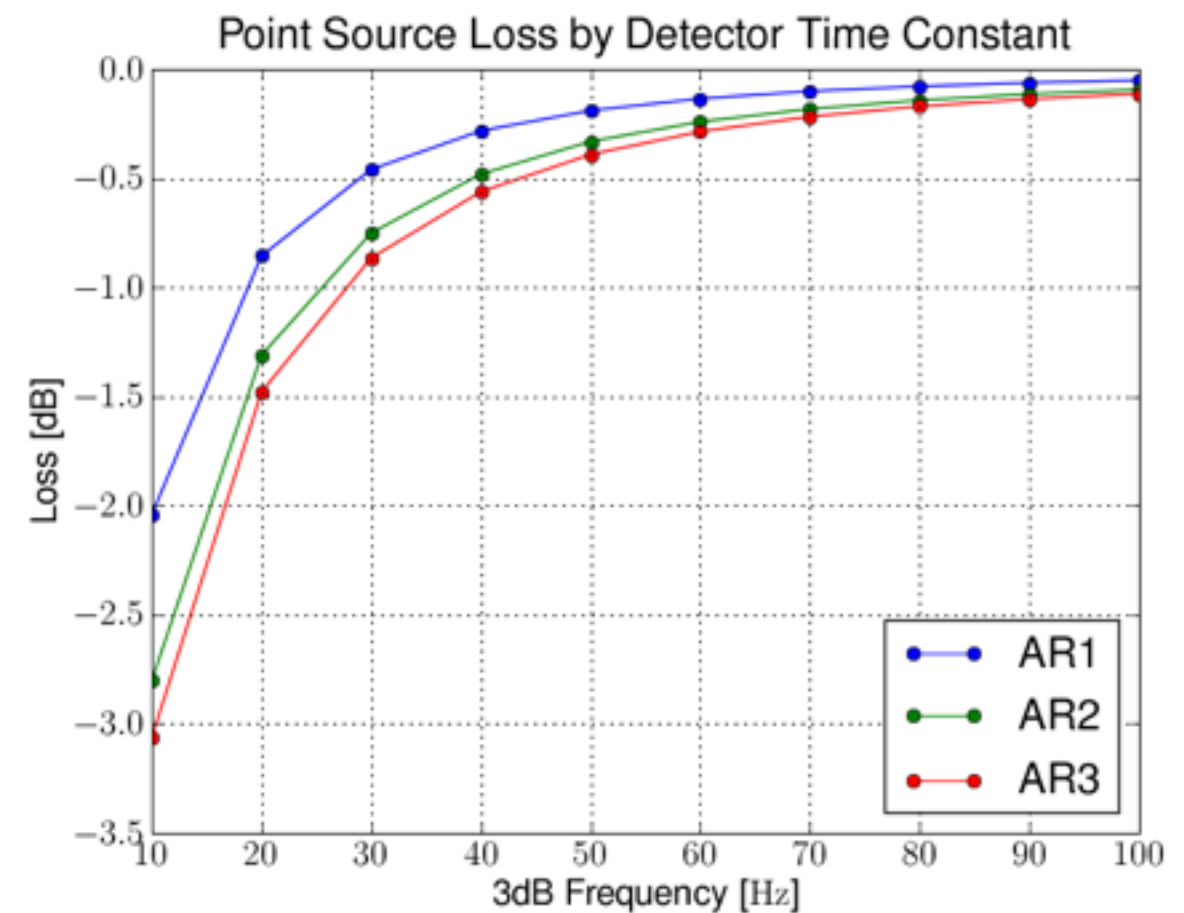
- The frequency response depends on the beam size θ_b , such that its -3dB point is given by

$$f_{-3dB} = 2 \log 2 \frac{\dot{\theta}}{\pi \theta_b}$$

	Season 2007	Season 2008
148 GHz	12.3 Hz	18.4 Hz
218 GHz	16.7 Hz	25.0 Hz
277 GHz	18.5 Hz	27.7 Hz

Sky Signal (Point Sources)

- Point sources can be affected by the detector time constant. The figure shows the power loss as a function of the -3dB point of the detector frequency response.
- The detector time constant can be measured using a chopping wheel or a bias step, such that it can be deconvolved with the TOD response to correct this effect.



Quartile	AR1 (148 GHz)	AR2 (218 GHz)	AR3 (277 GHz)
25 %	61.2 Hz	56.6 Hz	88.8 Hz
50 %	83.8 Hz	65.1 Hz	116.5 Hz
75 %	99.5 Hz	79.8 Hz	197.1 Hz

Sky Signal (Point Sources)

Table 4. Relevant values characterizing planet signals for 148 GHz. Columns: (2): Raleigh Jeans temperature of the planet. (3): Planet solid angle. (4): Dilution factor. (5): Peak power loading the detectors including efficiency factor. (6) Peak measured temperature in CMB equivalent units. (7) Crossing time of the planet.

Source		T_{RJ} [K]	Ω [nsr]	Ω/Ω_0	ΔP [pW]	T_{CMB} [K]	Δt [ms]
Saturn	min	140	6	2.7×10^{-2}	2.75×10^{-1}	6.39	56
	max		8	3.6×10^{-2}	3.67×10^{-1}	8.52	57
Jupiter	min	170	20	8.9×10^{-2}	1.11×10^{-0}	25.9	63
	max		40	1.8×10^{-1}	2.23×10^{-0}	51.7	69
Mars	min	168	0.32	1.4×10^{-3}	1.76×10^{-2}	0.409	50
	max		5.50	2.4×10^{-2}	3.03×10^{-1}	7.03	56
Uranus	min	120	0.20	8.9×10^{-4}	7.86×10^{-3}	0.183	50
	max		0.27	1.1×10^{-3}	1.06×10^{-2}	0.247	50
Neptune	min	120	0.09	4.0×10^{-4}	3.54×10^{-3}	0.0822	50
	max		0.10	4.4×10^{-4}	3.92×10^{-3}	0.0913	50

Calibration Parameters

$T_{RJ}/\delta W_{abs}$ (C) ^b	(K/pW)	13.57 ± 0.12	8.95 ± 0.06	4.90 ± 0.30
$T_{CMB}/\delta W_{abs}$	(K/pW)	23.22 ± 0.45	27.03 ± 0.65	26.65 ± 1.78
ϵ		0.130 ± 0.008	0.231 ± 0.012	0.292 ± 0.023

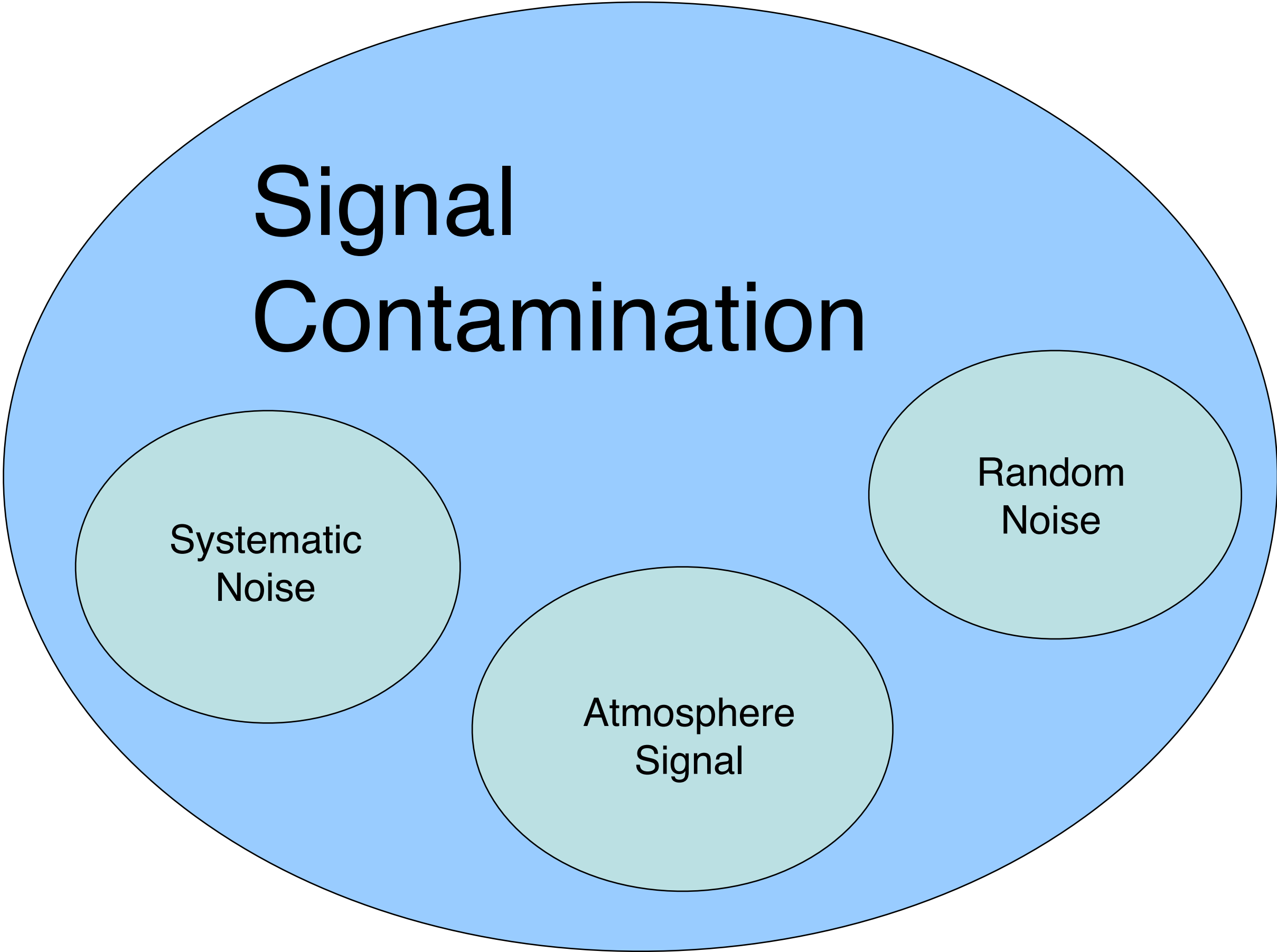
Parameters Summary

		Units	148 GHz	218 GHz	277 GHz
<i>Instrument parameters</i>					
Band center	(GHz)		148 ± 2.5	218 ± 2.5	277 ± 2.5
Bandwidth	(GHz)		20.6 ± 1.3	17.5 ± 0.9	25.3 ± 1.3
Ω_A^a	(nsr)		218 ± 4	118 ± 3	105 ± 6
Beam size ^a	(')		1.37 ± 0.03	1.01 ± 0.01	0.91 ± 0.03
<i>Relevant conversions</i>					
$\delta T_{\text{CMB}}/\delta T_{\text{RJ}}$			1.711 ± 0.030	3.020 ± 0.070	5.439 ± 0.145
$\delta W/\delta T_{\text{RJ}}$	(pW/K)		0.569 ± 0.036	0.483 ± 0.025	0.699 ± 0.036
Γ	($\mu\text{K}/\text{Jy}$)		6810 ± 262	5794 ± 198	4032 ± 241
<i>Calibration Parameters</i>					
$T_{\text{RJ}}/\delta W_{\text{abs}}$ (C) ^b	(K/pW)		13.57 ± 0.12	8.95 ± 0.06	4.90 ± 0.30
$T_{\text{CMB}}/\delta W_{\text{abs}}$	(K/pW)		23.22 ± 0.45	27.03 ± 0.65	26.65 ± 1.78
ϵ			0.130 ± 0.008	0.231 ± 0.012	0.292 ± 0.023

^aValues obtained by Adam Hincks [7]

^bValues obtained by Adam Hincks from calibrating to Uranus observations.

Signal Contamination

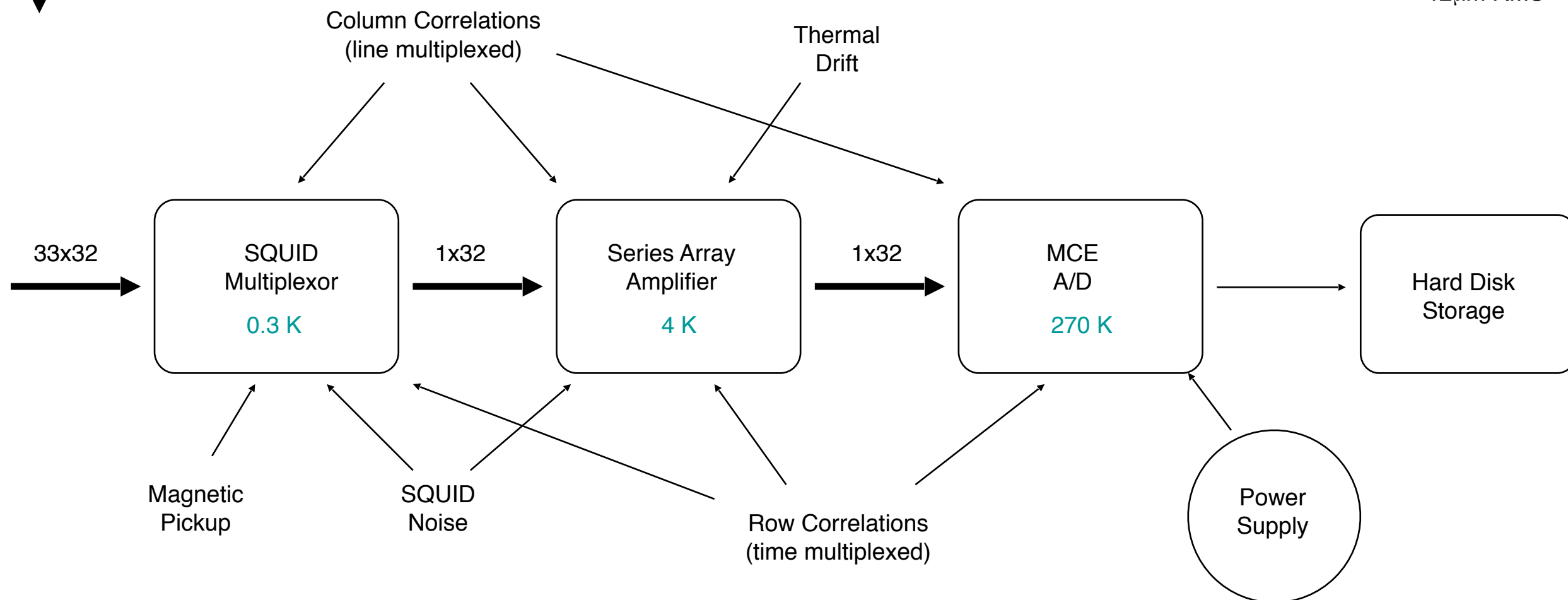
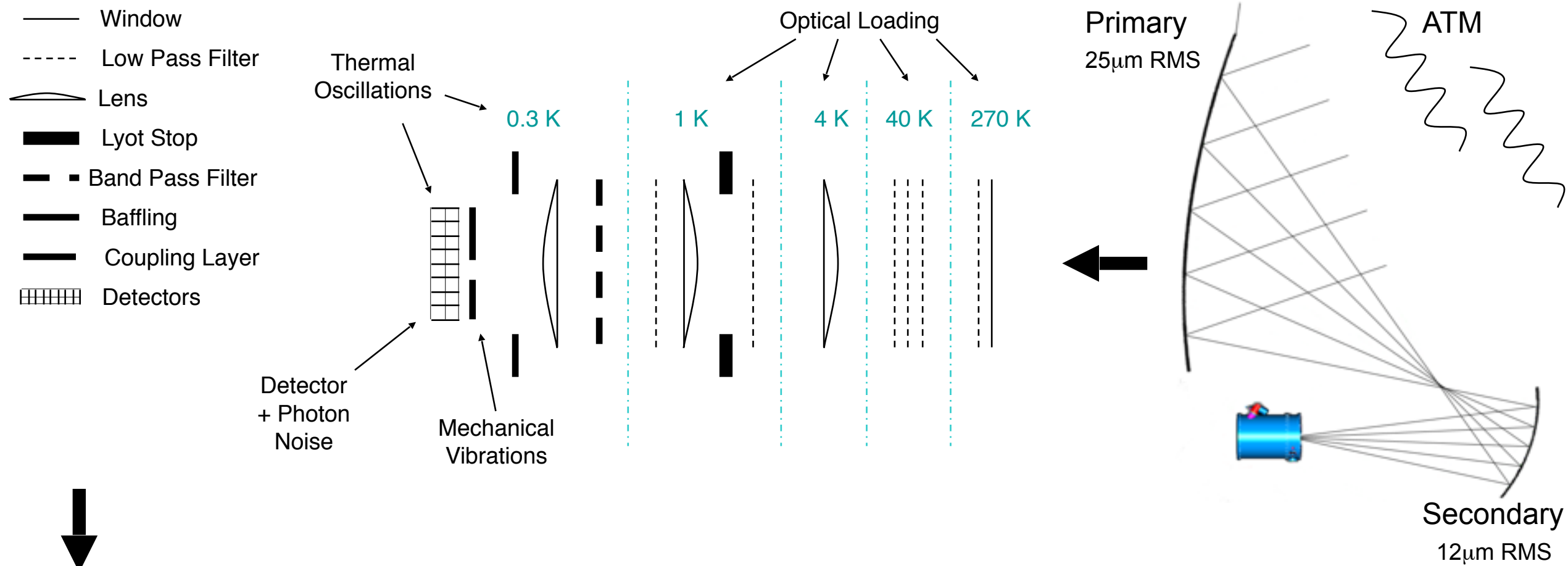


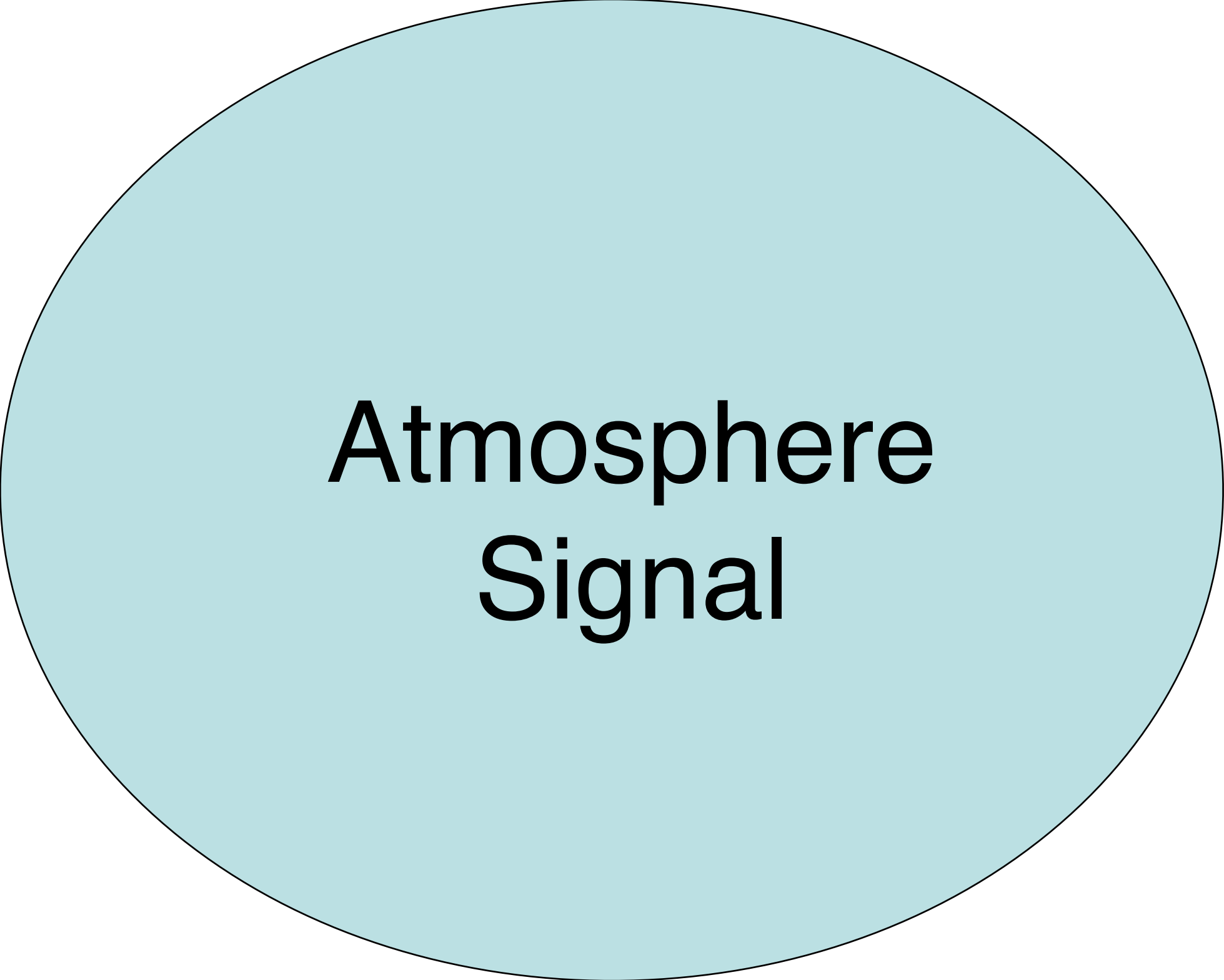
```
graph TD; SC([Signal Contamination]) --- SN([Systematic Noise]); SC --- AS([Atmosphere Signal]); SC --- RN([Random Noise]);
```

Systematic
Noise

Atmosphere
Signal

Random
Noise





Atmosphere Signal

Atmosphere

- The atmosphere is a significant absorber/emitter at the ACT bands, specially due to its water and oxygen content.
- Extended “wings” from emission lines generate a continuum, with a level that mostly depends on the Precipitable Water Vapor (PWV).
- Under the Rayleigh-Jeans regime, the emission is given by

$$I_{atm} = \frac{2kT_{atm}}{\lambda^2} (1 - e^{-\tau A}) = \frac{2kT_{RJ}}{\lambda^2}$$

where the transmission parameter (absorption) is $T_{atm} = e^{-\tau A}$

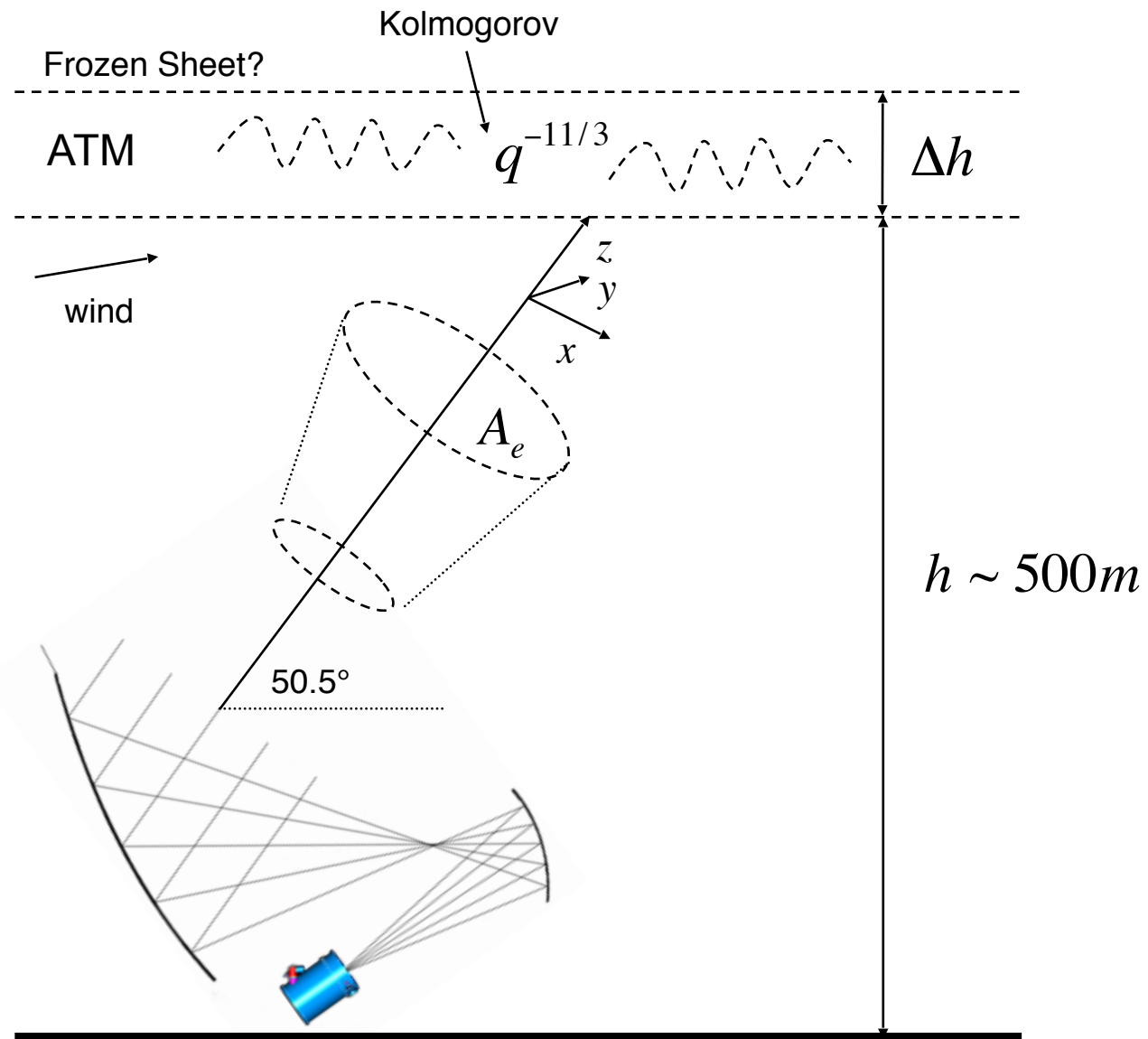
- The atmosphere emission/absorption can be modeled, mainly as a function of PWV. The modeling software ATM gives, at an elevation of 50.5°

- 148 GHz : $T_{RJ} = 6.0 \text{ PWV} + 3.5 \text{ K}$; $\tau A = 0.025 \text{ PWV} + 0.012$; $P_{atm} = 0.45 \text{ PWV} + 0.27 \text{ pW}$;
 218 GHz : $T_{RJ} = 12.6 \text{ PWV} + 4.1 \text{ K}$; $\tau A = 0.058 \text{ PWV} + 0.010$; $P_{atm} = 1.47 \text{ PWV} + 0.48 \text{ pW}$;
 277 GHz : $T_{RJ} = 18.8 \text{ PWV} + 9.3 \text{ K}$; $\tau A = 0.097 \text{ PWV} + 0.026$. $P_{atm} = 4.13 \text{ PWV} + 2.05 \text{ pW}$.

Atmosphere

Ind	PWV [mm]	T_{RJ} [K]	τA [nepers]	$\mathcal{T}_{atm}$	P_{atm} [pW]
<i>AR1 148 GHz</i>					
25%	0.32	5.42	0.0200	0.980	0.41
50%	0.49	6.44	0.0243	0.976	0.49
75%	0.85	8.60	0.0333	0.967	0.65
<i>AR2 217 GHz</i>					
25%	0.32	8.13	0.0546	0.947	0.95
50%	0.49	10.27	0.0690	0.933	1.20
75%	0.85	14.81	0.0995	0.905	1.73
<i>AR3 277 GHz</i>					
25%	0.32	15.32	0.0570	0.945	3.37
50%	0.49	18.51	0.0735	0.929	4.07
75%	0.85	25.28	0.1085	0.897	5.56

Atmosphere Fluctuations



Two possible regimes:

1. 3D regime: $f^{-11/3}$
2. 2D regime: $f^{-8/3}$

Church Model:

Predicts that we should be dominated by the 2D regime.

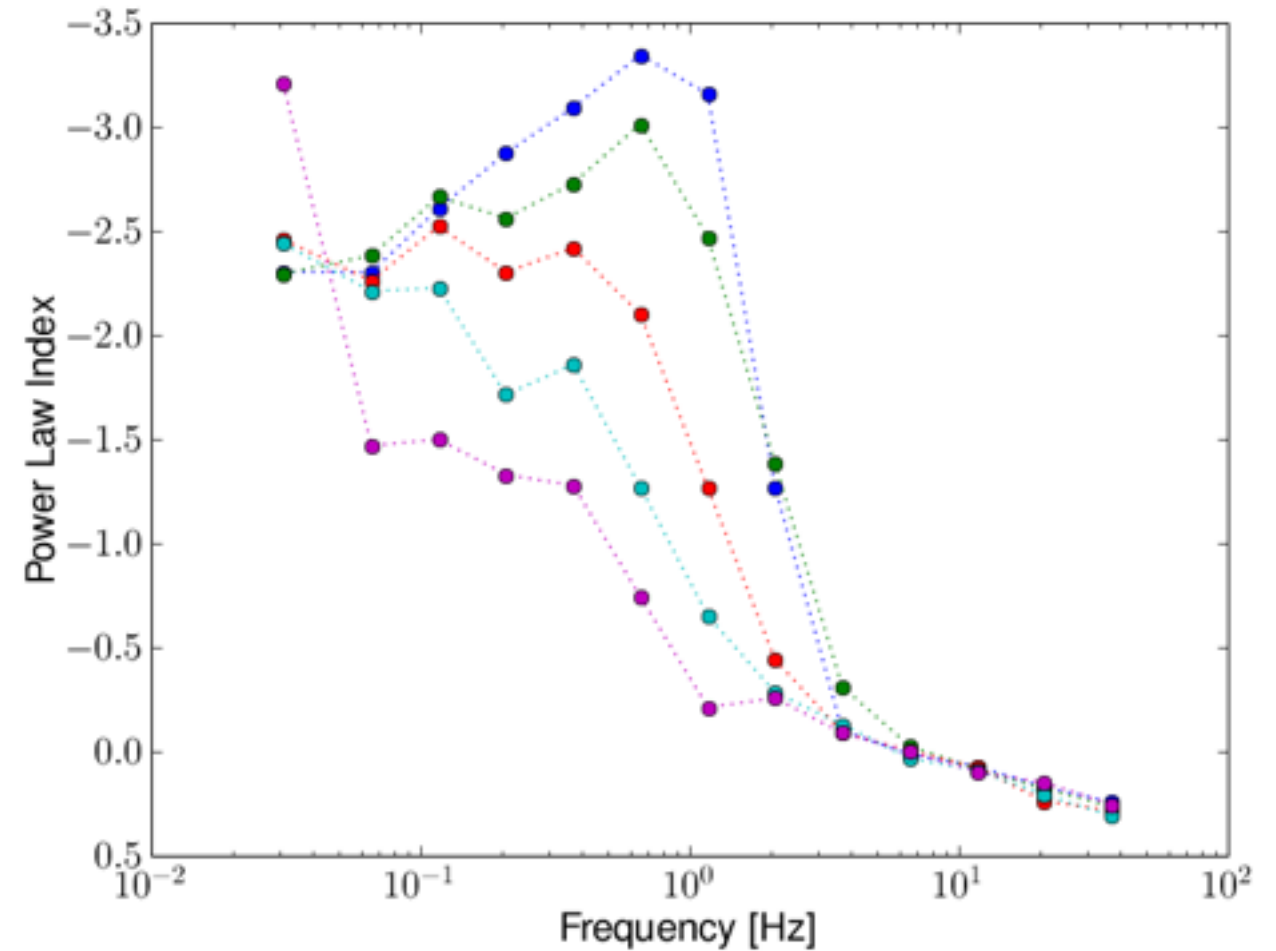
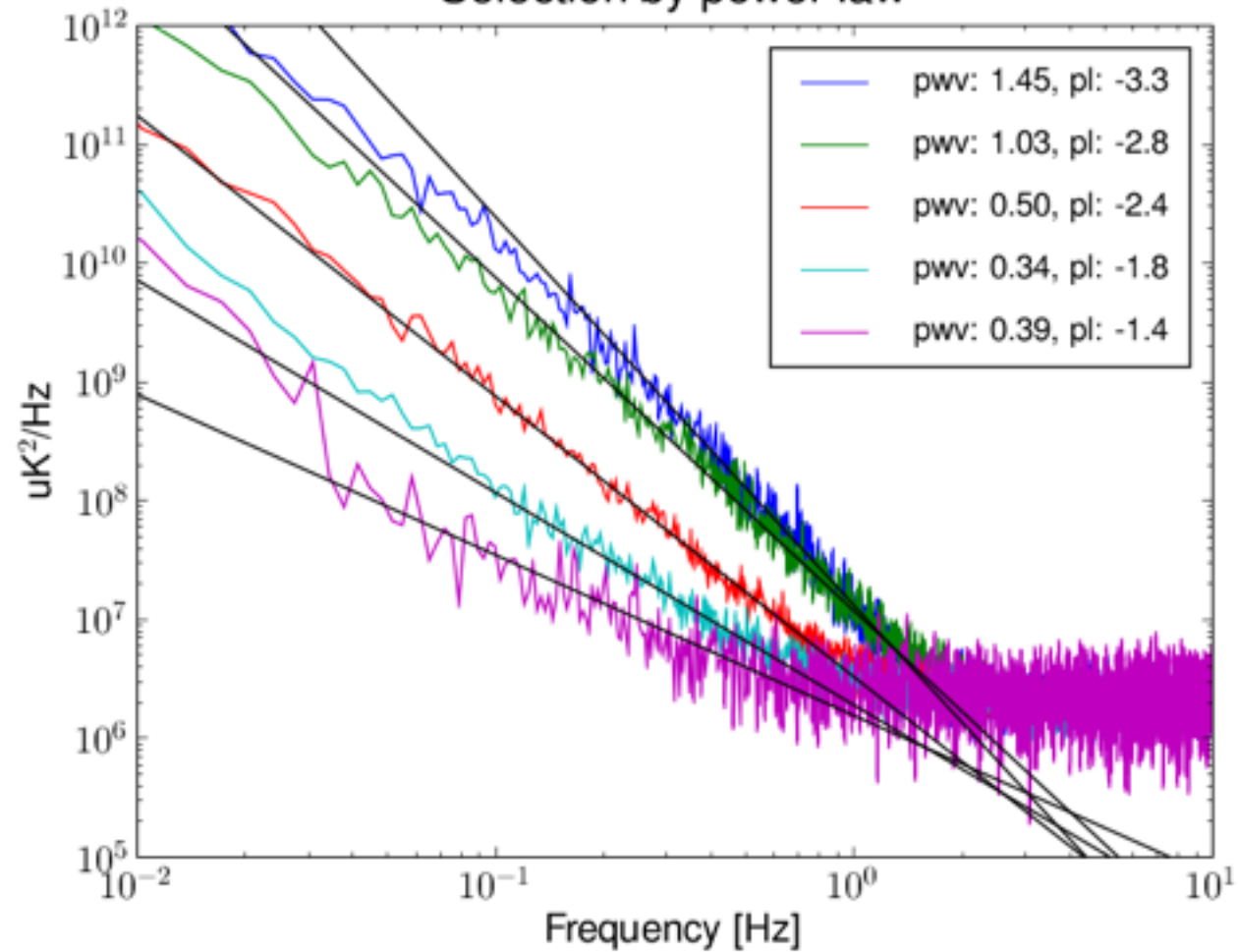
Lay & Halverson Model:

Predicts that we should be dominated by the 3D regime.

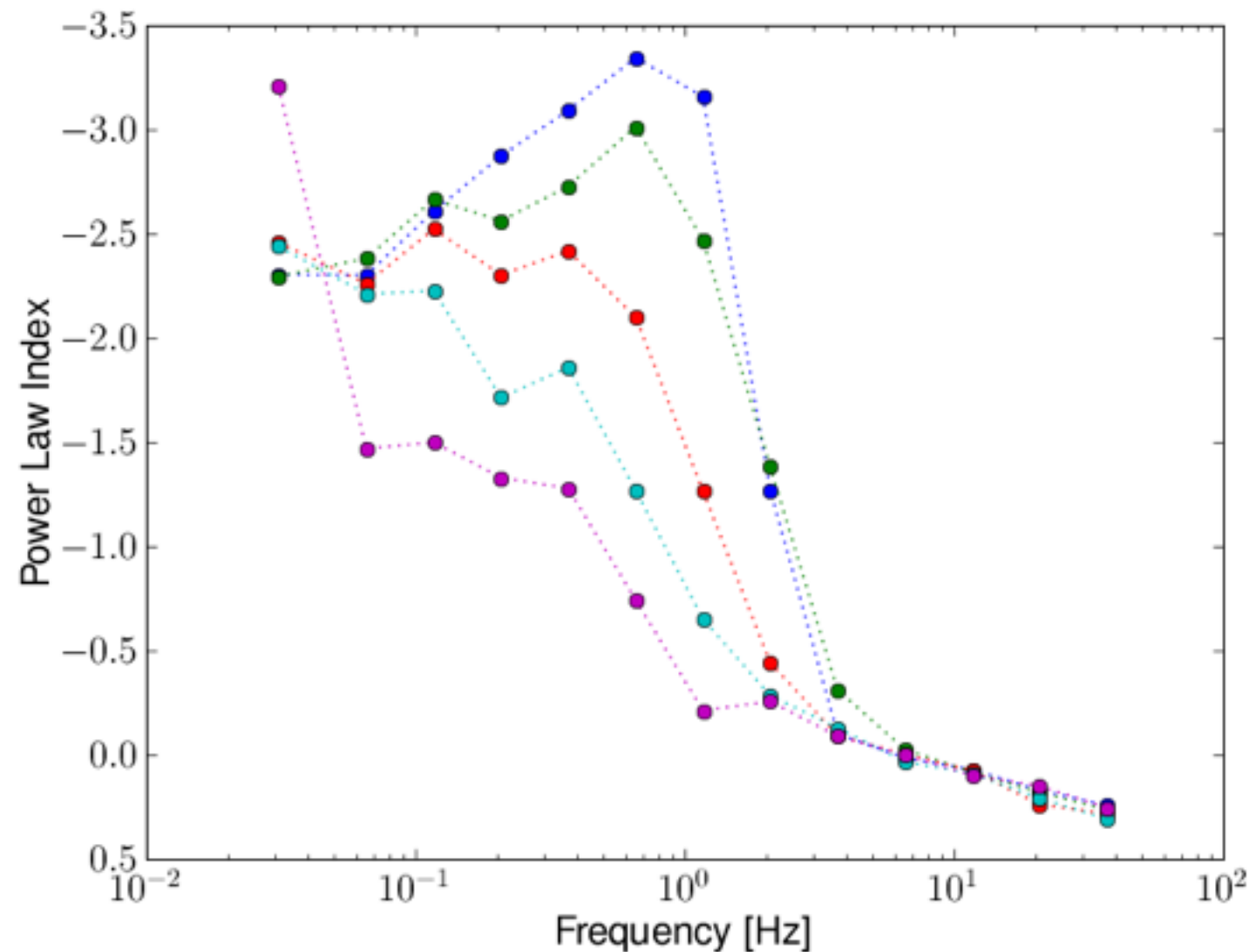
Atmosphere Signal

Stare data

Selection by power law



Atmosphere Signal



Some conclusions:

- The atmospheric fluctuations are dominated by the 2D regime.
- The 2D regime completely dominates at low TOD frequencies, while at higher frequencies there is some influence from the 3D regime.
- The power law is steeper for higher PWV.
- For very low PWV, the power law is dominated by the thermal instability of the camera ($n \sim 1.5$).
- The knee frequency ranges from 1-3 Hz for stare data, but increases for scan data.

Atmosphere Signal Removal

- The atmosphere appears mostly as a common mode between detectors. This common mode can be generalized as

$$\hat{m} = \mathbf{A}\hat{v}\mathbf{w}^{-1}$$

- The linear combination $\hat{v}$ can be used to find modes which are strongly correlated among detector TODs. This can be done using Singular Value Decomposition (SVD), defined as

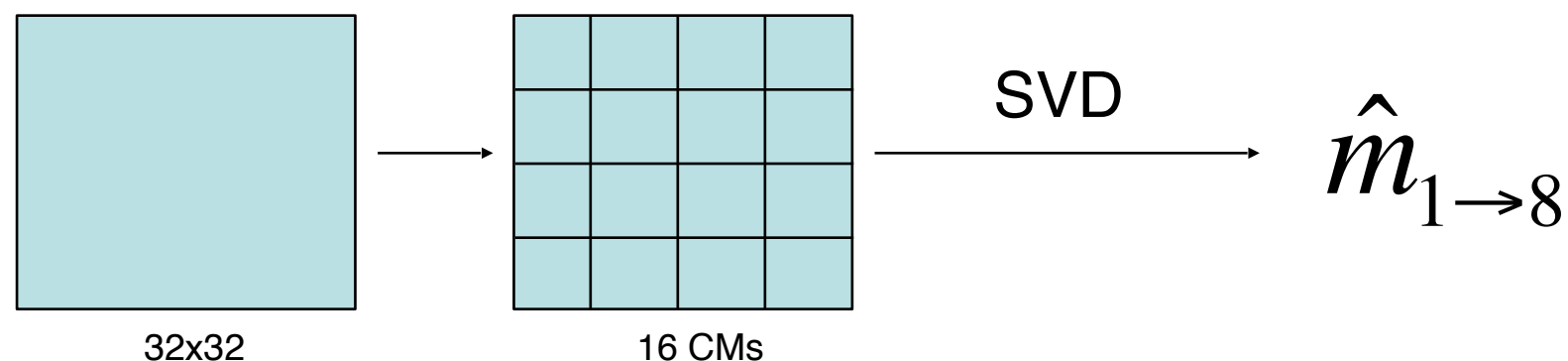
$$\left\{ \begin{array}{c} \mathbf{A} \end{array} \right\} = \left\{ \begin{array}{c} \text{vertical bar} \\ \hat{\mathbf{U}} \end{array} \right\} \left\{ \begin{array}{c} \text{small square} \\ \mathbf{W} \end{array} \right\} \left\{ \begin{array}{c} \text{horizontal bar} \\ \hat{\mathbf{V}}^T \end{array} \right\}$$

- The mode can be projected out of the data as

$$\mathbf{A}' = (\mathbf{I} - \hat{m}\hat{m}^T)\mathbf{A} = \mathbf{A}(\mathbf{I} - \hat{v}\hat{v}^T\mathbf{A}^T\mathbf{A}\mathbf{w}^{-2}) = \mathbf{A}(\mathbf{I} - \hat{v}_i\hat{v}_i^T)$$

Atmosphere Signal Removal

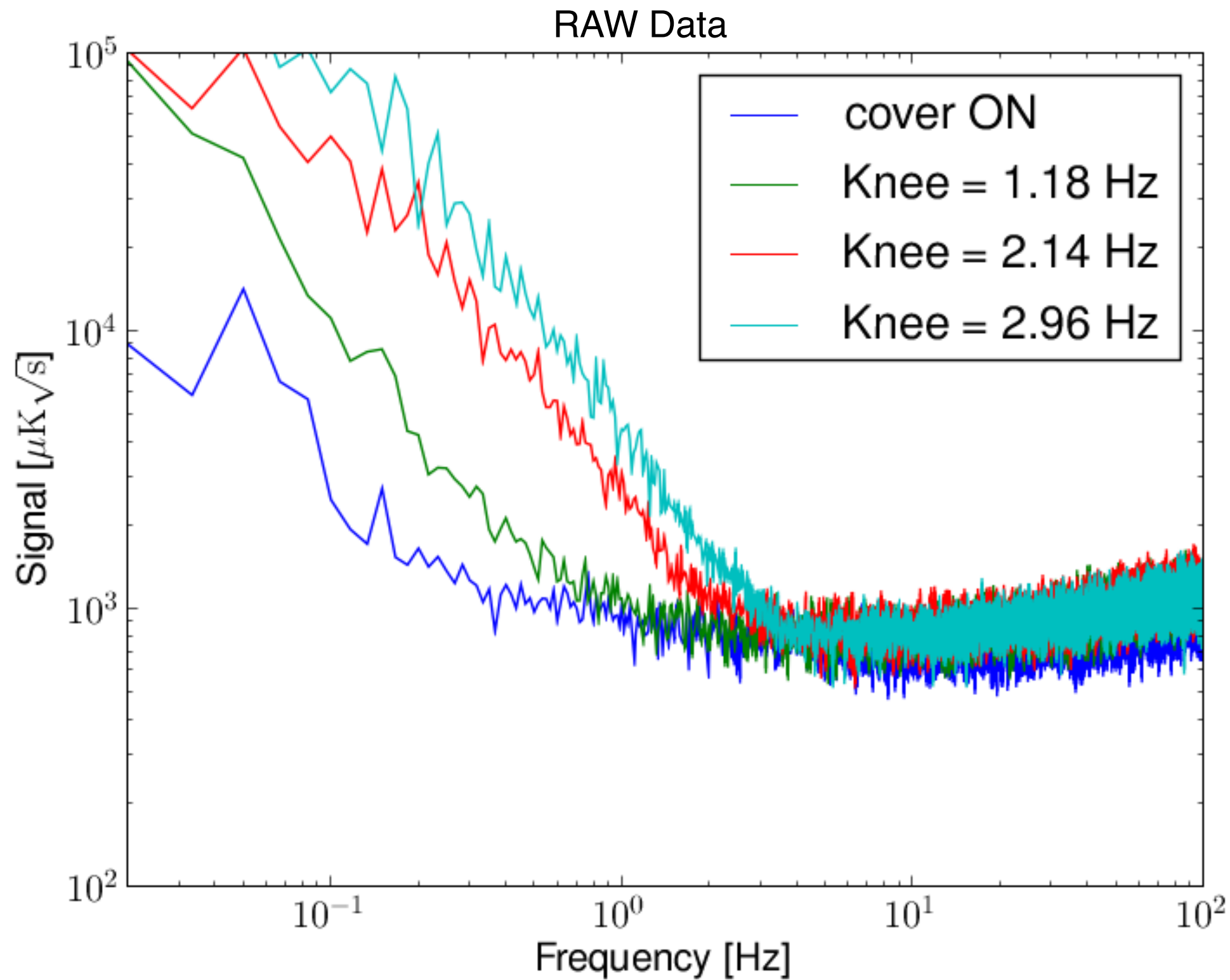
- Sometimes it is useful to apply the SVD with a prior, which means pre-combining detector TODs.
- Given that the effective beam at the turbulence distance is ~ 10 arcmin, we expect the atmosphere signal to be coherent within a third of the array.
- The “multi-common” mode is defined as:



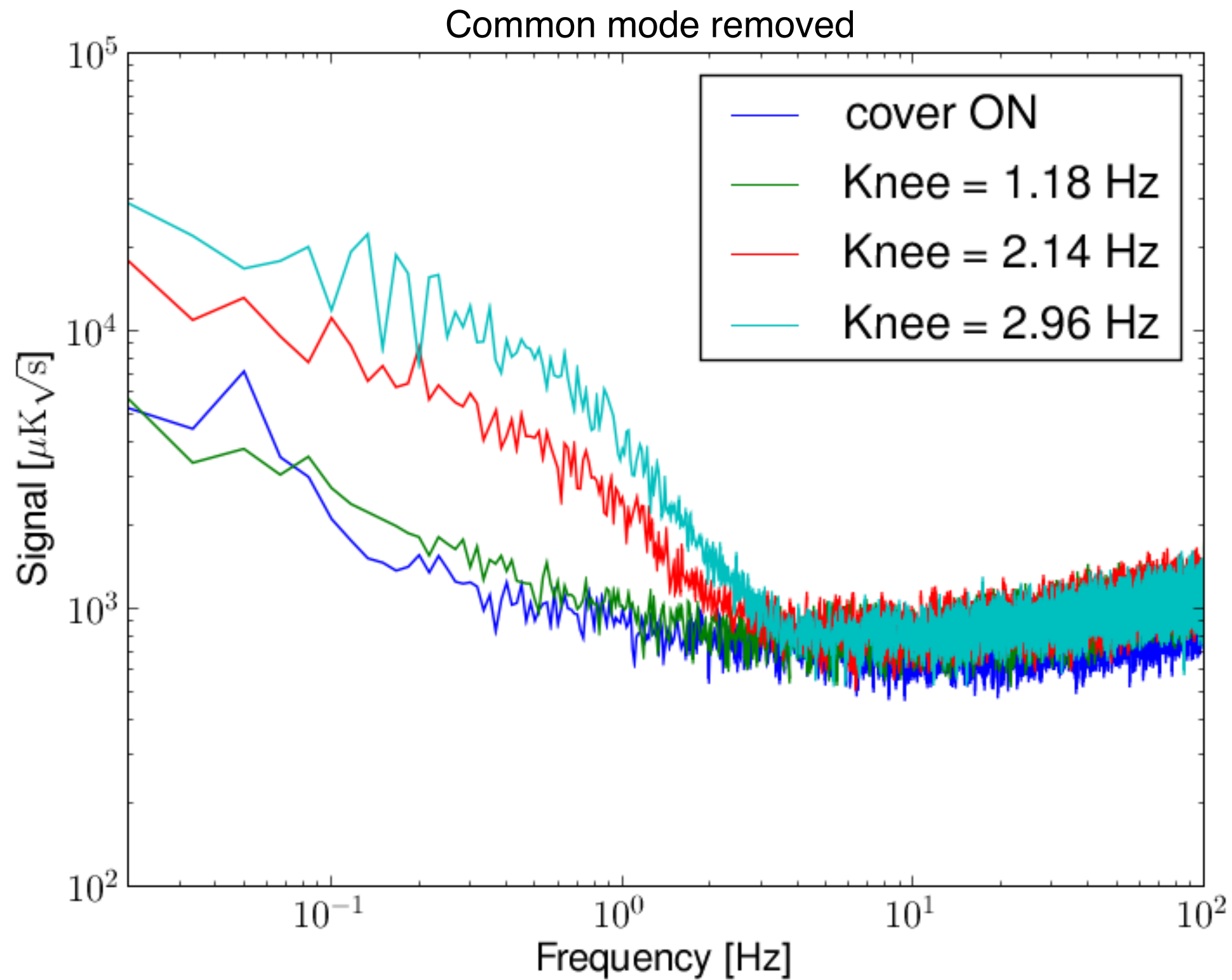
- Using modes obtained from live detector TODs have the disadvantage that it can bias the sky signal, as it is also correlated between detectors.

	Size	Freq 2007	Freq 2008
Common mode	24' (l = 450)	0.8 Hz	1.2 Hz
Multi-common mode	6' (l = 1800)	3.2 Hz	4.8 Hz

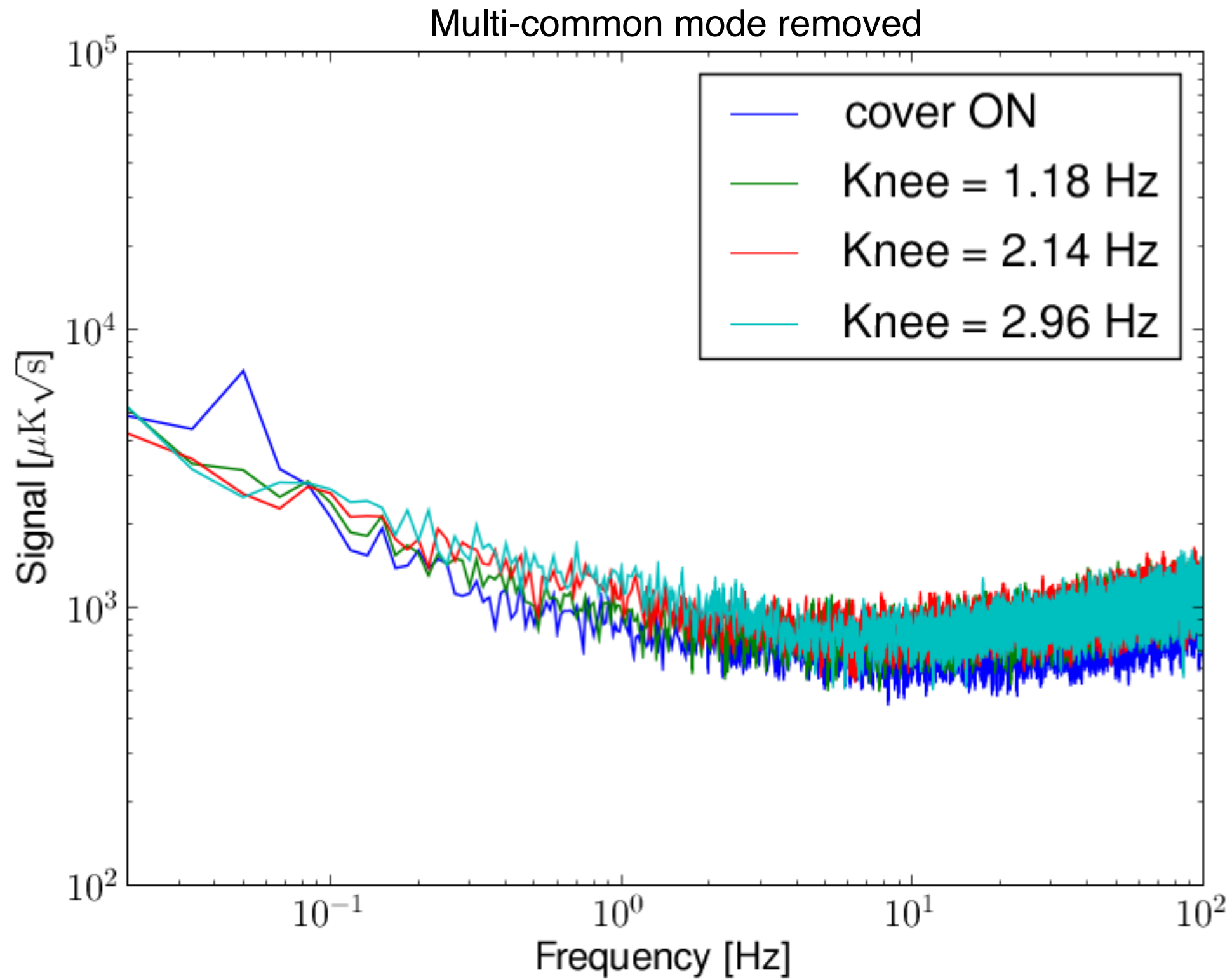
Atmosphere Signal Removal



Atmosphere Signal Removal

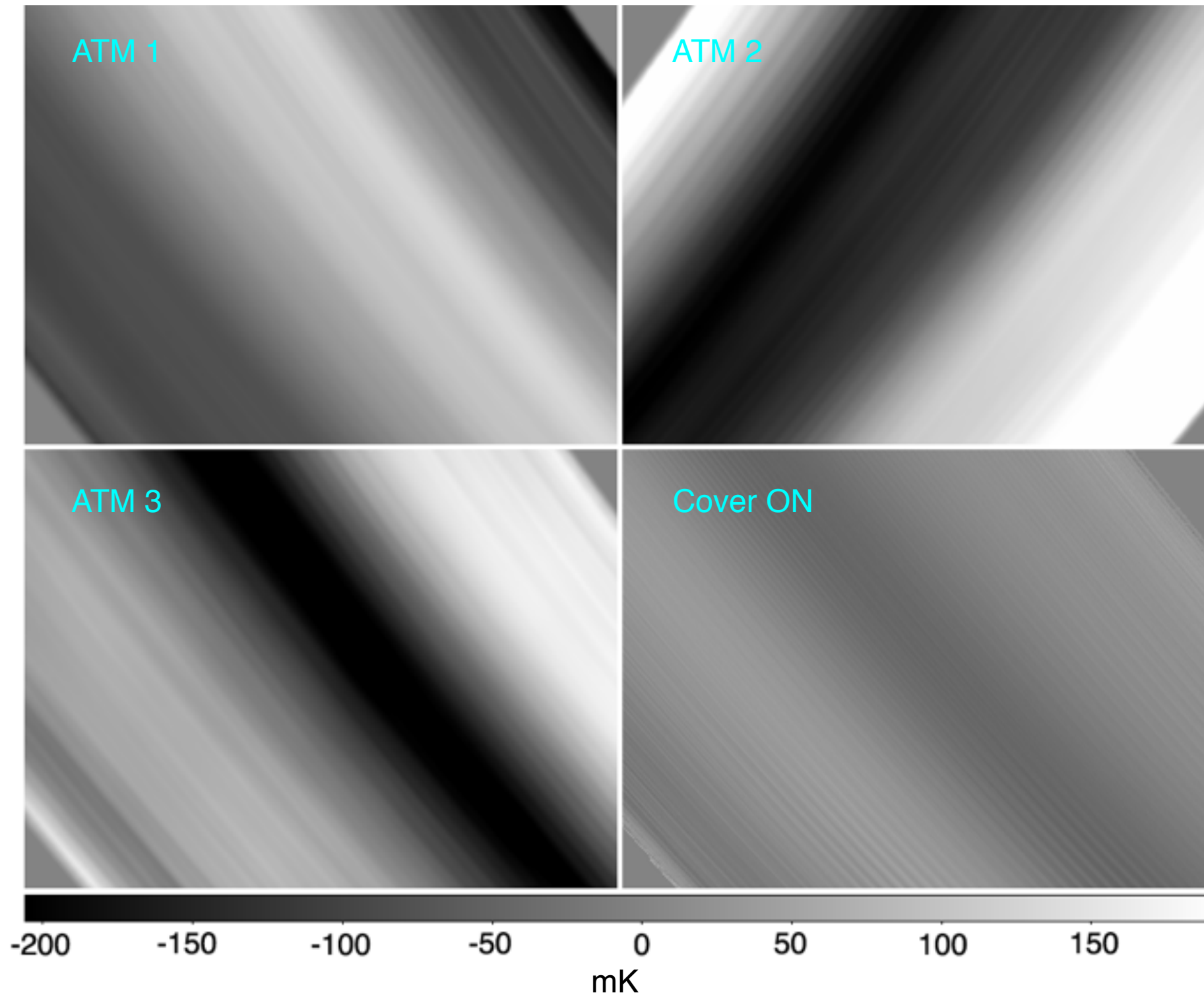


Atmosphere Signal Removal



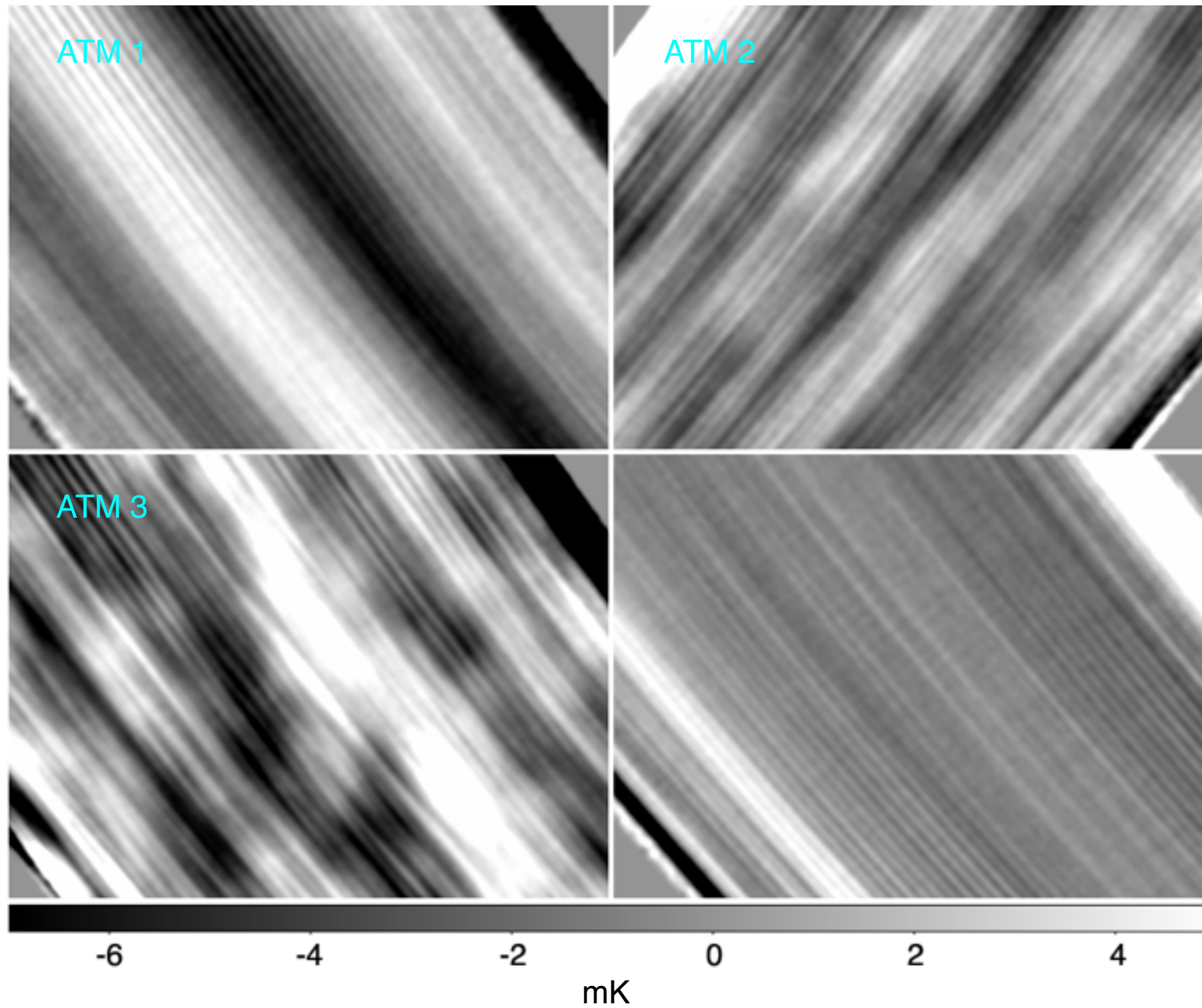
Atmosphere Signal Removal

Raw Data



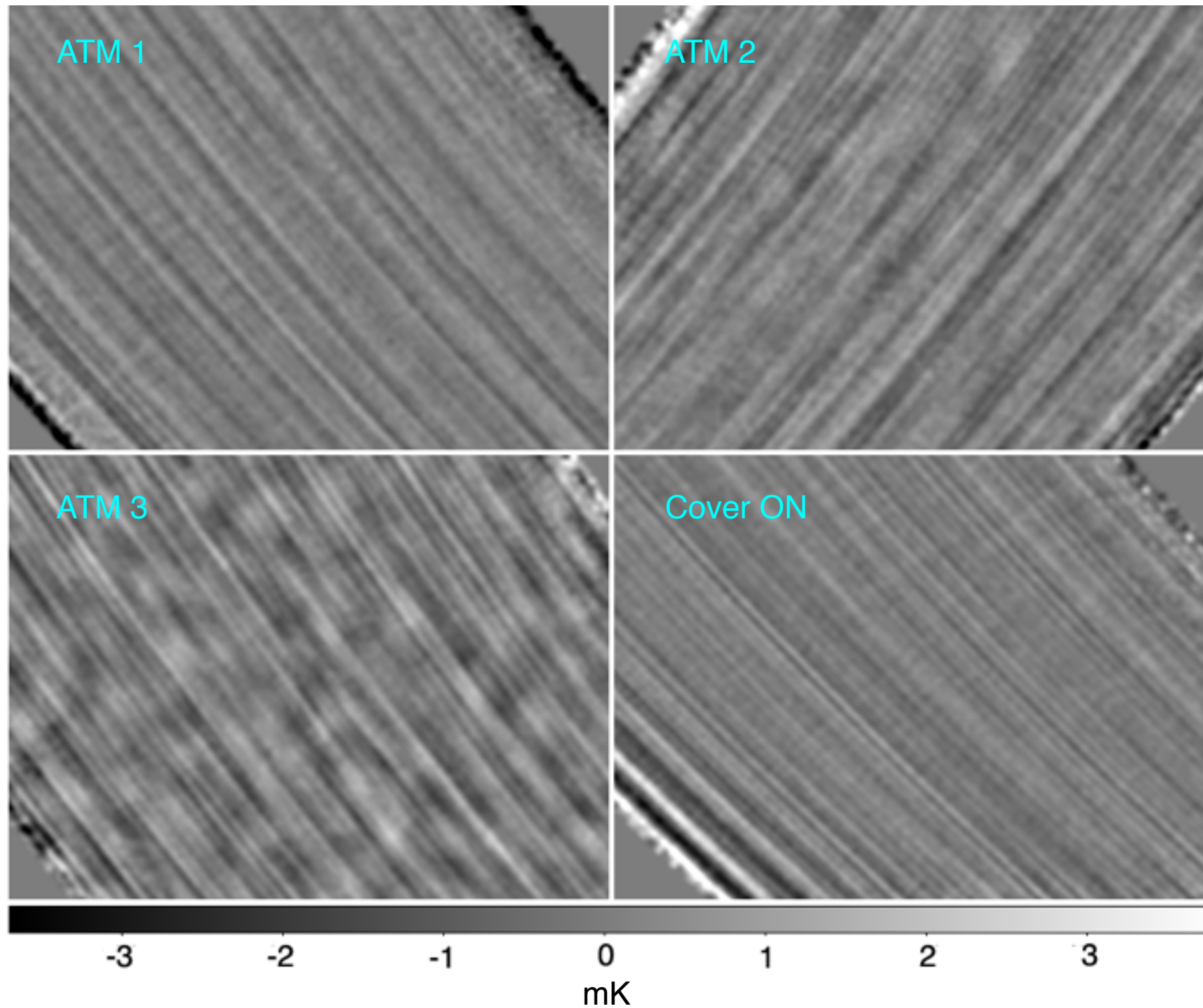
Atmosphere Signal Removal

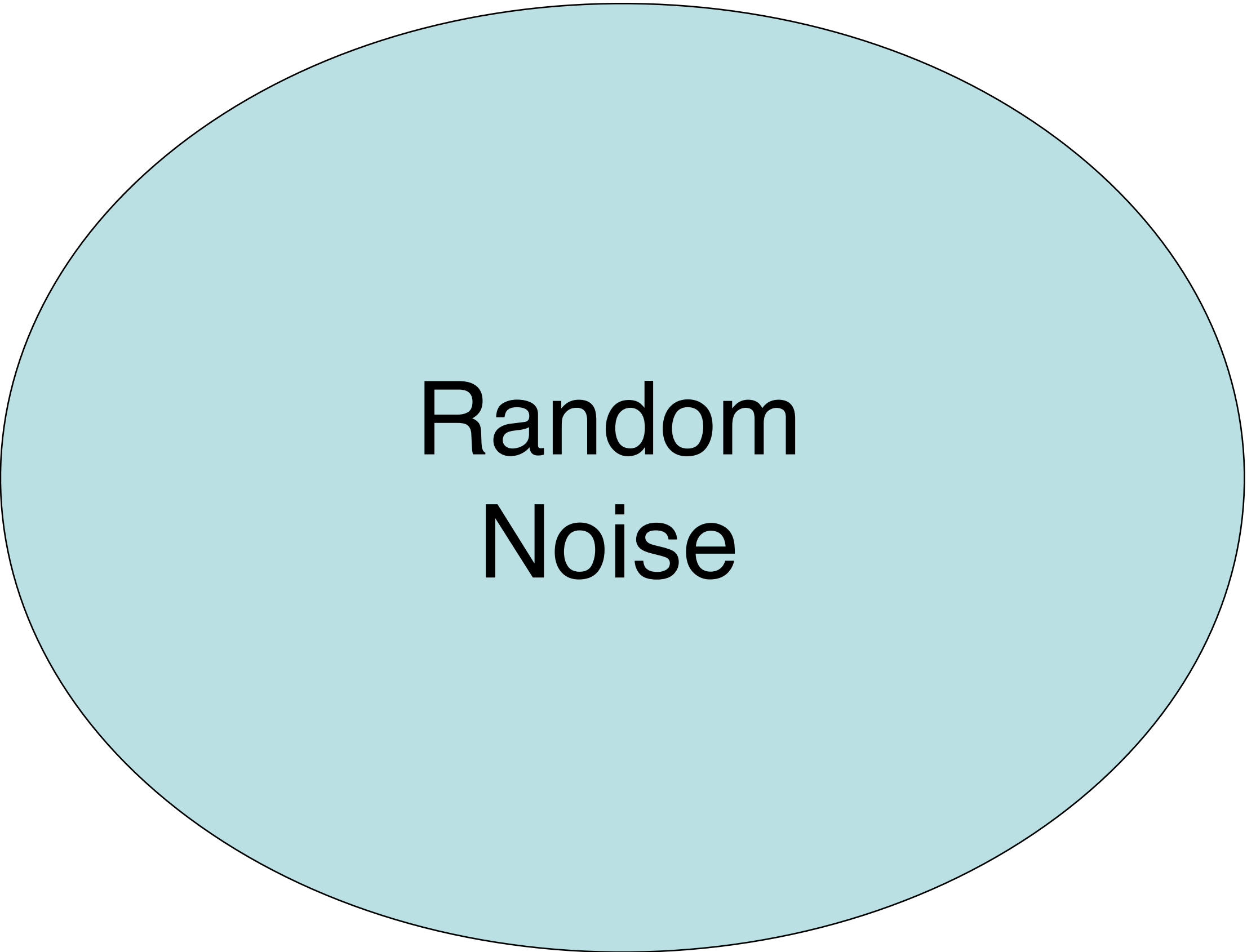
Common mode removed



Atmosphere Signal Removal

Multi-common mode removed





**Random
Noise**

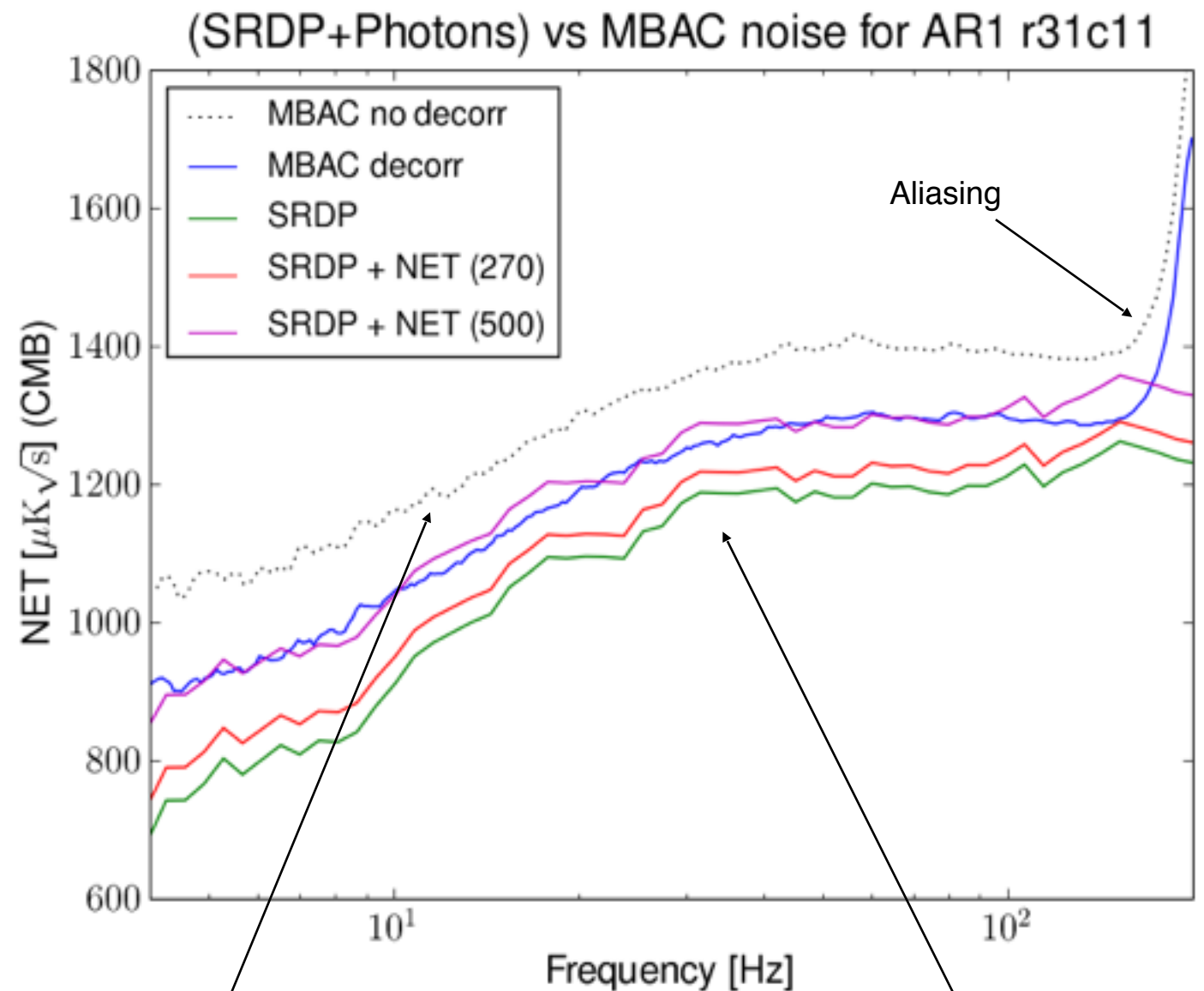
Random Noise

- It is originated by random processes, like for example electron thermal vibrations.
- It depends on intrinsic properties of the system and the signal.
- It is mostly uncorrelated between detectors.
- It decays as $1/\sqrt{N}$ by increasing the number of observations (integration time).
- It can be used to define the sensitivity of the system.

$$\text{NET}_{tot} = \left[\sum \frac{1}{\sigma_i^2} \right]^{-1/2}$$

$$\text{NET}_{typ} = \text{NET}_{tot} \sqrt{N_{det}}$$

Detector Noise



The correlated noise is equivalent to $520 \mu\text{K}\sqrt{\text{s}}$ added in quadrature

Excess noise dominates at high frequencies

The mayor noise sources affecting the detector are:

- “G” noise from thermal junctions and electron-phonon decoupling:

$$P_G = \sqrt{4kGT^2}$$

- TES Johnson noise:

$$P_j = kT_e \Delta \nu \quad e_j = \sqrt{4kT_e R}$$

- TES excess noise: of unknown nature, dominates at higher frequencies.

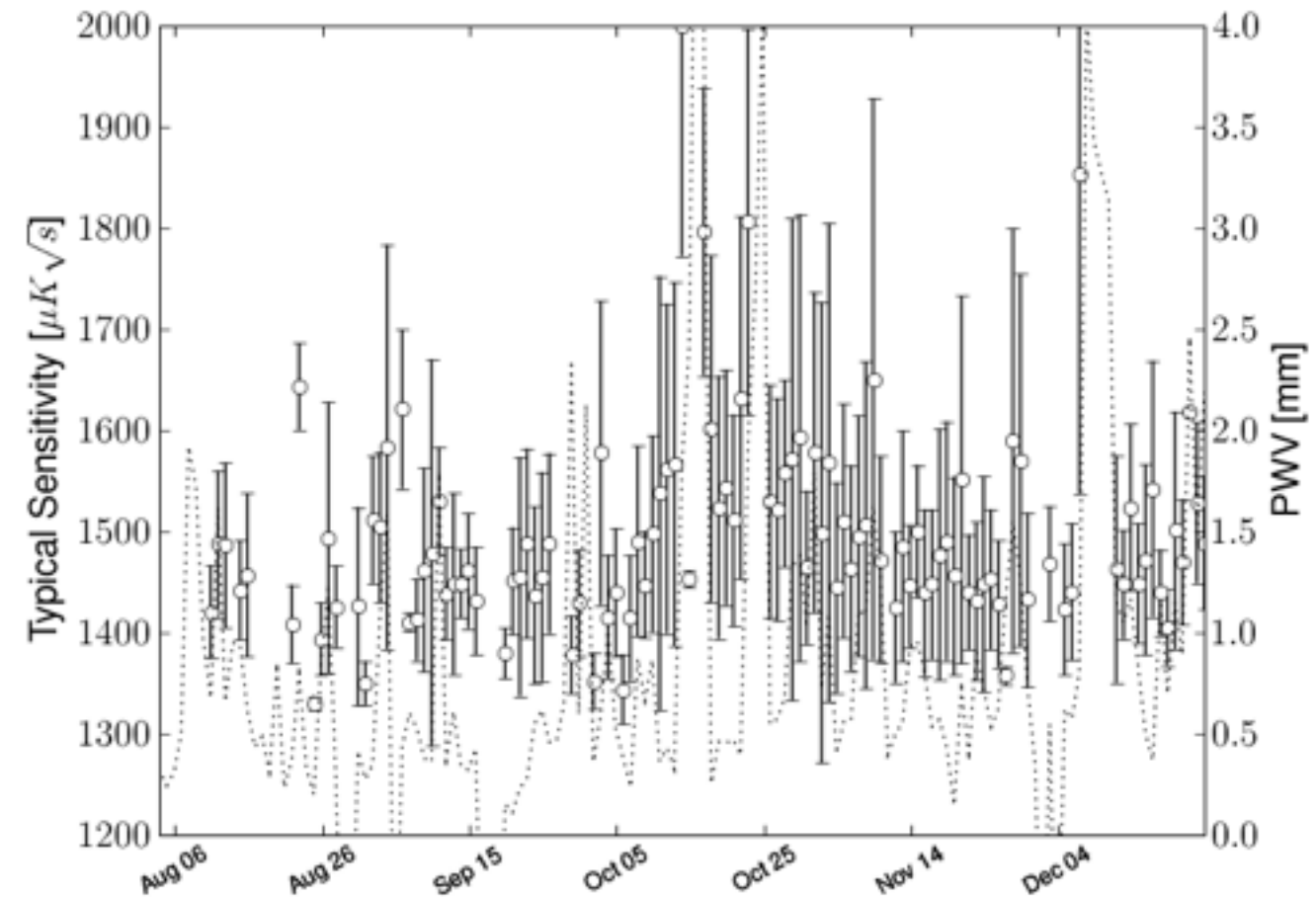
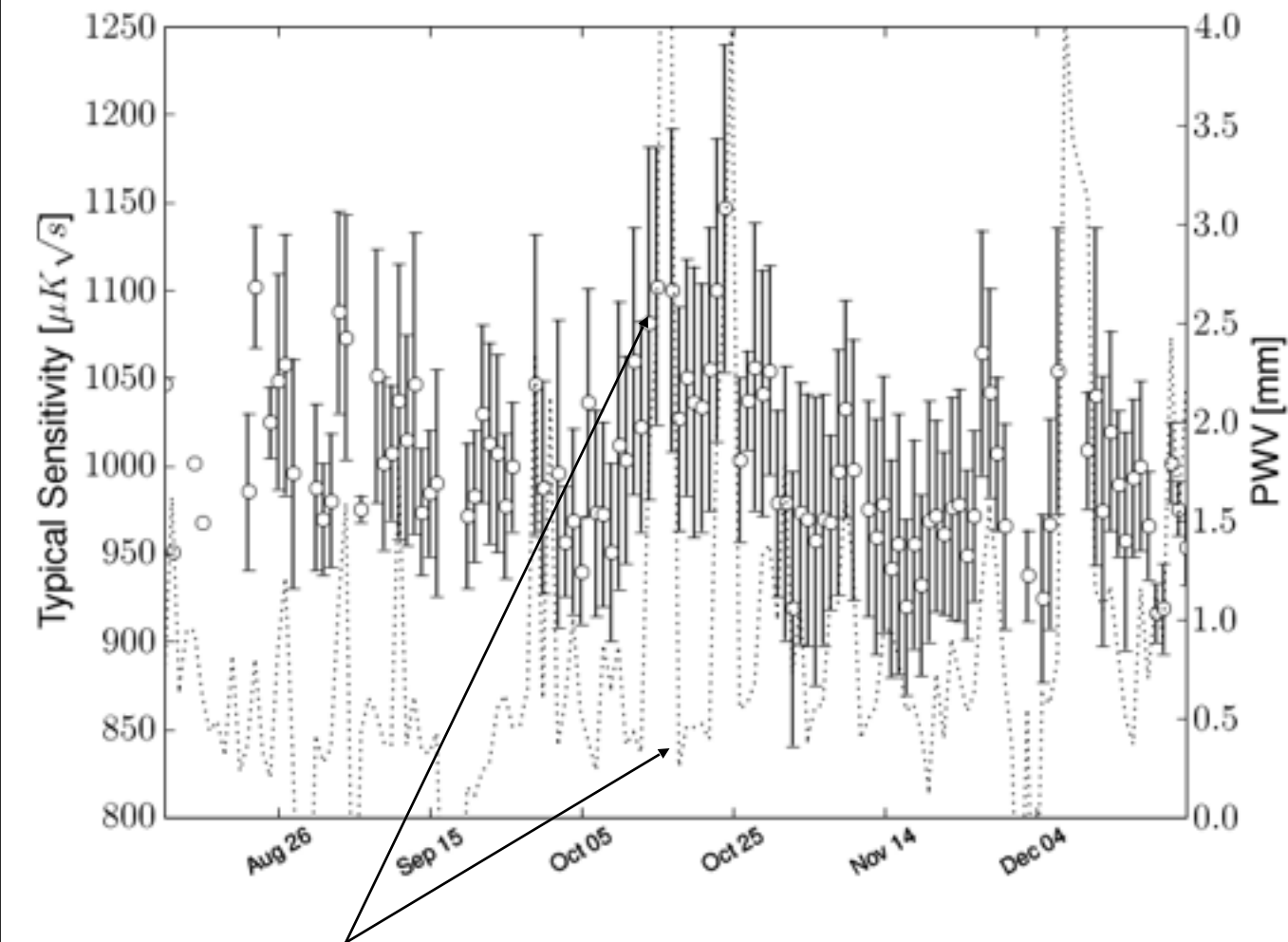
Other noise sources:

- Photon Noise: for AR1 it can contribute $270 \mu\text{K}\sqrt{\text{s}}$ @ PWV 3mm
- Readout noise: the SQUID noise is only $12 \mu\text{K}\sqrt{\text{s}}$ but it can get aliased producing $85 \mu\text{K}\sqrt{\text{s}}$

Sensitivity

AR1

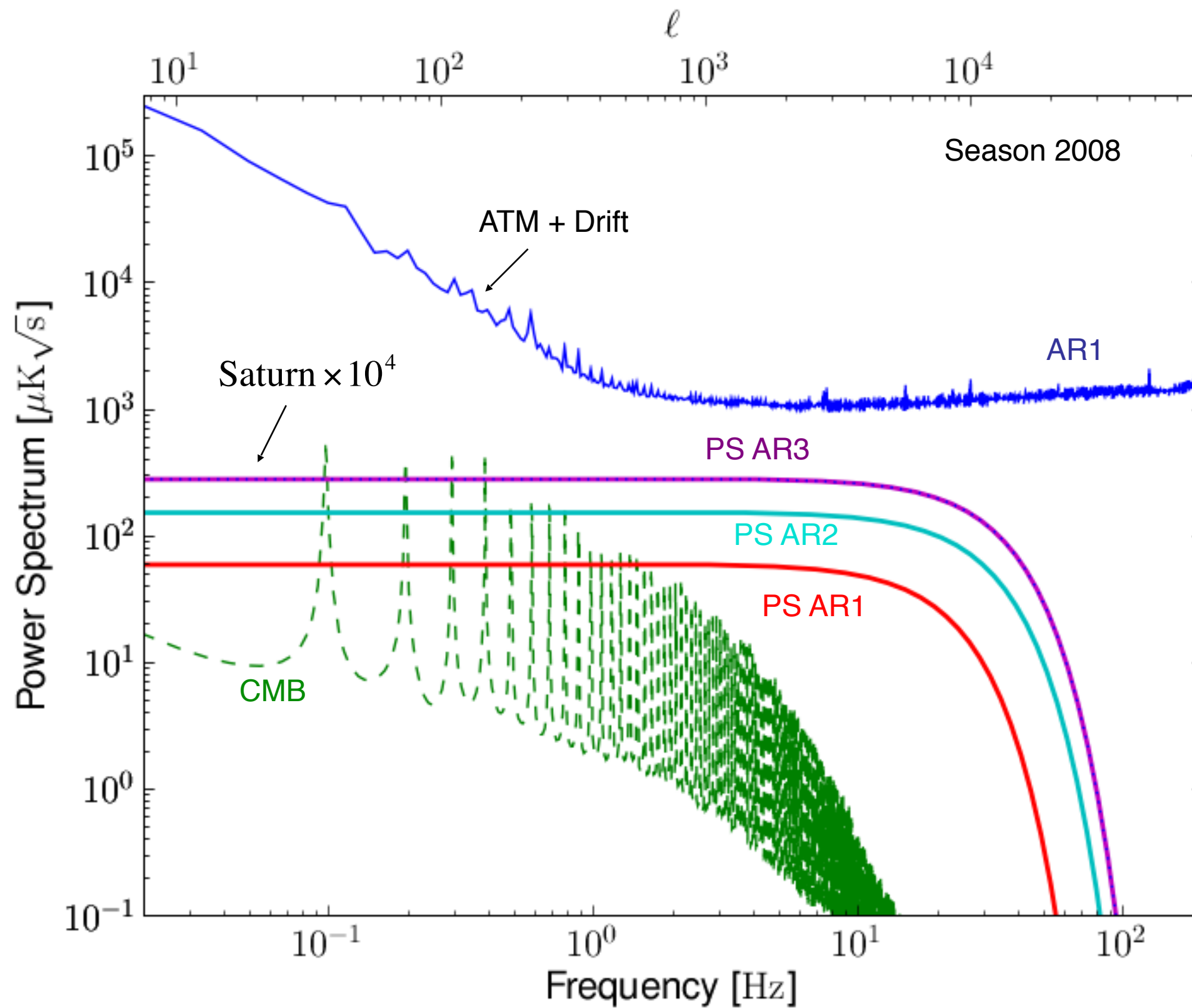
AR2

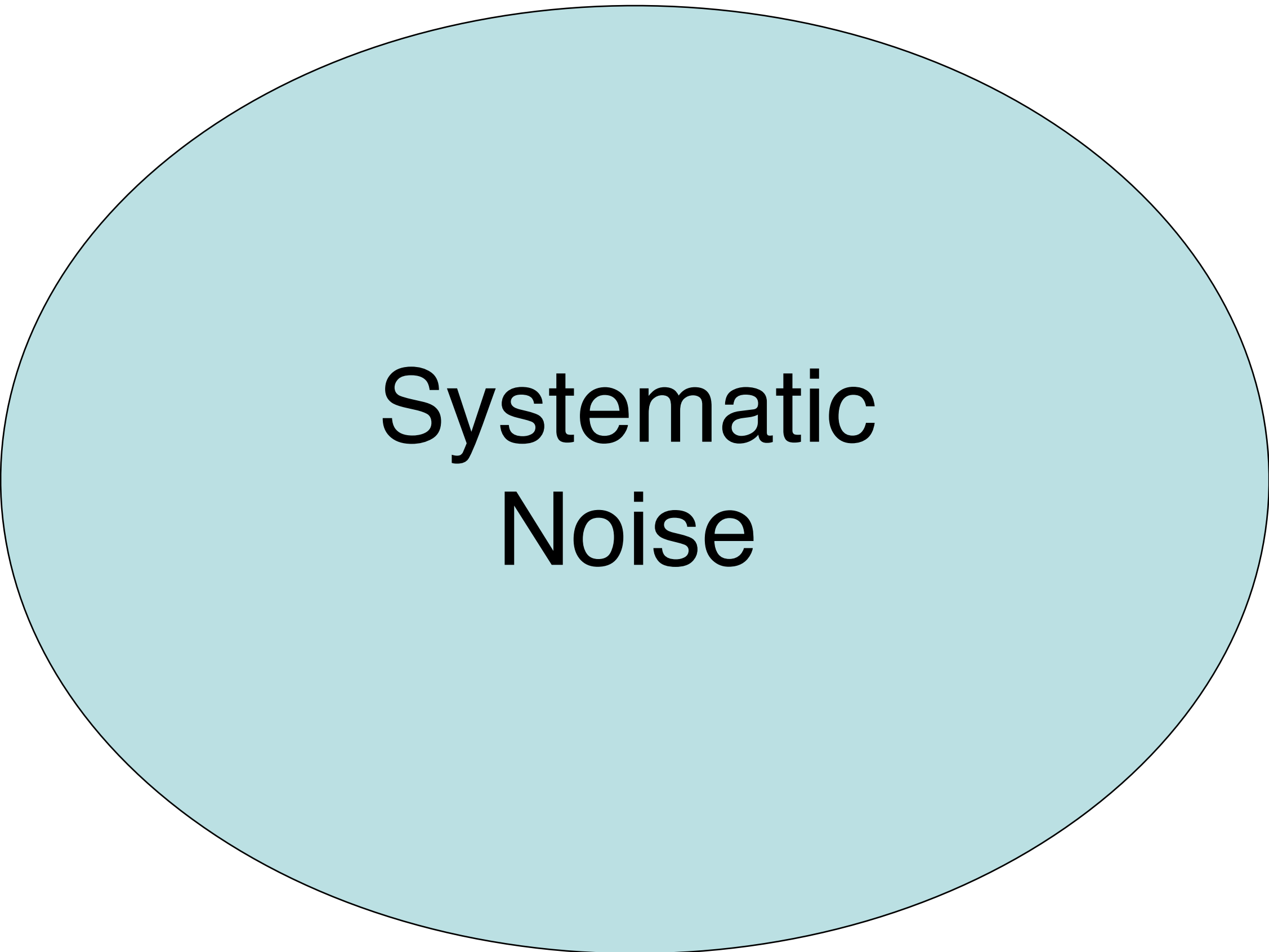


Correlation with PWV

Range	NEP _{typ} $[\mu K \sqrt{s}]$ 148 GHz	NEP _{typ} $[\mu K \sqrt{s}]$ 218 GHz
5 - 20 Hz	980 ± 70	1430 ± 110
100 - 120 Hz	1220 ± 40	1480 ± 130

Signal to Noise Ratio

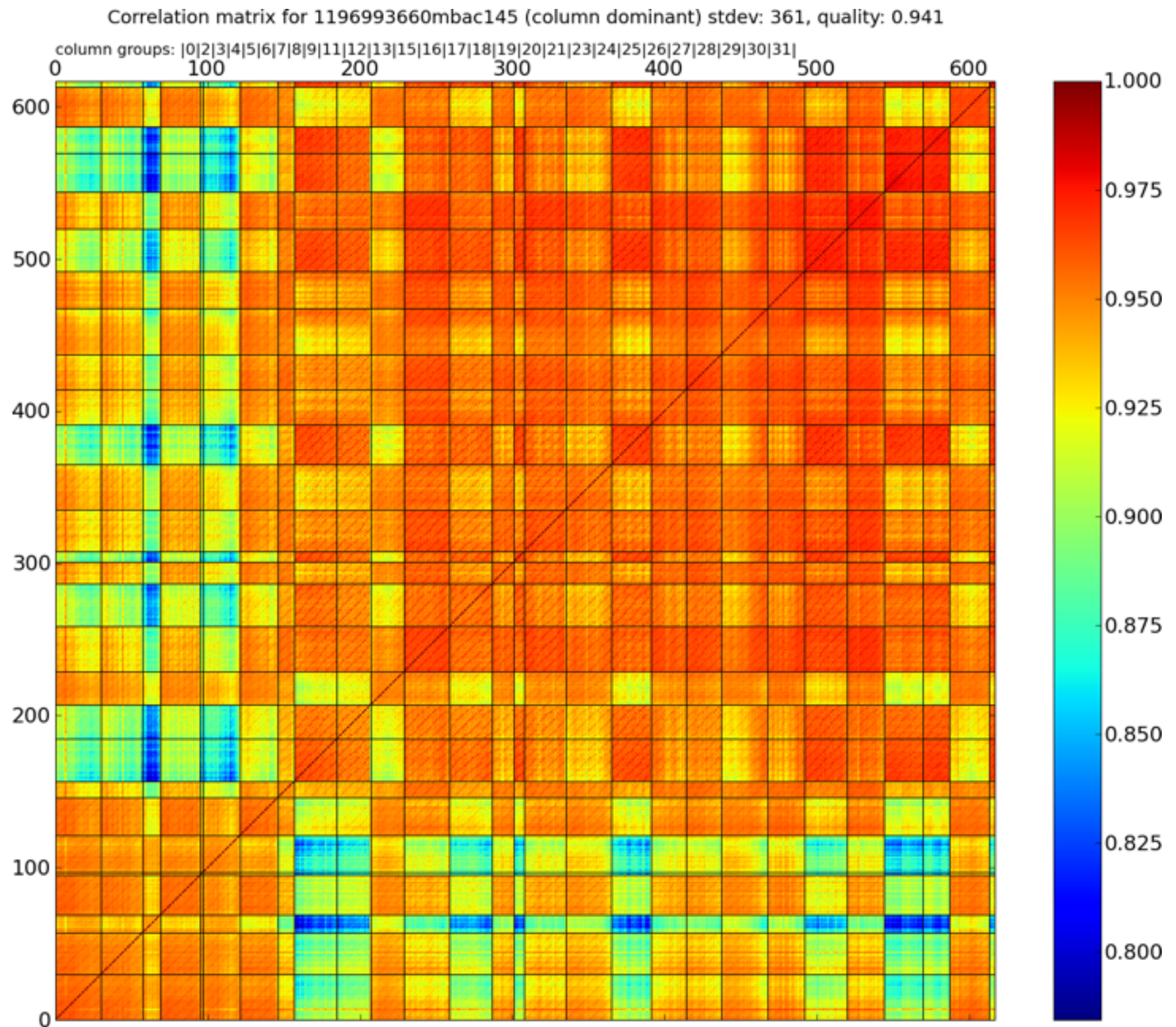




**Systematic
Noise**

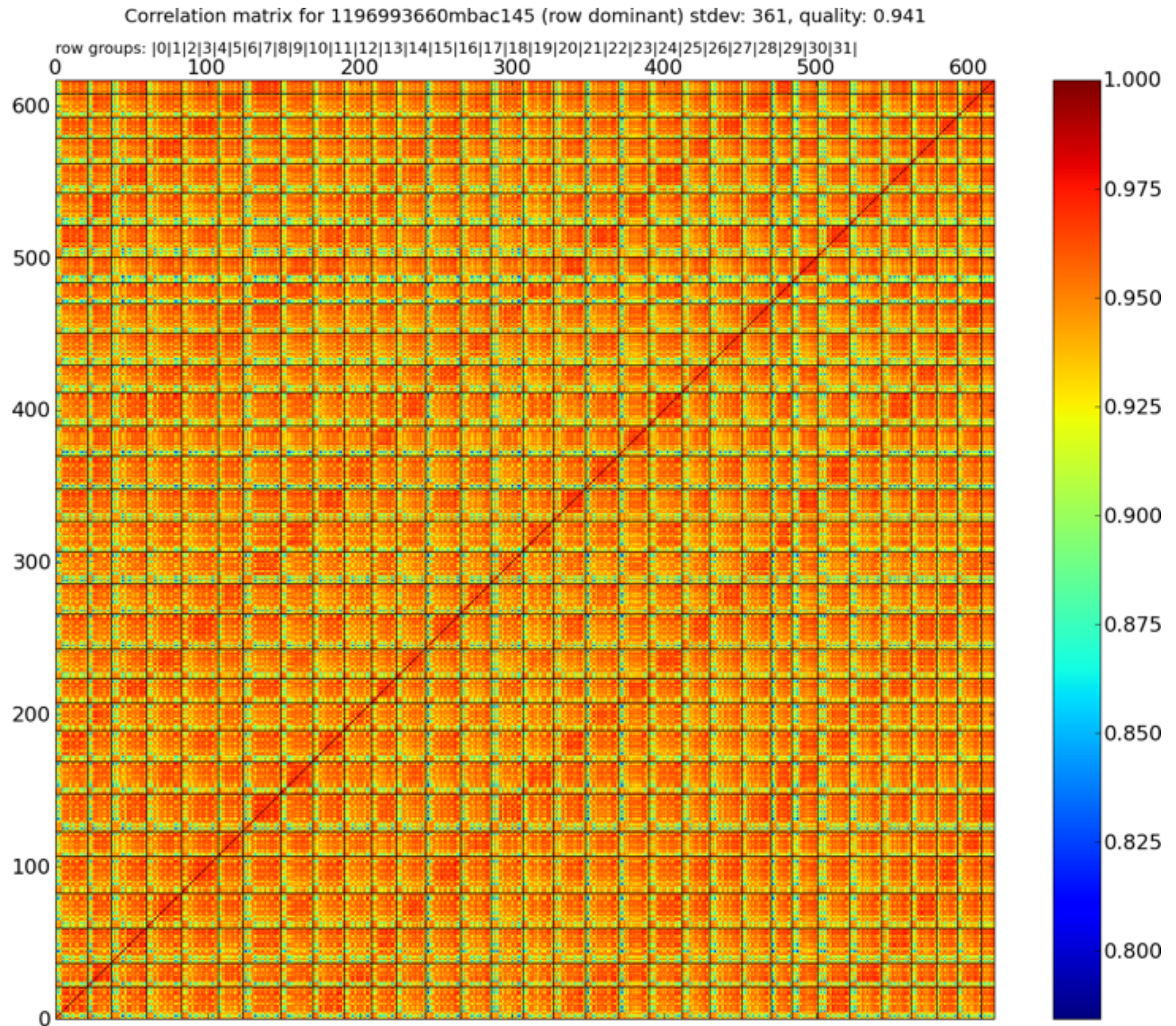
Correlations

$$Q = \frac{2}{N(N-1)} \sum_{i < j}^N c_{i,j}^2$$

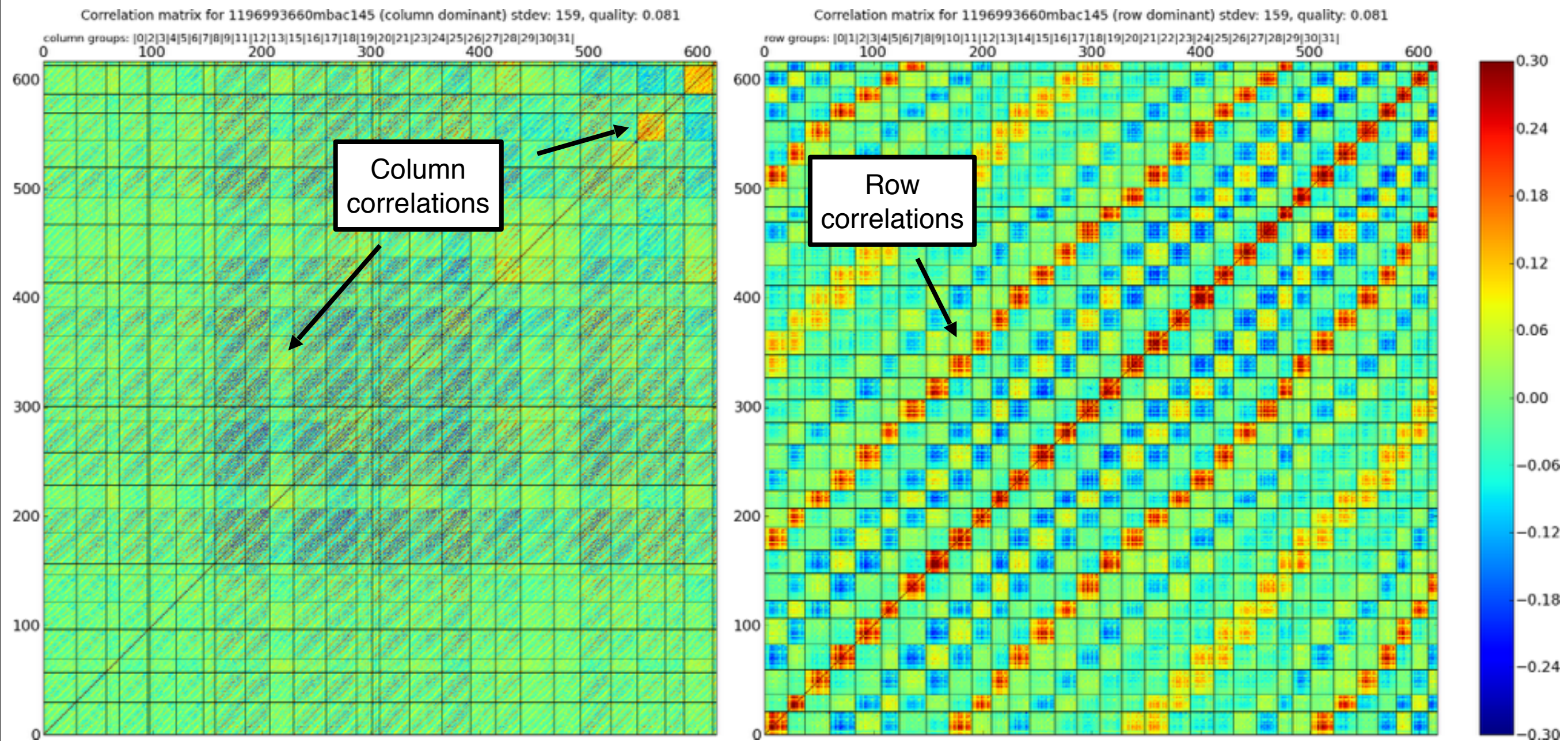


Correlations

$$Q = \frac{2}{N(N-1)} \sum_{i < j}^N c_{i,j}^2$$

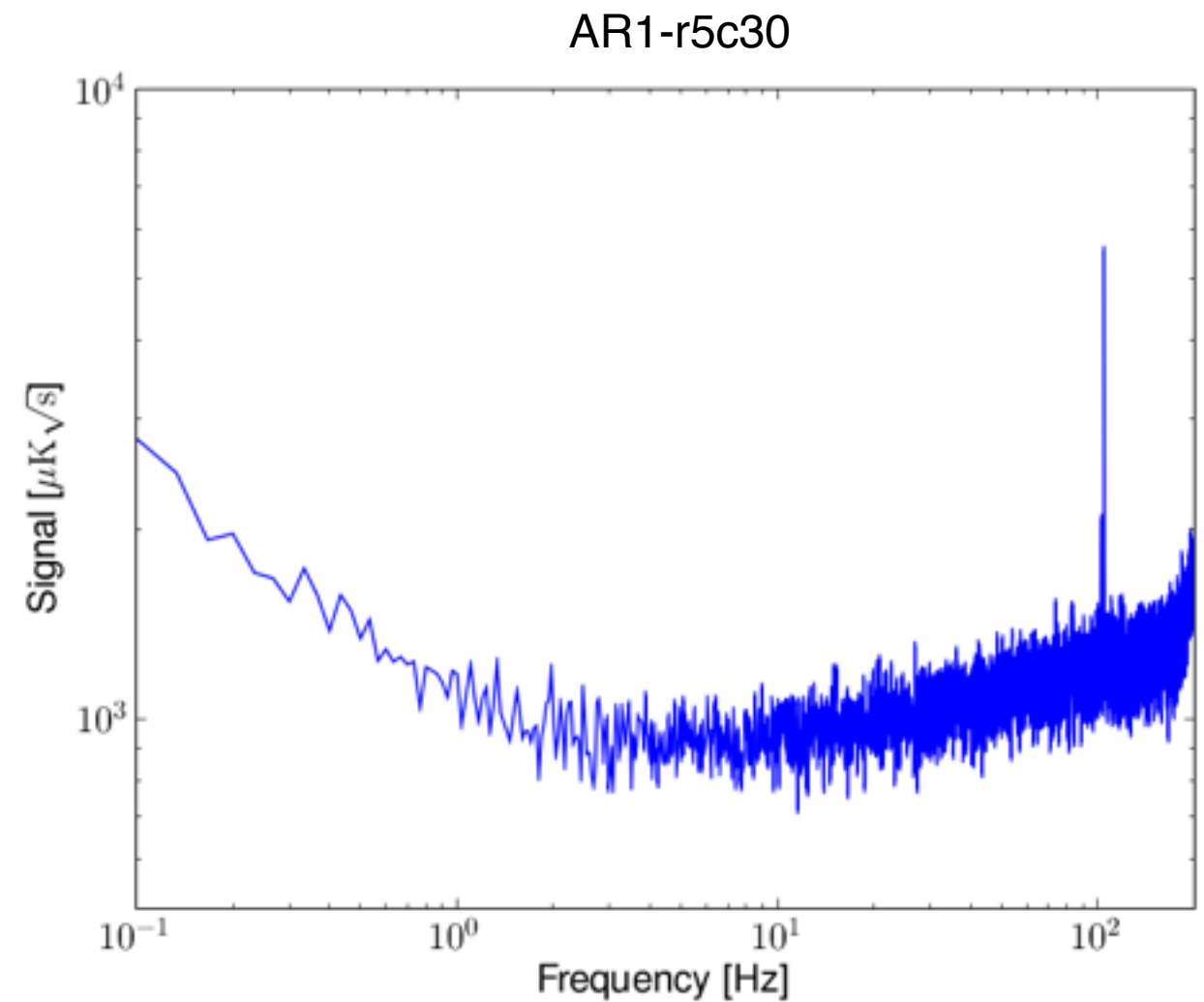
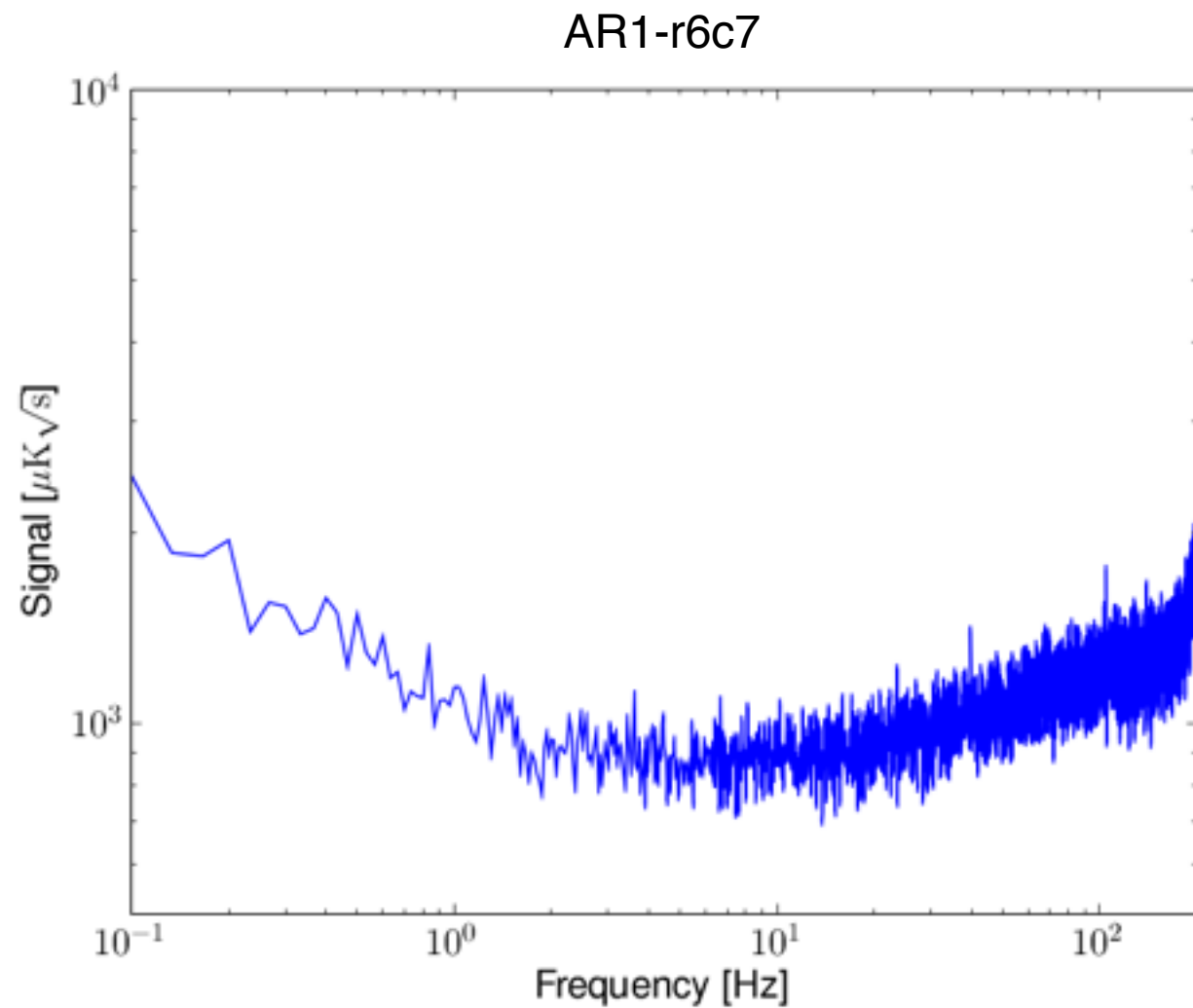


Multi-common mode removed



Residual correlations are left after removing the multi-common mode (mainly atmosphere)

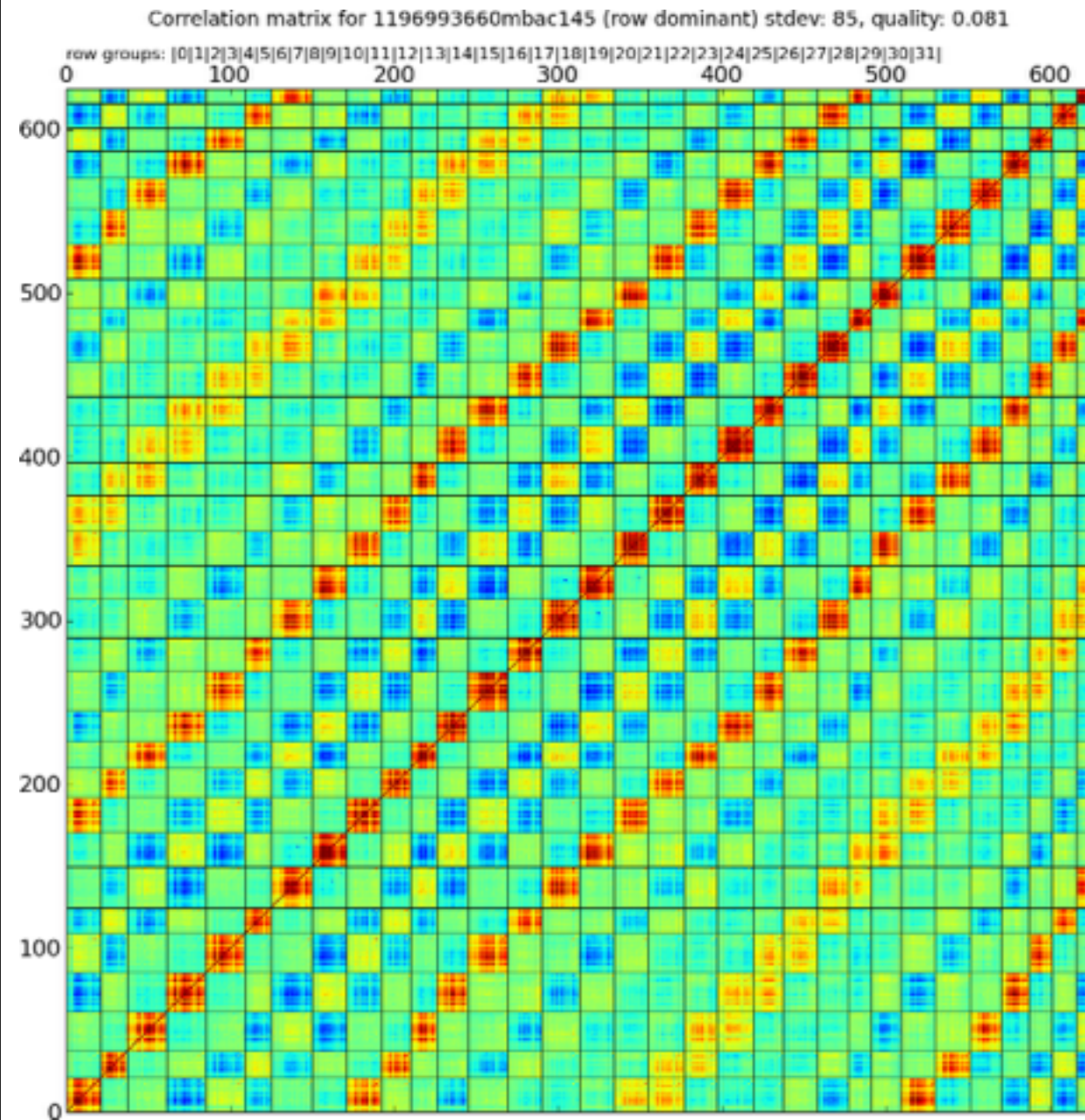
Column Correlation Example



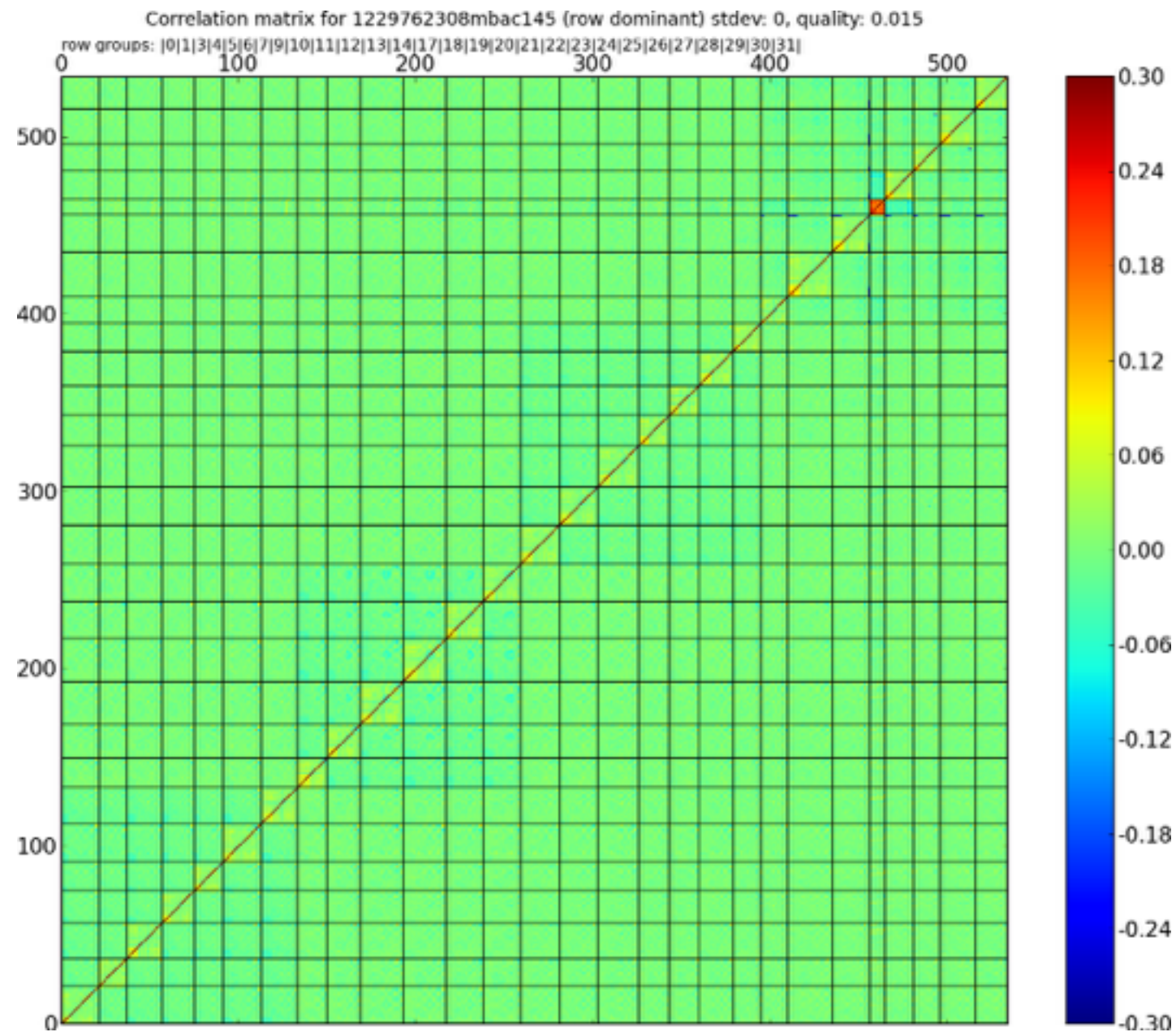
Multi-common mode and synchronous pickup removed

Row Correlation Origin

Switching Power Supplies

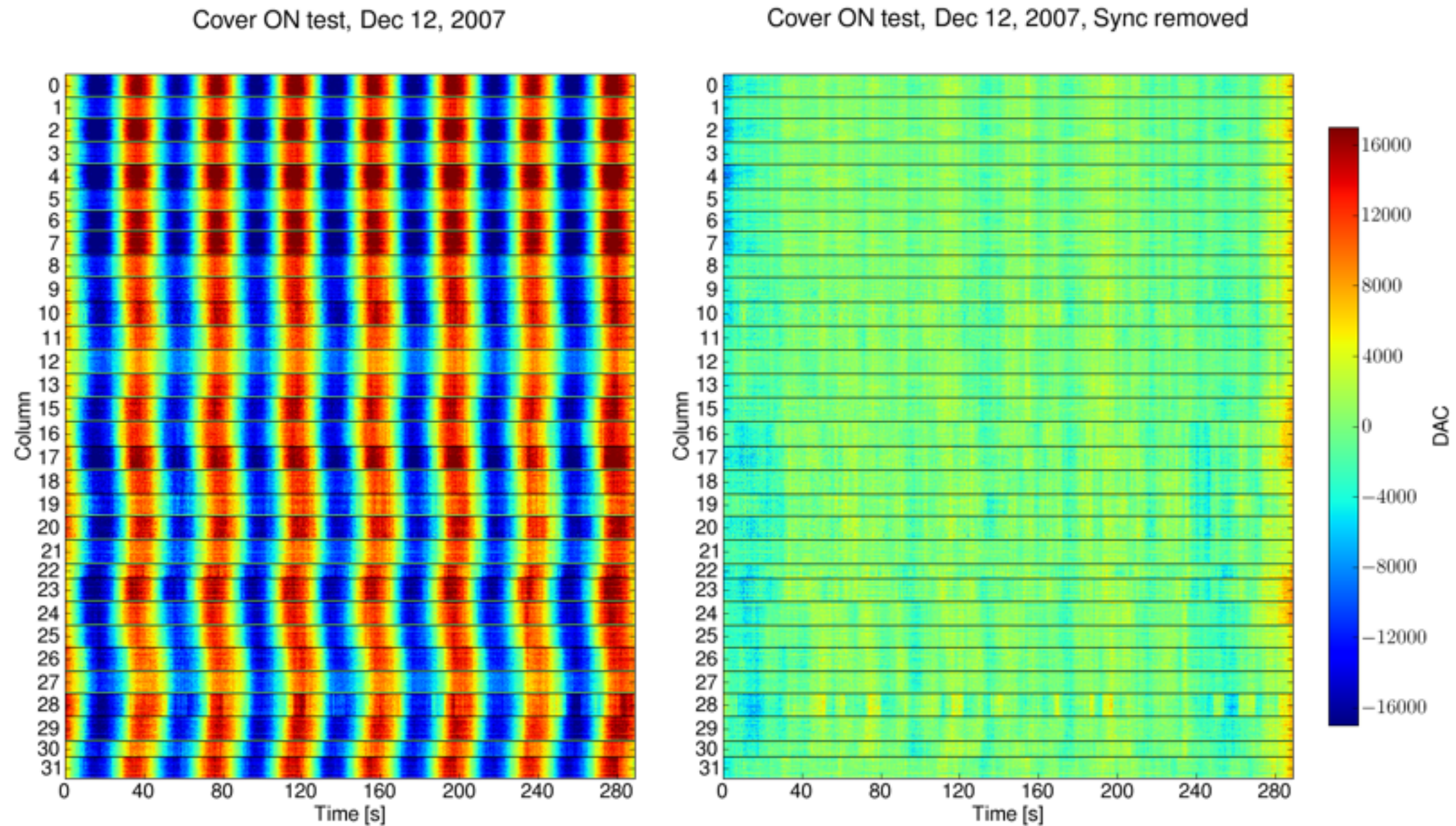


Linear Power Supplies



Time multiplexing allows glitches to affect some rows more than others.

Magnetic Pickup

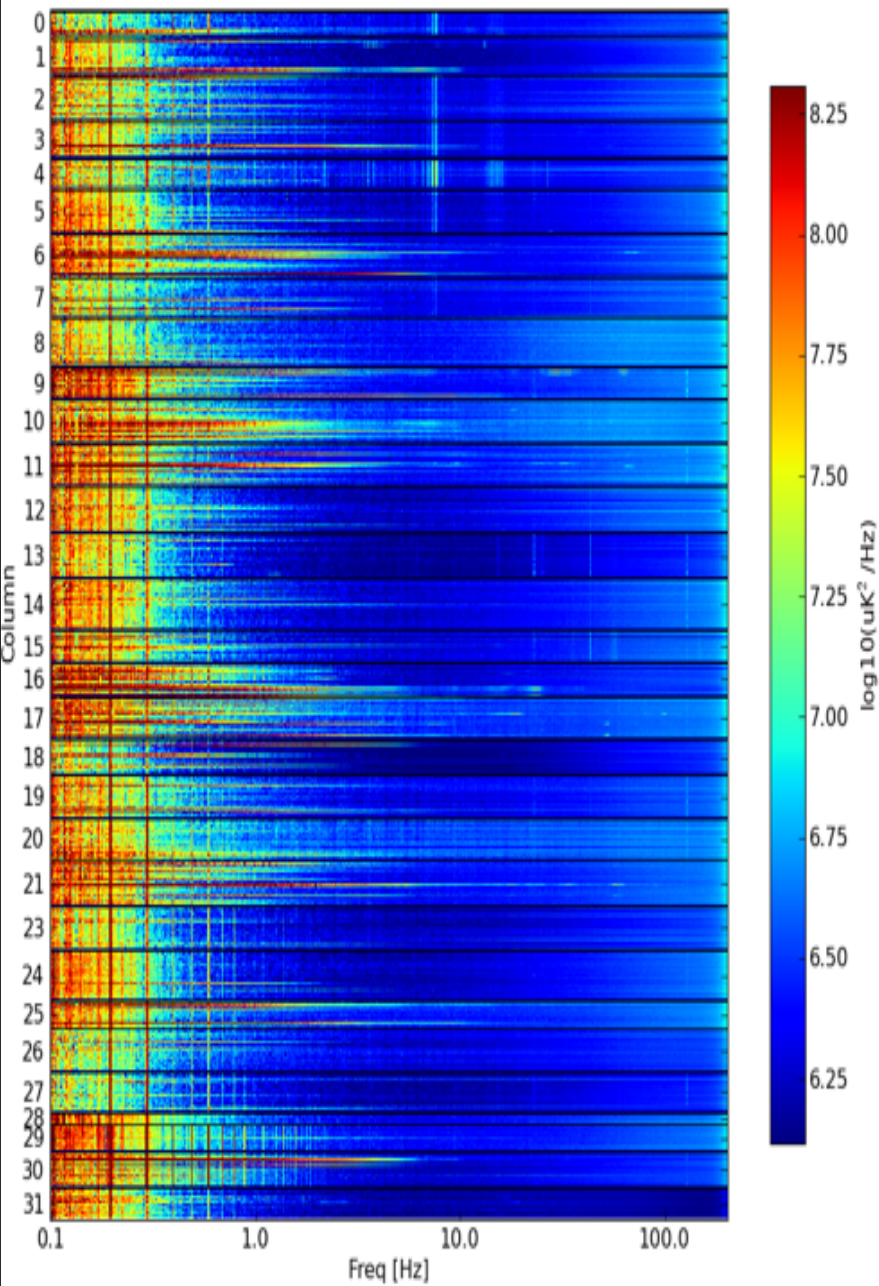


- SQUID voltage proportional to magnetic flux.
- Circuit loop voltage proportional to change in magnetic flux.
- Lower effect in season 2008 due to higher scan speed.

Mechanical Vibrations

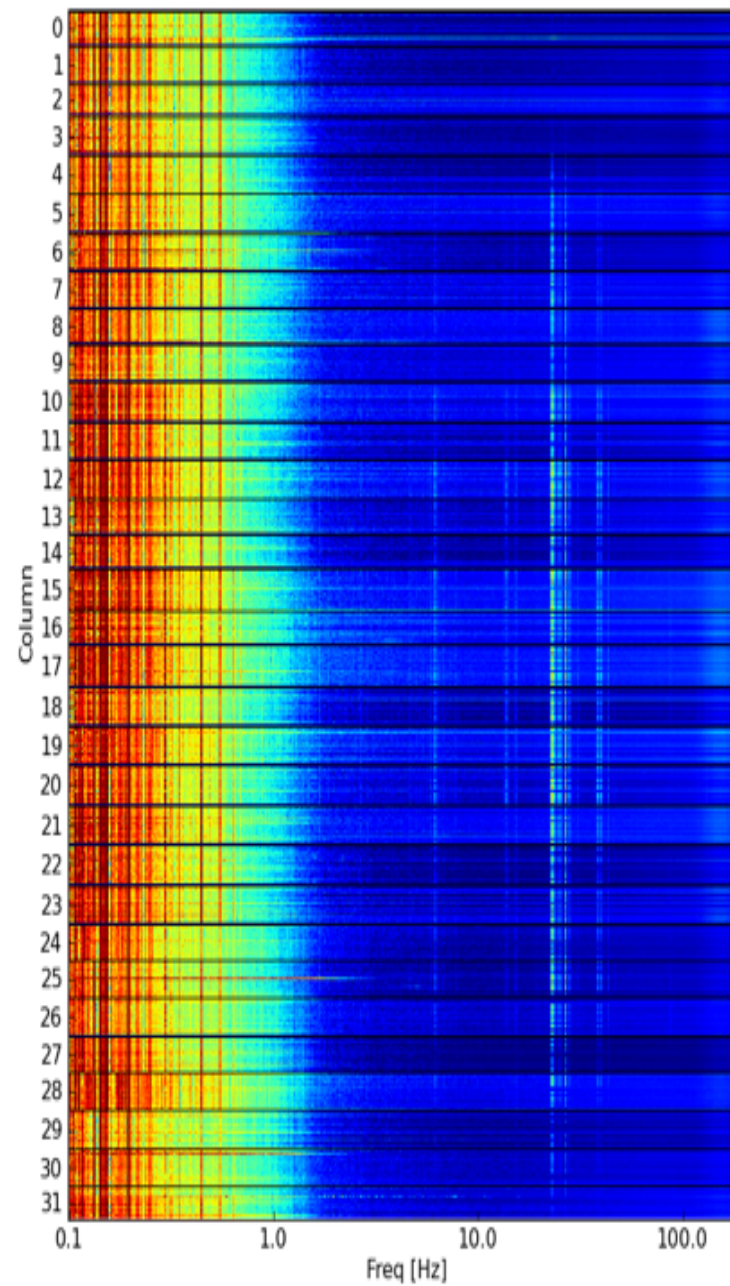
AR1

Waterfall TOD 1227160581 mbac145 (Column Dominated)



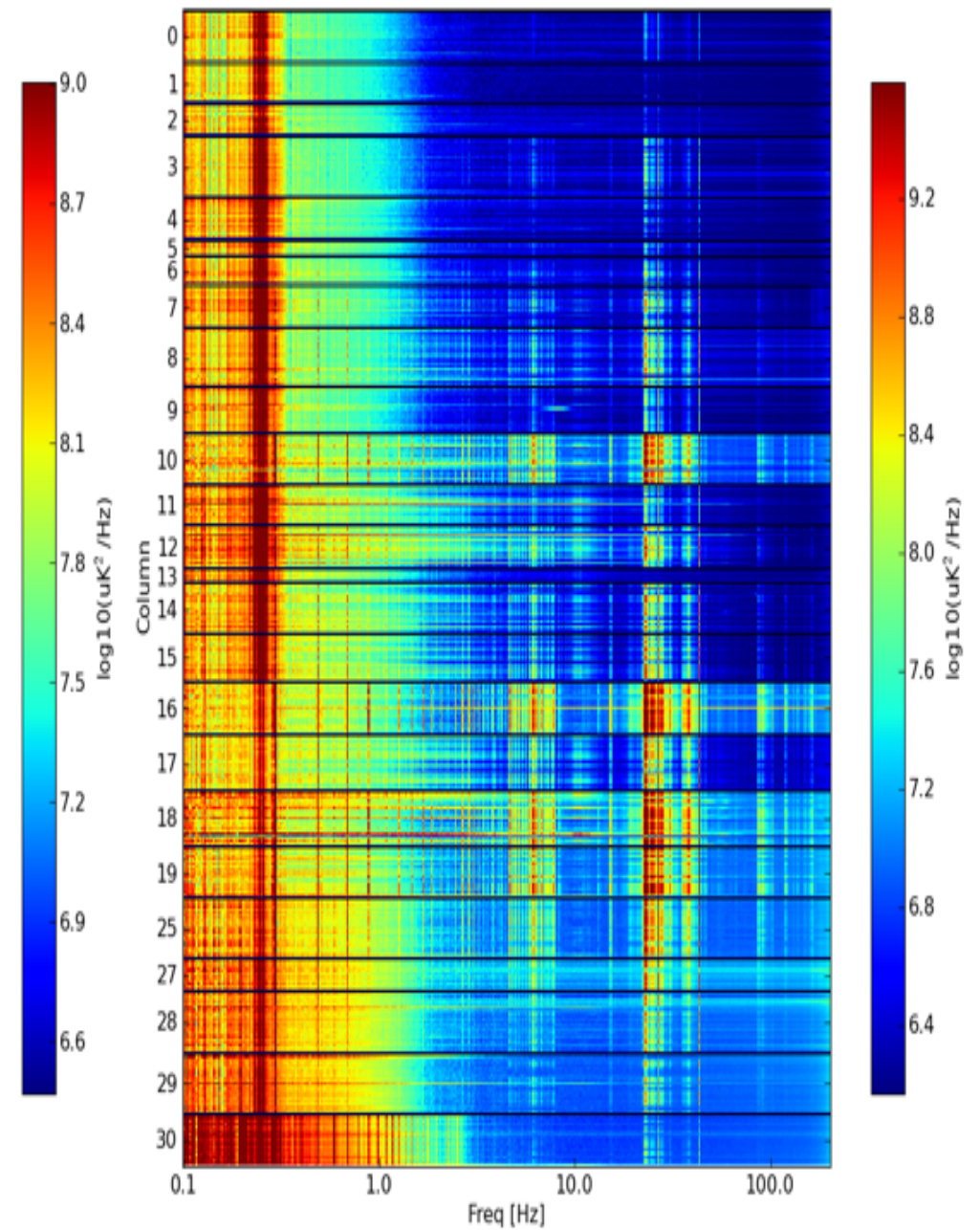
AR2

Waterfall TOD 1227160581 mbac215 (Column Dominated)



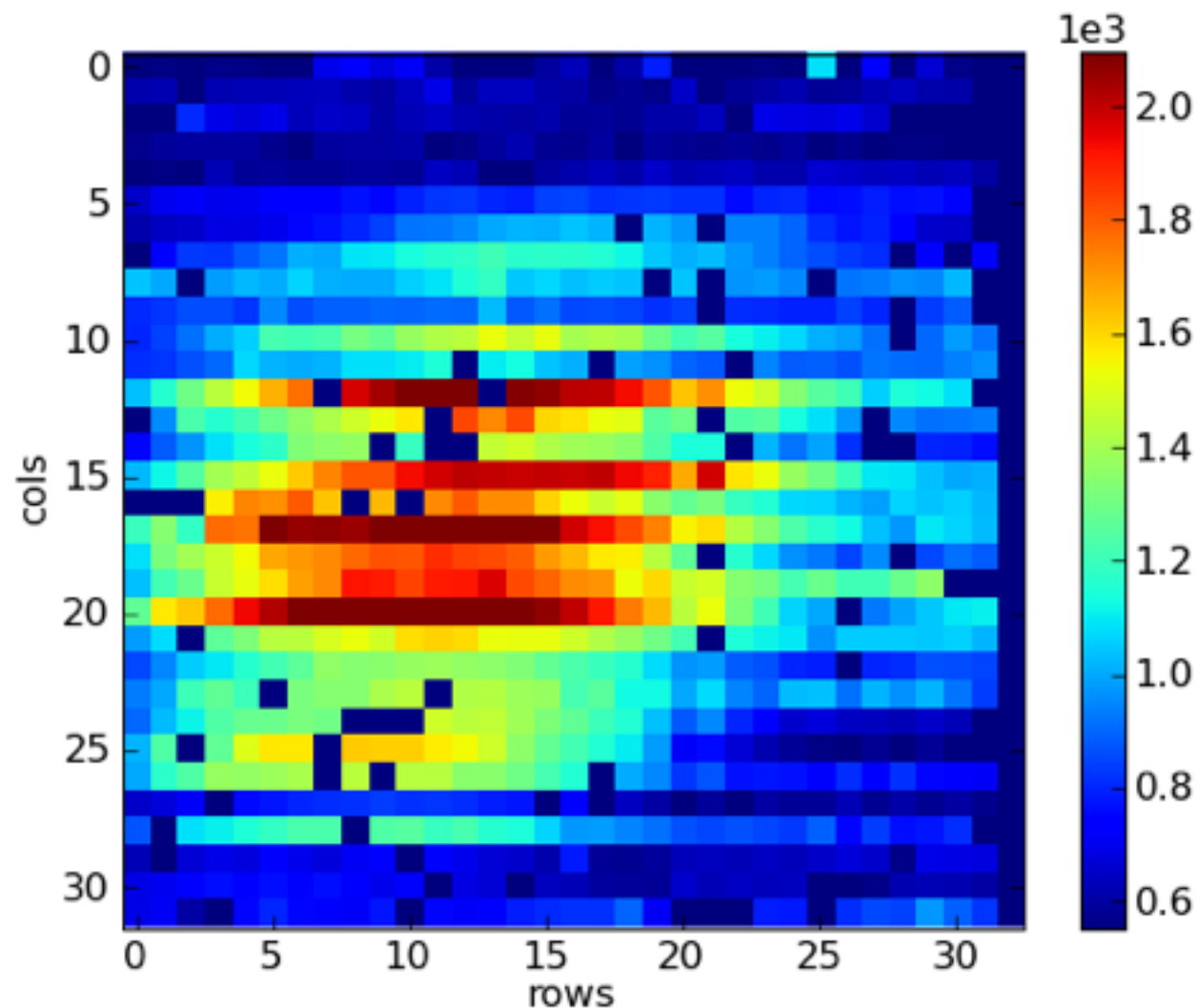
AR3

Waterfall TOD 1227160581 mbac280 (Column Dominated)

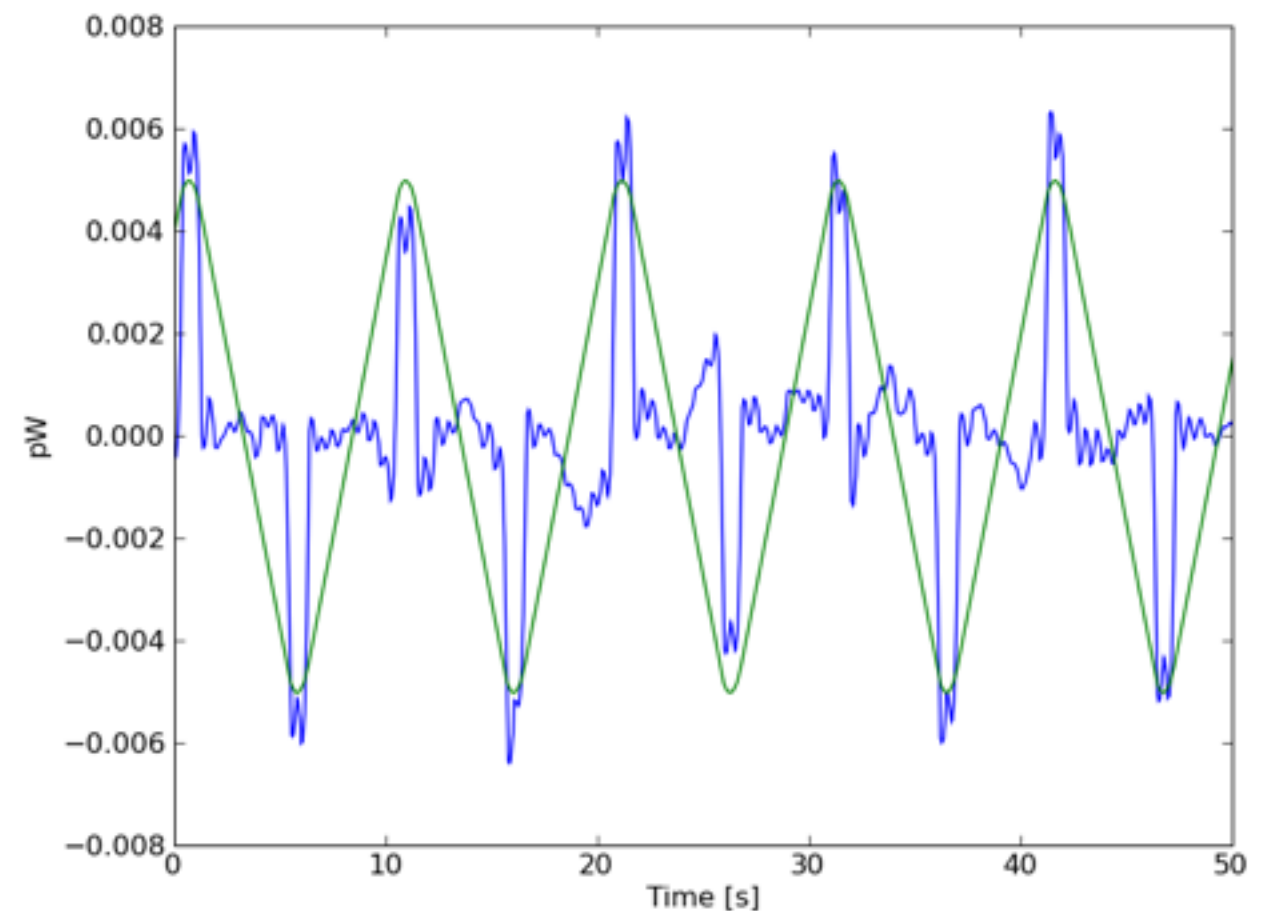


Coupling Layer Vibrations

Noise Quality TOD 1227160581 mbac215



AR3 LPF 2 Hz



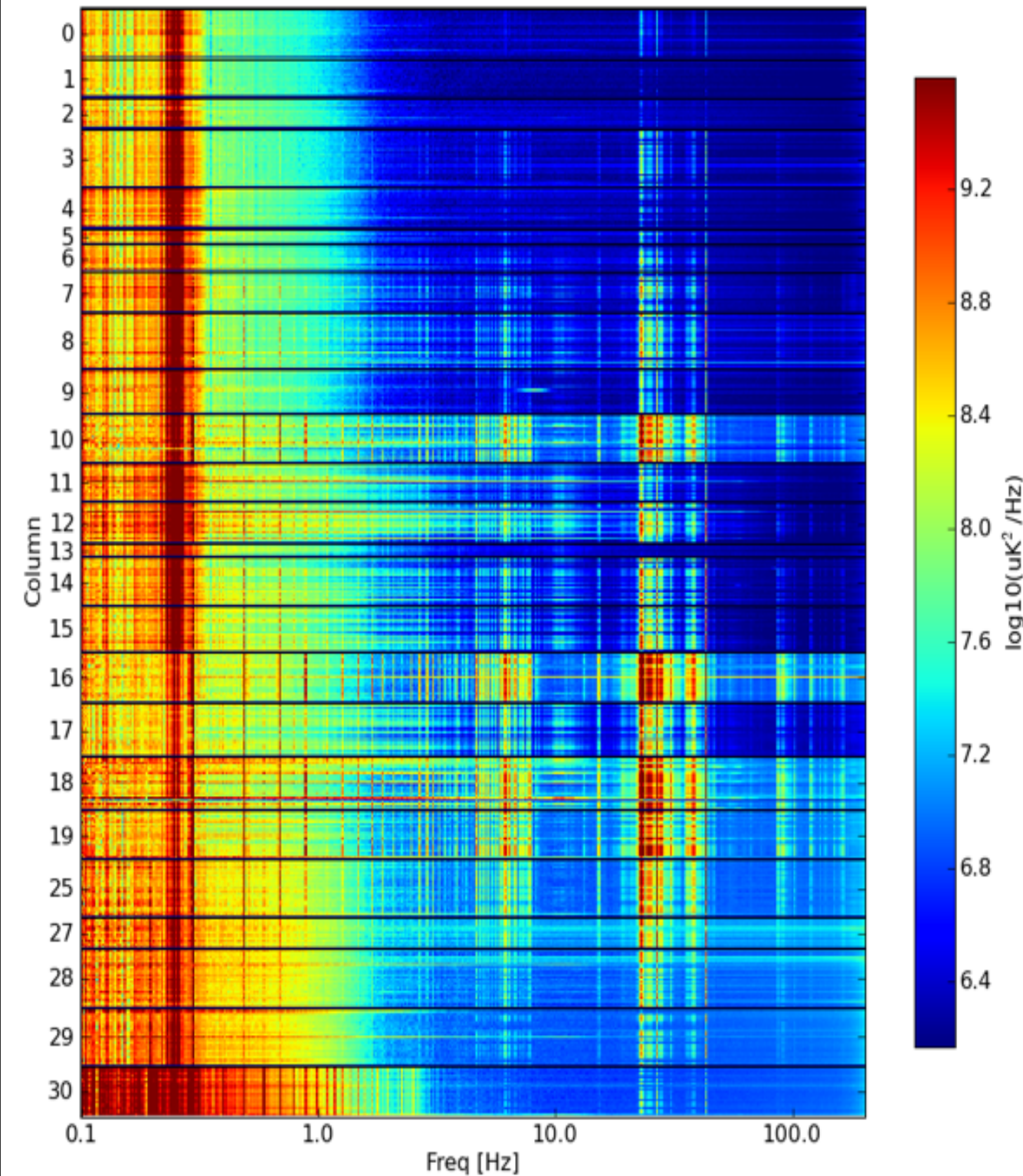
Strong example

$$NQ = \sqrt{\text{var}(\text{PSD}_{10 \rightarrow 200\text{Hz}})}$$

Resonances

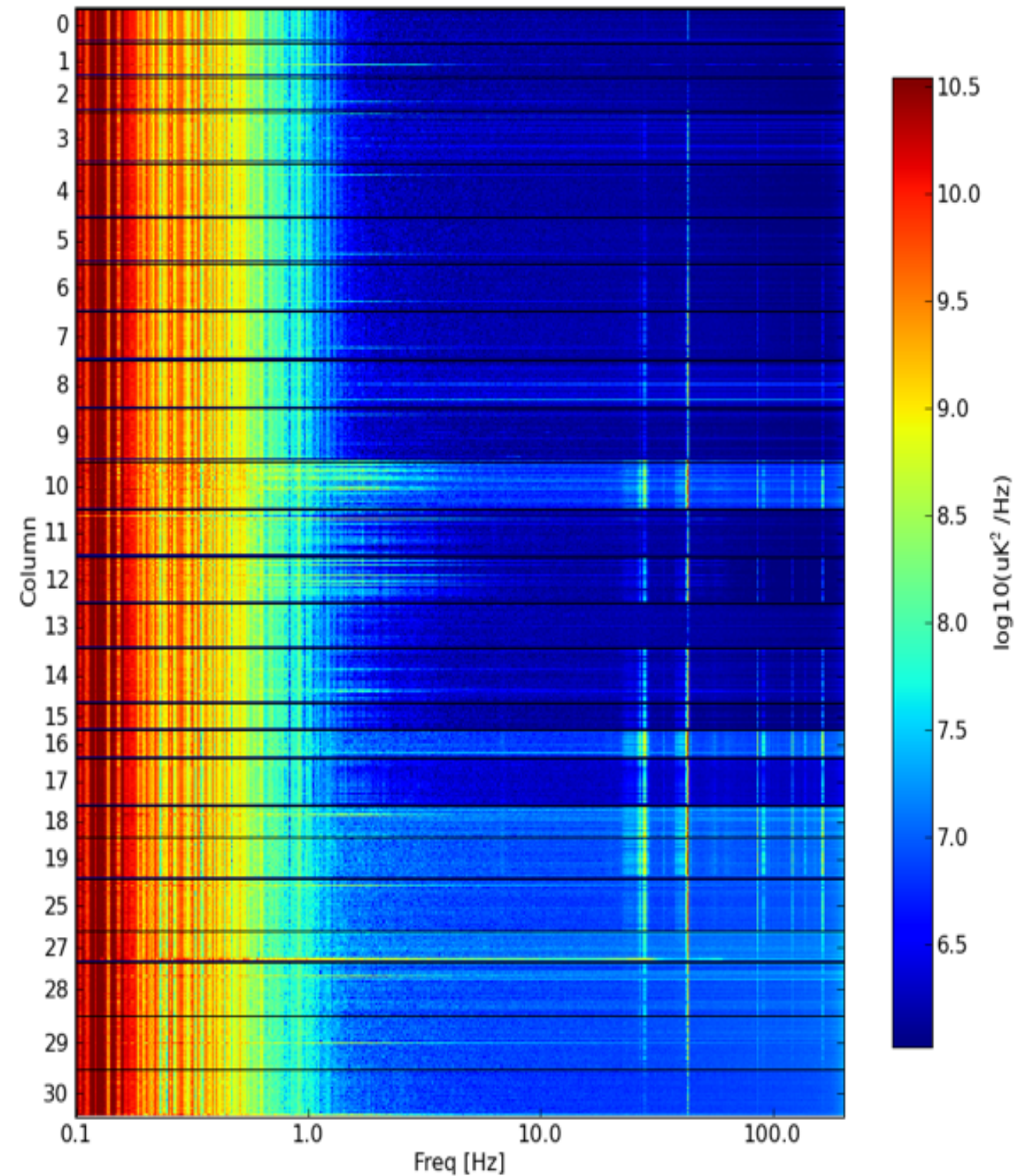
Waterfall TOD 1227160581 mbac280 (Column Dominated)

AR3 Scan



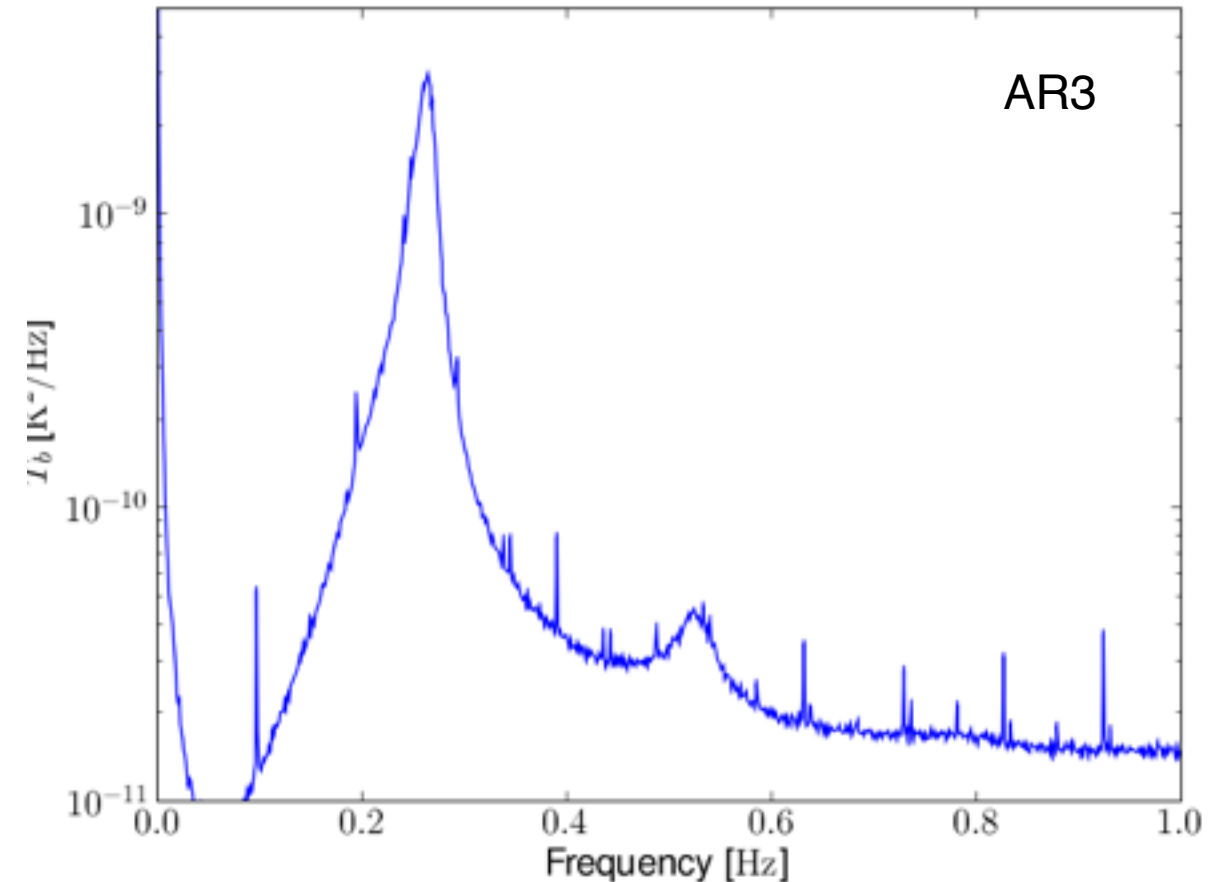
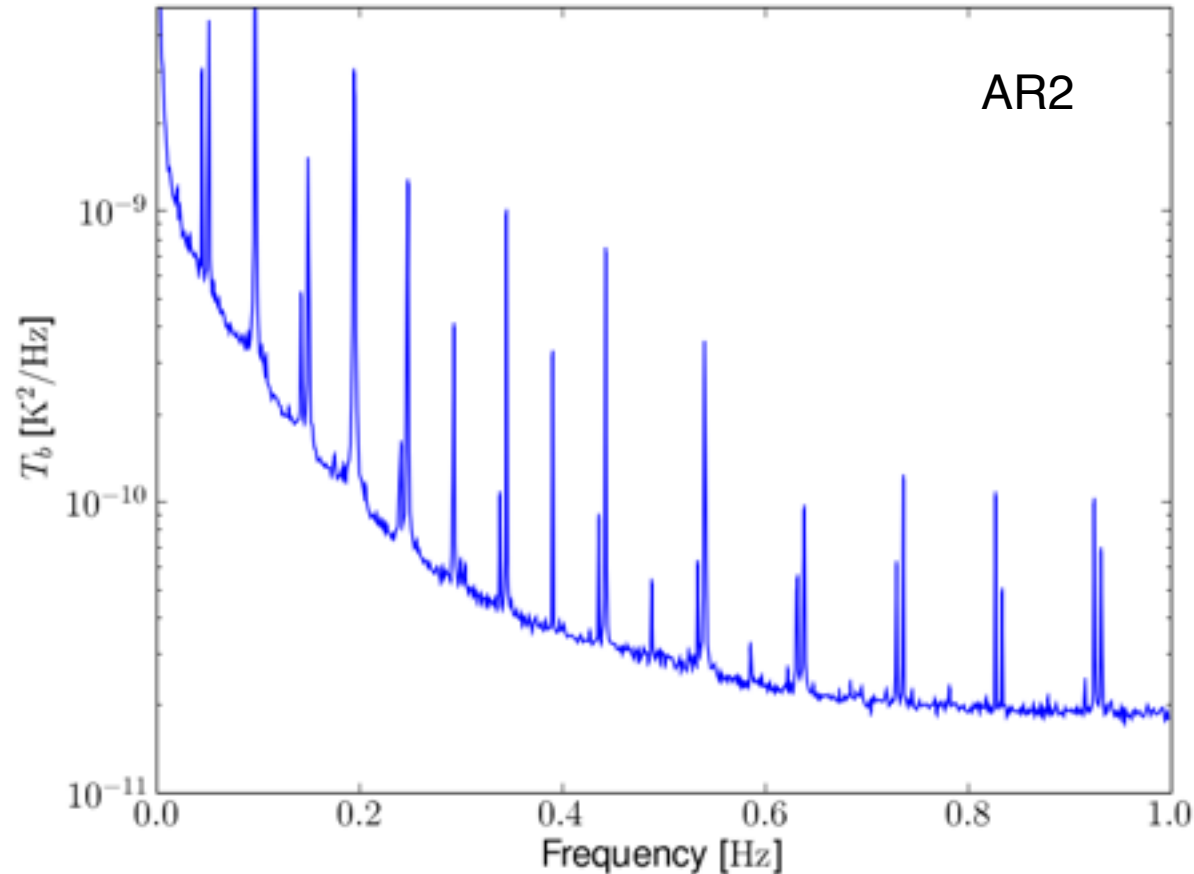
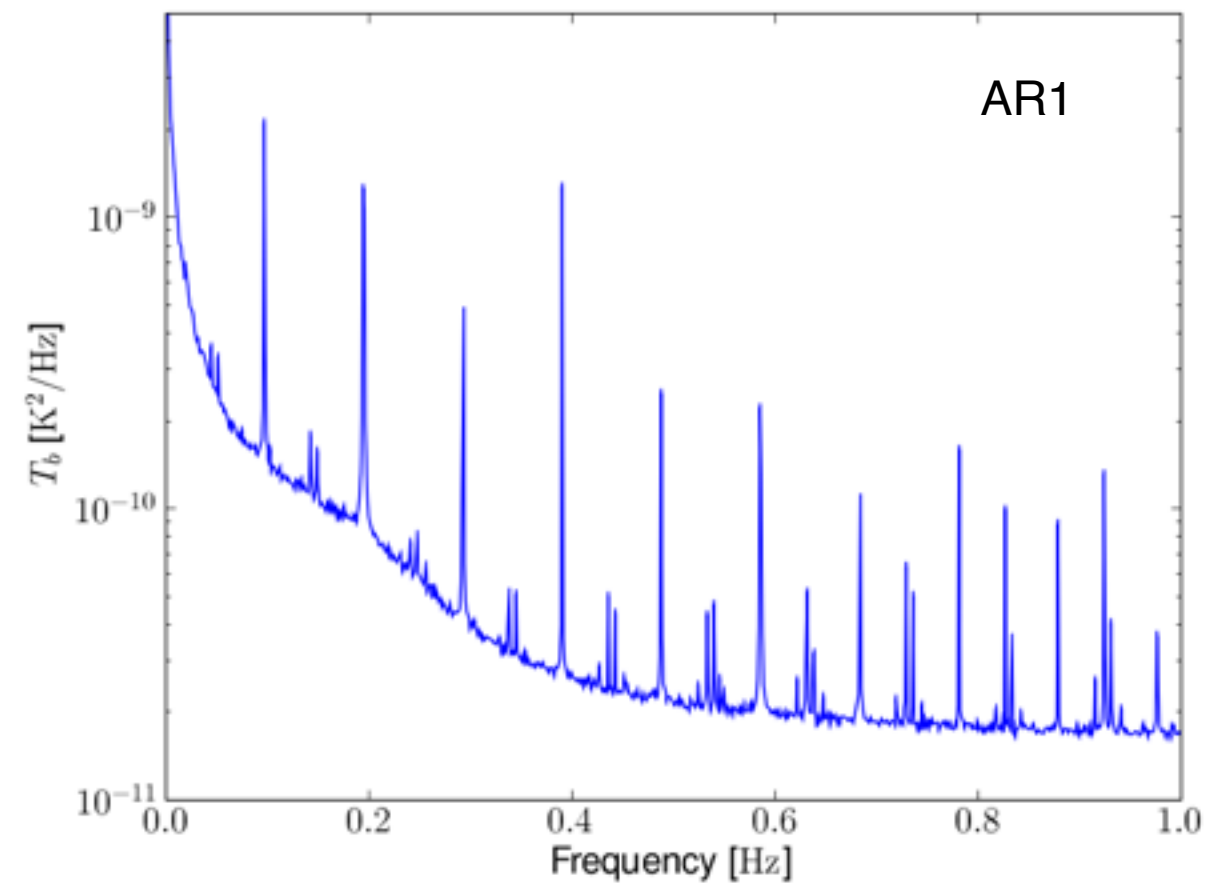
Waterfall TOD 1226756780 mbac280 (Column Dominated)

AR3 Stare



Thermal Oscillations

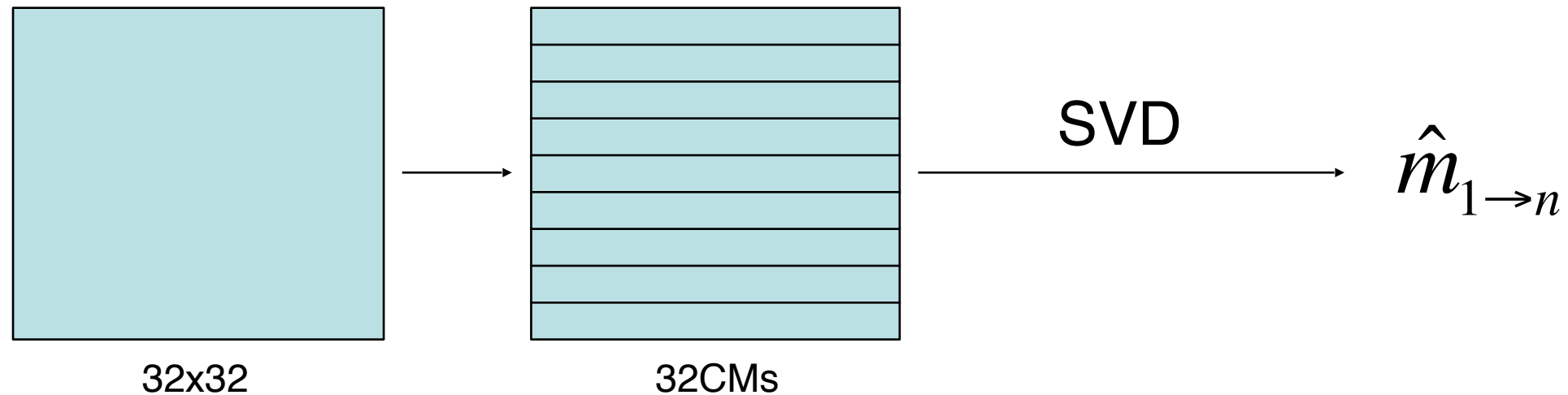
- Temperature controlled by a PI loop.
- Average T_{bath} power spectrum over ~ 1500 data-files.
- Scan frequency is 0.1 Hz.



Mode Identification

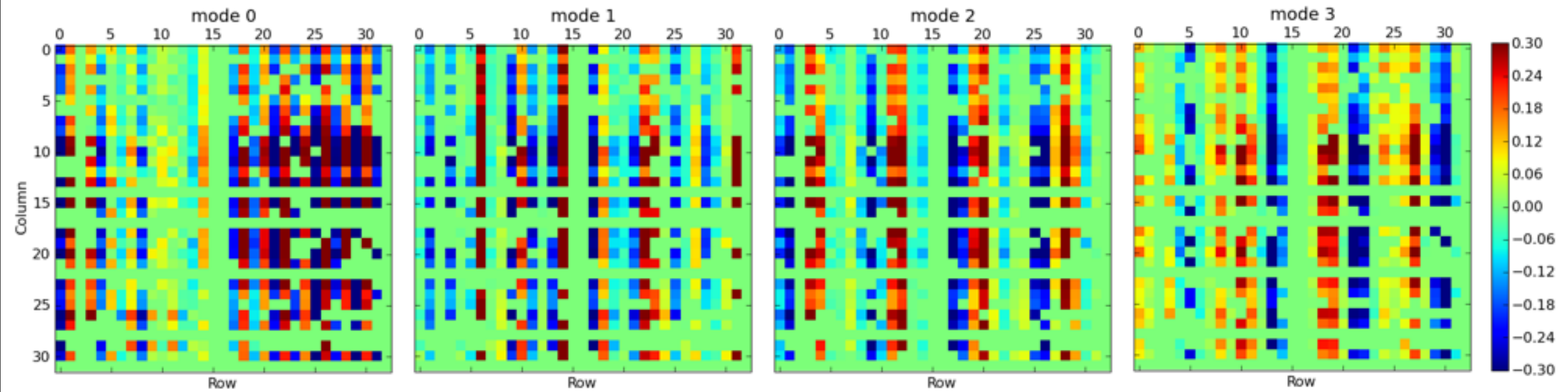
Use a prior before the SVD analysis to optimize the correlated modes to represent a certain kind of correlation.

Row correlations:

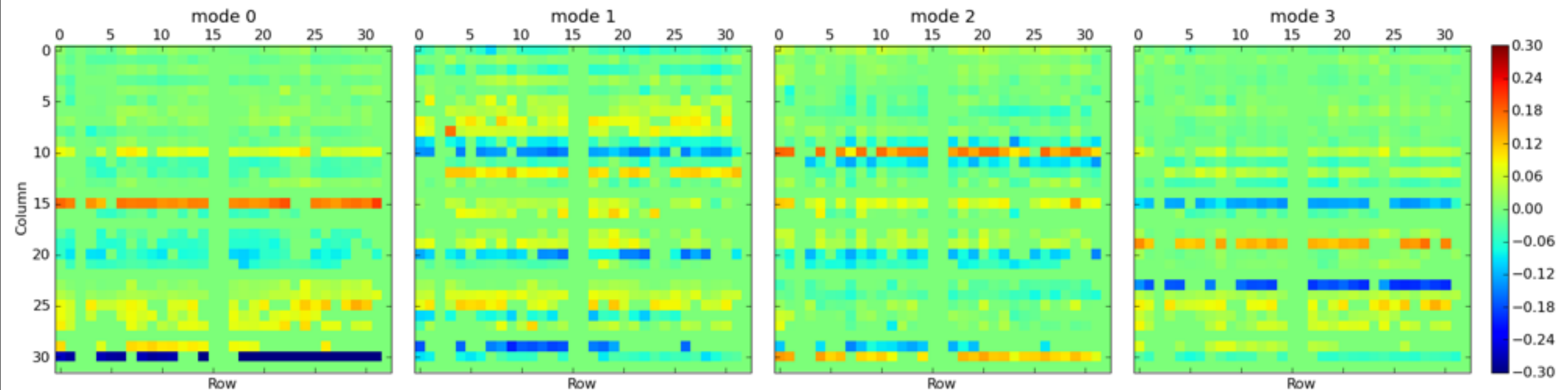


Mode Identification

Row correlations:



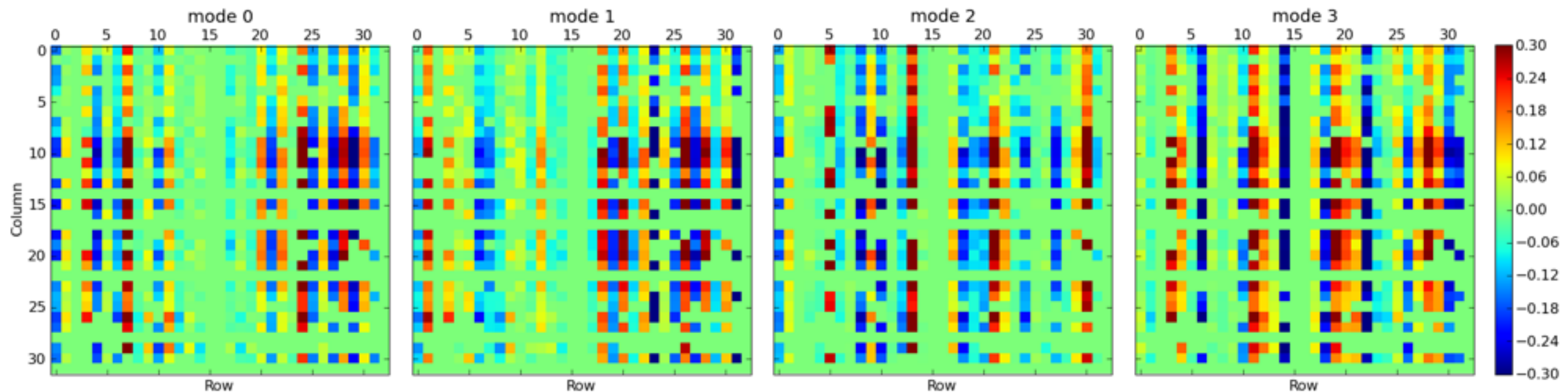
Column correlations:



Dark Modes

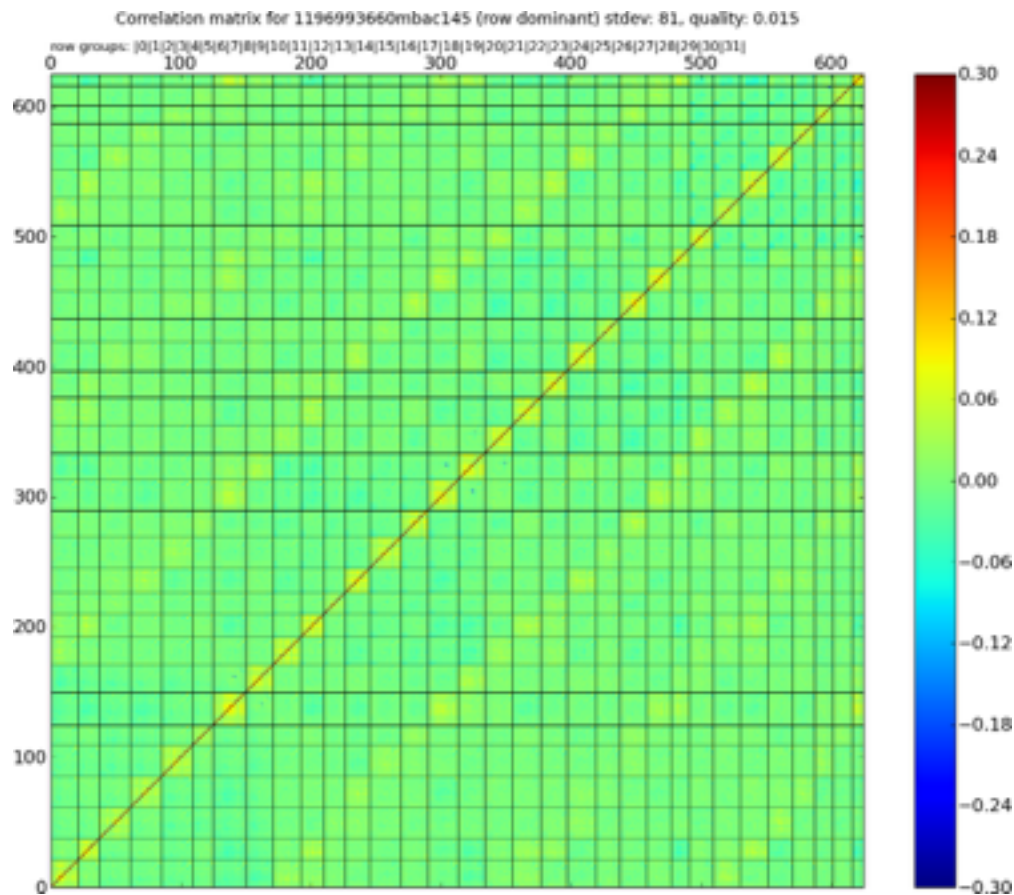
- Systematics associated with the readout also manifest in the dark detectors.
- The strongest modes among the dark detectors can be identified using SVD analysis.

Dark mode correlations:

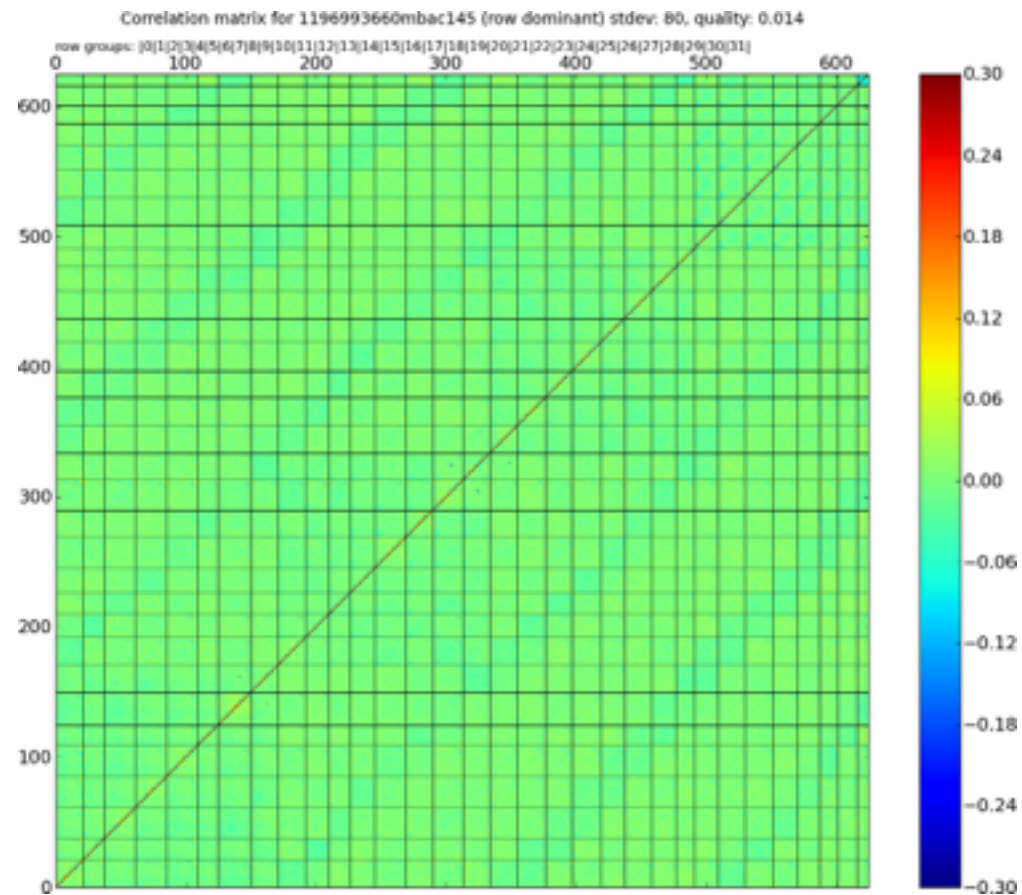


Decorrelation Results (Row)

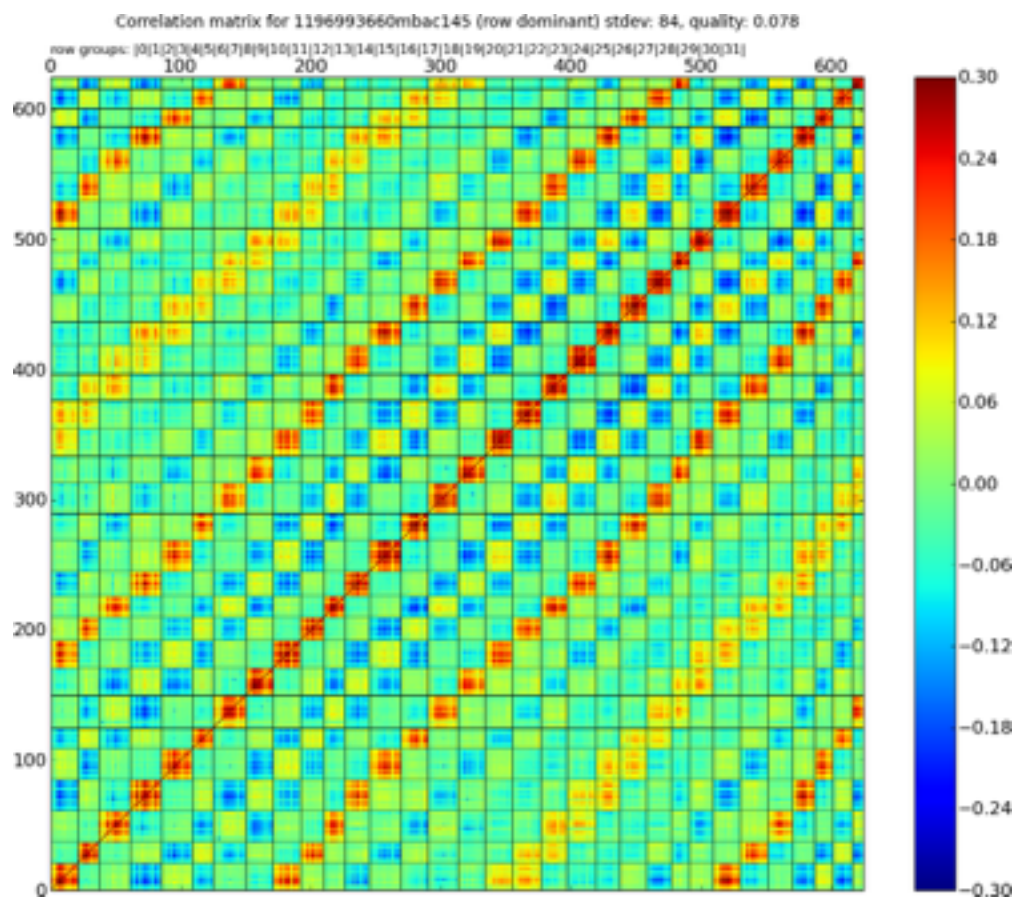
Dark Modes (12)



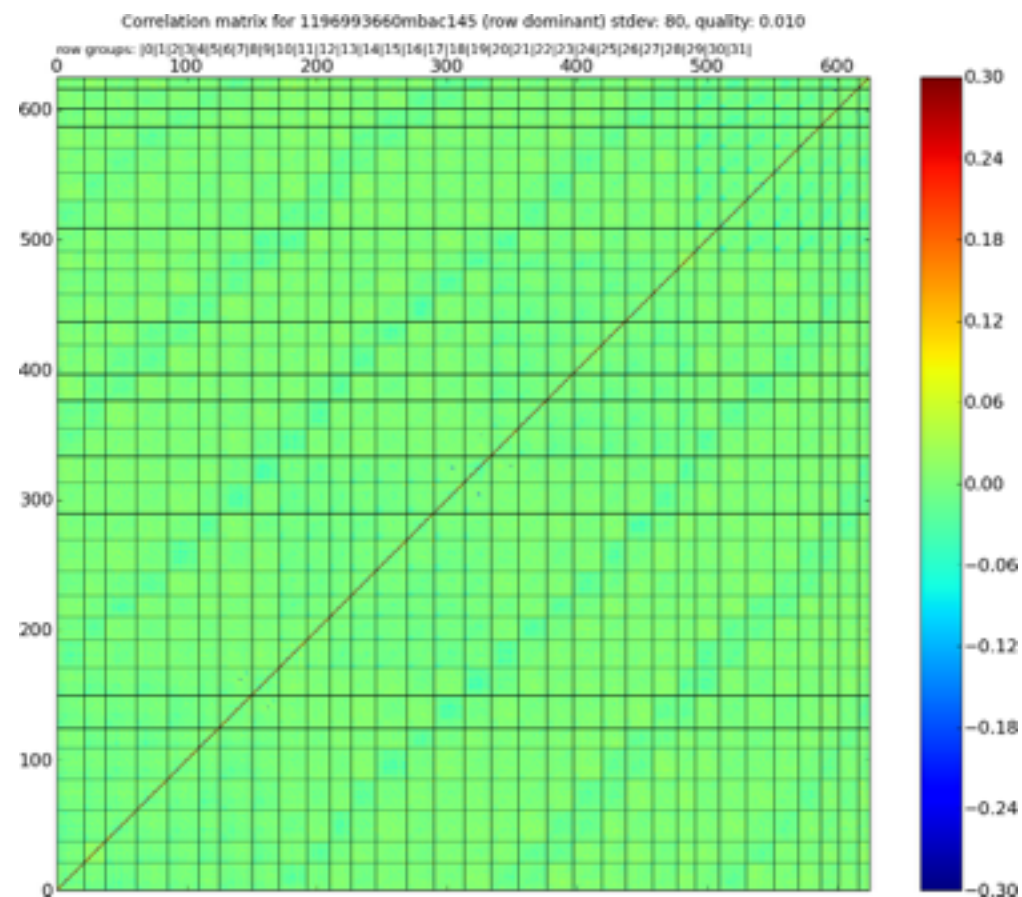
Row Modes (8)



Column Modes (8)



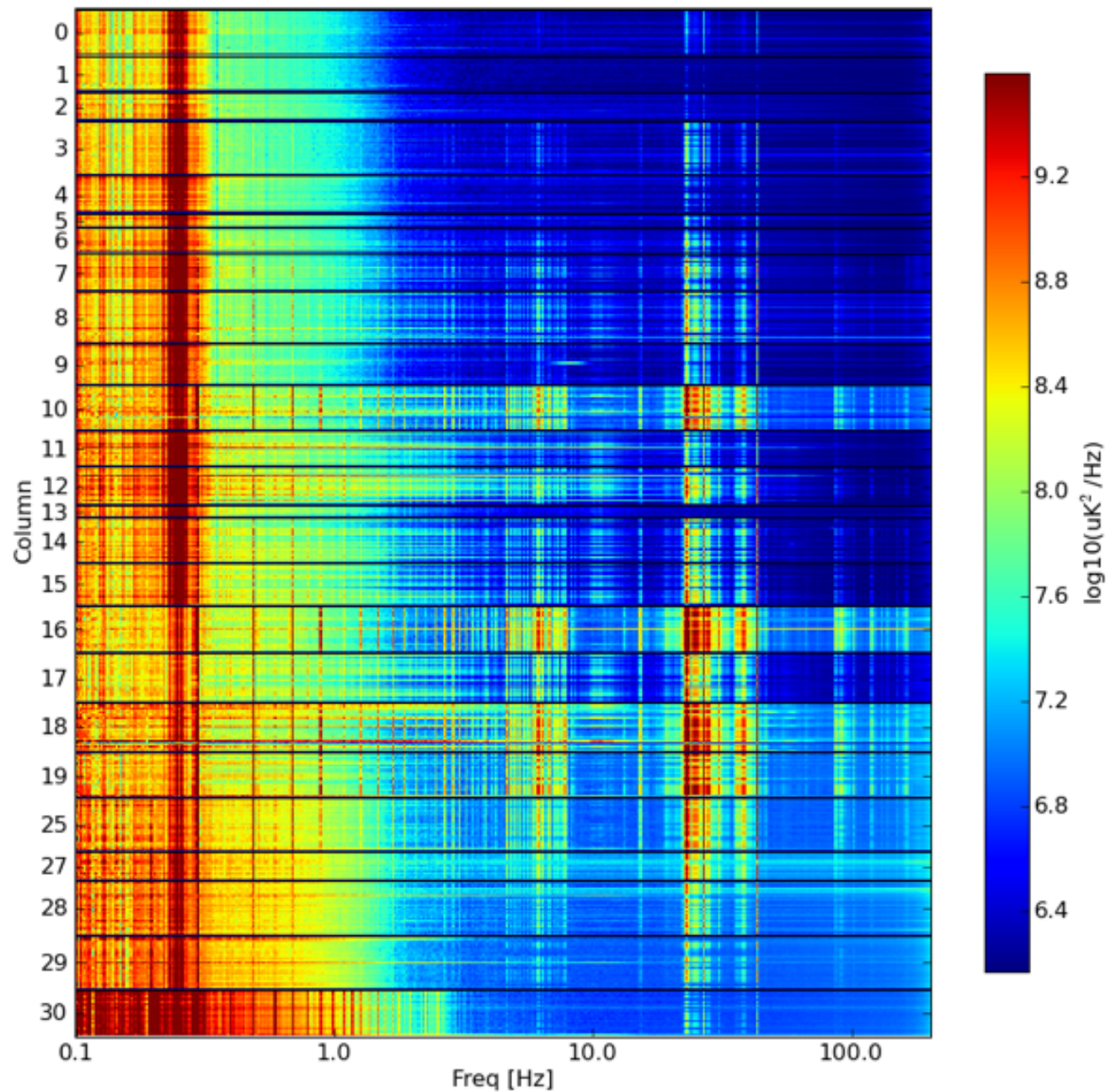
SVD Modes (12)



Decorrelation Results

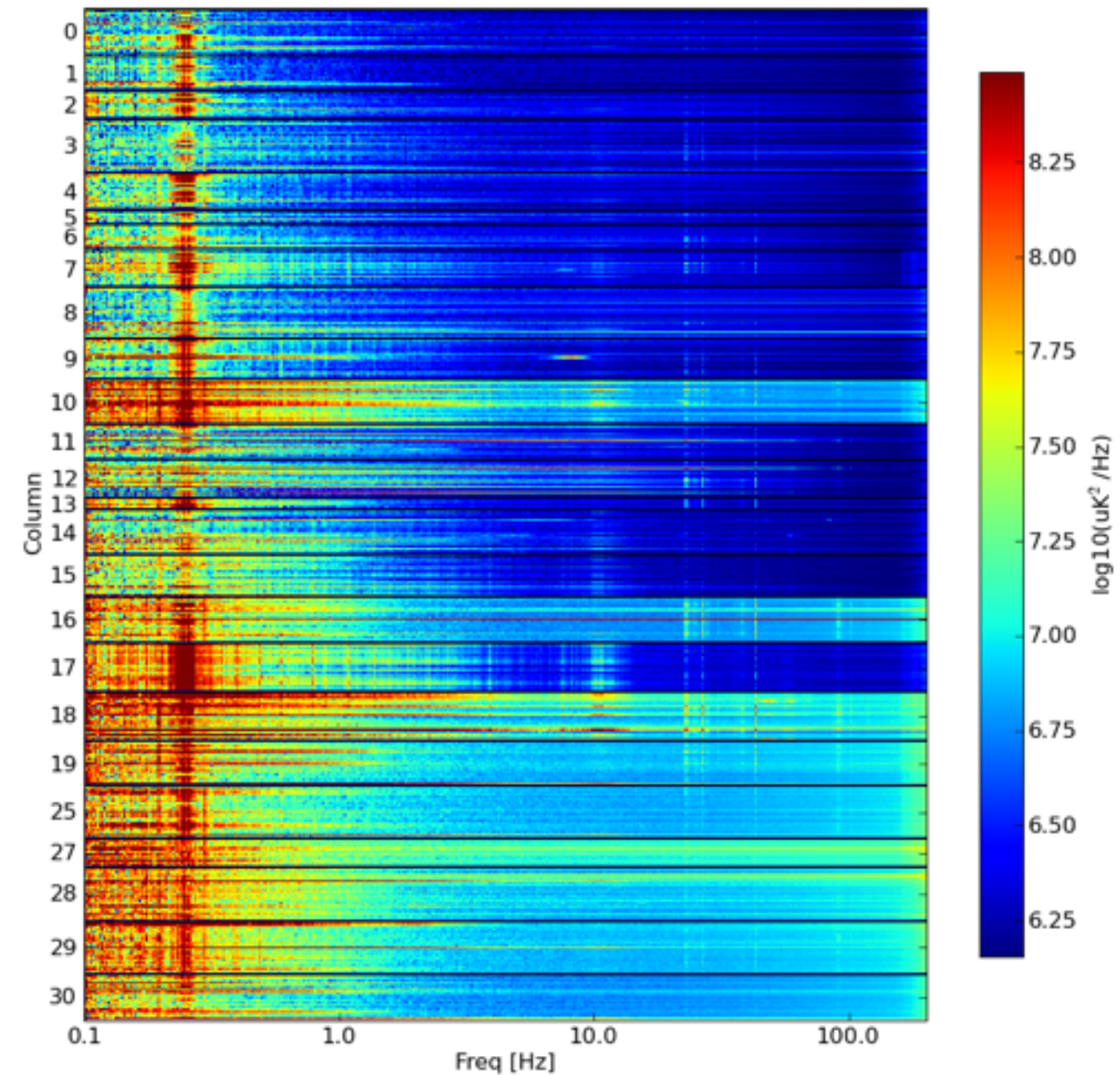
AR3 Raw

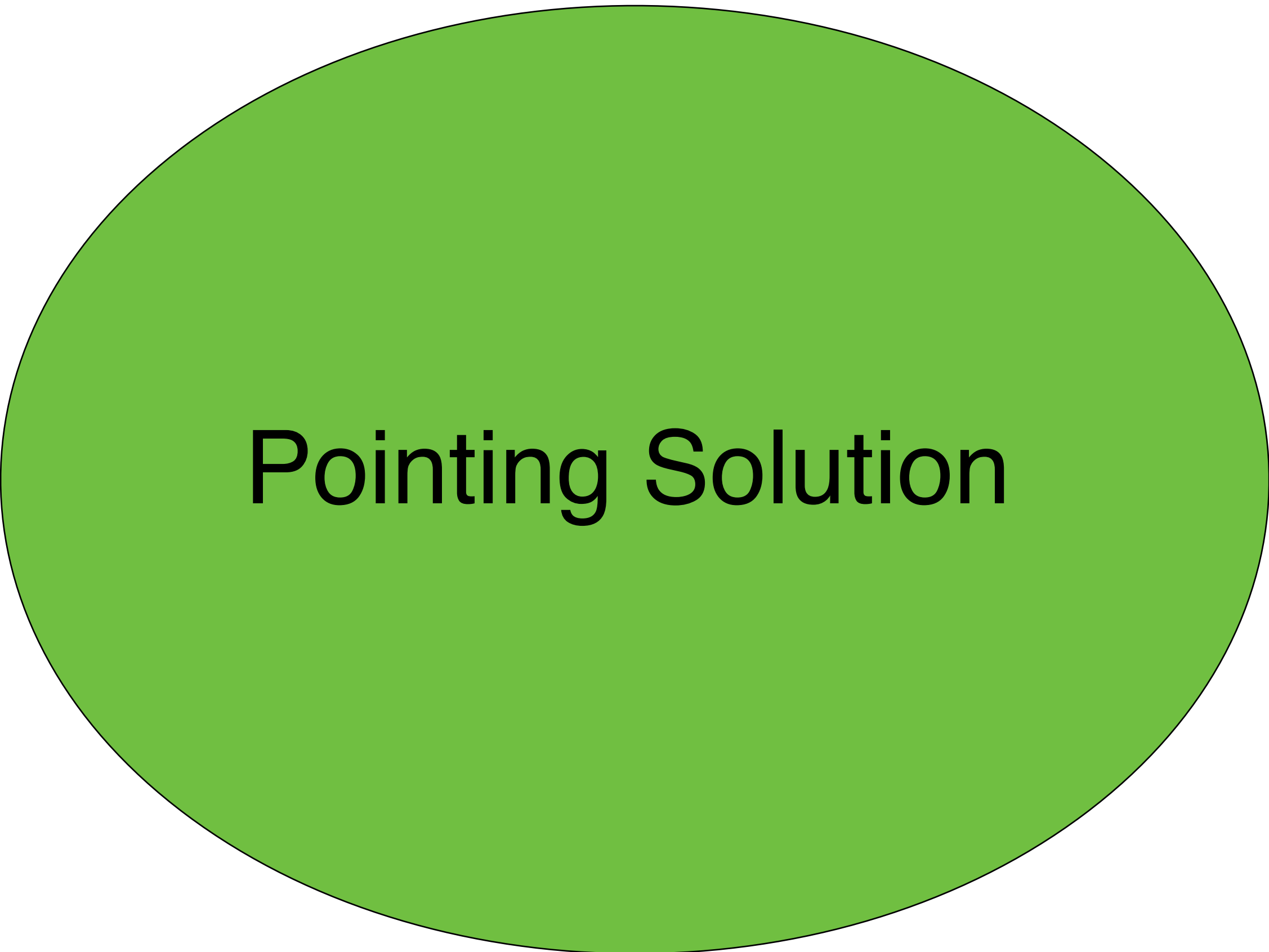
Waterfall TOD 1227160581 mbac280 (Column Dominated)



AR3 + CM + CC4

Waterfall TOD 1227160581 mbac280 (Column Dominated)

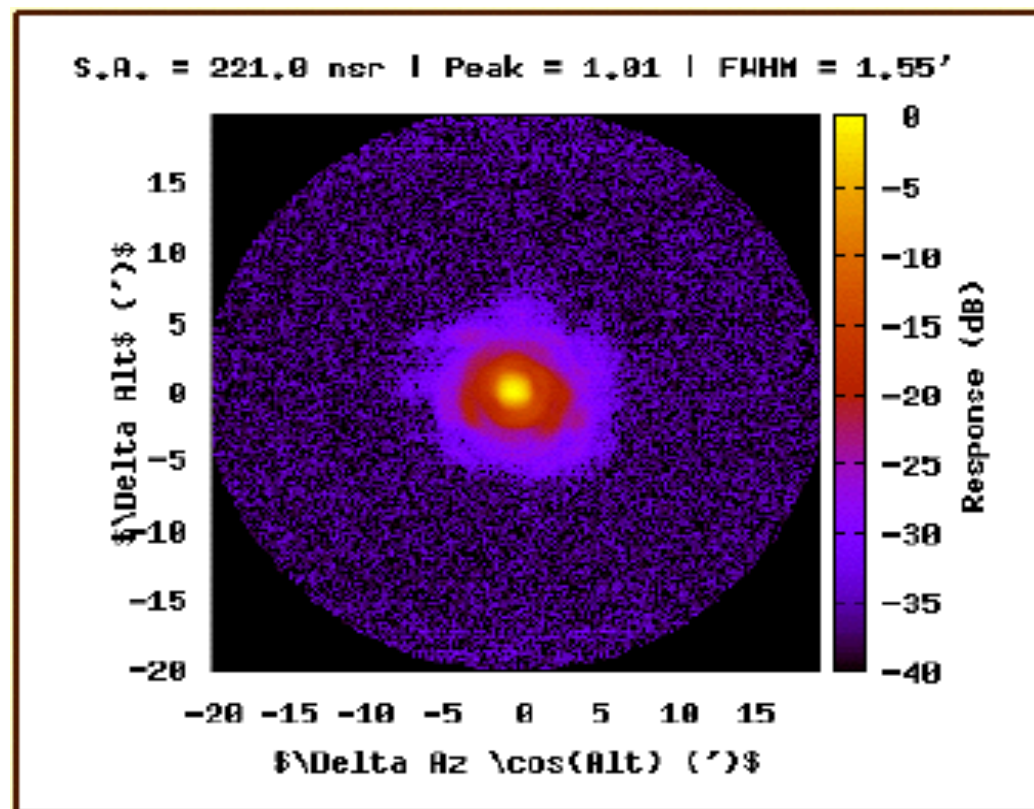




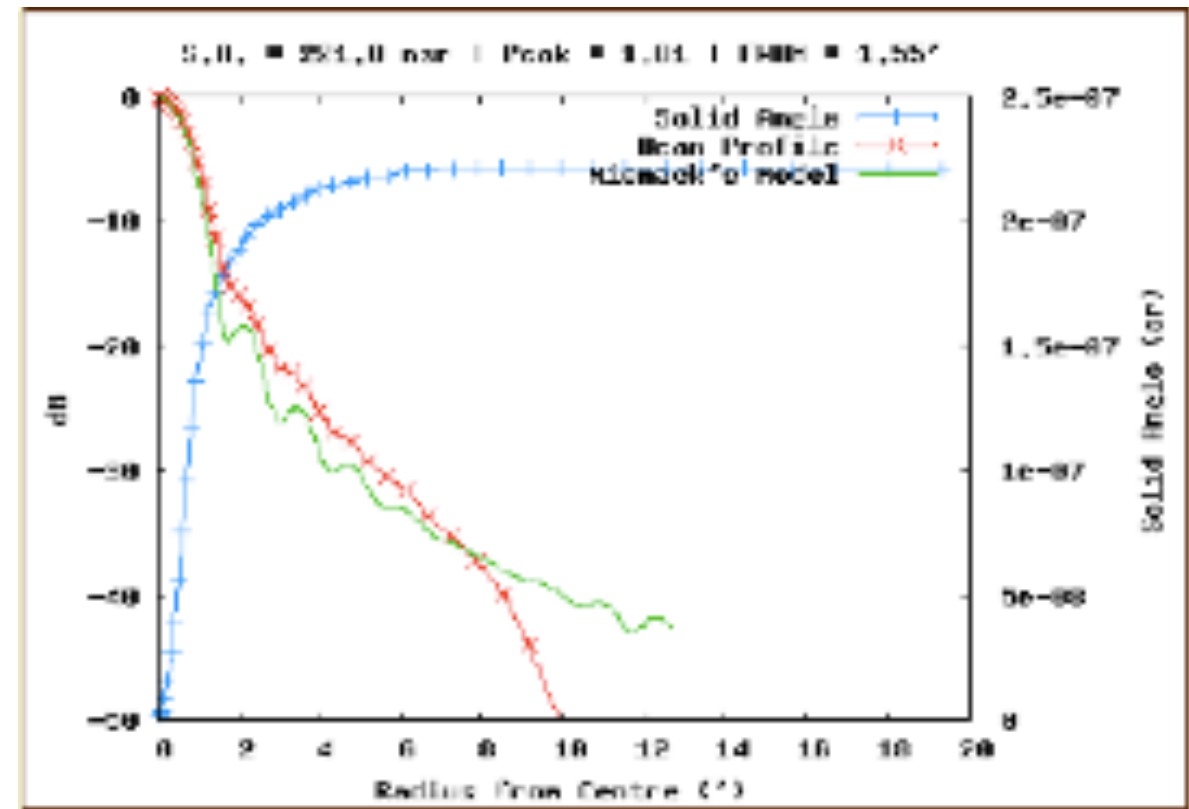
Pointing Solution

Instrument Beam / PSF

Adam Hincks



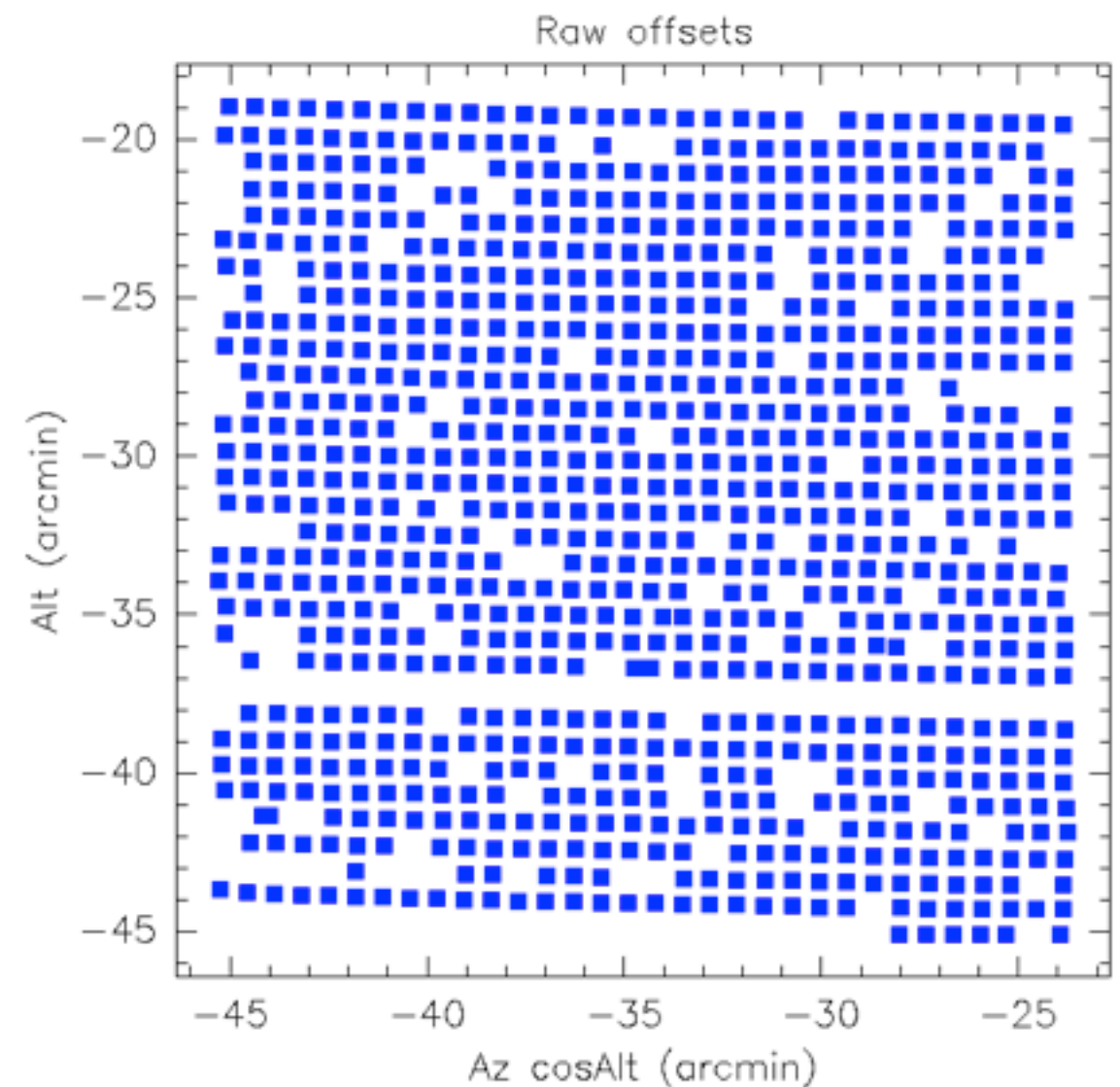
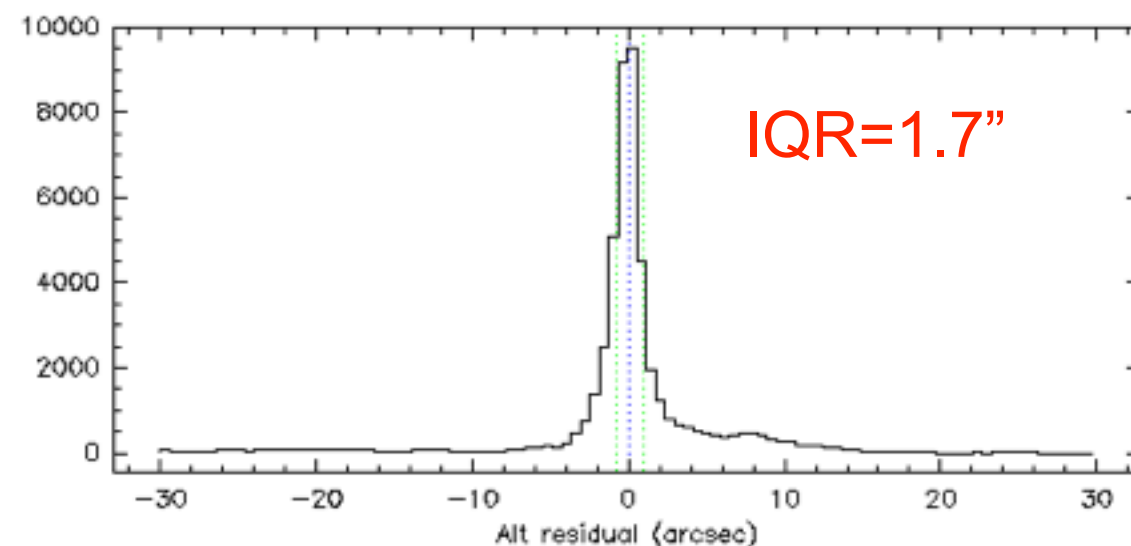
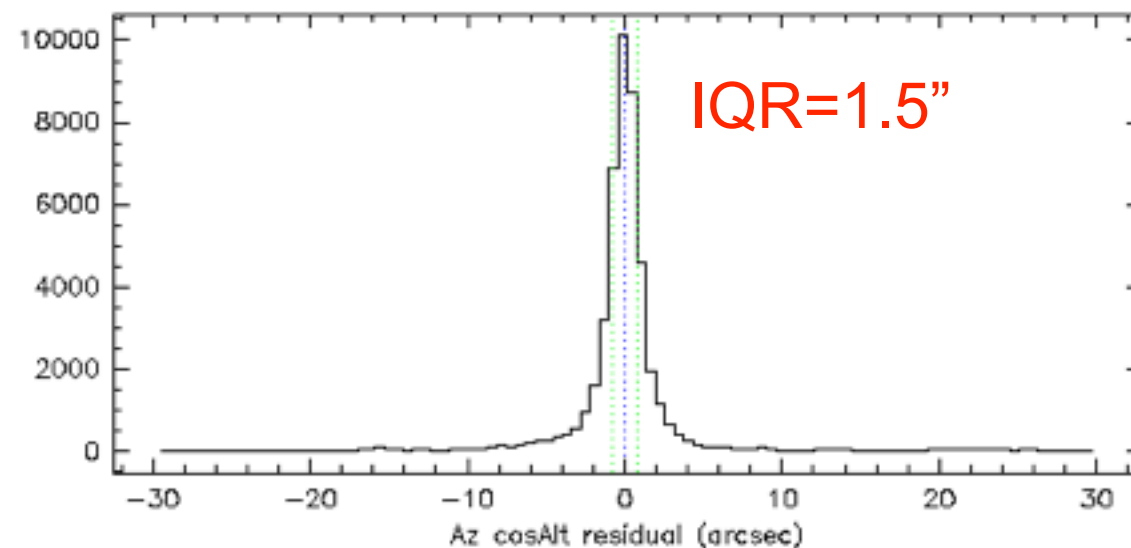
One 6-minute stare at saturn

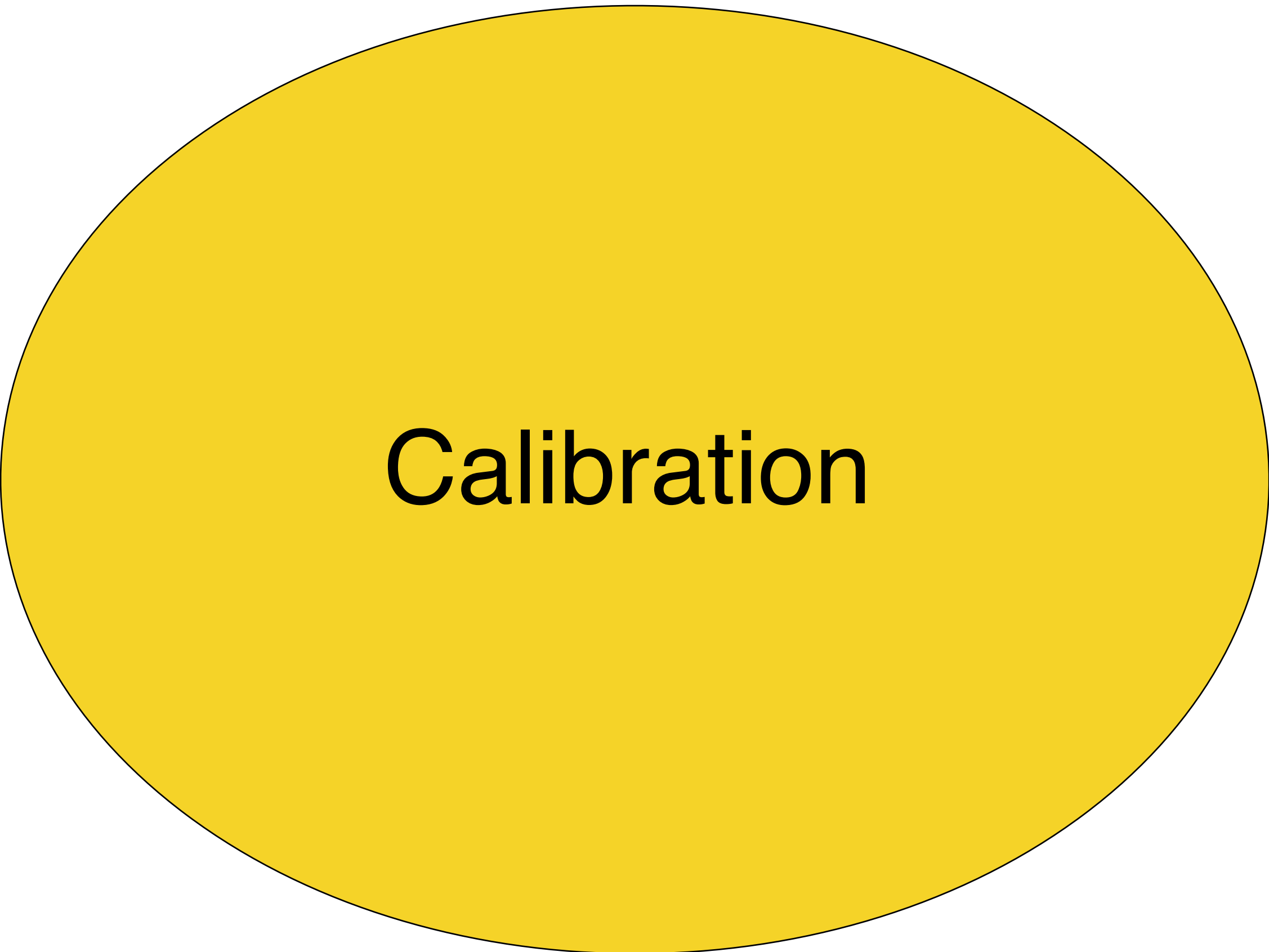


Az-averaged beam profile (red),
model (green)

Pointing accuracy

- Beam FWHM = 90", 60", and 50" in 3 wavelengths.
- Pointing repeatable to 2" on planets.
- Bright radio sources in all fields as a check.
- The overall pointing solution is a function of time of the day and day in the year.





Calibration

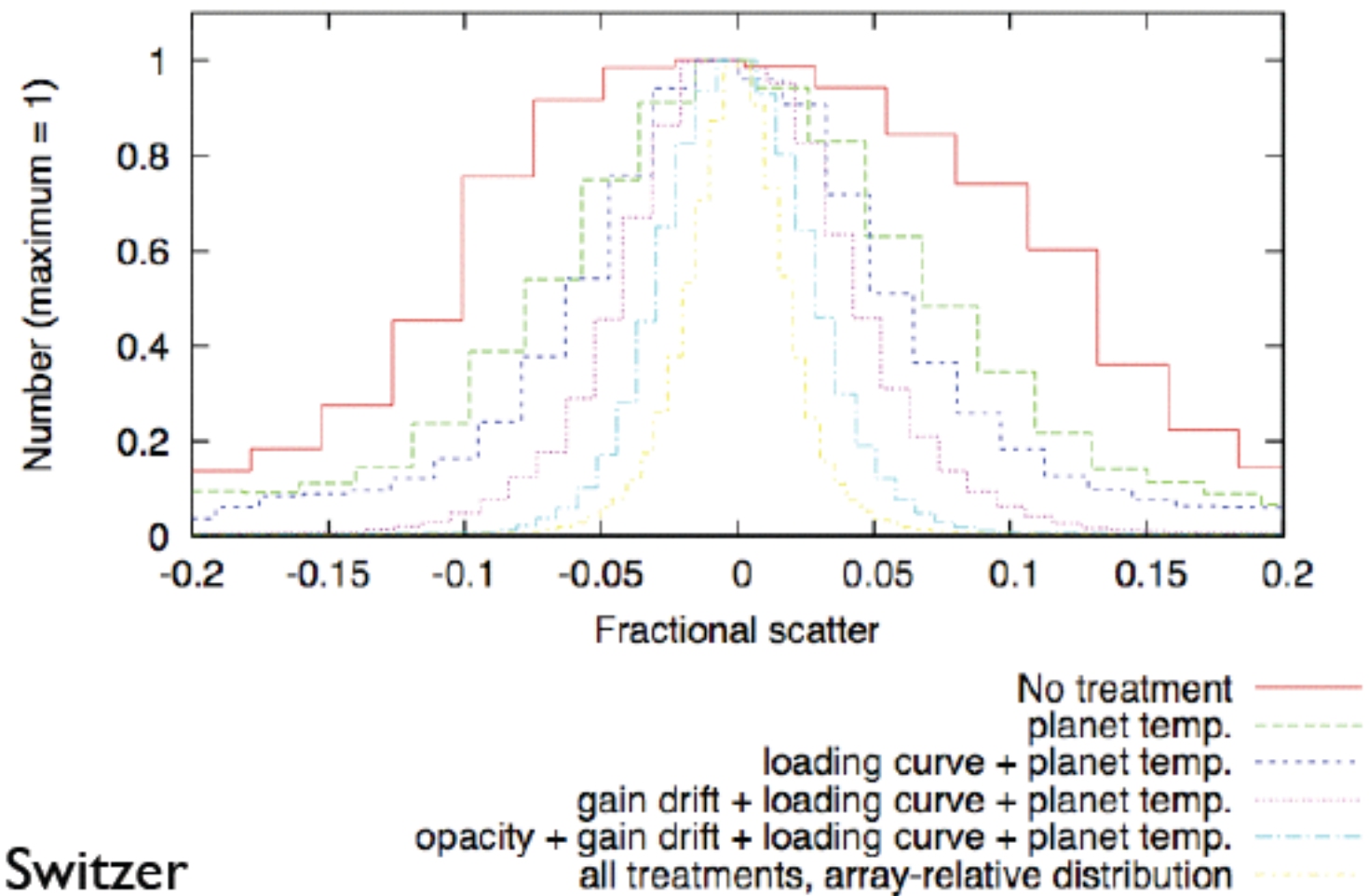
Calibration

- The data is acquired in DAC units.
- The responsivity is the relation between the current measured in the TES and the power received by it. It is used to convert from DAC to pW
- The overall efficiency of the telescope determines the relation between power and sky temperature. It is obtained using planets.
- Per detector coupling efficiencies are corrected using a flatfield obtained from the atmosphere fluctuations.
- The atmosphere opacity is calculated as a function of the PWV.
- The final maps are cross-calibrated to WMAP.

Gain calibration

Accounts for:

- Saturn brightness variation
- Early evening calibration
- Model of gain vs power load
- Optical depth through atmosphere
- Calibration pulse response



E. Switzer



Map making

Map making

- Consists in finding the best solution for a sky map considering all the data and a noise model.
- The mapper minimizes: $\chi^2 = (d - Mx)^T N^{-1} (d - Mx)$

where d is the data, N is the noise covariance matrix, M is the pointing matrix and x is the map solution

- This is solved using Preconditioned Conjugate Gradient (PCG) method on large computers.
- The art is in modeling the noise correctly.

Map-making

- The map projection equation:

$$d = \mathbf{M}x + n$$

- Least square solution:

$$\mathbf{M}^T \mathbf{N}^{-1} \mathbf{M} x = \mathbf{M}^T \mathbf{N}^{-1} d \quad \mathbf{N} = nn^T$$

- Preconditioned Conjugate Gradient (PCG) equation:

$$\mathbf{P} \mathbf{M}^T \mathbf{N}^{-1} \mathbf{M} x = \mathbf{P} \mathbf{M}^T \mathbf{N}^{-1} d$$

- A naïve preconditioner is the inverse of the weight matrix

$$\mathbf{W} = \mathbf{M}^T \mathbf{M}$$

Noise Modeling

- The noise is modeled using the main correlated modes in the covariance matrix of the data in a per-TOD basis.
- The frequency dependence of the noise is accounted for by binning the data in frequency space before computing the correlated modes.
- The modes are found using SVD decomposition.
- The code is called NINKASI and it was developed by Jon Sievers.
- It takes around 1 minute per iteration and converges after 100-2000 iterations.

Current ACT Maps

This problem can be solved iteratively. Considering the huge amount of data from ACT, a supercomputer is needed.

Ninkasi is a parallel computing software specially developed for this task.



UToronto SciNet cluster contains $3e4$, 2.53 GHz Nehalem cores. It takes $\sim 1e5$ CPU hours for one season of data (1000 iterations, ~ 1 minute per iteration on 4800 cores for 5 TB of data)



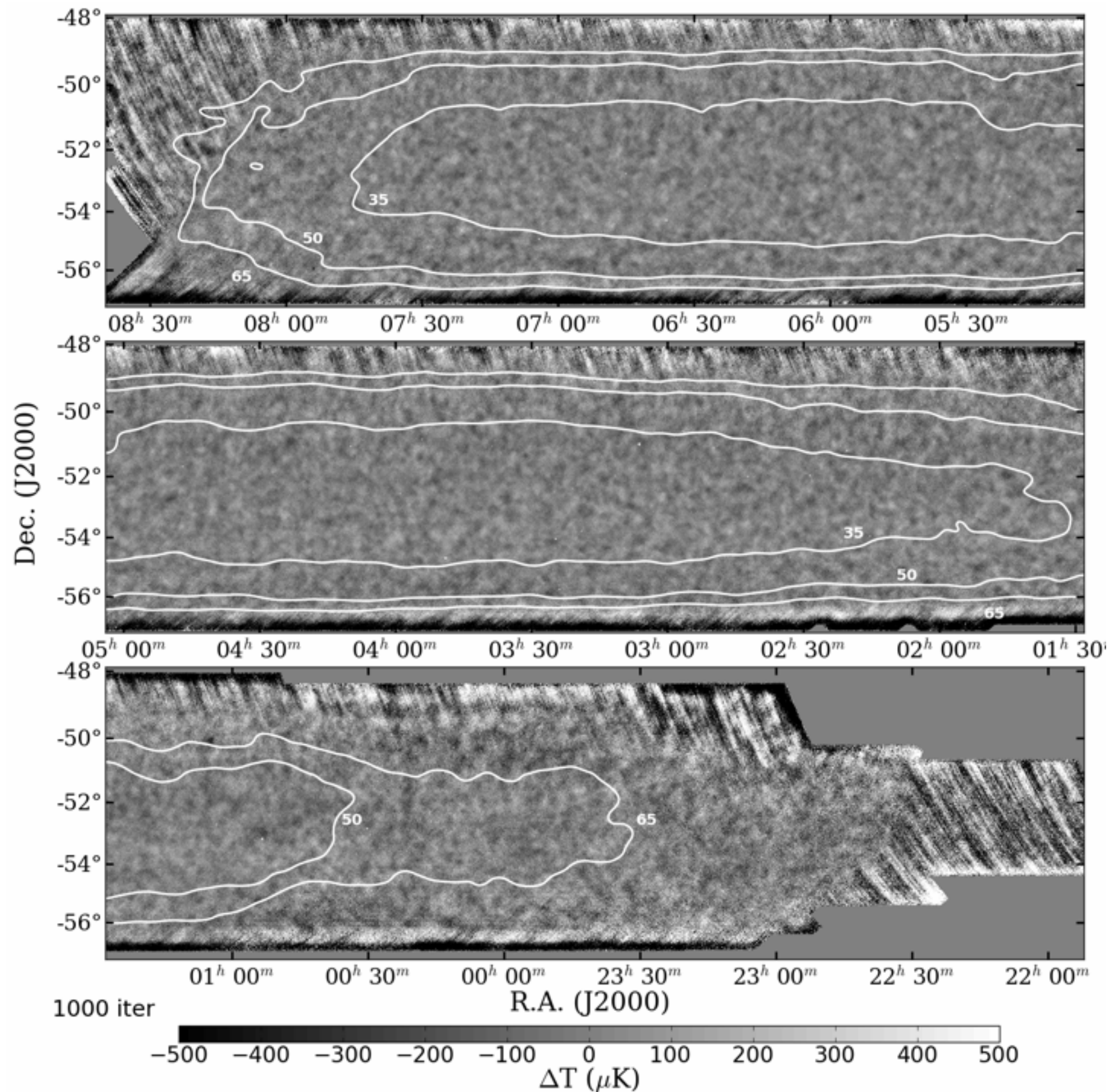
MAP VERIFICATIONS

You need to trust before releasing

Map self compensation

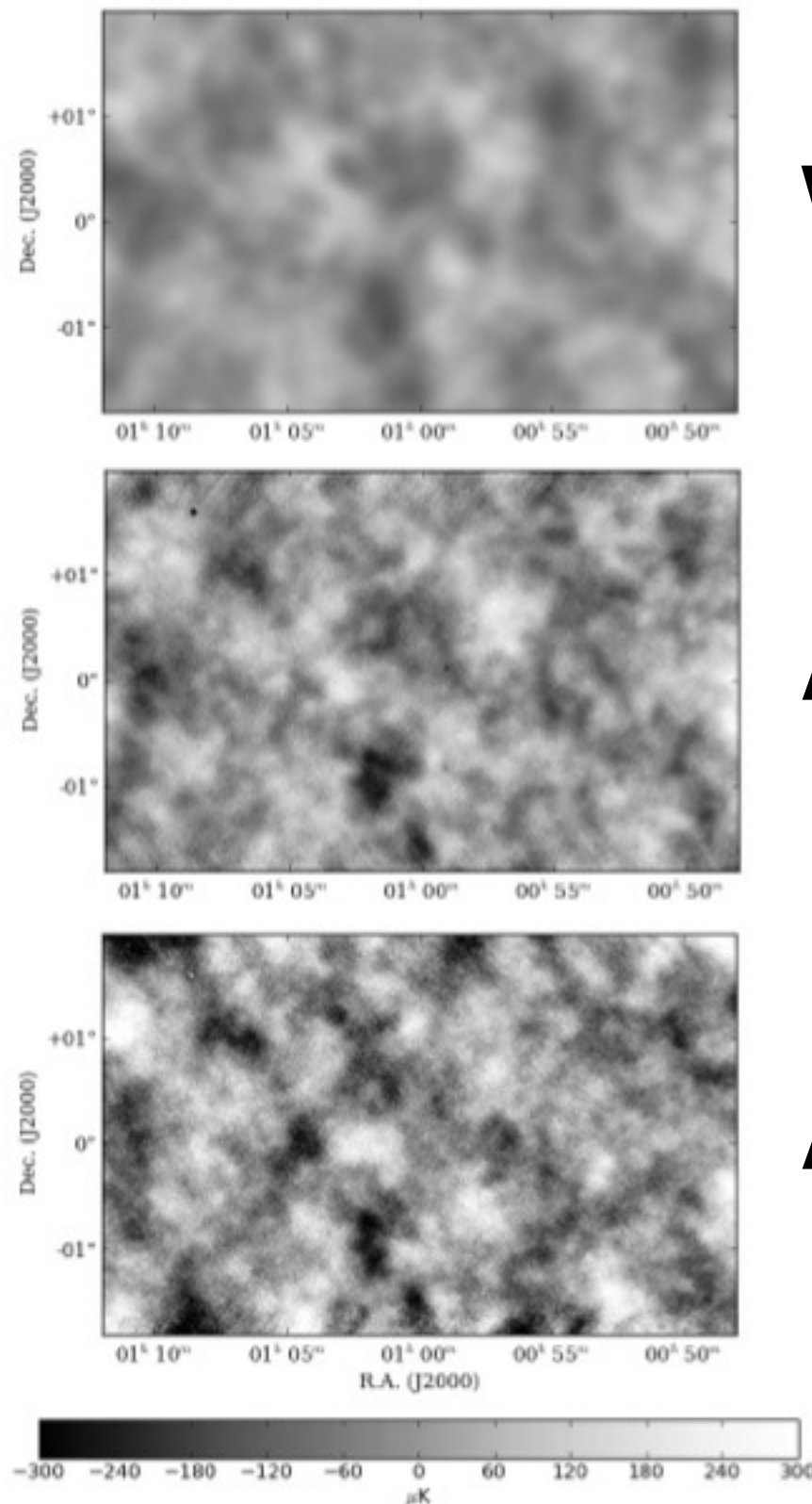
- First you make a map and detect all the visible point sources.
- Then you de-project the expected (simulated) signal of those point sources from the TODs and map a “CMB-only” map.
- Then you de-project that CMB map from the TODs to produce “noise-only” data, and re-compute the noise matrix.
- Finally you re-map your point source free TODs with the new noise matrix and add back the point source signal after mapping.

Southern map from 2008 data



The contours connect areas with the same noise in the map in units of $\mu\text{K} \cdot \text{arcmin}$

Mapper Transfer Function

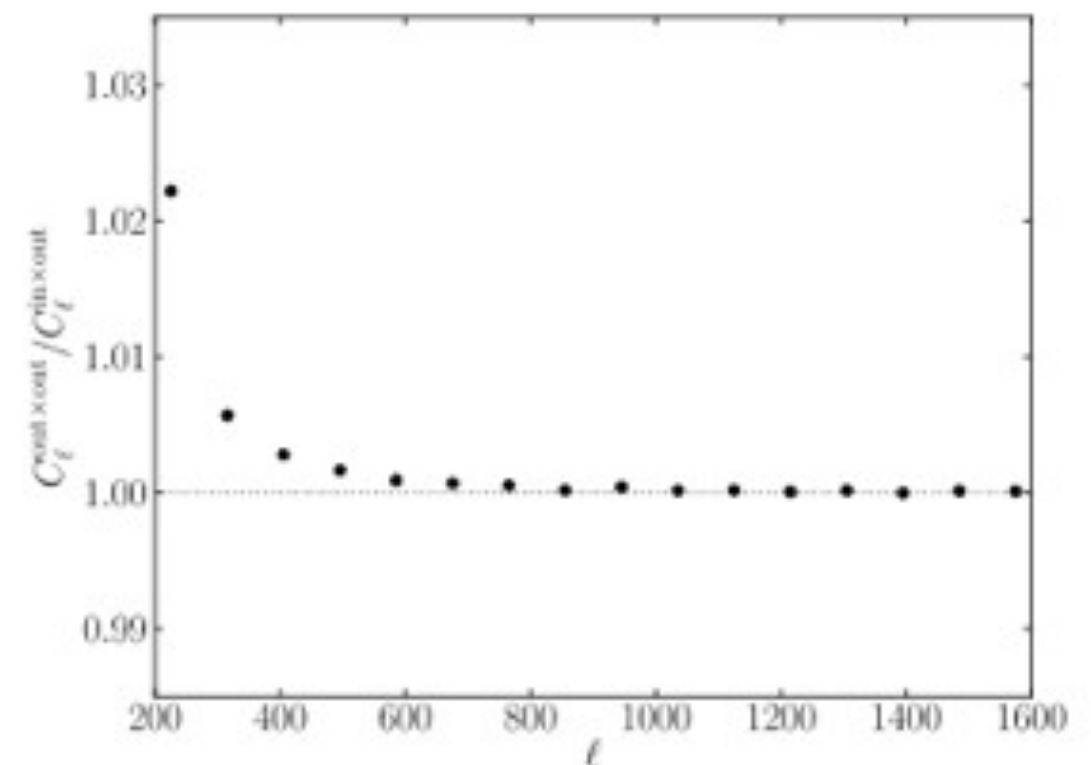


WMAP

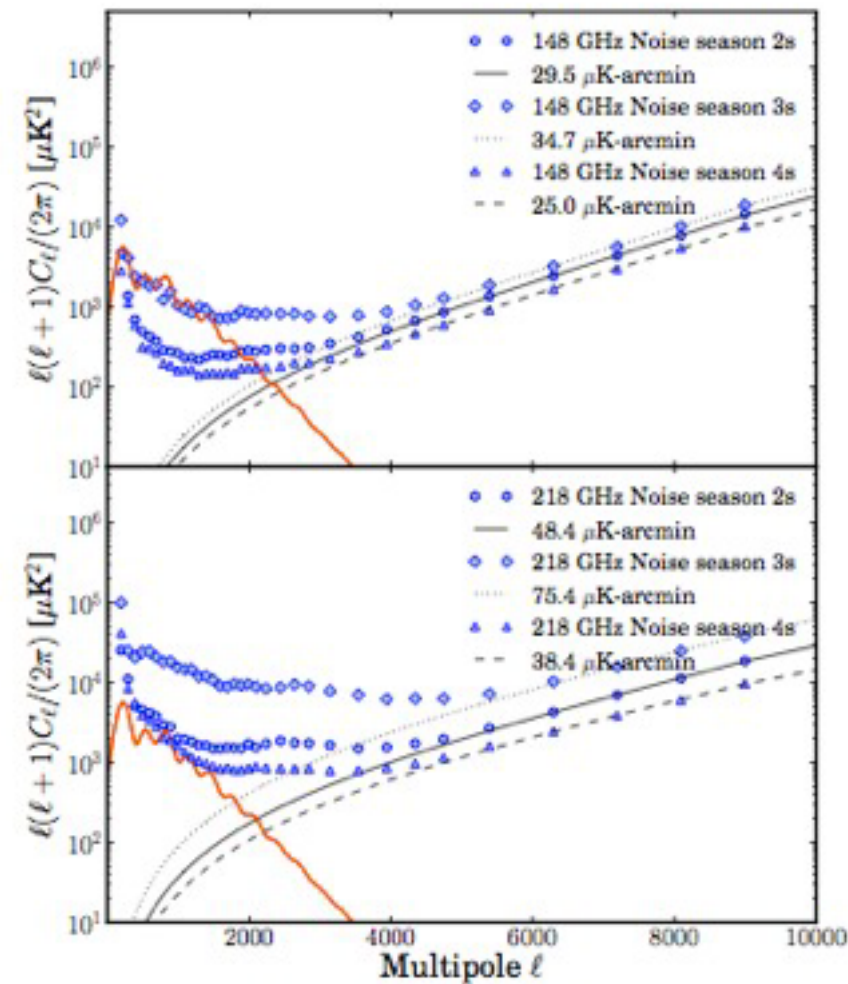
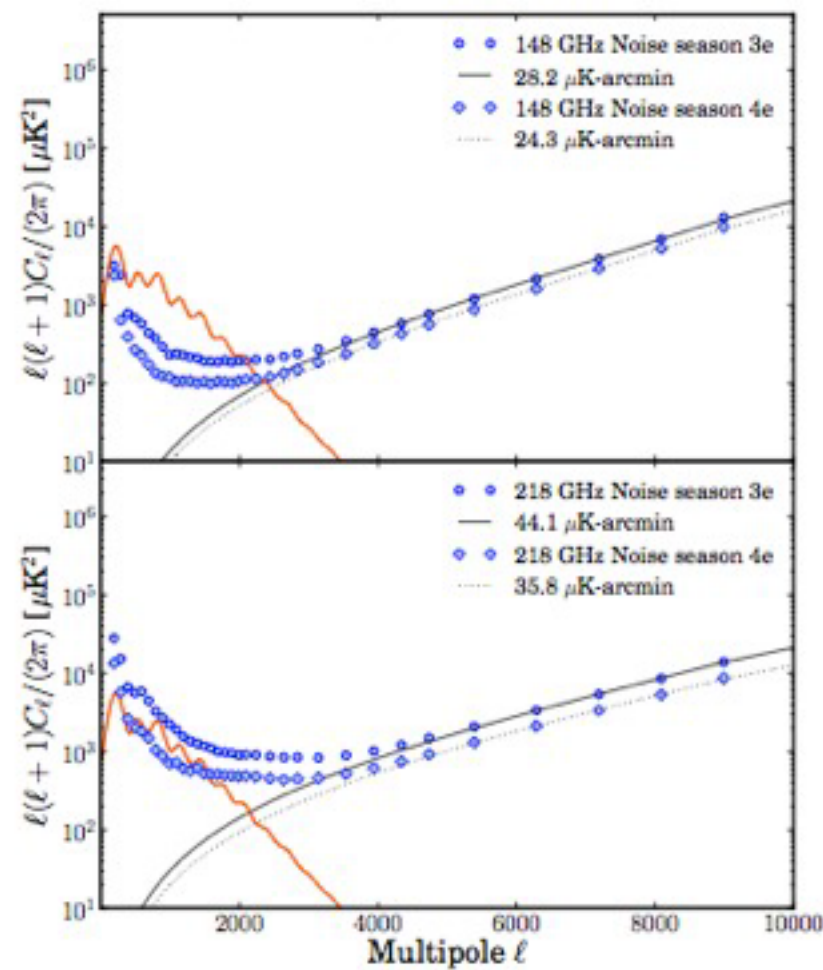
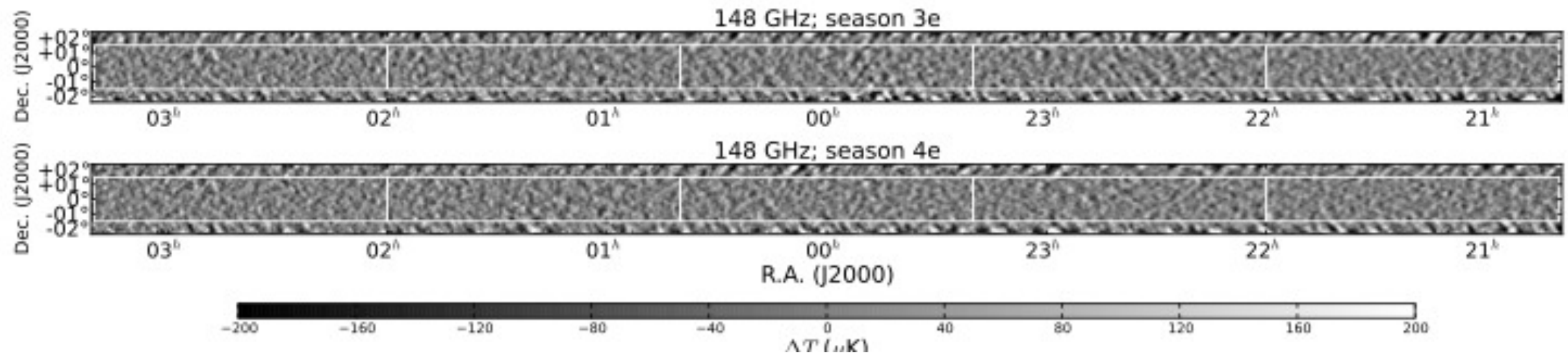
ACT 150GHz

ACT 220GHz

A simulated map (in) was added to the time streams and mapped together with the real data (sim-inject map). Then the real data map (previously computed) was subtracted from the sim-inject map to produce the output map (out). The transfer function was computed as the power spectrum of the output map divided by the cross-spectrum of the output map and the simulated map.



Map Noise



Measuring the power spectrum

- First a the best patches of the map are selected for analysis.
- The maps are pre-whitened, which is a technique that reduces the dynamical range of the power spectrum adding a window function (Das et al 2013).
- Then the sources and dust are masked out, and the edges of the mask are tapered to reduce ringing.
- A pseudo-power spectrum is calculated in 2D space and binned in annulus according to a 2D noise weighting.
- The effects of the pre-whitening and the taper are compensated.
- Several tests are performed to make sure that the result is correct!

Understanding the noise in the maps

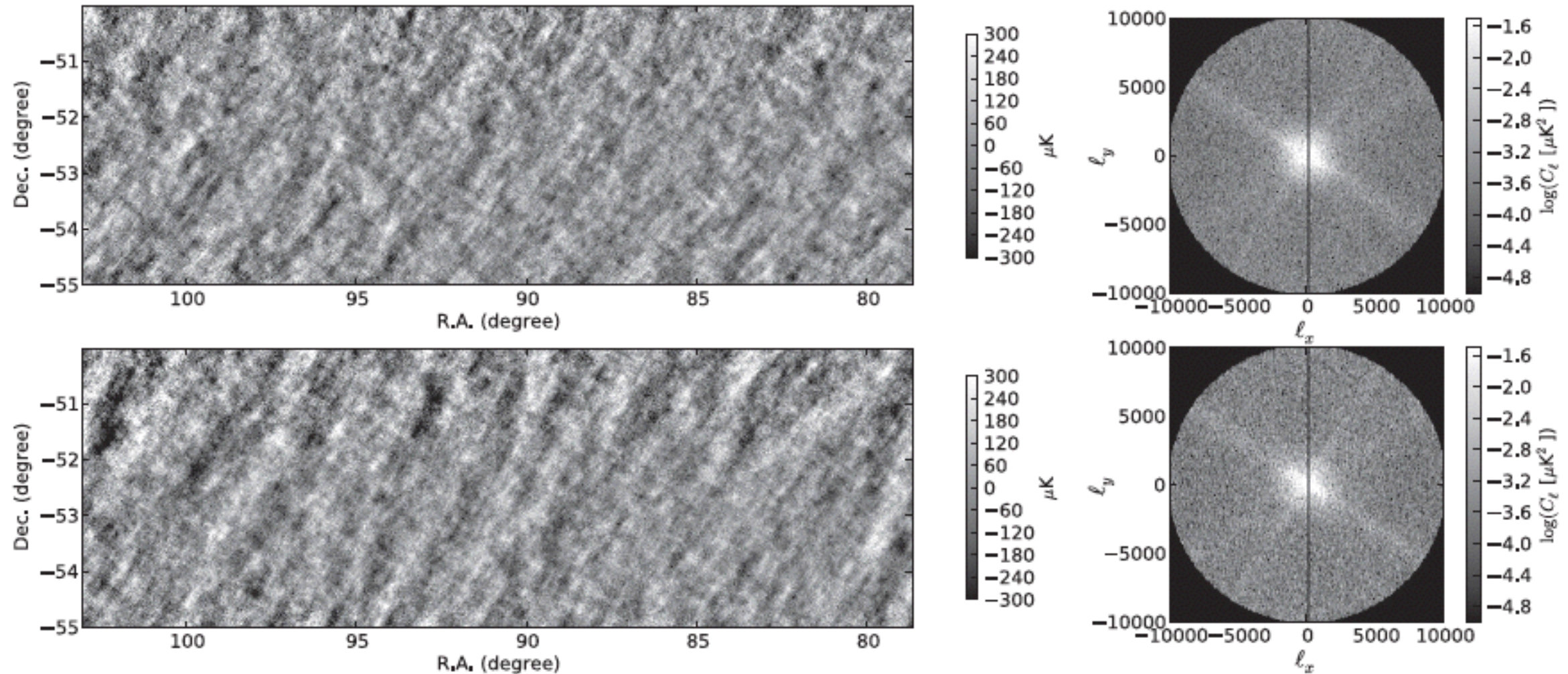
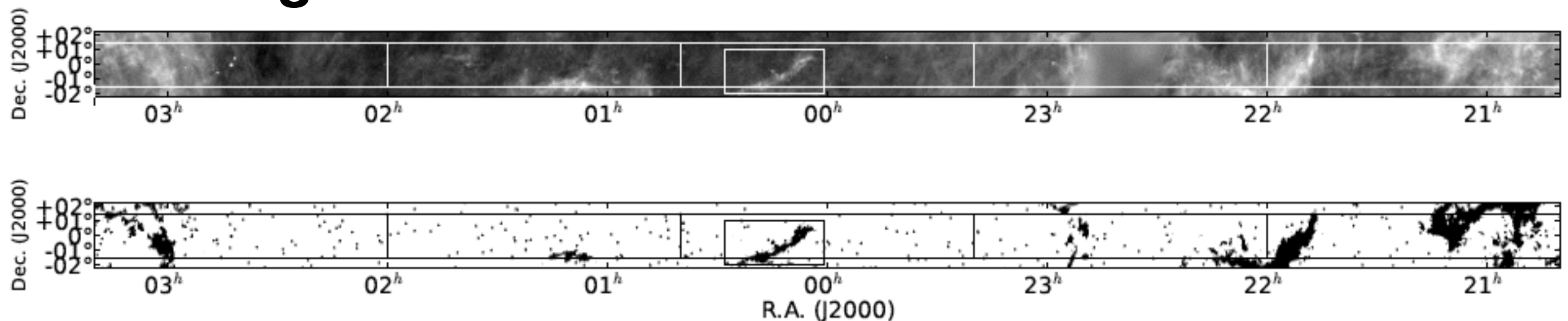


Figure 4. Anisotropic noise in data and simulated patches. Top: difference map of two splits in a 148 GHz data patch (left) and its 2D power spectrum (right). Bottom: same as above, except for a simulated patch. This random realization was seeded by the noise power spectrum of data patch shown in the top panel, as described in the text.

Simulated data has an important role in understanding the mapper and the noise. These simulations, for example, allow us to understand the 2-dimensional distribution of the noise, which is later used to compute the power spectrum correctly.

Computing the power spectrum

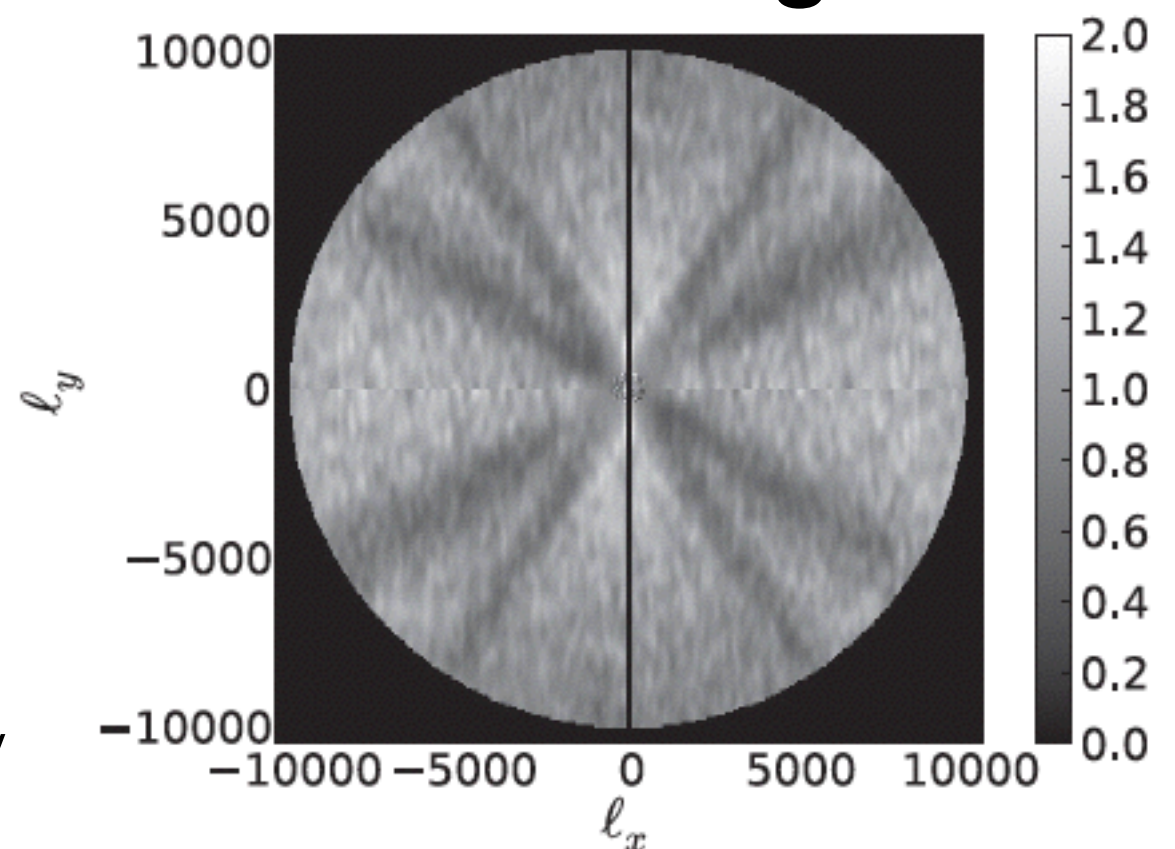
Masking



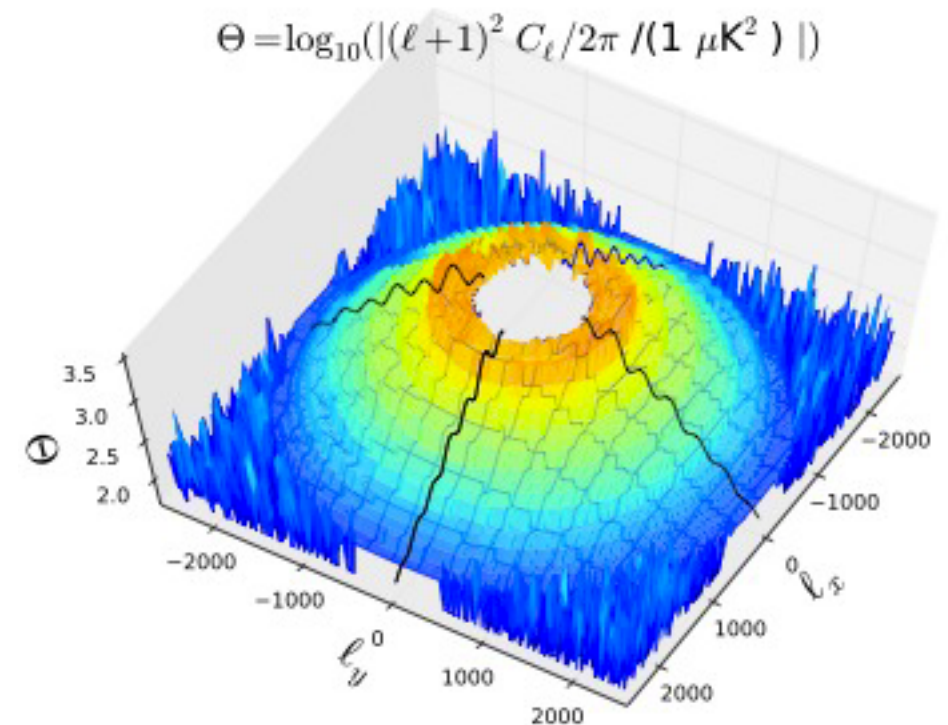
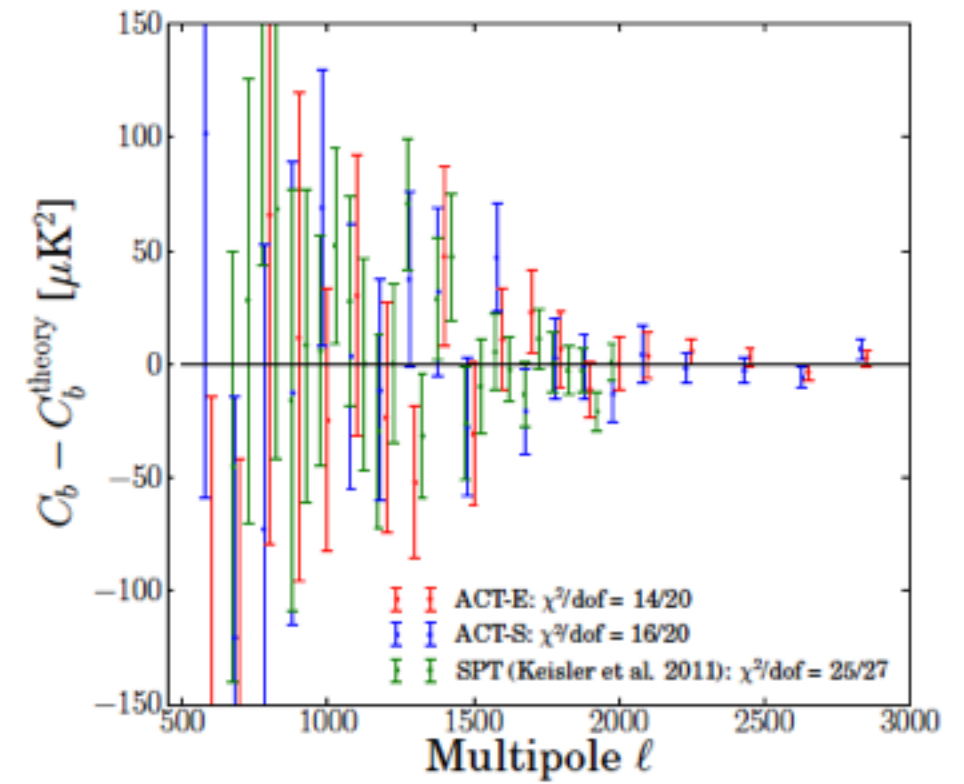
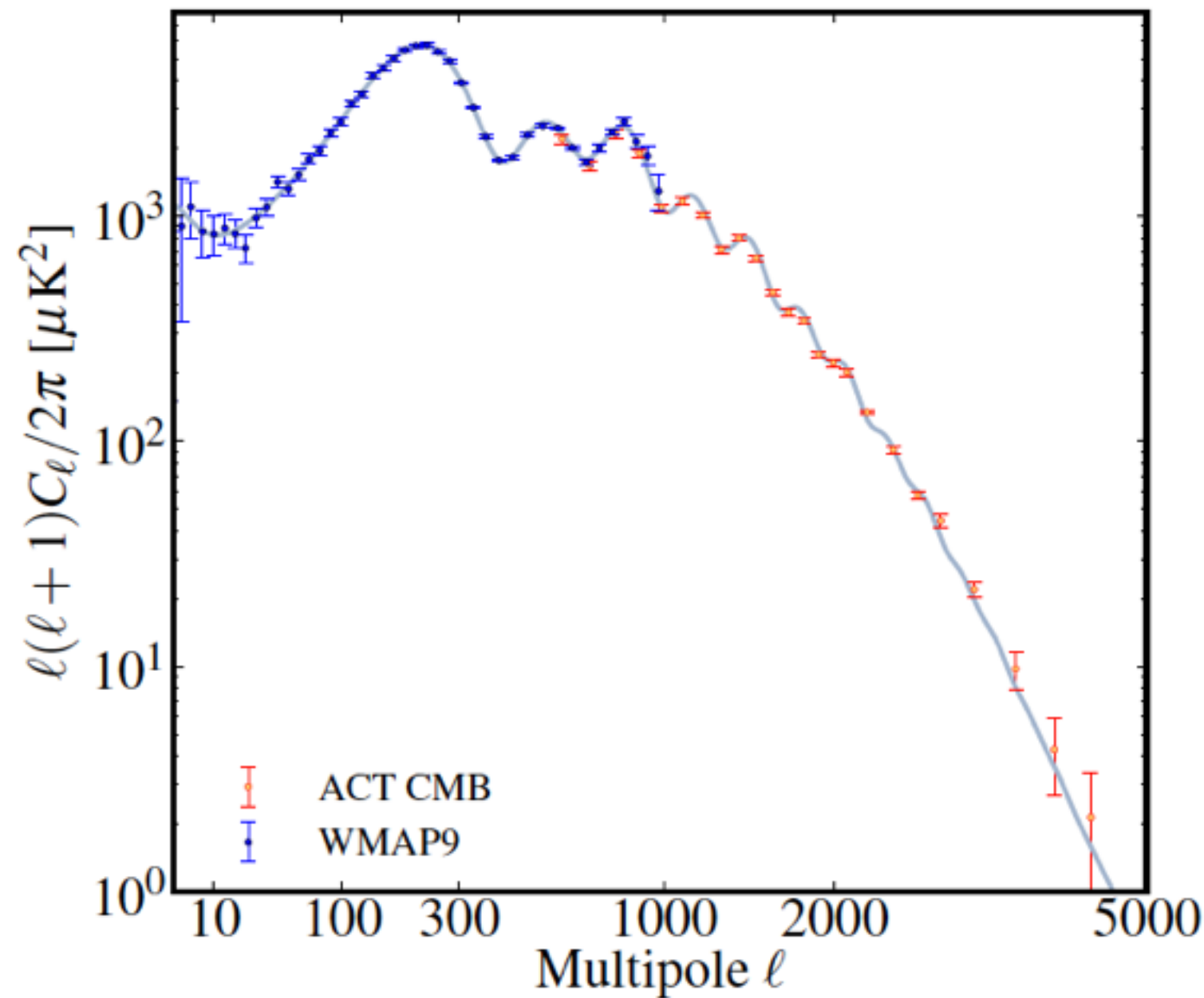
Point sources and dust must be masked out before computing the power spectrum. Then the map must be tapered to avoid ringing and power leakage.

The noise in the maps is anisotropic due to the preferred scan directions and cross-linking. To compensate this the power spectrum is weighted accordingly

2D PS weights



The Result



NULL tests

TABLE 4

NULL TEST χ^2 VALUES FOR THE SEASON CONSISTENCY TESTS PERFORMED ON THE ACT DATA. THE PROBABILITY TO EXCEED (PTE) THE χ^2 IS SHOWN IN PARENTHESES.

Frequency	Region	Seasons	Seasons	Seasons	dof
		2008-2009	2009-2010	2008-2010	
148 GHz	South	32.2 (0.36)	30.7 (0.43)	35.0 (0.24)	30
	Equator	-	39.7 (0.11)	-	30
220 GHz	South	27.7 (0.11)	15.9 (0.72)	21.5 (0.37)	20
	Equator	-	24.2 (0.23)	-	20

TABLE 5

χ^2 (PTE) VALUES FOR THE TOD SPLIT NULL TESTS PERFORMED ON THE ACT DATA.

Frequency	Region	Season	TOD			dof
			(1-2)x(3-4)	(1-3)x(2-4)	(1-4)x(2-3)	
148 GHz	South	2008	19.7 (0.92)	37.7 (0.16)	37.1 (0.17)	30
		2009	30.3 (0.45)	31.8 (0.38)	22.6 (0.83)	30
		2010	35.7 (0.22)	28.6 (0.54)	21.5 (0.87)	30
	Equator	2009	33.9 (0.29)	26.5 (0.65)	40.9 (0.09)	30
		2010	34.6 (0.26)	35.6 (0.22)	24.0 (0.77)	30
220 GHz	South	2008	33.1 (0.03)	28.2 (0.10)	15.3 (0.76)	20
		2009	14.4 (0.81)	11.3 (0.94)	14.8 (0.79)	20
		2010	8.8 (0.99)	16.0 (0.72)	21.0 (0.40)	20
	Equator	2009	24.9 (0.21)	19.3 (0.50)	13.3 (0.87)	20
		2010	11.8 (0.92)	16.3 (0.70)	14.0 (0.83)	20

TABLE 6

NULL TEST χ^2 (PTE) VALUES FOR THE INNER VS OUTER DETECTORS.

Frequency	Region	Season	In/Out			dof
			(1o-2i)x(3o-4i)	(1o-3i)x(2o-4i)	(1o-4i)x(2o-3i)	
148 GHz	South	2008	26.2 (0.66)	28.2 (0.56)	26.2 (0.67)	30
		2009	37.7 (0.16)	17.3 (0.97)	27.3 (0.61)	30
		2010	34.7 (0.26)	27.3 (0.61)	25.6 (0.70)	30
	Equator	2009	49.5 (0.01)	33.3 (0.31)	45.2 (0.04)	30
		2010	35.2 (0.23)	45.8 (0.03)	39.7 (0.11)	30
218 GHz	South	2008	25.3 (0.19)	23.9 (0.24)	21.0 (0.40)	20
		2009	13.7 (0.85)	12.3 (0.91)	25.8 (0.17)	20
		2010	13.8 (0.84)	15.0 (0.78)	26.3 (0.16)	20
	Equator	2009	20.9 (0.41)	37.7 (0.01)	23.2 (0.28)	20
		2010	23.4 (0.27)	24.2 (0.24)	13.5 (0.85)	20

TABLE 7

NULL TEST χ^2 VALUES FOR TURNAROUNDS

Frequency	Region	Season	Turnarounds			dof
			(1t-2nt)x(3t-4nt)	(1t-3nt)x(2t-4nt)	(1t-4nt)x(2t-3nt)	
148 GHz	South	2008	21.9 (0.85)	24.8 (0.74)	34.6 (0.26)	30
		2009	28.3 (0.56)	35.3 (0.23)	26.7 (0.64)	30
		2010	30.5 (0.44)	30.4 (0.44)	35.0 (0.24)	30
	Equator	2009	27.4 (0.60)	29.3 (0.50)	34.0 (0.28)	30
		2010	35.1 (0.24)	43.9 (0.05)	21.9 (0.86)	30
218 GHz	South	2008	25.9 (0.17)	25.3 (0.19)	20.6 (0.42)	20
		2009	15.8 (0.73)	13.0 (0.88)	14.3 (0.82)	20
		2010	11.2 (0.94)	11.6 (0.93)	21.1 (0.4)	20
	Equator	2009	31.3 (0.06)	19.4 (0.5)	16.6 (0.68)	20
		2010	14.1 (0.82)	24.3 (0.23)	16.7 (0.67)	20

ACTPol Collaboration: Official Logo Banner (Structural)



[From Left to Right]

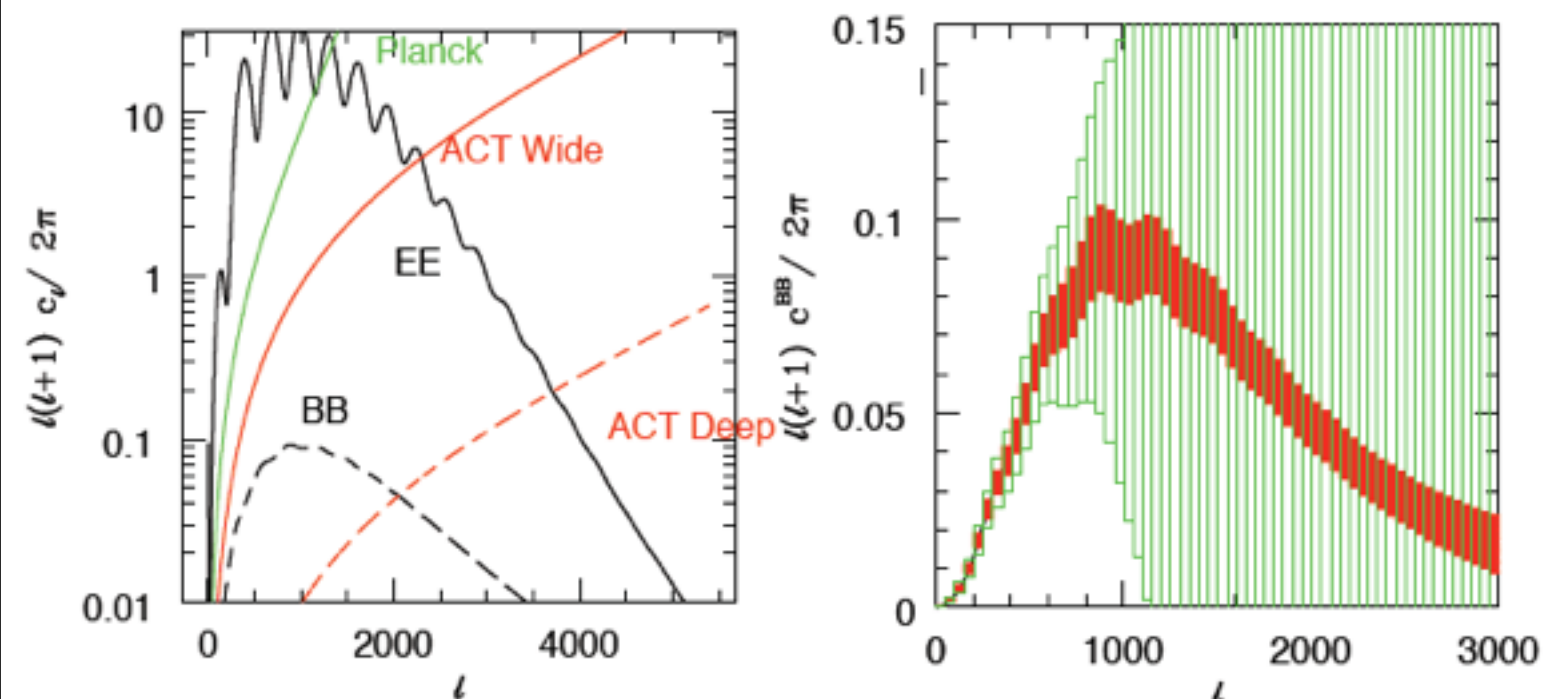
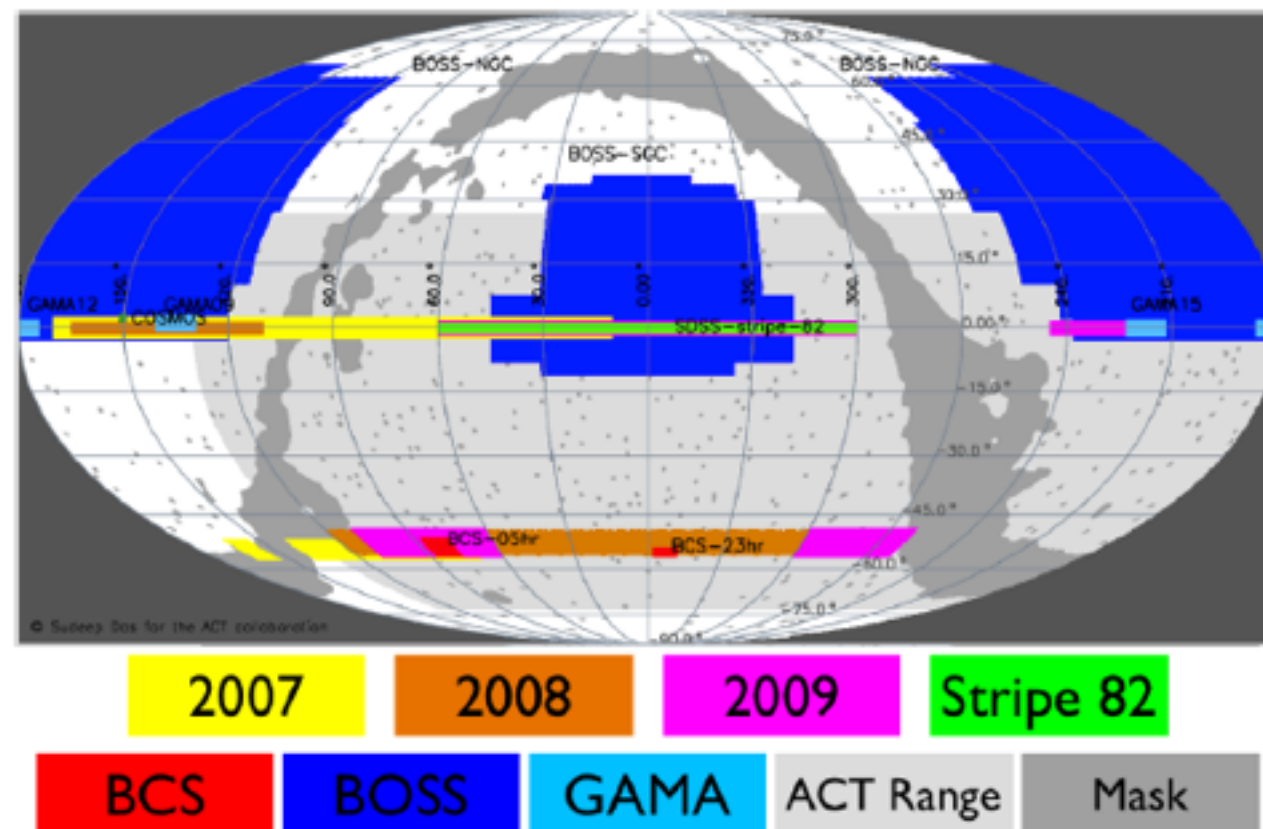
- 1.) Pontificia Universidad Católica de Chile
- 2.) University of Oxford
- 3.) Stony Brook University
- 4.) West Chester University of Pennsylvania
- 5.) National Aeronautics and Space Administration Goddard Space Flight Center (NASA GSFC)
- 6.) University of British Columbia
- 7.) Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
- 8.) Carnegie Mellon University
- 9.) University of Pennsylvania
- 10.) Haverford College
- 11.) Institute for Advanced Study (IAS)
- 12.) National Institute of Standards and Technology (NIST)
- 13.) University of California, Berkeley
- 14.) Canadian Institute for Theoretical Astrophysics (CITA)
- 15.) Princeton University
- 16.) Cardiff University
- 17.) University of Michigan
- 18.) University of KwaZulu-Natal
- 19.) University of Miami
- 20.) University of Pittsburgh
- 21.) Academia Sinica
- 22.) Rutgers, The State University of New Jersey
- 23.) Cornell University
- 24.) The Johns Hopkins University

Science Goals

Characterize small scale CMB in temperature and polarization with sensitive measurements of high- ℓ TT, TE, EE, and BB spectra

TT and EE: Neutrino number, spectral index of inflation, primordial helium

Lensing B-modes: Sensitive to the sum of the neutrino masses and properties of dark energy

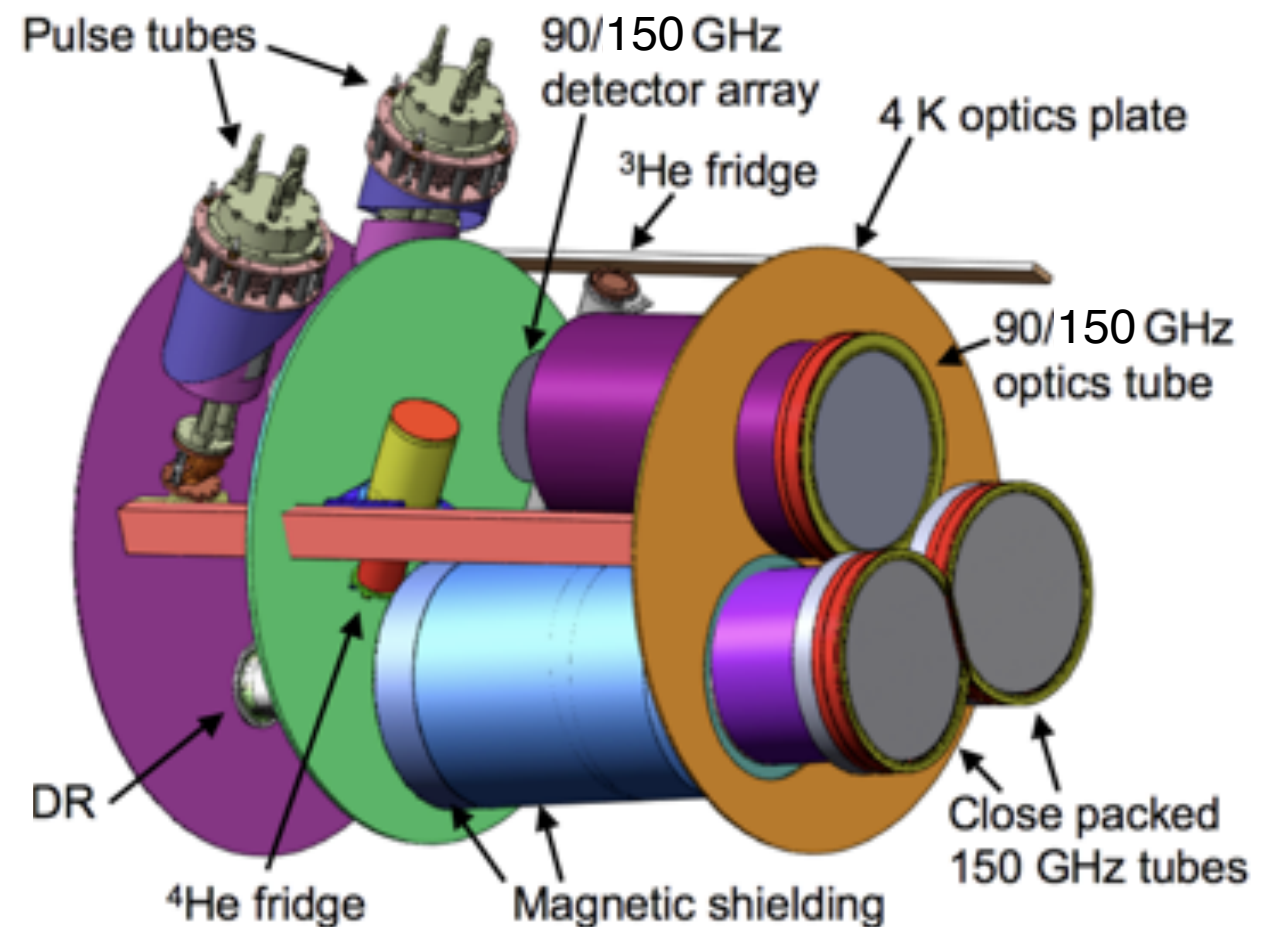


Cross-correlation science:
Wide Survey ($\sim 4000 \text{ deg}^2$)
Overlap with SDSS-III BOSS

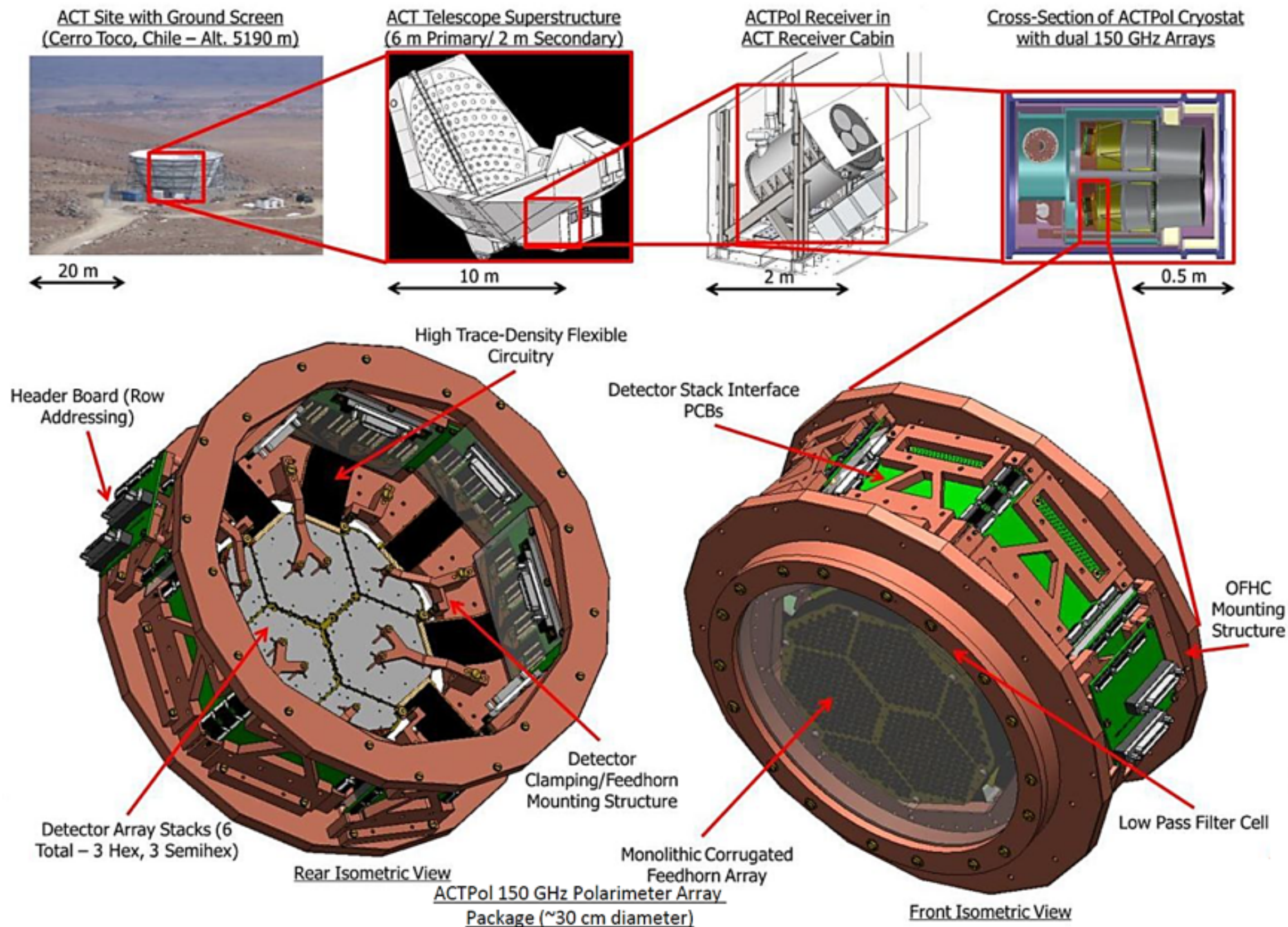
Deep Survey (5 $\sim 25 \text{ deg}^2$ fields)
Overlap with XMM-LSS, CFHTLS,
HerMES, UKIDSS, DES, GAMA, etc

ACTpol: New Camera for ACT

- Improved SZ sensitivity
- High l power spectra
 - TT constrains n_s
 - EE constrains running of n_s
- Gravitational Lensing
 - Matter fluctuations at $z \sim 3$
 - Measure sum of neutrino masses and dark energy
- Non-Gaussianity
- Cross-correlations
- First deployment in July 2012
- Full deployment in 2013



Instrument Overview



Polarimeter design

High-Trace Density Flexible
Circuitry

Detector clamping/Feedhorn
mounting structure

ACTPol PA1 Overview:
Diameter = 26.3 cm
Height = 14.9 cm
Mass = ~11.5 kg

Detector Stack Interface
PCBs

OFHC Mounting
Structure

Monolithic
Corrugated Si-
feedhorn array

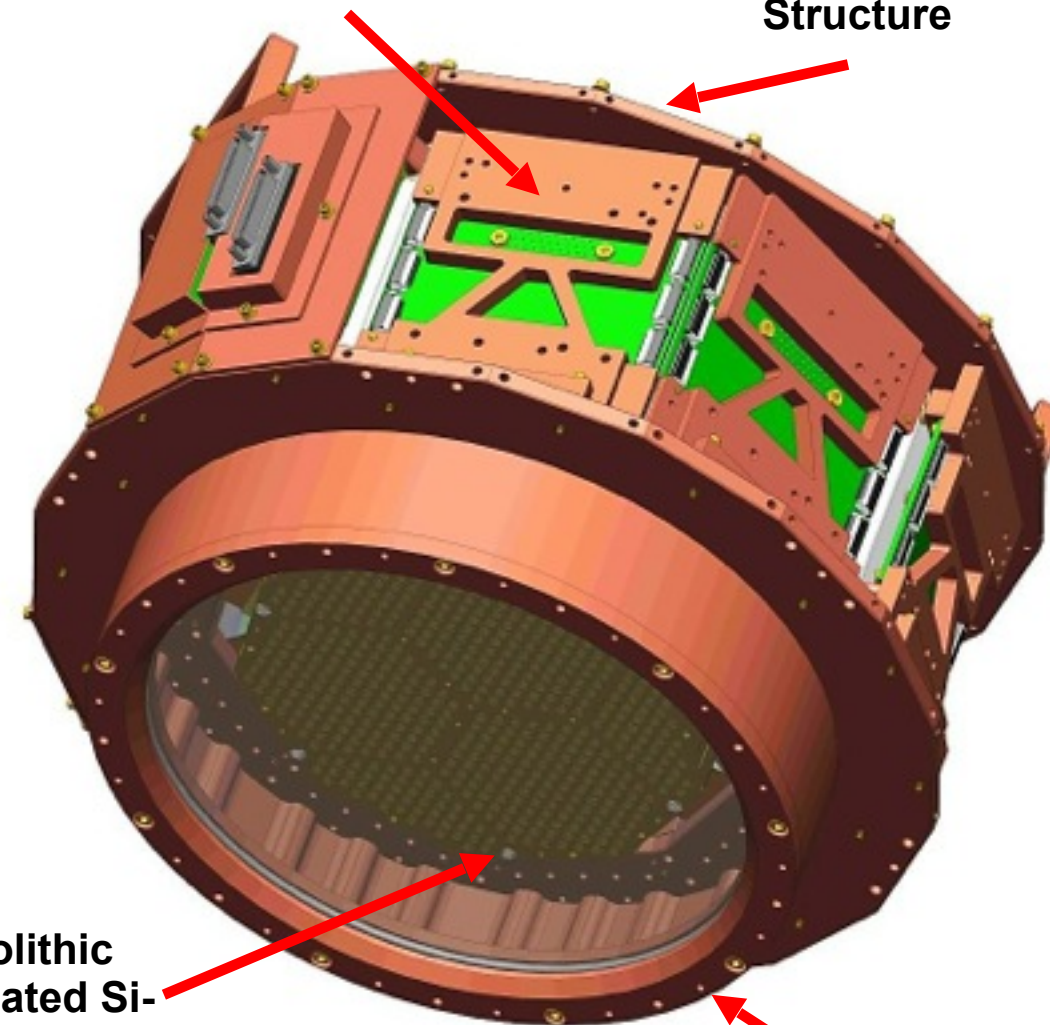
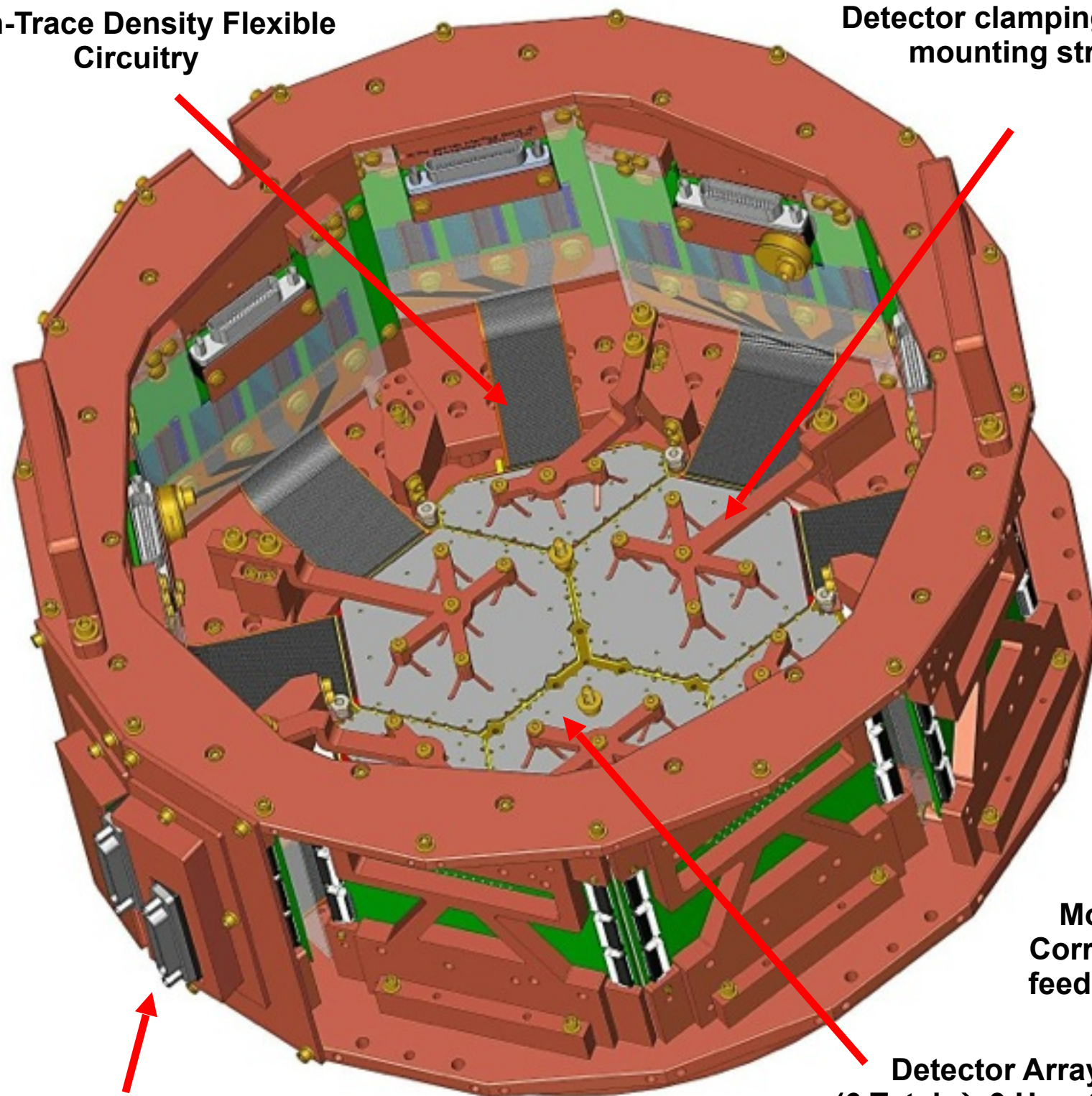
Front Isometric View

LPE Filter Cell

Detector Array Stack
(6 Total → 3 Hex, 3 Semi-hex)

Rear Isometric View

Header Board (Row
Addressing)

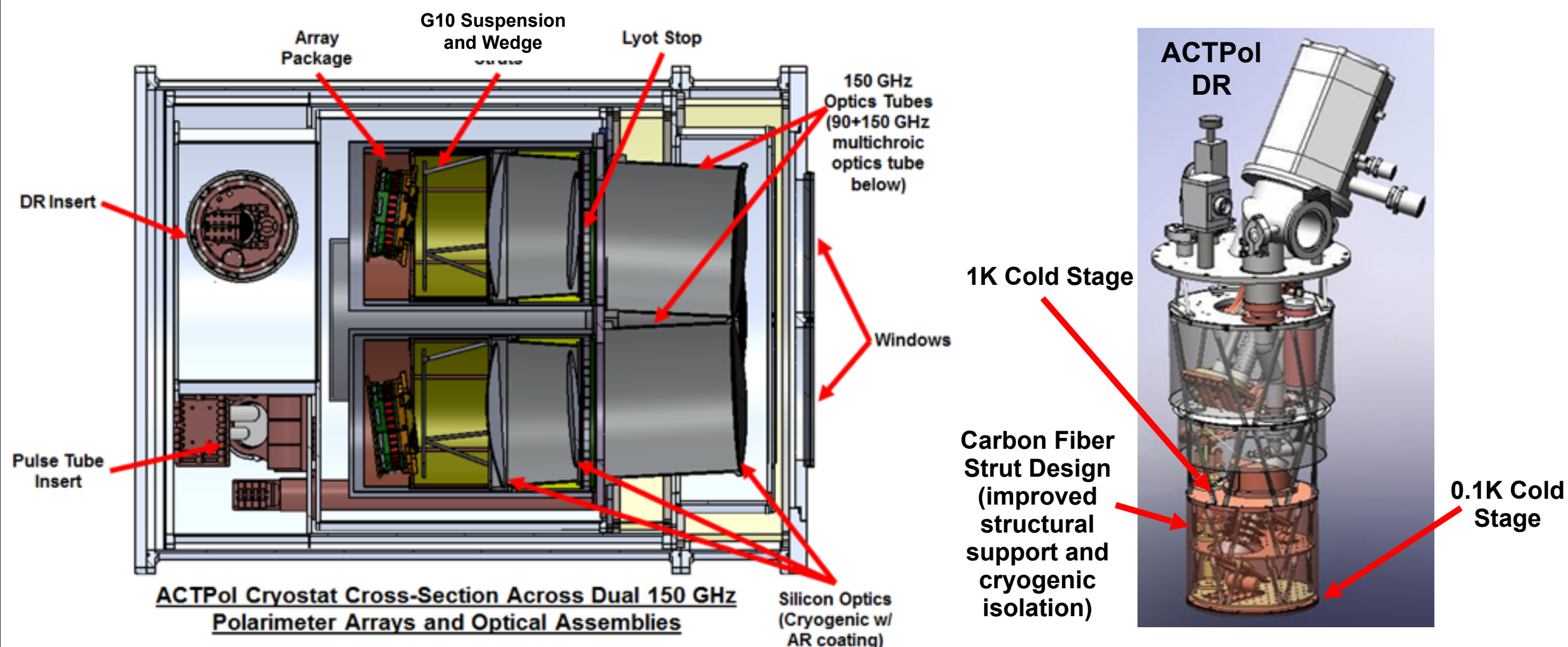


Cryogenics

ACTPol will operate a pulse-tube backed dilution refrigerator (DR) developed with Janis Research Co.

- Allows for cryogen-free cooling with no thermal cycling
- Only CMB experiment to operate at 90mK bath
- Increased mapping speed

Cryogenic Load Assignments: PT410 Module: 40K, 4K
DR Module: 1K, 0.1K



Cryogenics



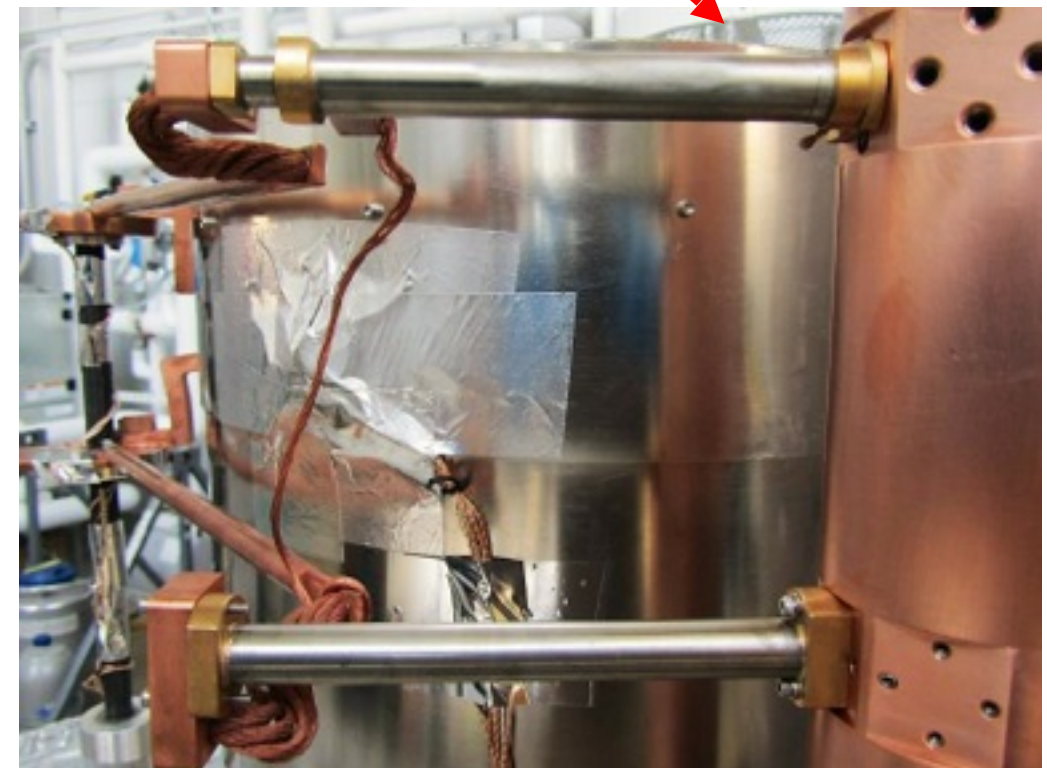
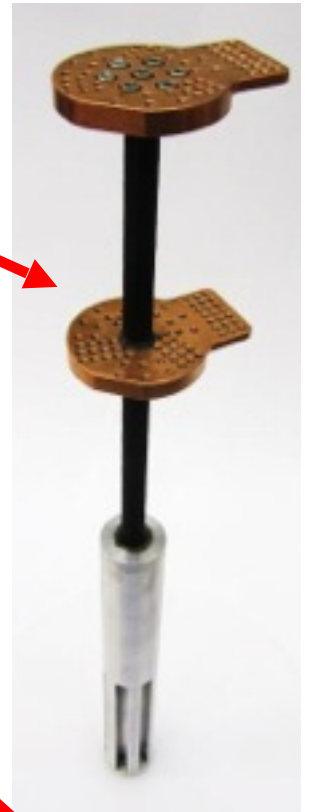
**40K Shield
Installation (Janis)**



**DR Module
Integration**

**Central Thermal Bus-
Bar Tower (1K, 0.1K
stages isolated by
braided carbon fiber
rod)**

**Passive Gas-Gap Heat
Switches provide
additional thermal
backing of 1K, 0.1K
stages from PT410
Module**

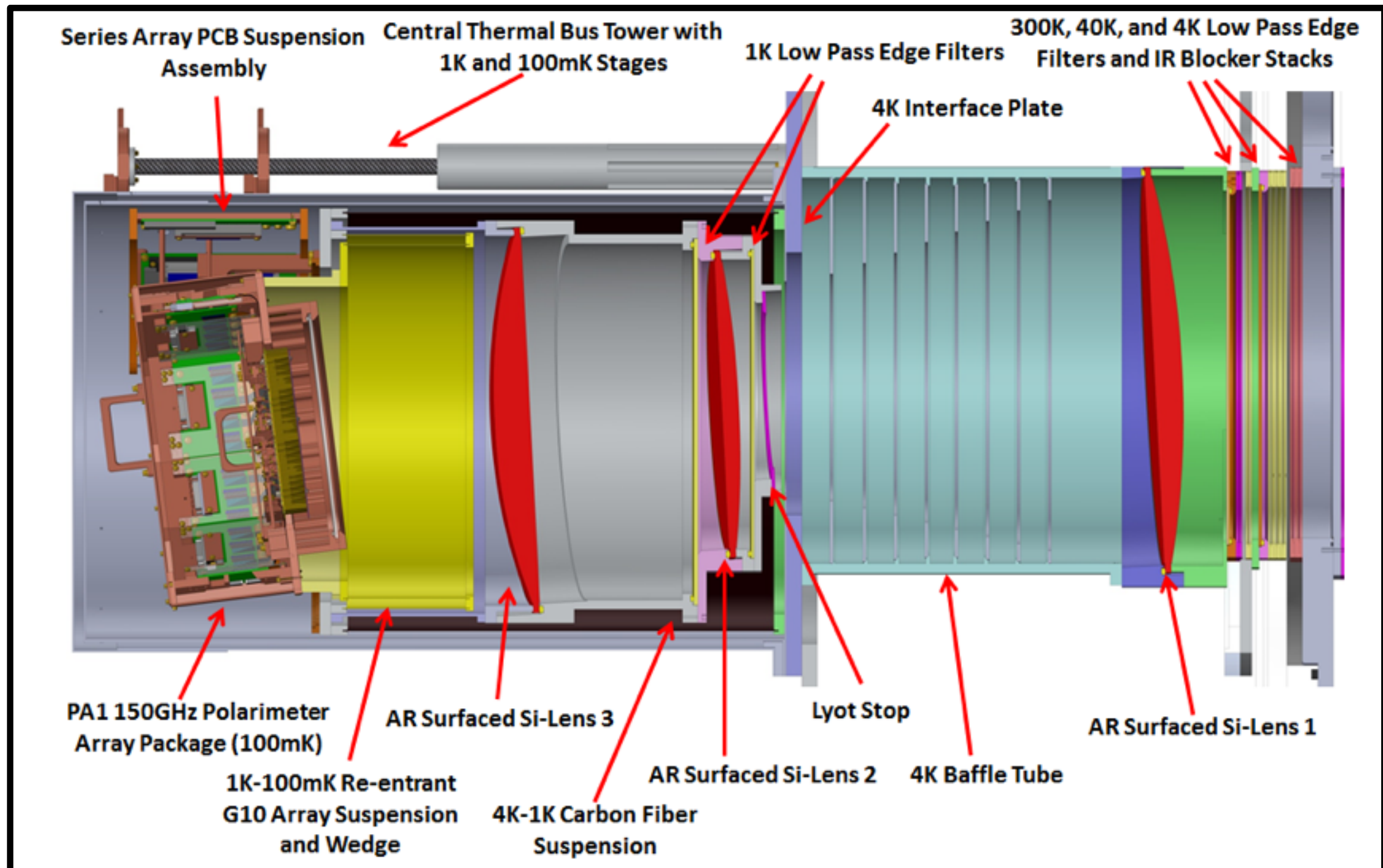


Optics Tube

At full deployment, ACTPol will field three optics tubes:

First Season (2012): 1 x 150GHz

Full Deployment (2013-beyond): 2 x 150GHz, 1 x 90/150GHz (Multichroic)



Optomechanical Assembly

Three silicon lenses reimage the Gregorian focus of the telescope

**Optical throughput limited by max. filter size:
size: ~30cm $\rightarrow$ ~1° field of view**

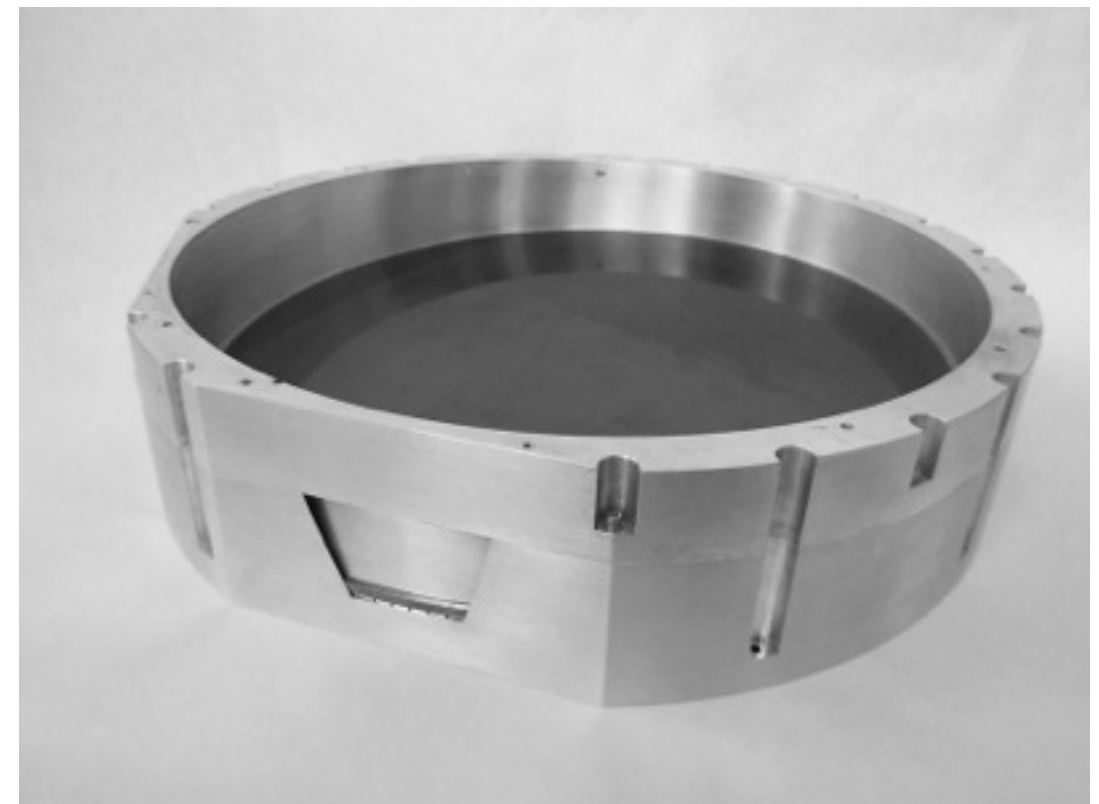
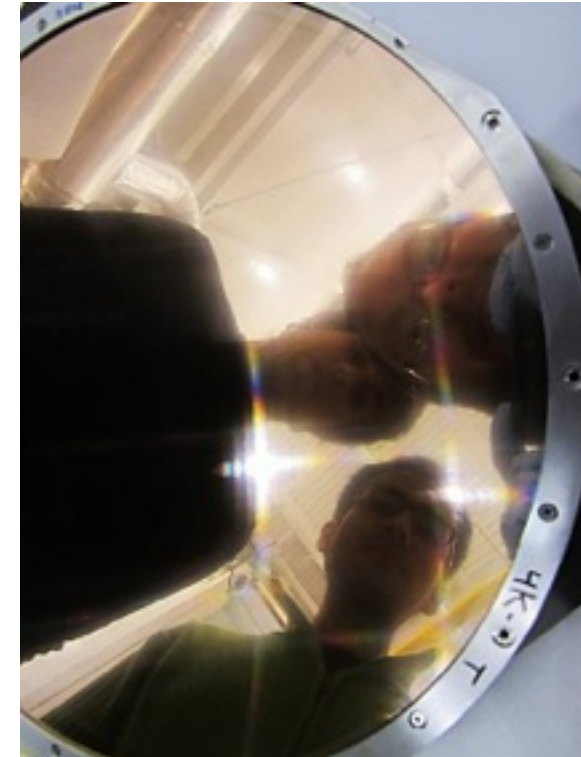
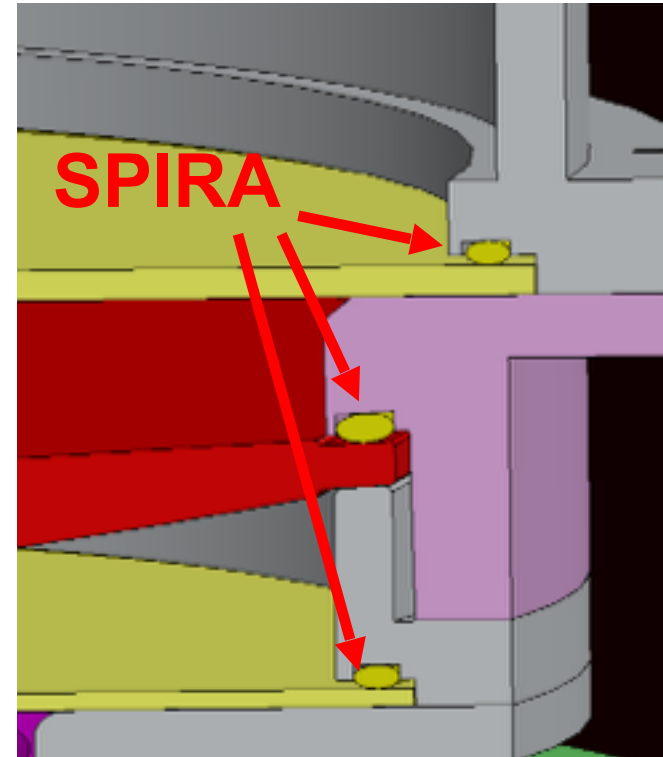
**Lens Geometry: Cylindrically Symmetric
Plano-Convex**

$\rightarrow$ Min./Max. Diameter = 23.8 cm/ 31.8 cm

**Force on lens flange during thermal
contraction regulated using SPIRA shield of
known spring constant**

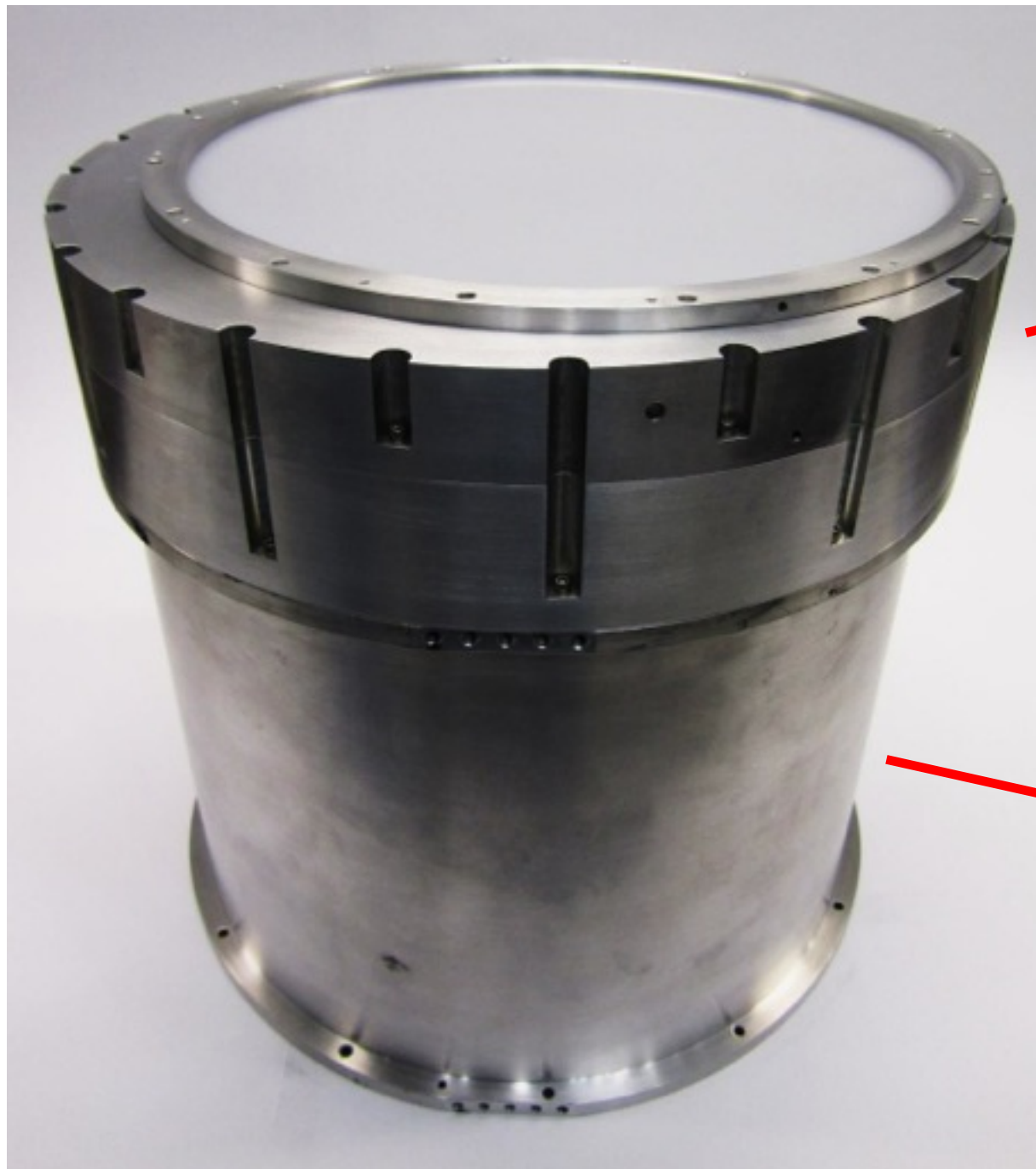
$\rightarrow$ Max. force on lens = ~150 pounds

LPE filters use same mounting technique

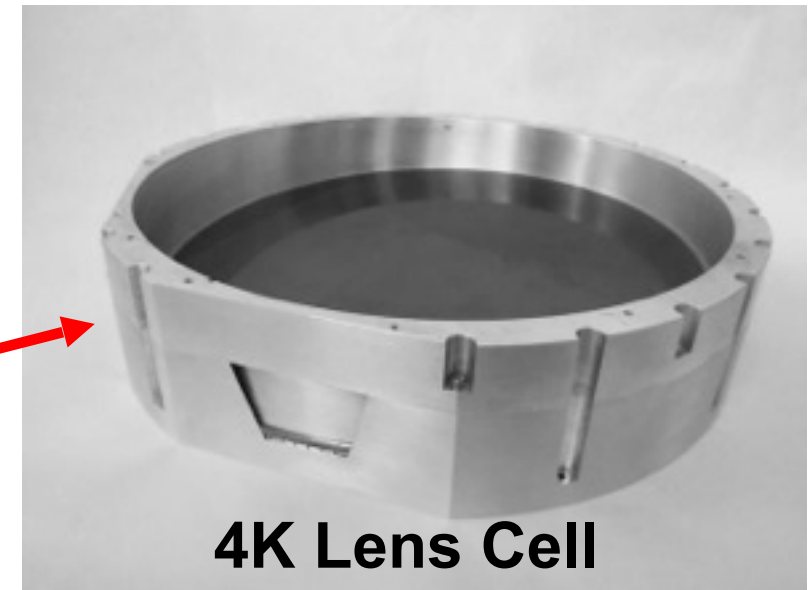


Optomechanical Assembly

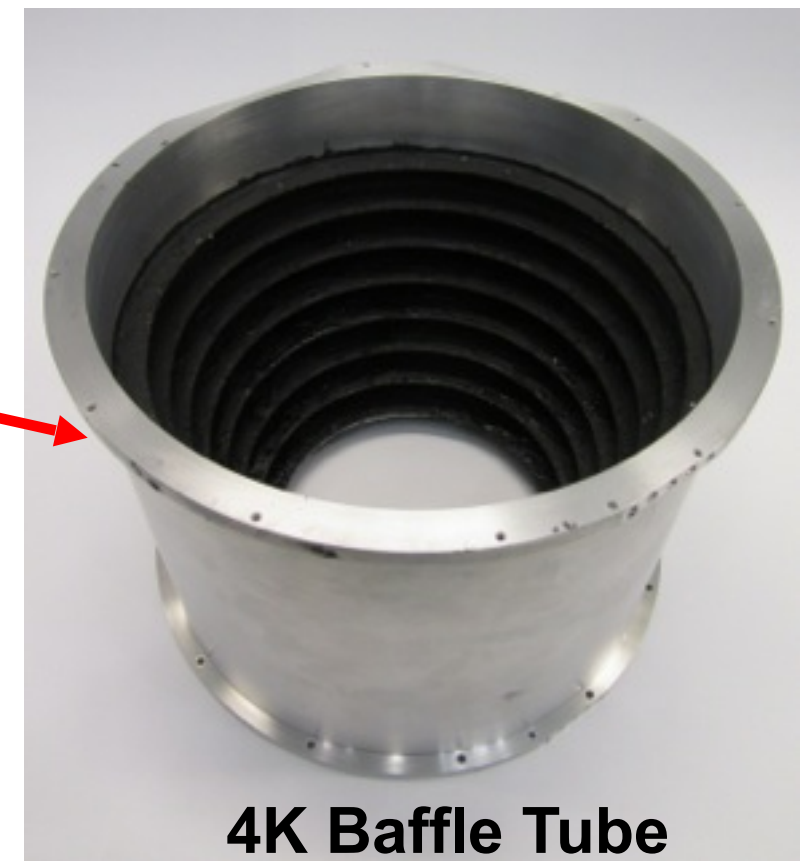
Integration status of ACTPol 150GHz 4K Upper Optics Tube



4K Upper Optics Tube Subassembly



4K Lens Cell



4K Baffle Tube

Optomechanical Assembly

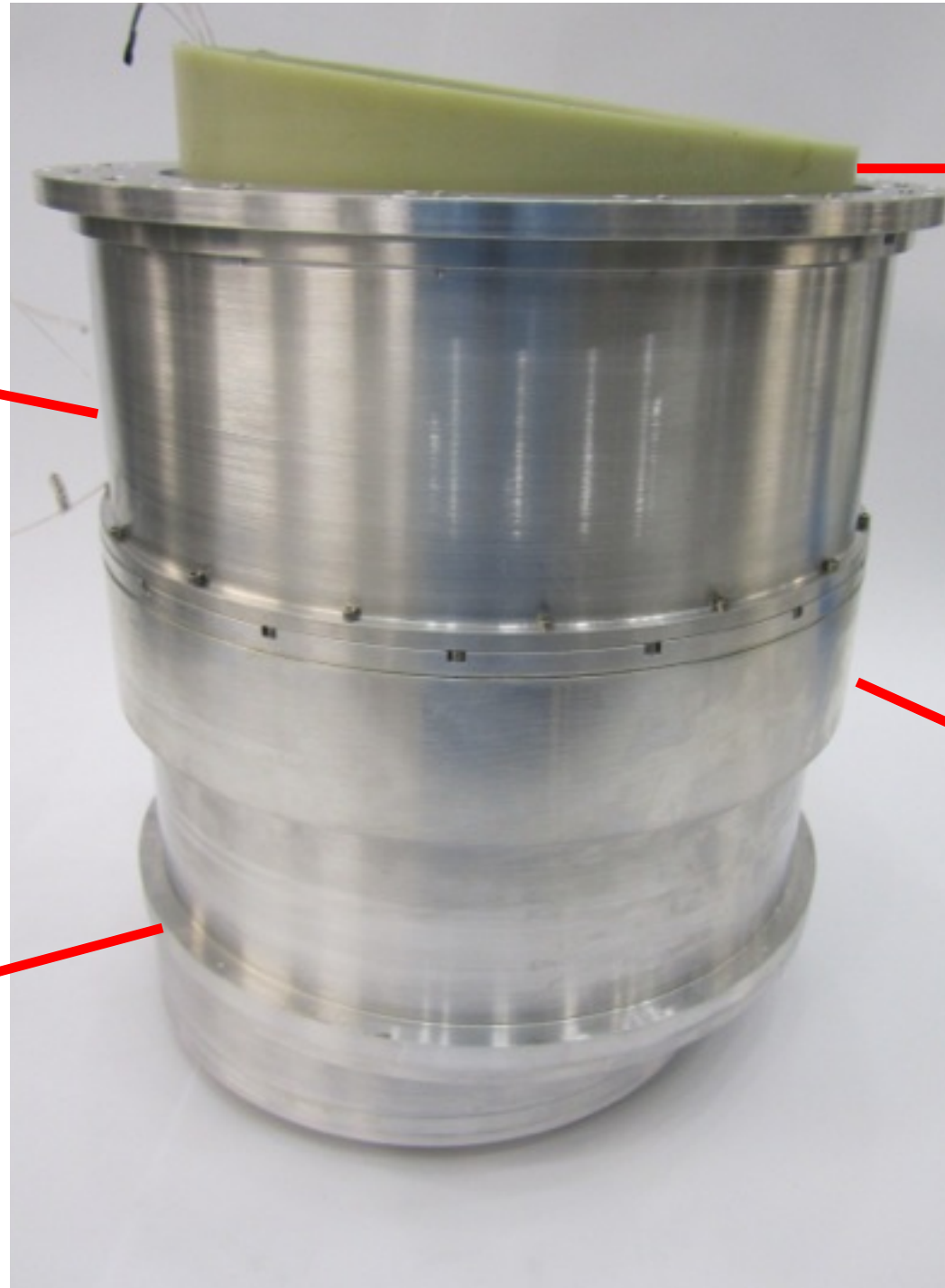
Integration status of ACTPol 150GHz 1K Lower Optics Tube



**1K-0.1K Re-entrant G10
Array Suspension**



**1K Lens 2 Cell/
Lyot Stop Aperture**



1K Lower Optics Tube Subassembly



G10 Array Mount Wedge



1K Lens 3 Cell

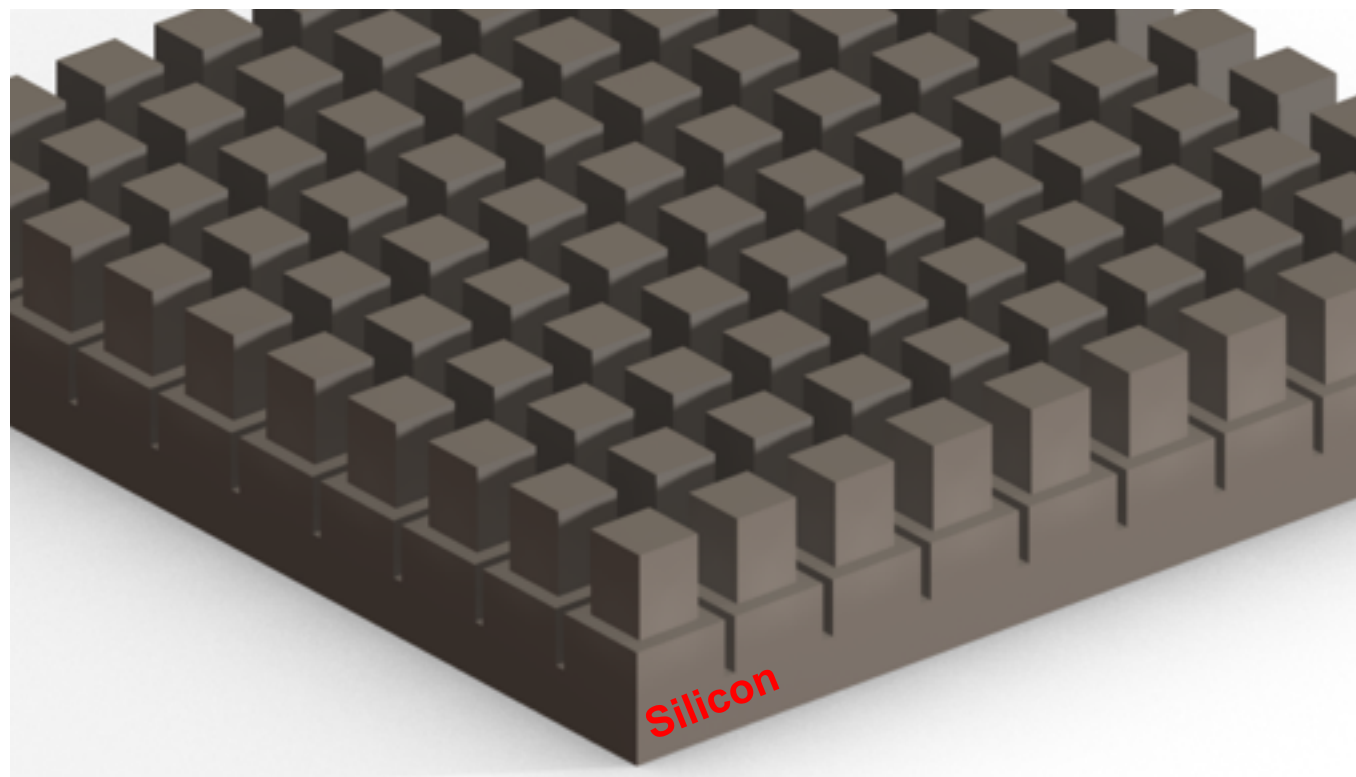
Novel AR coating

ACTPol Si-Lenses are low-loss with $n = 3.4$ providing excellent image quality → AR-coating required to preserve signal

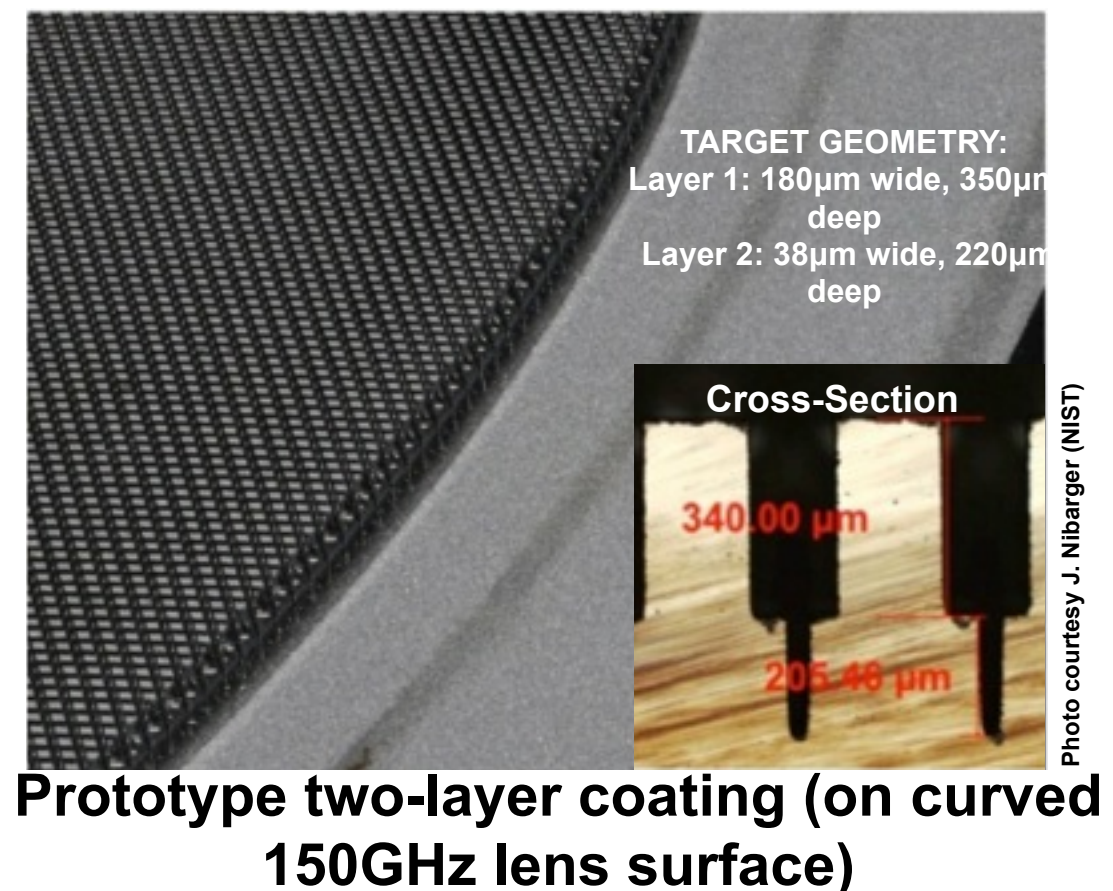
Two-layer AR-coating concept has been developed for use on ACTPol Si-lenses

Precision five-axis dicing saw used to cut two-layer AR-grid onto flat and curved lens surfaces (CMM)

Depth of cut controlled across lenses to $5\mu\text{m}$



Isometric view of AR-coating concept



Novel AR coating

Two-layer AR-coating concept maintains $<0.25\%$ reflection per lens and broadens bandwidth

Predict reflectance of $<-30\text{dB}$ across 150GHz band

Three-layer AR-coating under development for multichroic use, with $<1\%$ reflection projected

Measurements of flat-surface, prototype AR-surface with VNA match expected results!

U. Michigan developing custom gantry-dicing apparatus for AR-coating for next two optics tubes

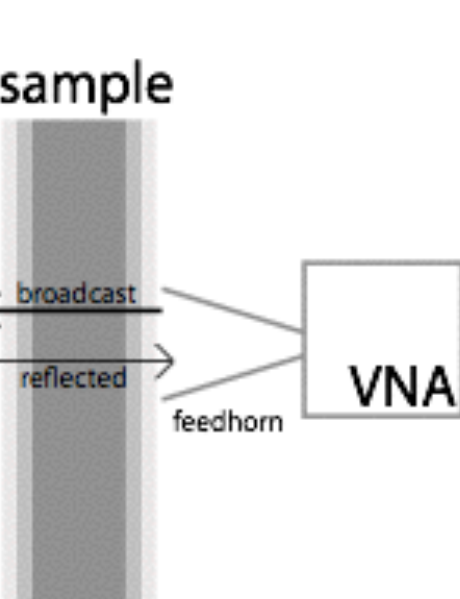
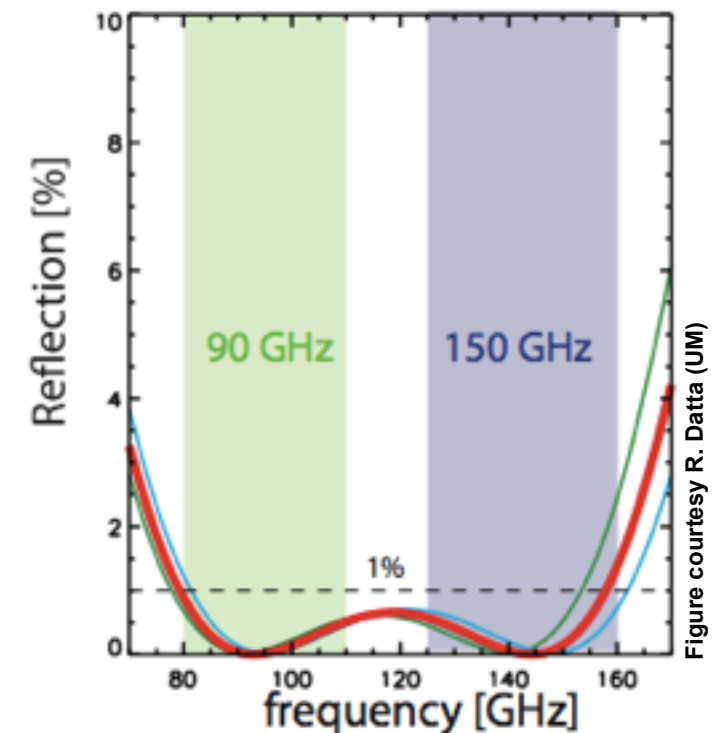
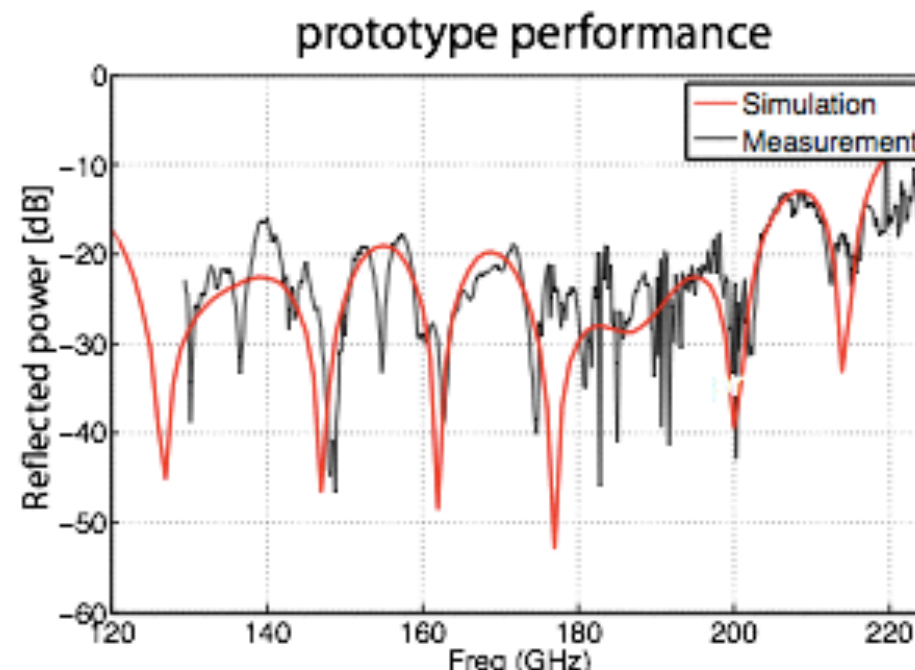


Figure courtesy R. Datta (UM)



Prototype two-layer coating (on curved 150GHz lens surface)

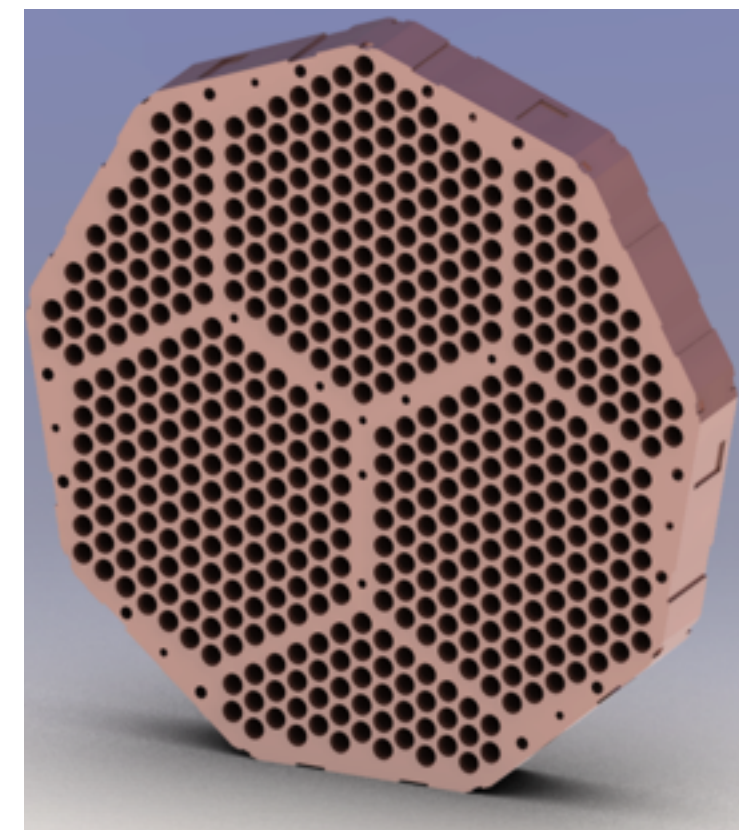
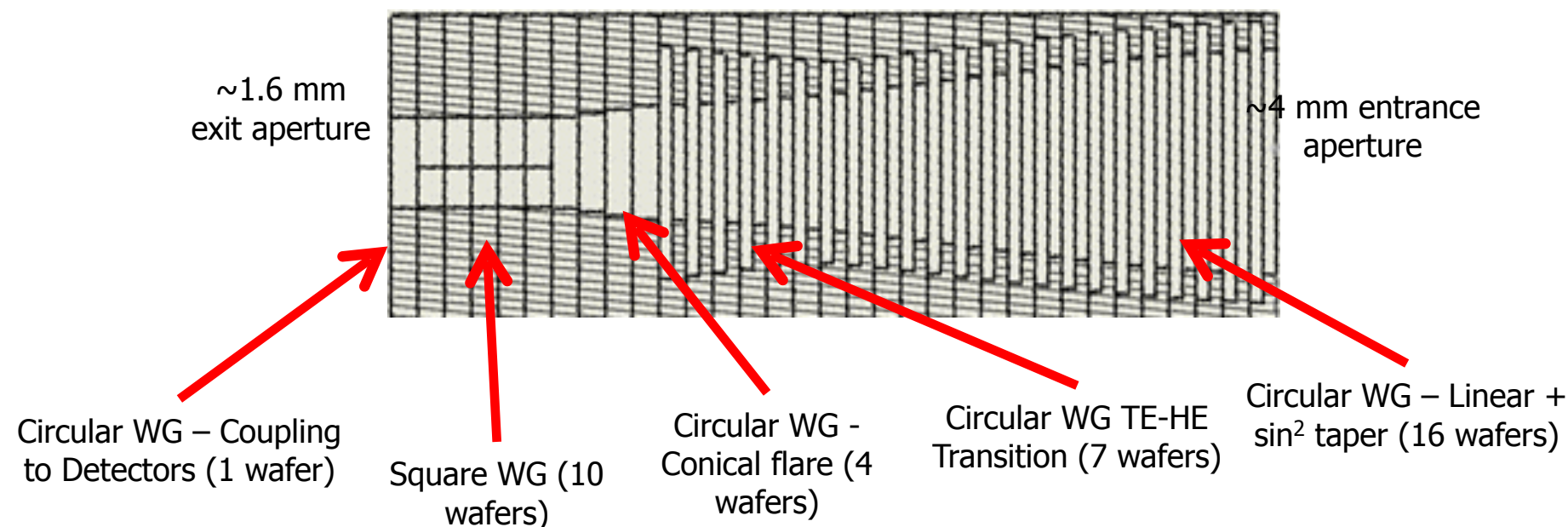
Feedhorn array

ACTPol will utilize large-scale (137 mm dia.) monolithic corrugated Si feedhorn arrays based on platelet design

Comprised of 37 Au-plated Si wafers forming corrugation profile → Wafer thickness = 500 μm

ACTPol feedhorn wafers fabricated at NIST using multi-step DRIE process → 6" wafers

Si-wafers epoxied in perimeter trenches, treated with a Ti:Cu seed layer, and Au-electroplated → excellent adhesion



Feedhorn array

Use of Au-plated Si-wafers allows for improved thermal coupling to Au-plated Si-detector stack components

Feedhorn corrugation profile allows for a broad bandwidth (>25%)

Profile also effective in suppression of cross-polarization and side lobes (<-30dB)

300K measurements show 1% reflection across the band and ~-30dB cross-pol at center of band

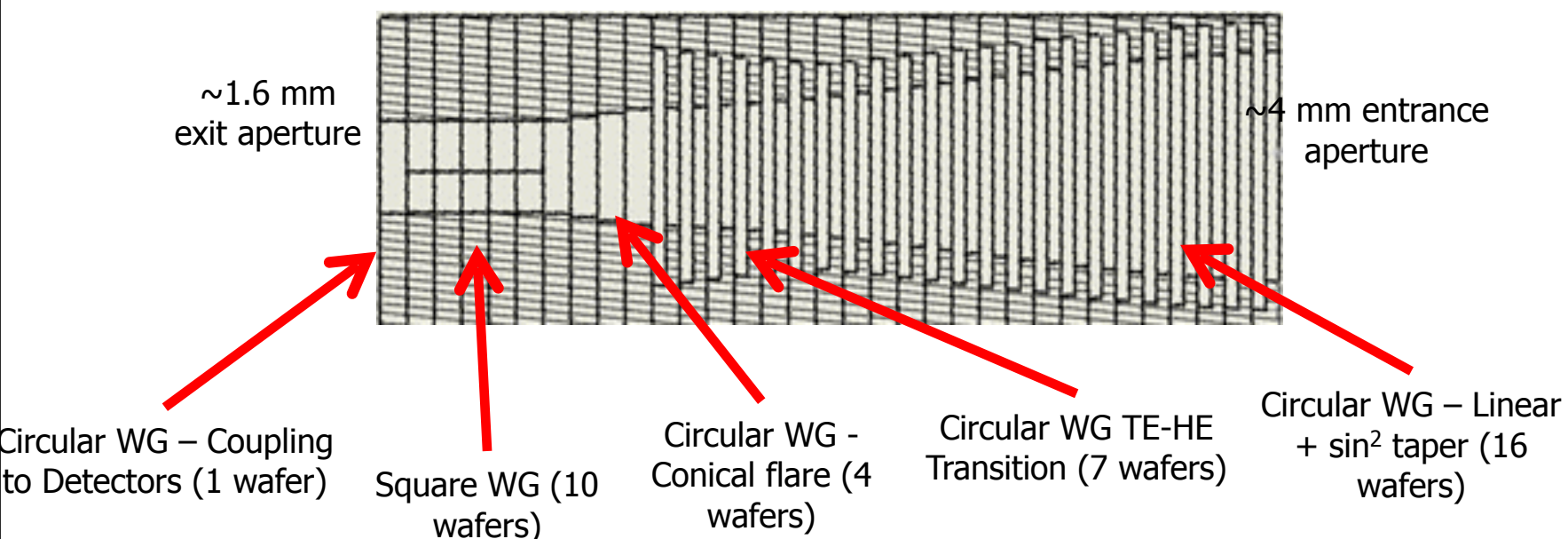
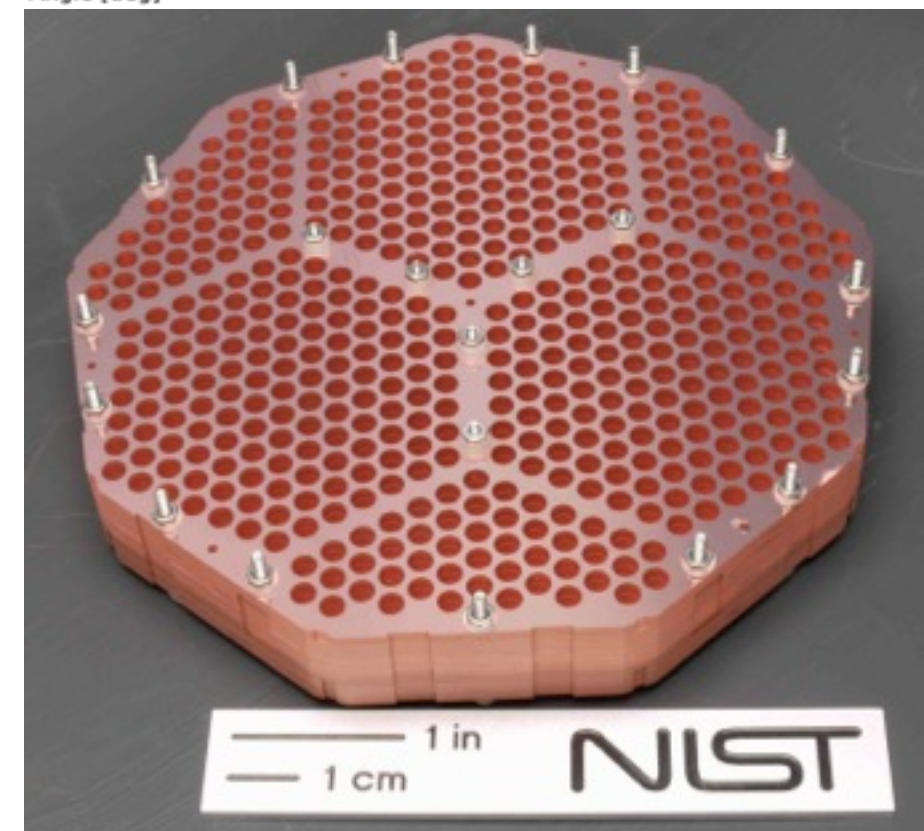
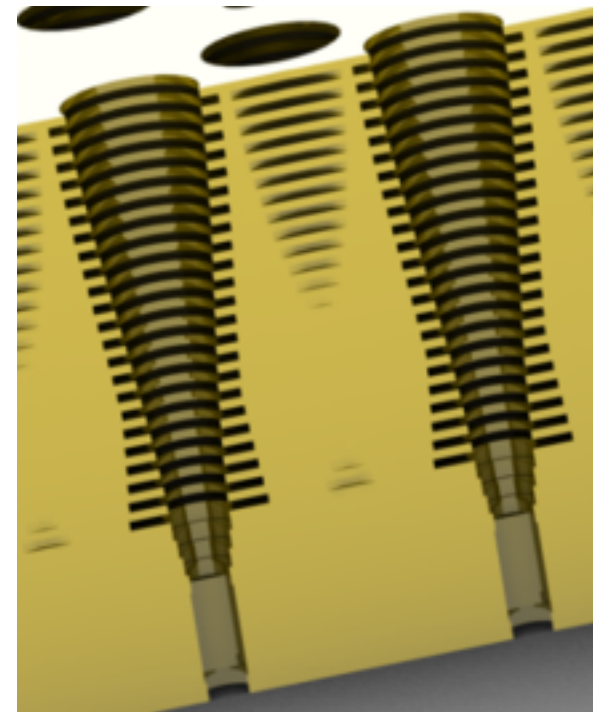
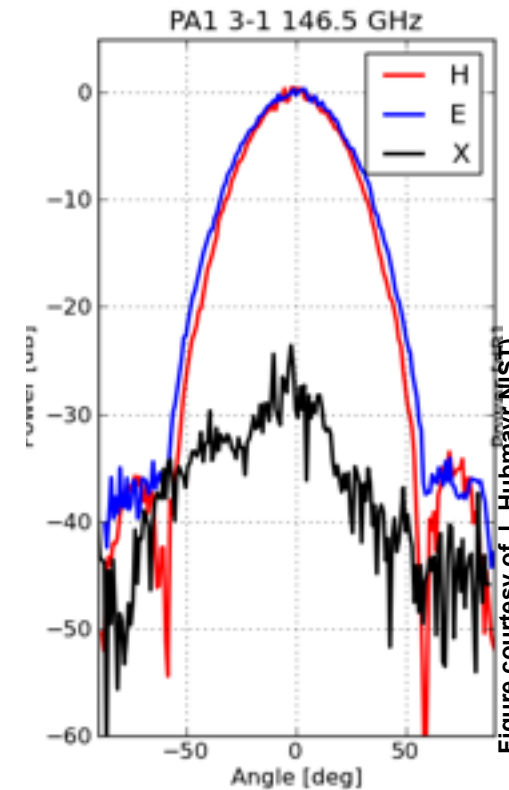


Photo courtesy J. Nibarger (NIST)

Detector stack design

Example: ACTPol PA1 Semi-hex Detector Stack

Backshort corral feature (25 microns tall) to limit light escape around each pixel/array.

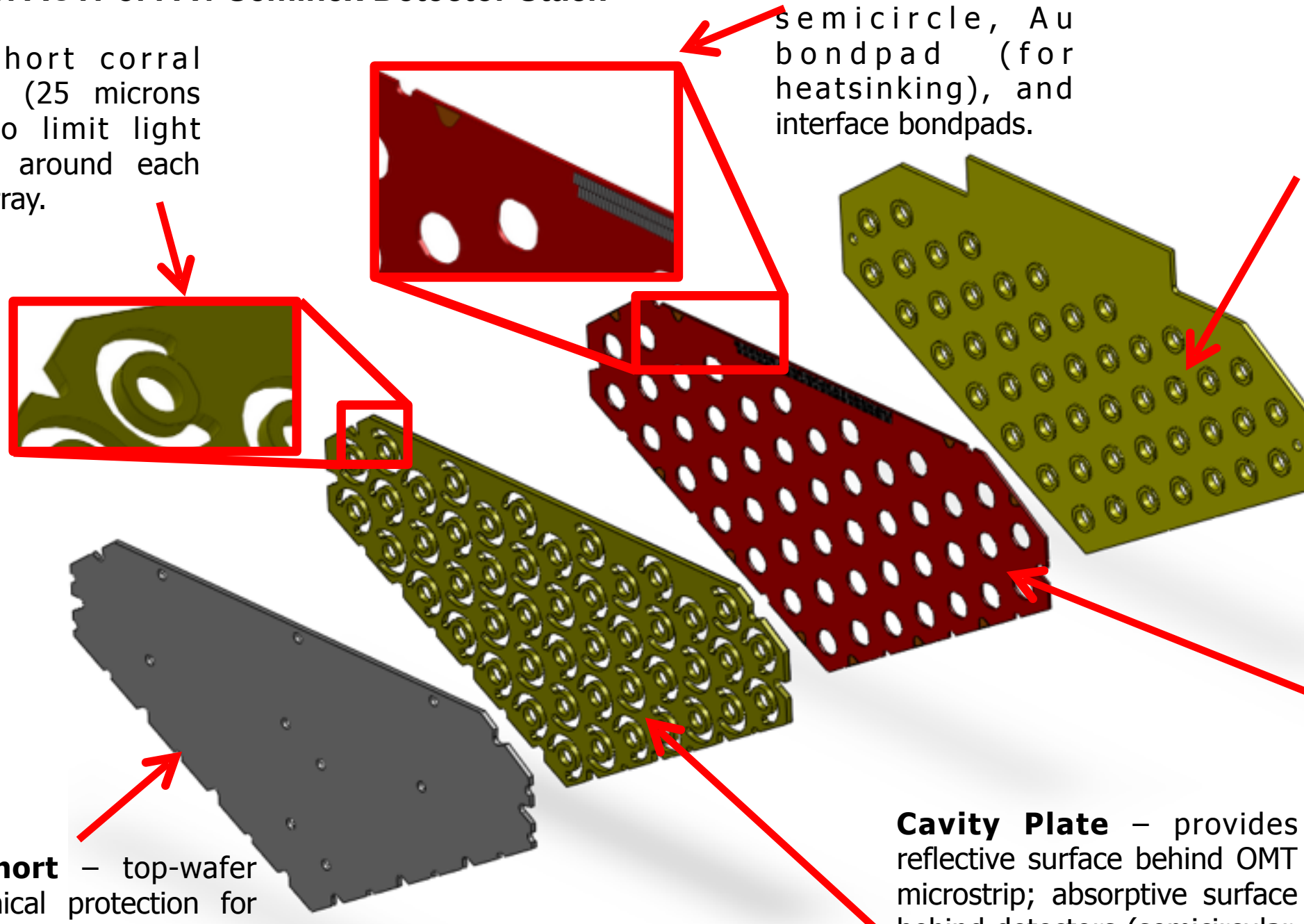
Detail of epoxy semicircle, Au bondpad (for heatsinking), and interface bondpads.

Waveguide Interface Plate (WIP) – Waveguide interface between feedhorns and detector plate. Boss features on detector side for loss reduction (wafer: 500 microns; Boss: 250 microns thick).

Detector Wafer – houses the ACTPol polarimeters and connections to interface electronics. (275 microns thick)

Cavity Plate – provides reflective surface behind OMT microstrip; absorptive surface behind detectors (semicircular, Eccosorb-filled moats). (625 microns thick)

Backshort – top-wafer mechanical protection for detector stack; contains the moat Eccosorb (500 microns thick)



Detector stack

Example: ACTPol PA1 Semihex Detector Stack

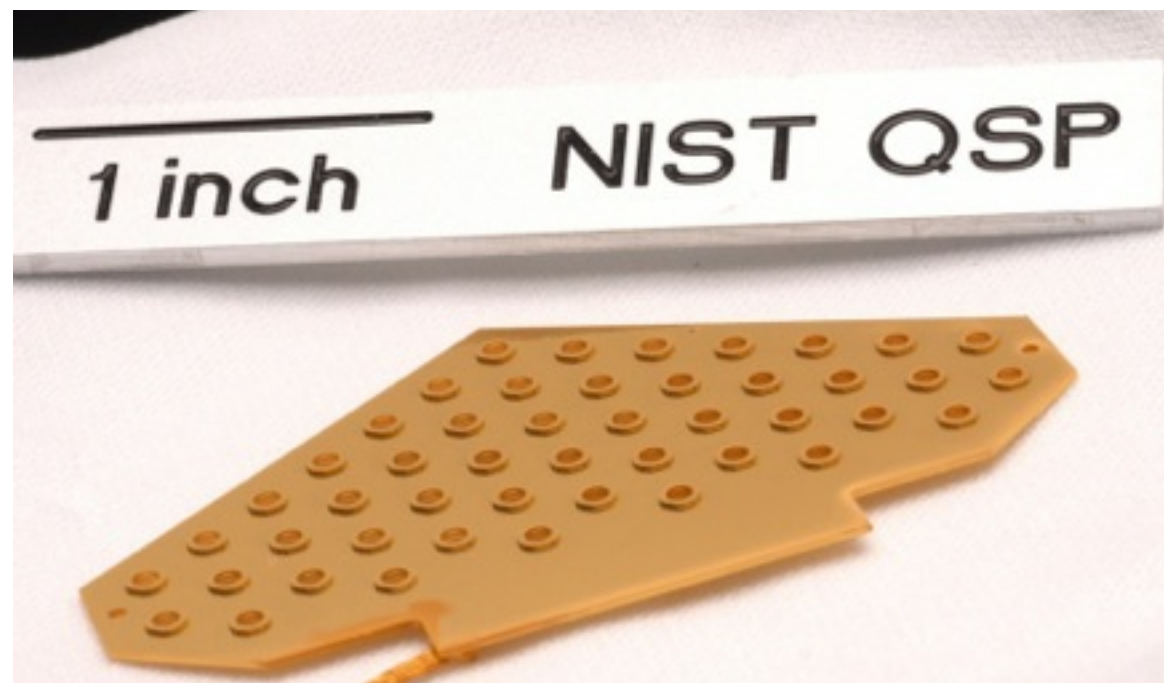


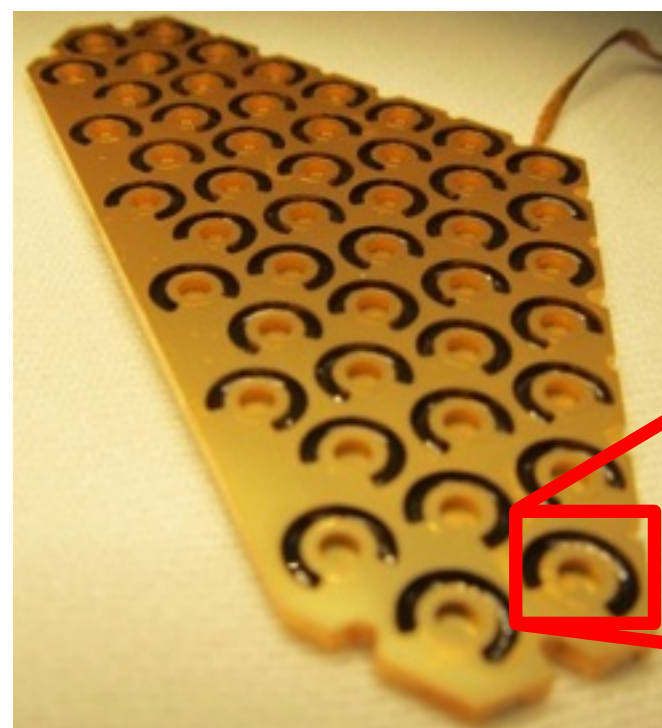
Photo courtesy D. Schmidt(NIST)

ACTPol PA1 Semihex Waveguide Interface Plate (WIP)



Photo courtesy D. Schmidt(NIST)

ACTPol PA1 Semihex Detector Wafer



ACTPol PA1 Semihex Backshort/Cavity Plate



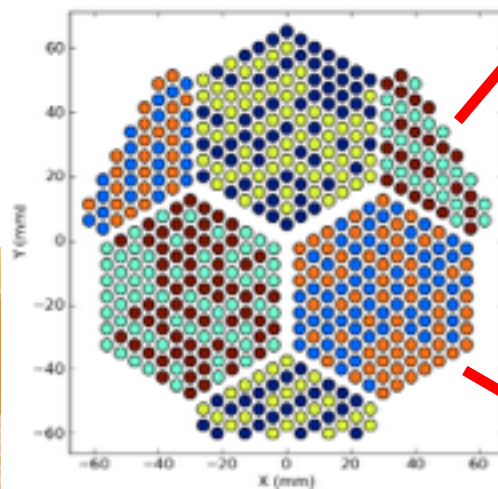
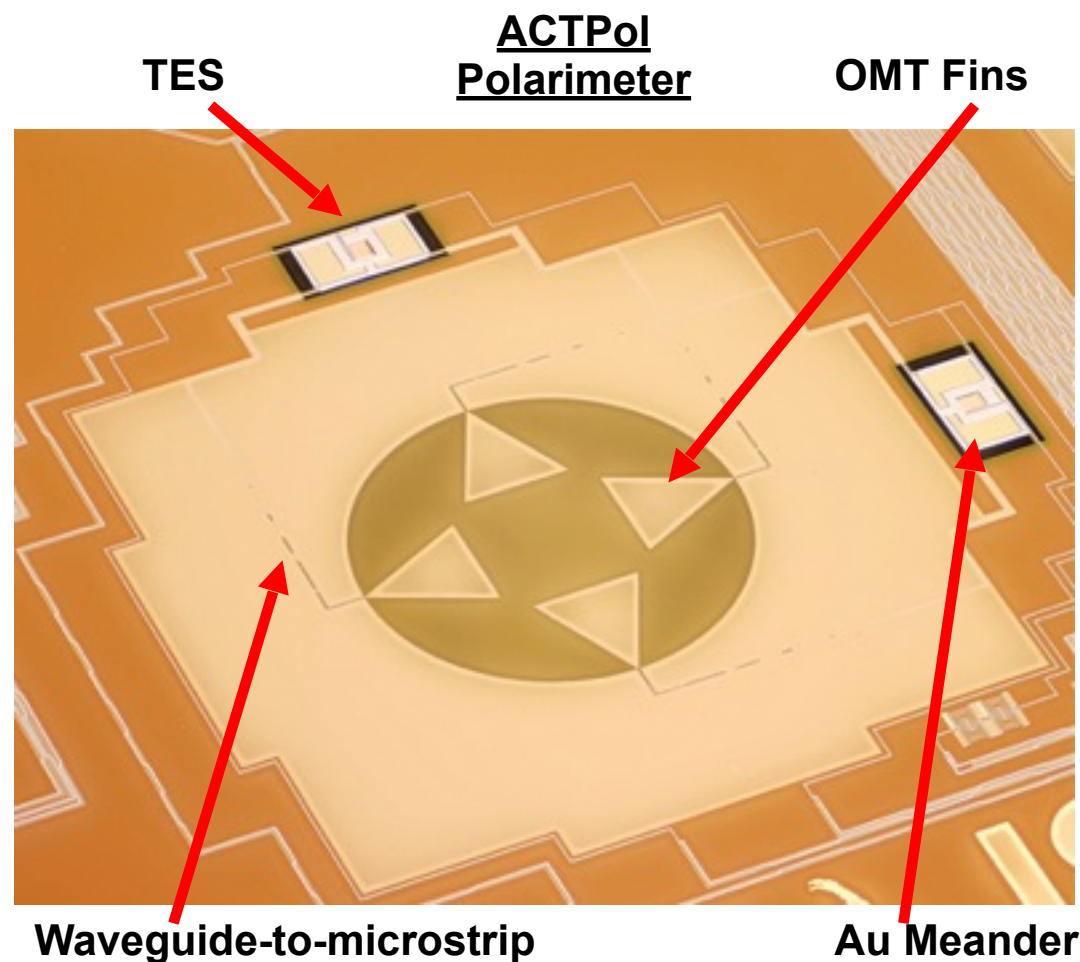
Detail of backshort moat/corral structures

Detector stack

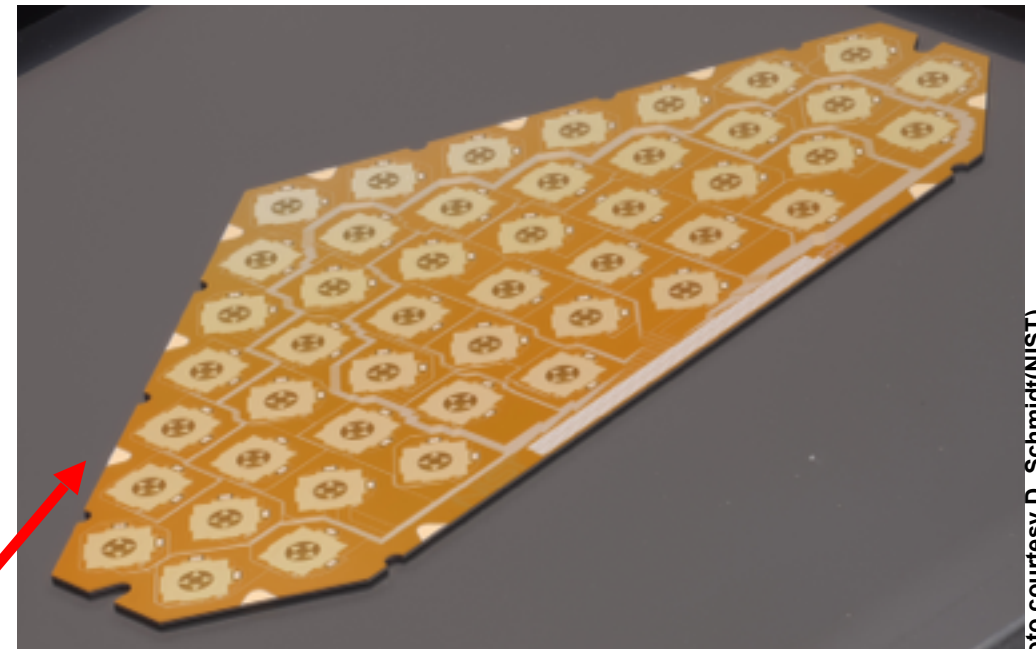
ACTPol PA1 consists of a focal plane of three-semihex and three-hex detector wafer stacks

In total, ACTPol PA1 has 1044 TES bolometers used to measure the response of 522 feedhorn coupled polarimeters (~3000 TES bolometers/~1500 polarimeters at full deployment)

Over each polarimeter array, equal number of pixels are oriented at 0° , 45° for coverage of Stokes Q+U parameters



Targets:
 $T_c = 150\text{mK}$
Sensitivity = $6\text{ }\mu\text{K}\sqrt{\text{s}}$



ACTPol PA1 Semi-hex Detector Wafer (47 Pixels)

Photo courtesy D. Schmidt(NIST)

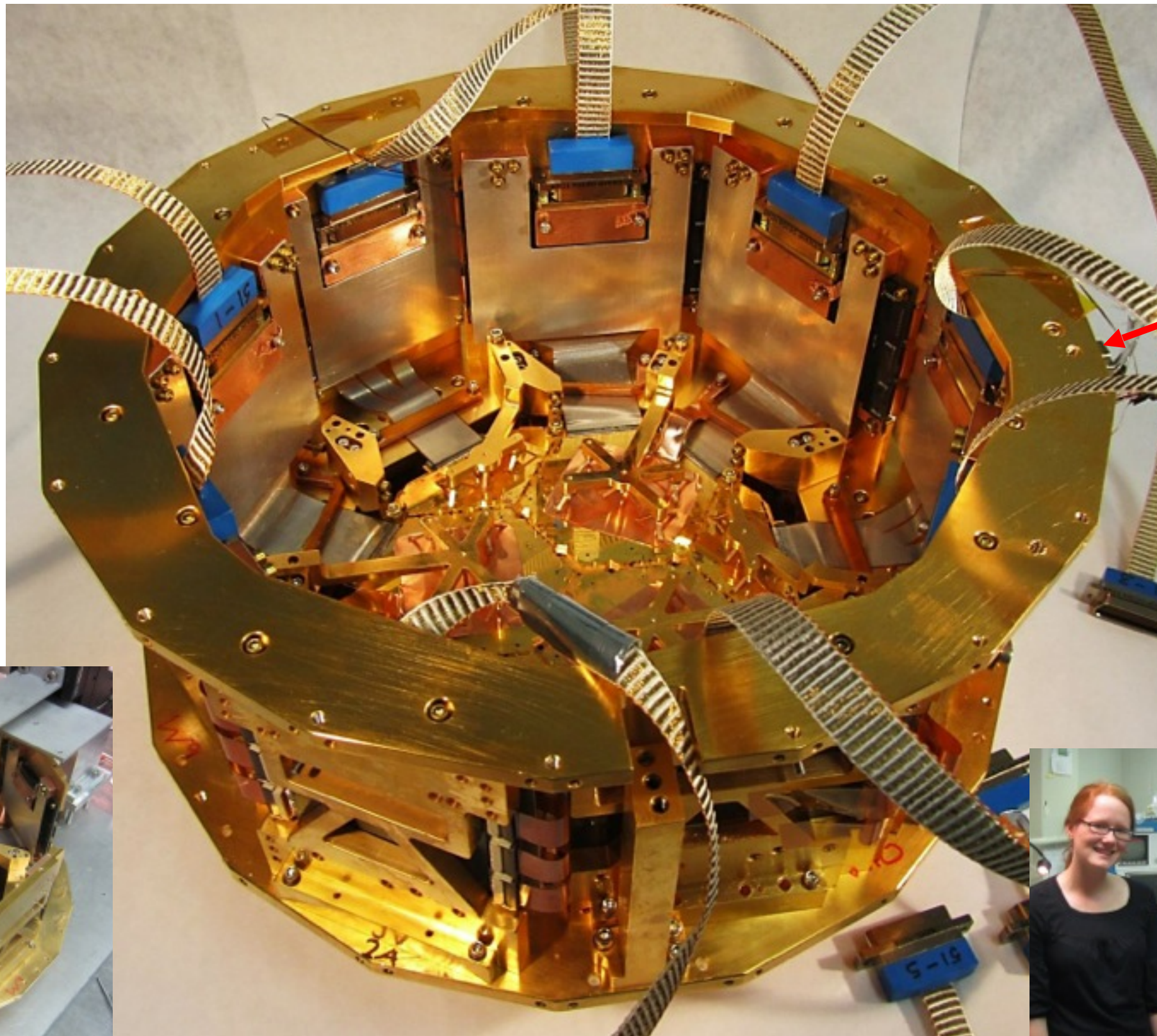


ACTPol PA1 Hex Detector Wafer (127 pixels $\rightarrow$ most on a CMB wafer yet!)

Photo courtesy D. Schmidt(NIST)

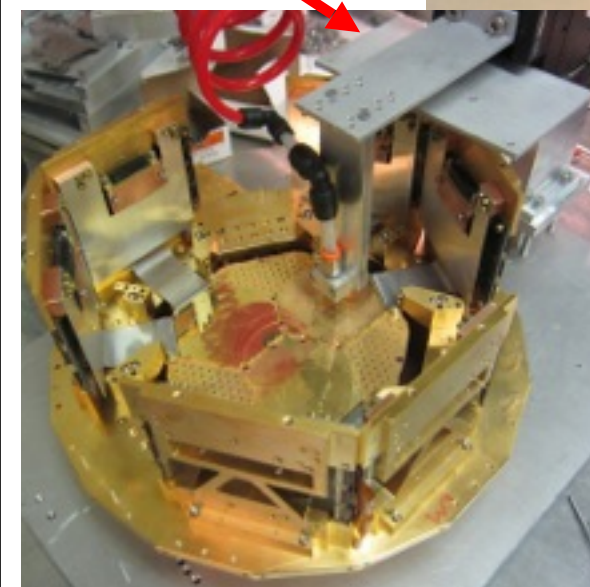
Photo courtesy A. Fox (NIST)

Array Package



**ACTPol First 150
GHz Polarimeter
Array Package
Assembly**

**ACTPol Detector
Installation Jig
Assembly**



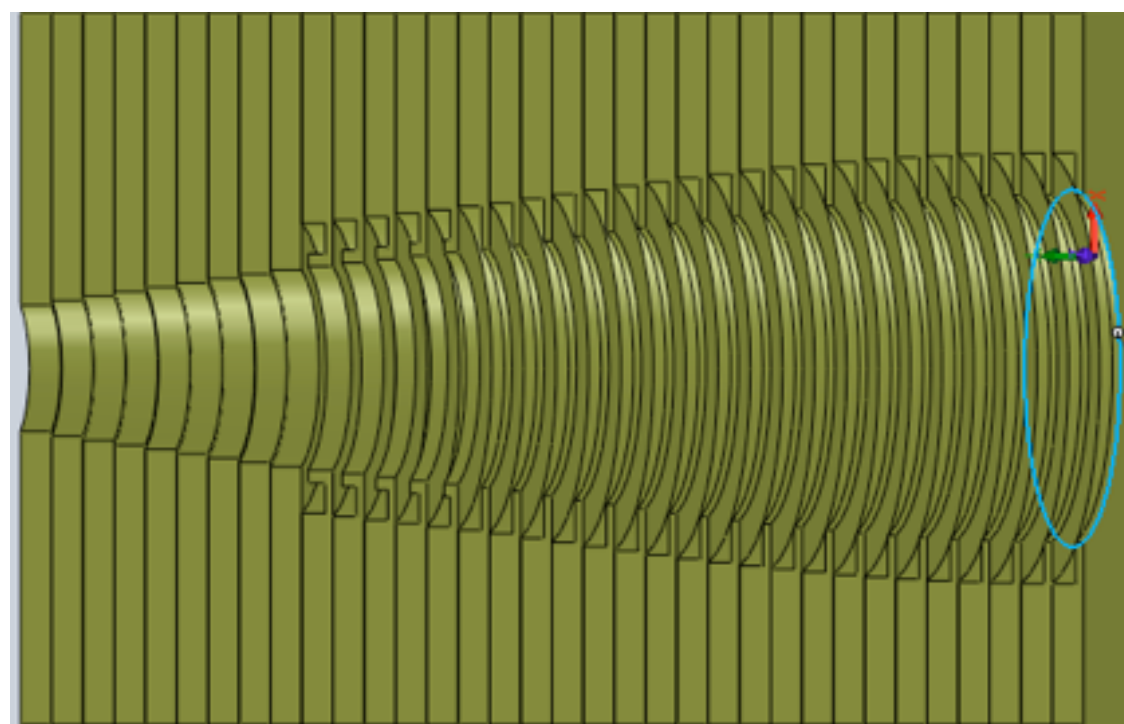
Multichroic polarimeters

In 2013, ACTPol will deploy a multichroic polarimeter array package, featuring NIST polarimeters of simultaneous 90/150 GHz sensitivity

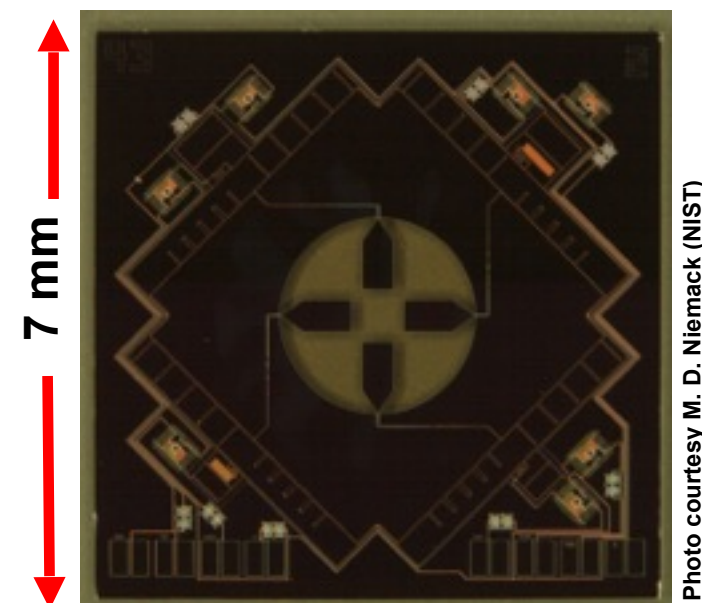
Multichroic design is crucial for efficient focal plane design, with four TES bolometers per pixel, and frequencies defined by on-chip filters

Wide bandwidth provided by ring-loaded corrugated feedhorn profile and OMT design

Design Concept of 'Ring-Loaded' Corrugated Feedhorn Profile

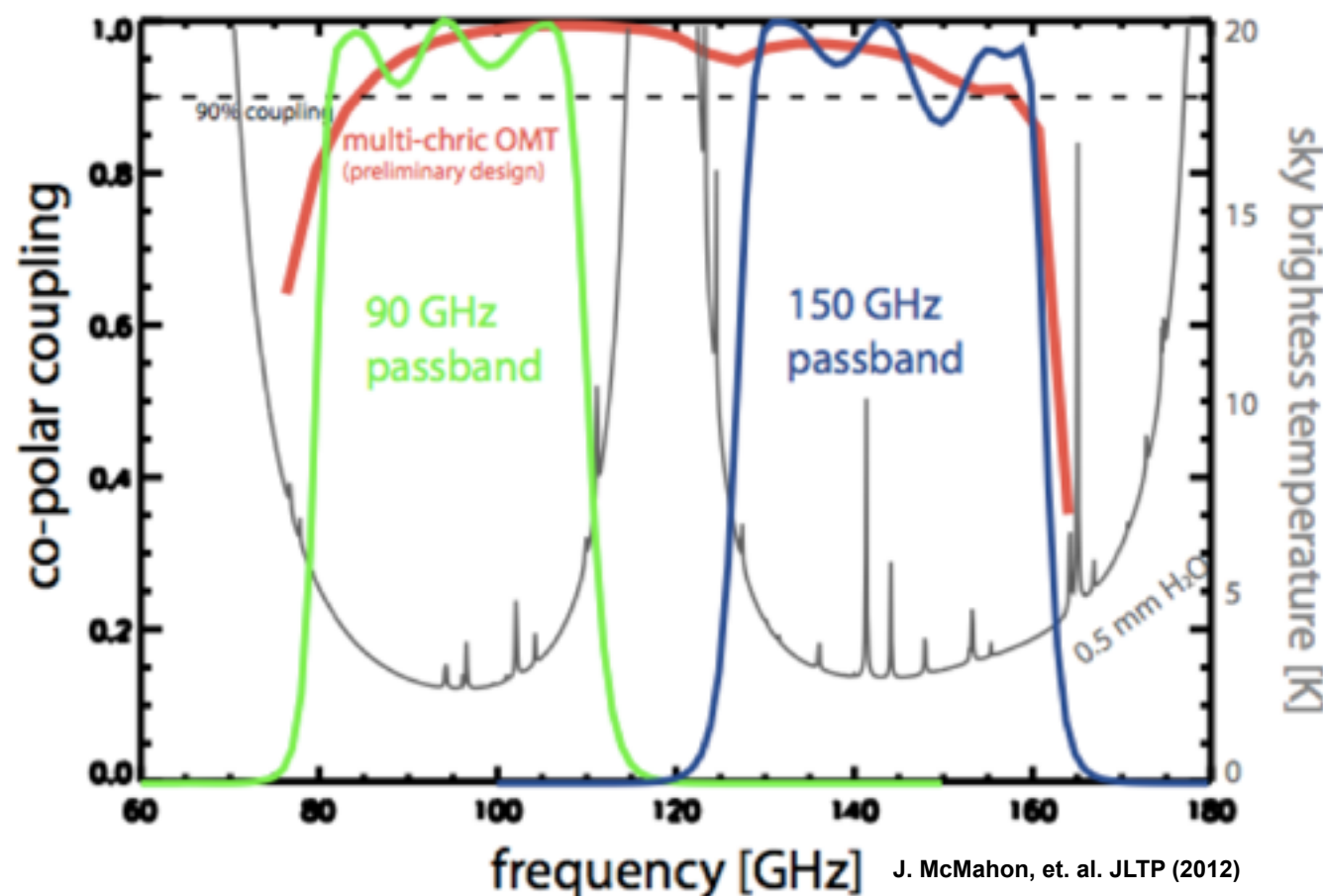


J. McMahon, et. al. JLTP (2012)

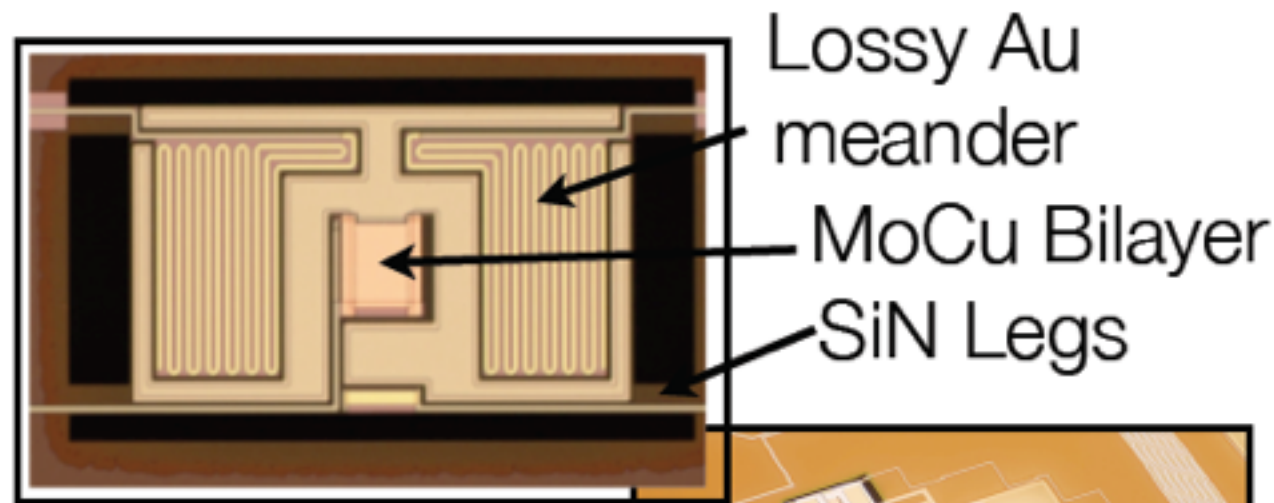


**Prototype NIST
Multichroic
Polarimeter**

**Simulated Bandpass of 90/150GHz Multichroic
Polarimeter**



ACTPol Detectors



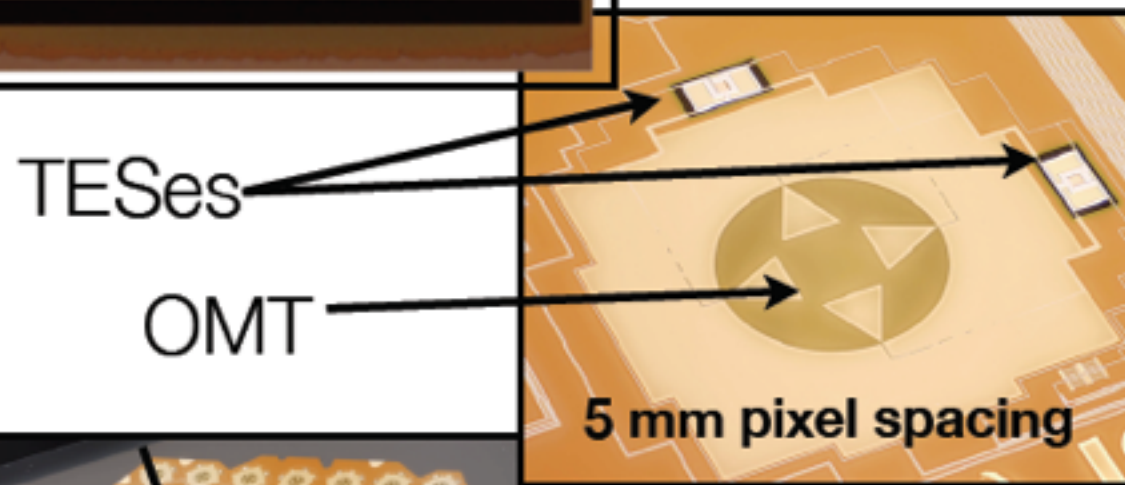
Ortho-mode transducer (OMT) coupled transition edge sensor (TES) bolometers

MoCu bilayer targets $T_c = 150$ mK

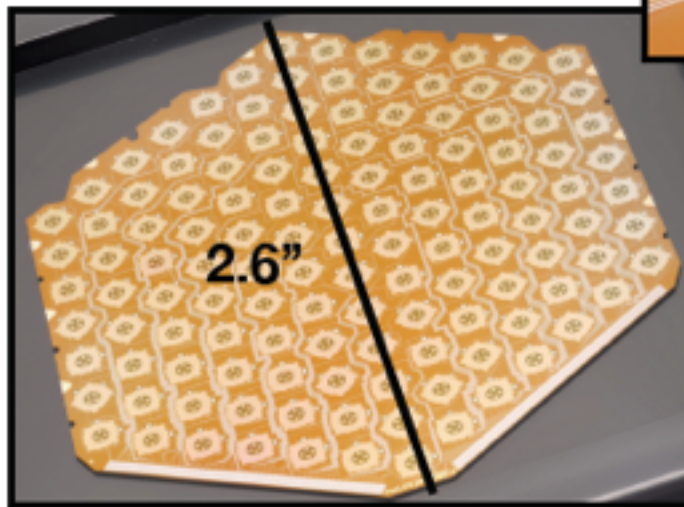
Two wafer shapes:
hex and semihex

Detector wafers fabricated at NIST

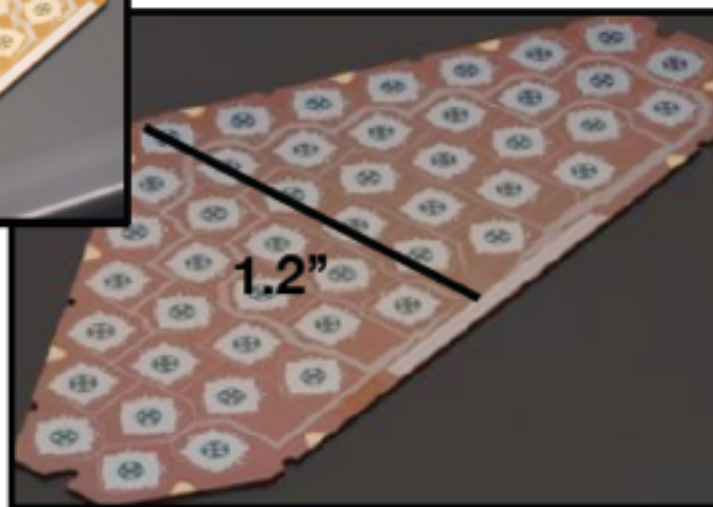
Readout using time domain multiplexing with three stages of SQUID amplification



Hex Wafer:
127 pixels



Semi-hex Wafer:
47 pixels



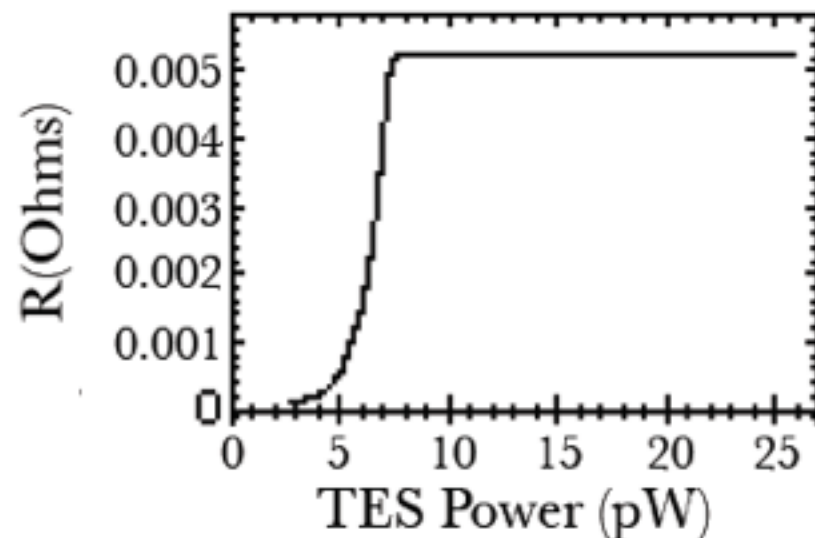
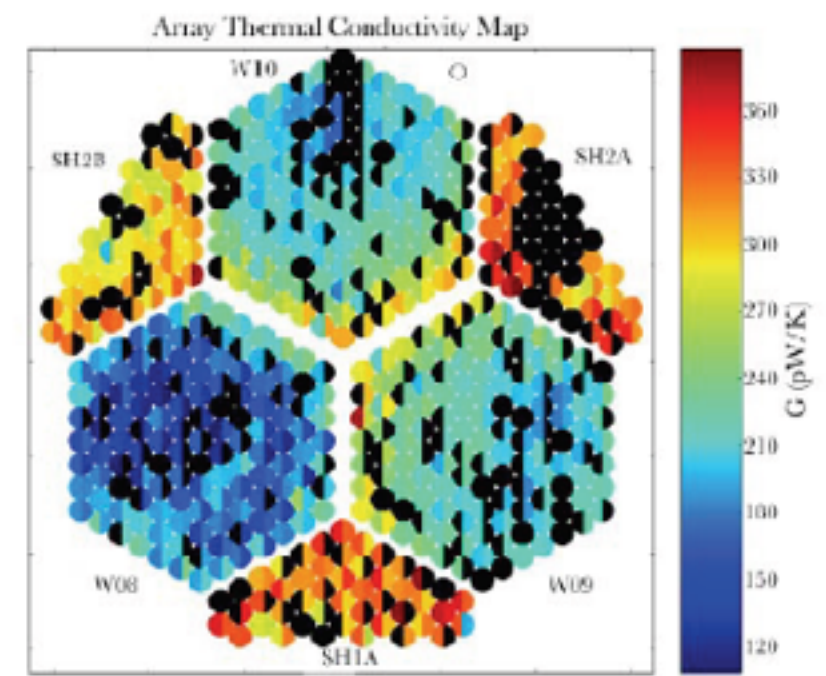
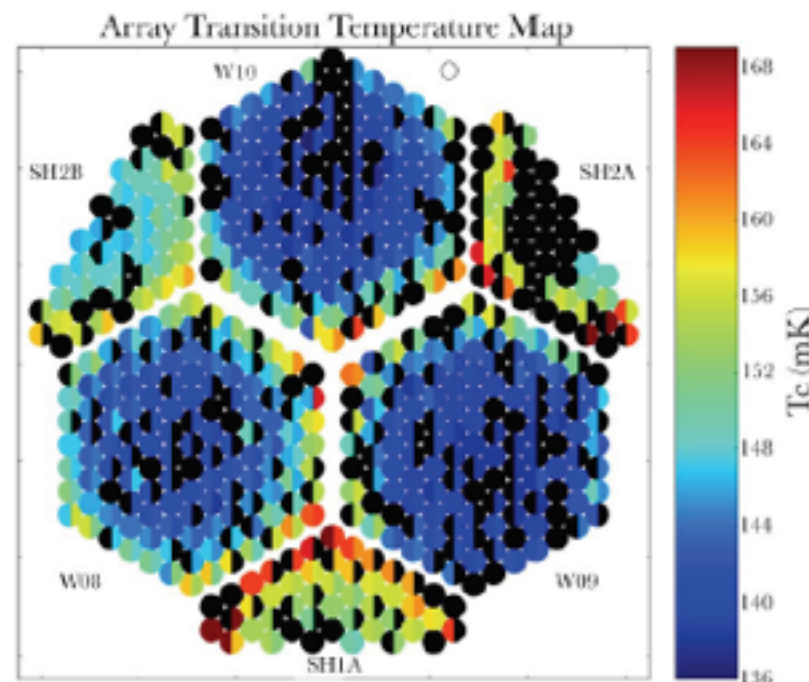
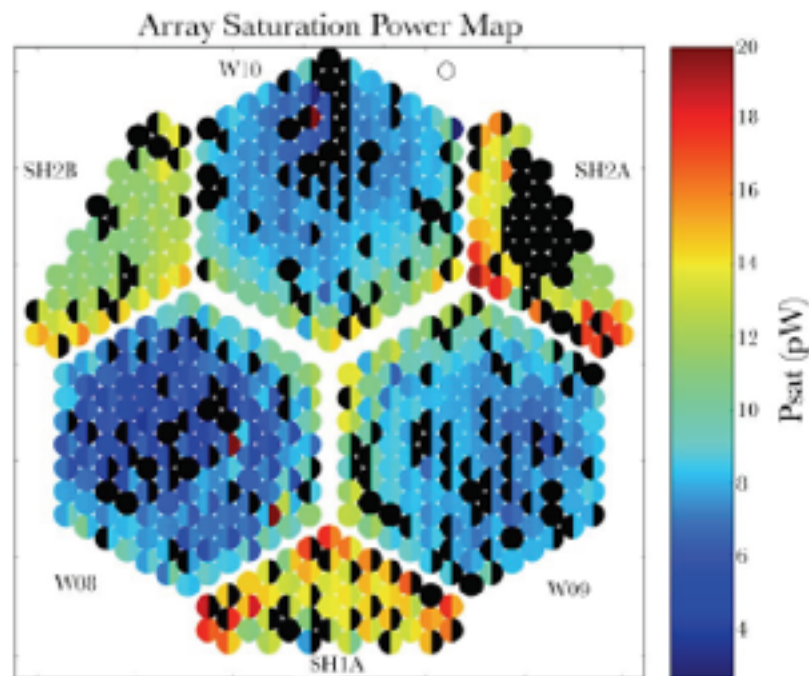
Array Characterization

Extensive characterization of full array in the ACTPol receiver conducted in the lab prior to deployment

P_{sat}^* : Target = 13.5 pW

T_c : Target = 150 mK

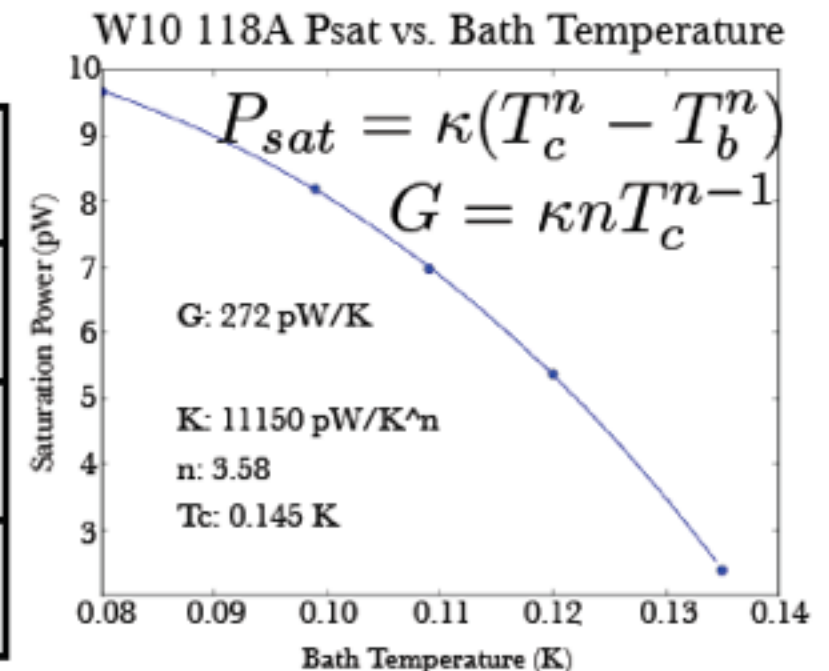
G : Target = 240 pW/K



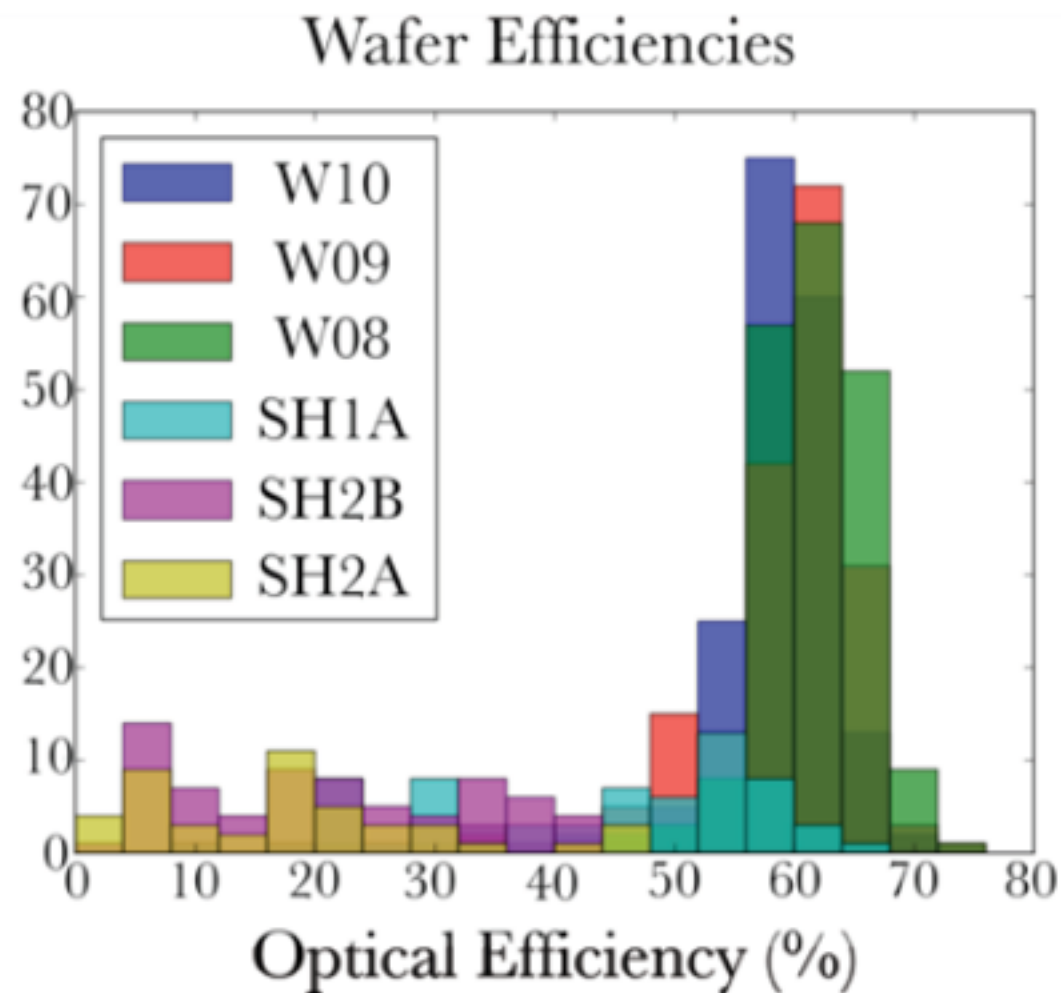
* measured with window cover at $T_{\text{bath}} = 80 \text{ mK}$

Average array values:

	Hexes	Semihexes
P_{sat} (pW)	8	13
T_c (mK)	144	155
G (pW/K)	210	320



Optical Characterization



Detector Optical Efficiencies:

W10, W09, W08: 60%

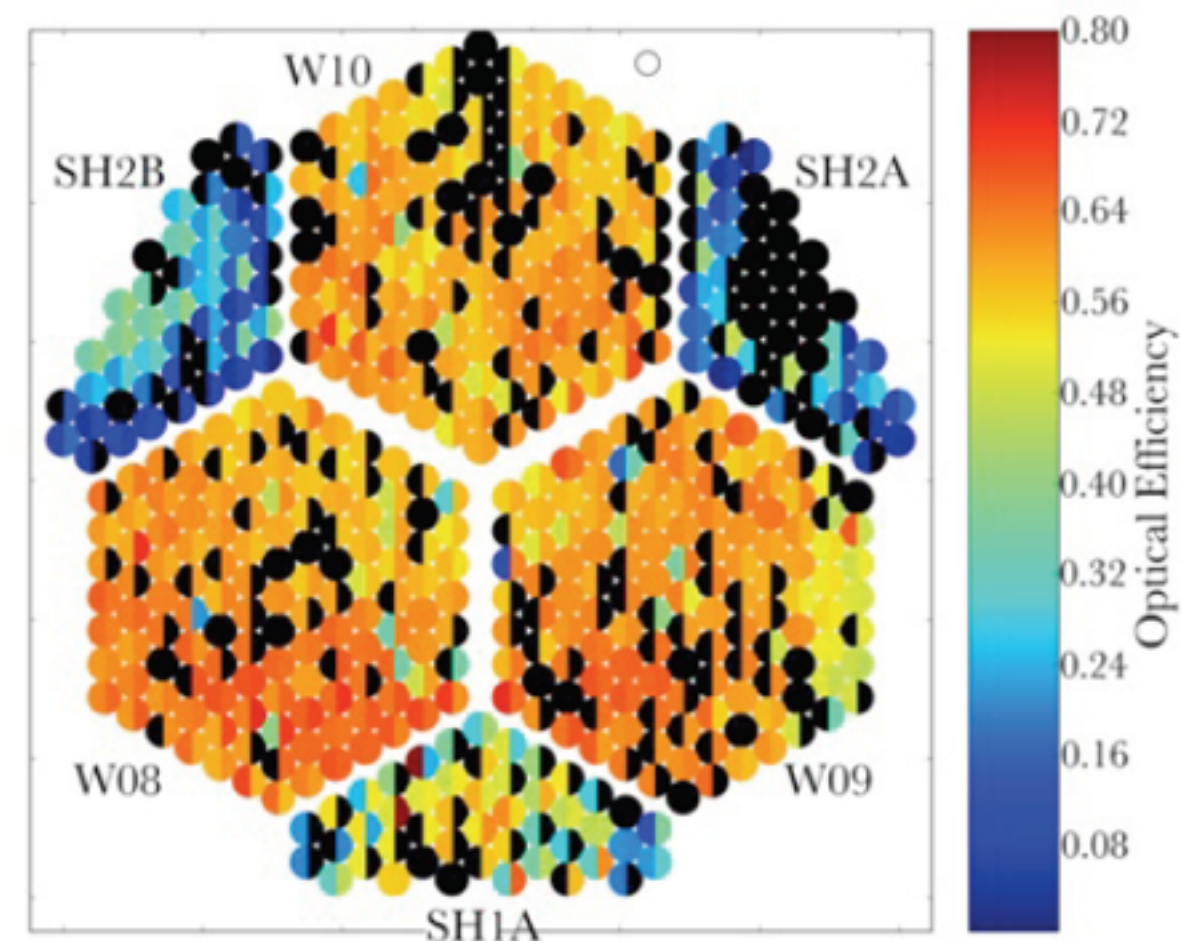
SH1A: 47%

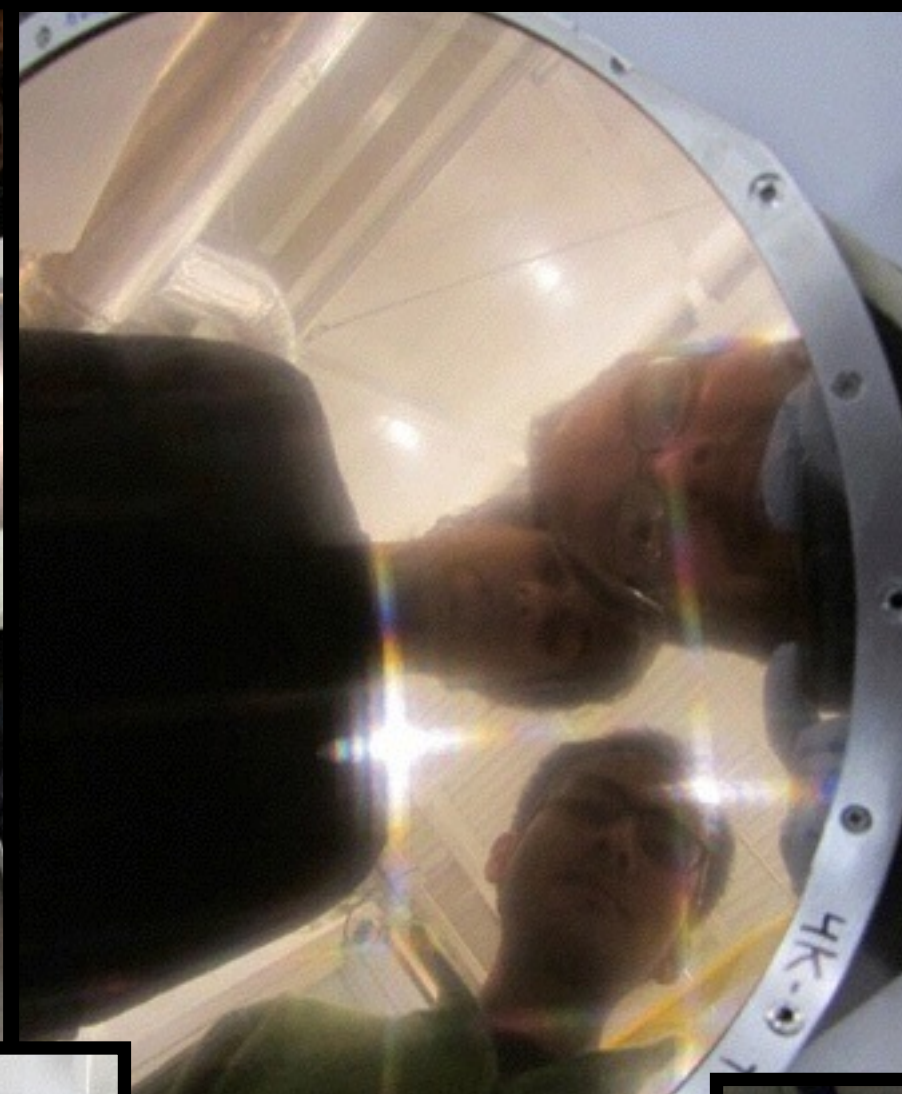
SH2B and SH2A: 21%

Results to be confirmed with planet measurements

See poster:

310: "Characterization of Transition Properties and Optical Efficiencies of ACTPol Transition-edge Sensors" - Christine Pappas



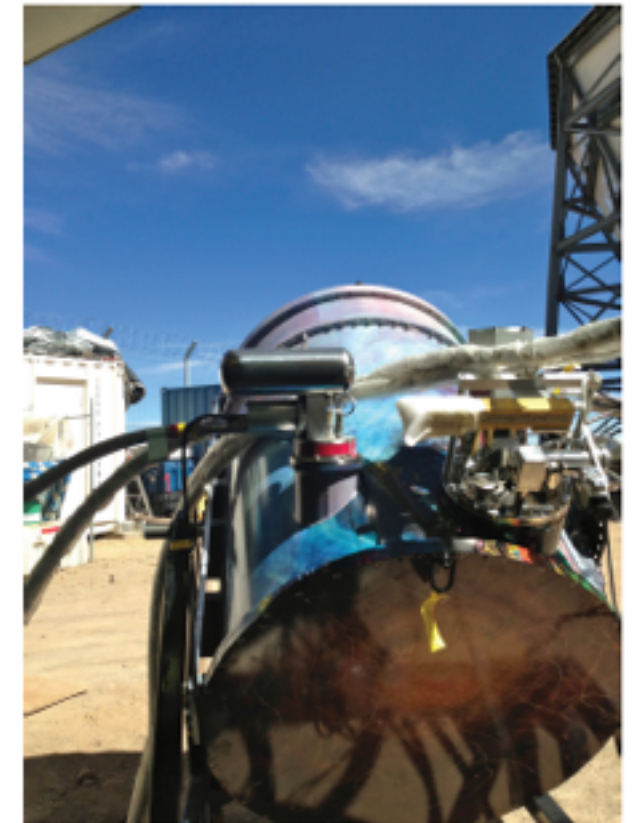
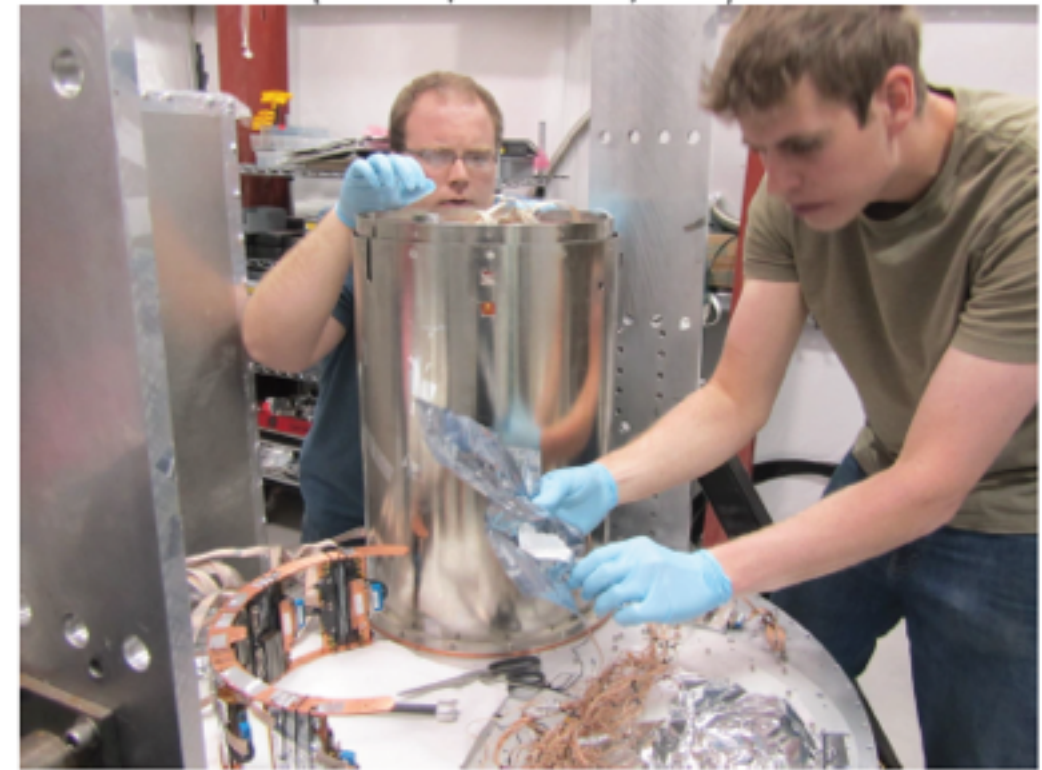


Deployment

February 2013: Receiver arrives at site in Chile

March - April 2013: Final on-site receiver integration

April - May 2013: Post-shipping cooldown for validation of cryogenic and detector performance



Time Constants

Intrinsic thermal time constant of detector:

$$\tau = \frac{1}{2\pi f_{3db}} \sim \frac{C}{G}$$

Low pass filters the response of the detectors

Three methods of measurement:

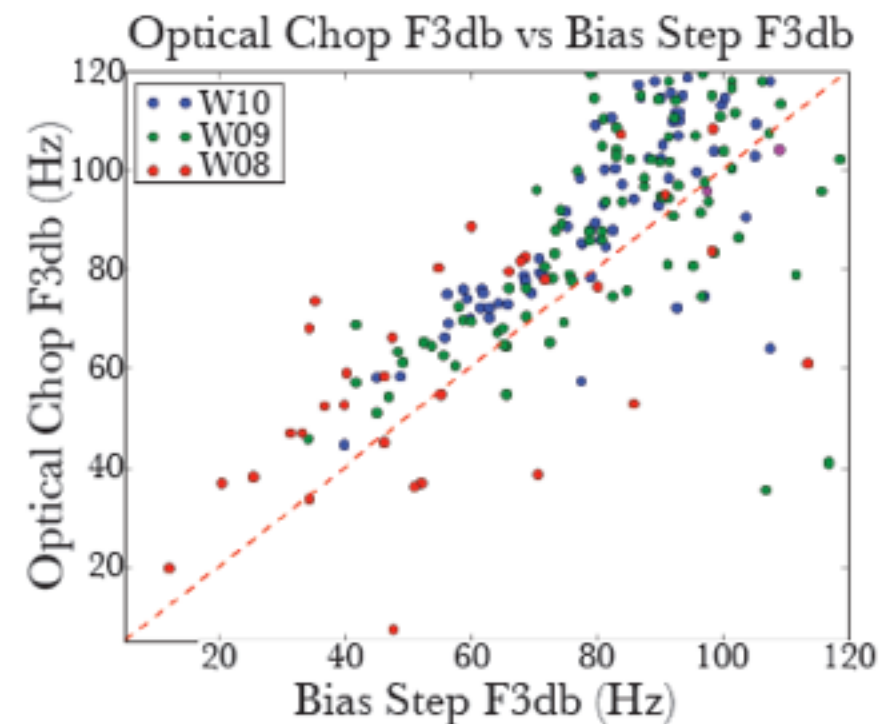
1) Optical chop

$$I_{peak} = I_0 \sqrt{\frac{1}{1 + \left(\frac{f}{f_{3db}}\right)^2}}$$

2) Bias step

$$I(t) = I_0 + \Delta I e^{\frac{t}{\tau}}$$

3) Planet scans



Initial comparison between optical chop and bias step measurements shows good correlation

Want a fast and repeatable method of calibration -> bias steps

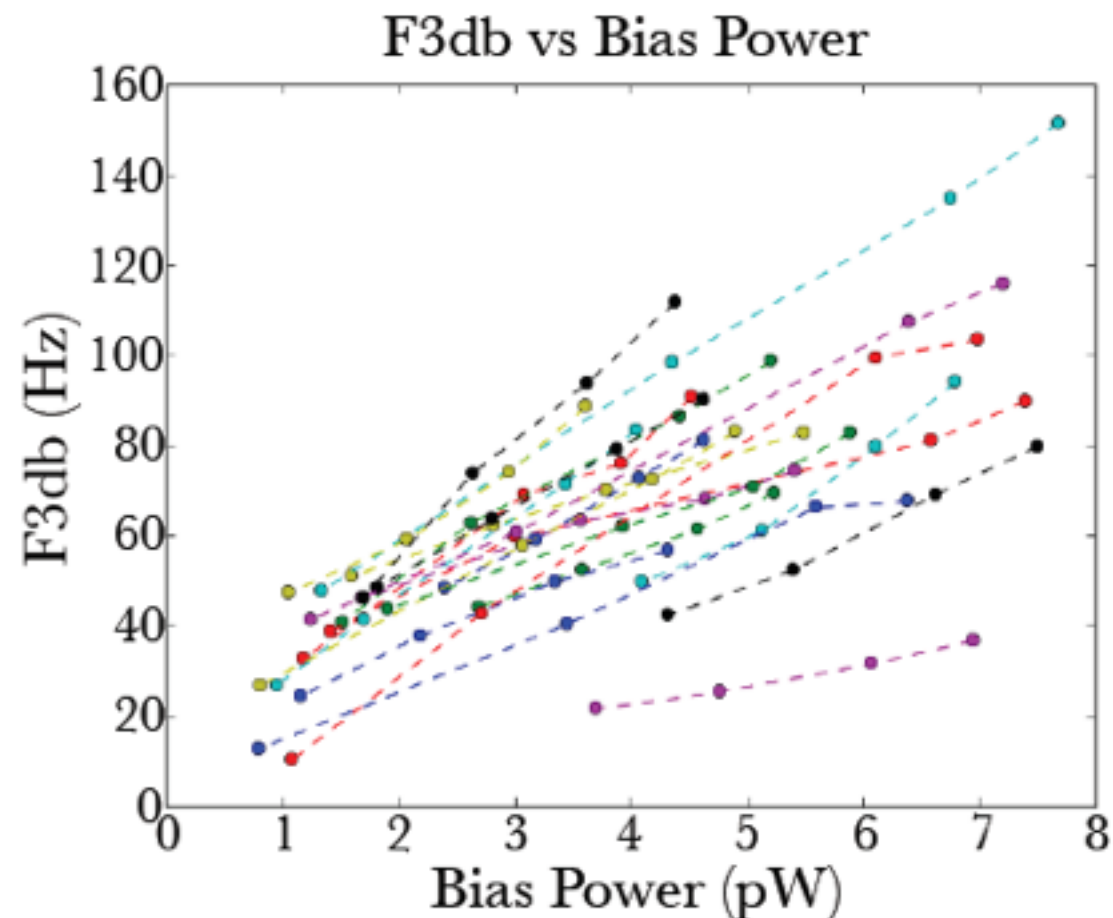
Further comparison of methods soon with planet scans

Time Constants

Effect of bias conditions on time constant:

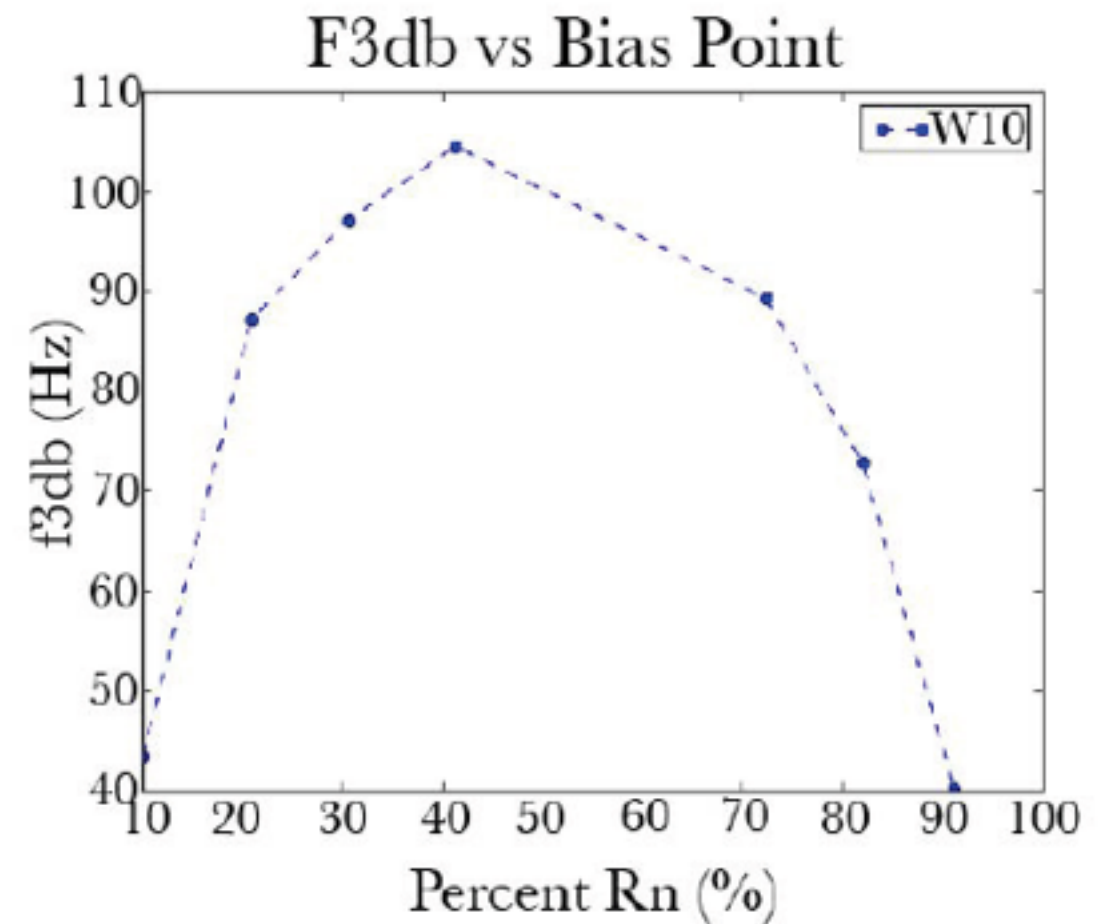
$$f_{3db} = \frac{G}{2\pi C} \left(1 + \frac{(1 - \frac{R_{sh}}{R_0})\alpha_I}{(1 + \beta_I + \frac{R_{sh}}{R_0})GT_0} P_{J0} \right)$$

Detectors slow with decreased bias power:



Fastest response achieved in middle of transition

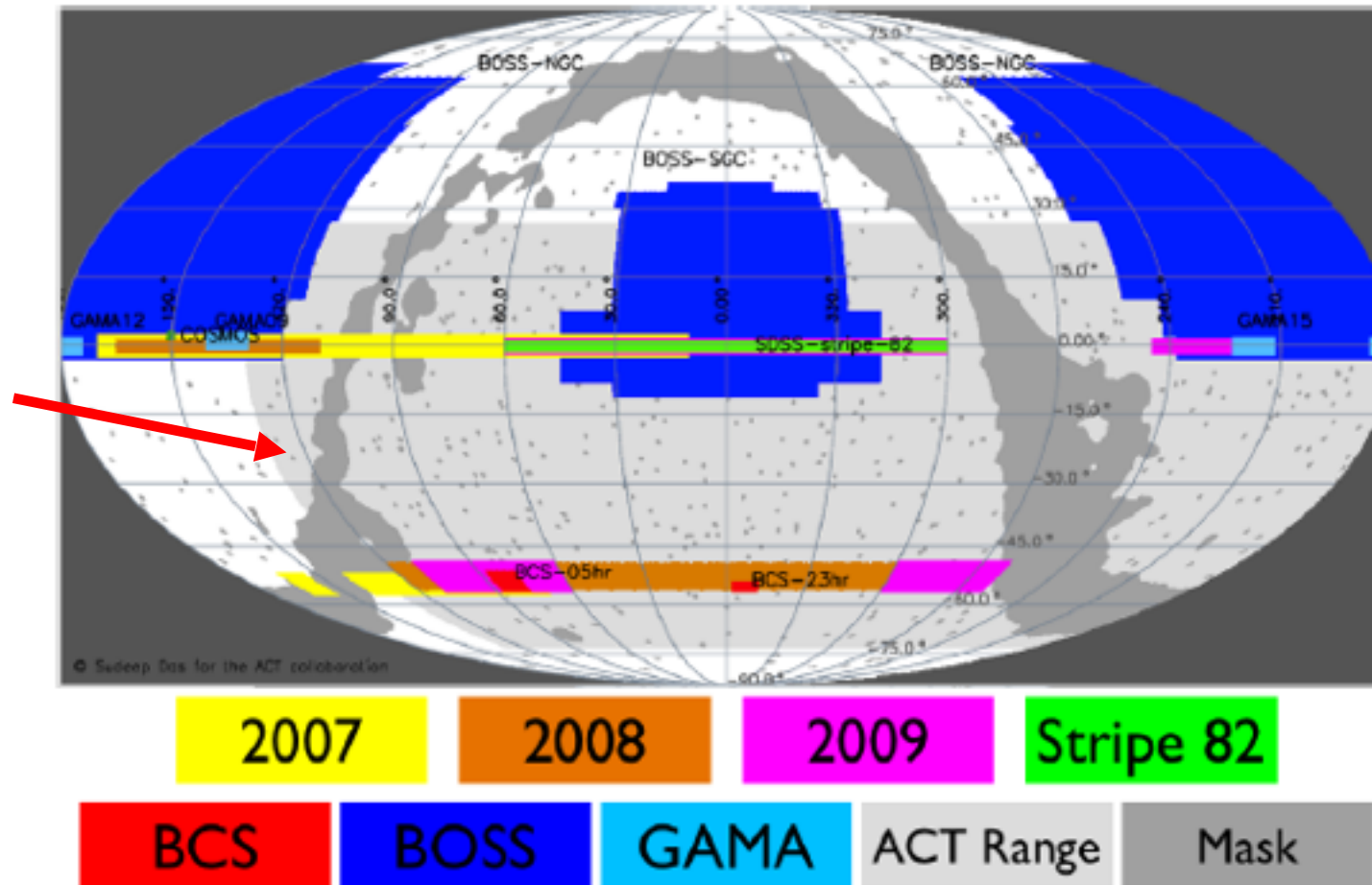
Adequate time constants achieved across broad range of transition:



ACTpol Scan Strategy

As a mid-latitude (23° S) site, the location and coverage of ACT allows for overlap with many observatories for follow-up observations (increased data richness)

ACT range covers
>25,000 sq.deg. with
overlap of many
leading cosmology
facilities



ACT collaborators
lead a multi-national
data follow-up effort
(SALT-20 nights, VLT
, Gemini (Chile),
BOSS, SDSS, XMM-
LSS, HerMES...)

M.D. Niemack et. al, arXiv:1006.5049v1
(2010)

Projected scan sensitivities for first three ACTPol seasons:

[1] ACTPol Deep (~600 deg² total):
Temp. → 3 μ K/arcmin² Pol. → 4 μ K/arcmin²

[2] ACTPol Wide (3500 deg²):
Temp. → 20 μ K/arcmin² Pol. → 28 μ K/arcmin²

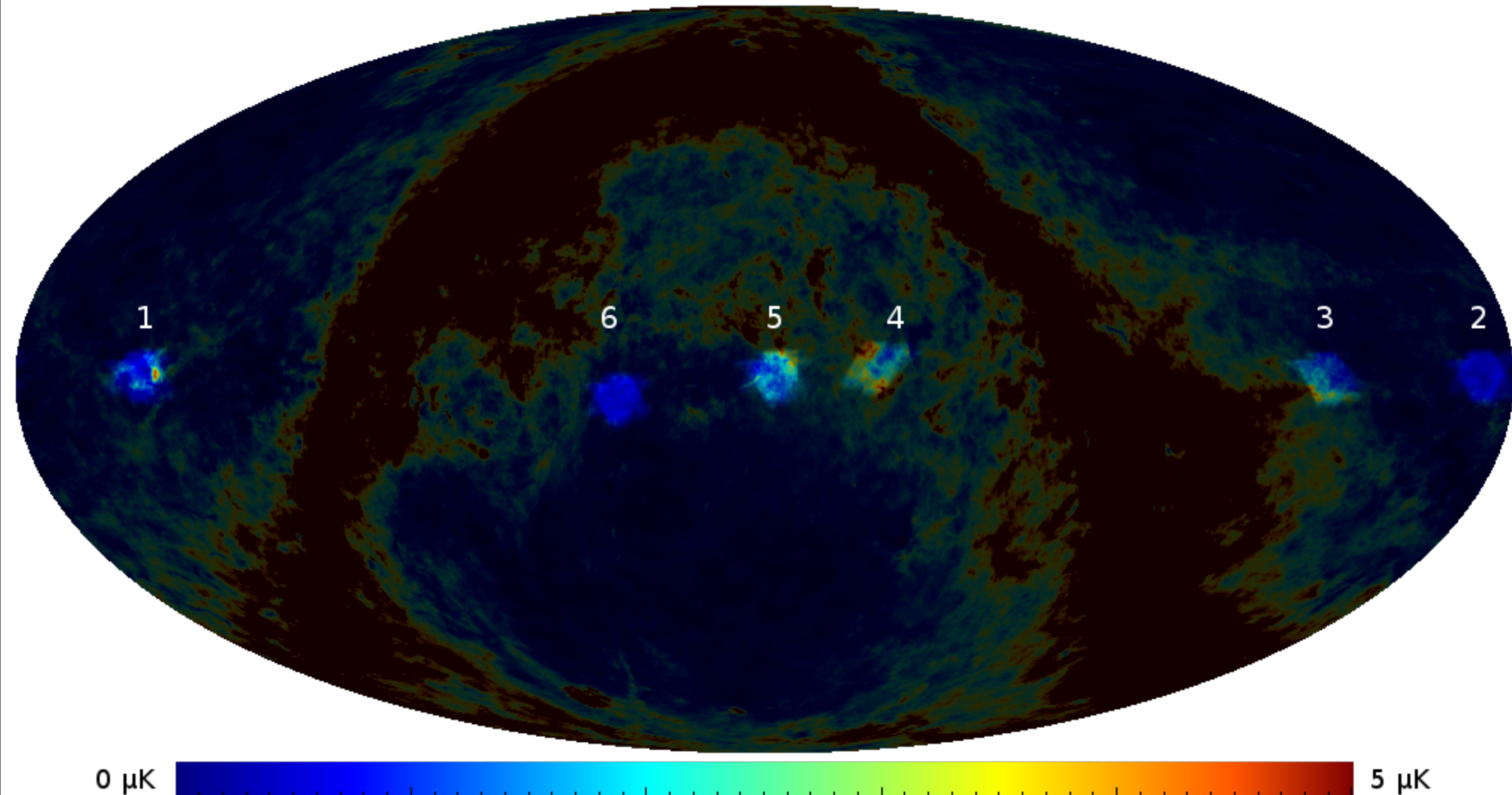
[3] *POSSIBLE: ACTPol Ultra-Wide (~60% of entire sky)*

ACTPol will have ~1 arcminute resolution and 4x sensitivity of MBAC!

Due to:
→ 3x colder bath temp
→ 2x number of detectors at 150GHz
→ Improved optical throughput

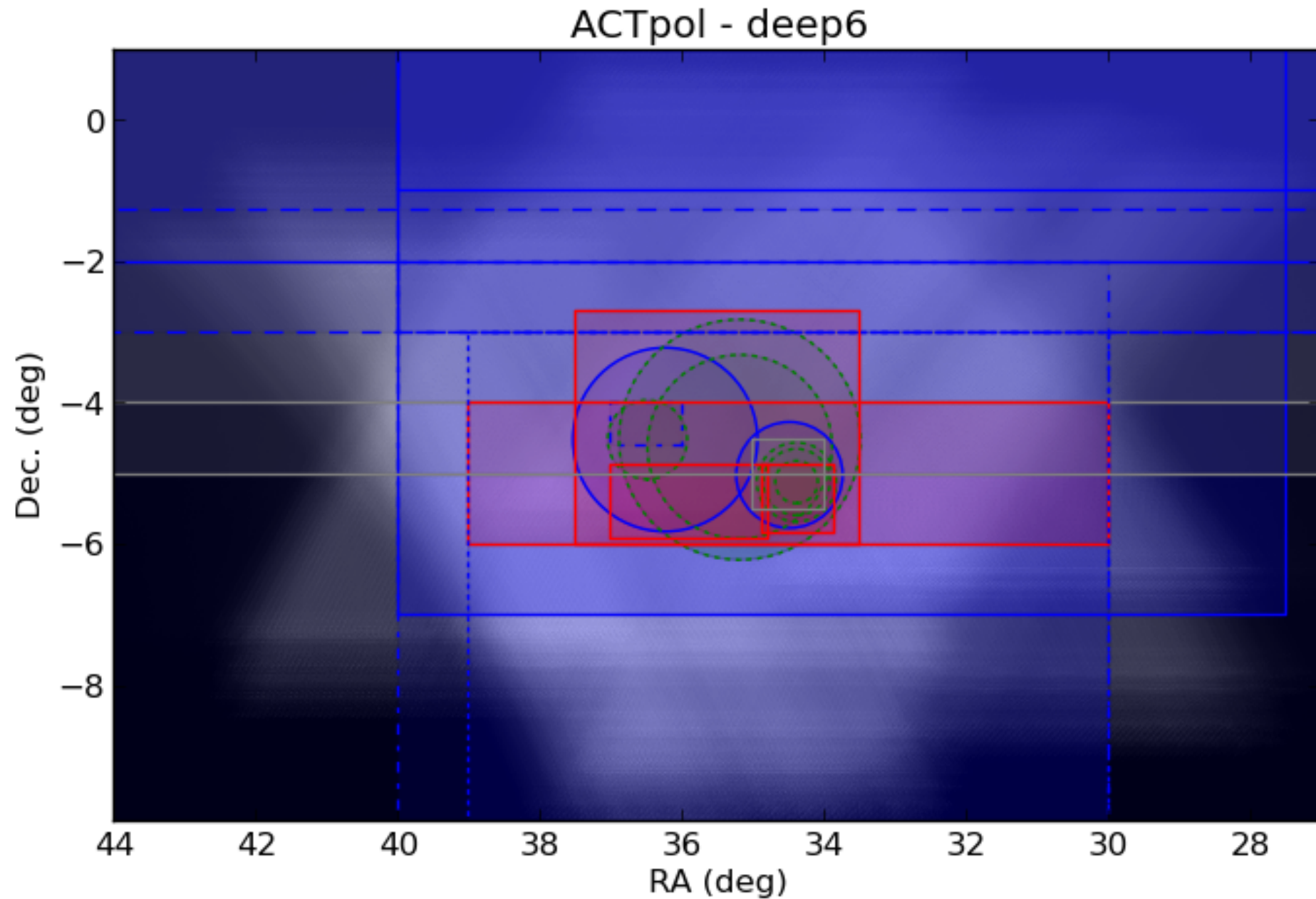
Deep Fields

Completed one season of observations, day and night observations. $\sim 120 \text{ deg}^2$ deep survey, wide survey to follow

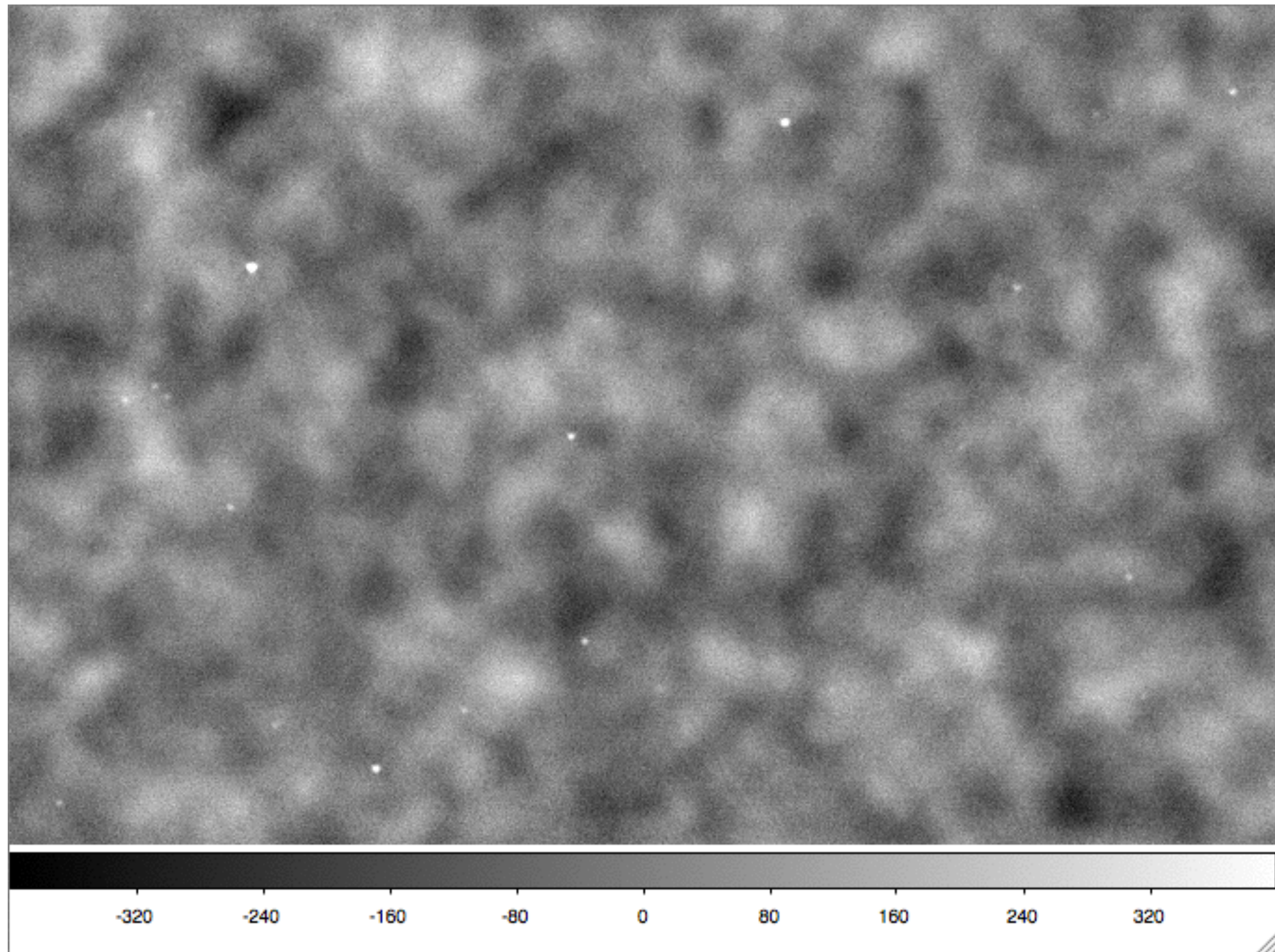


Overlap with complementary datasets

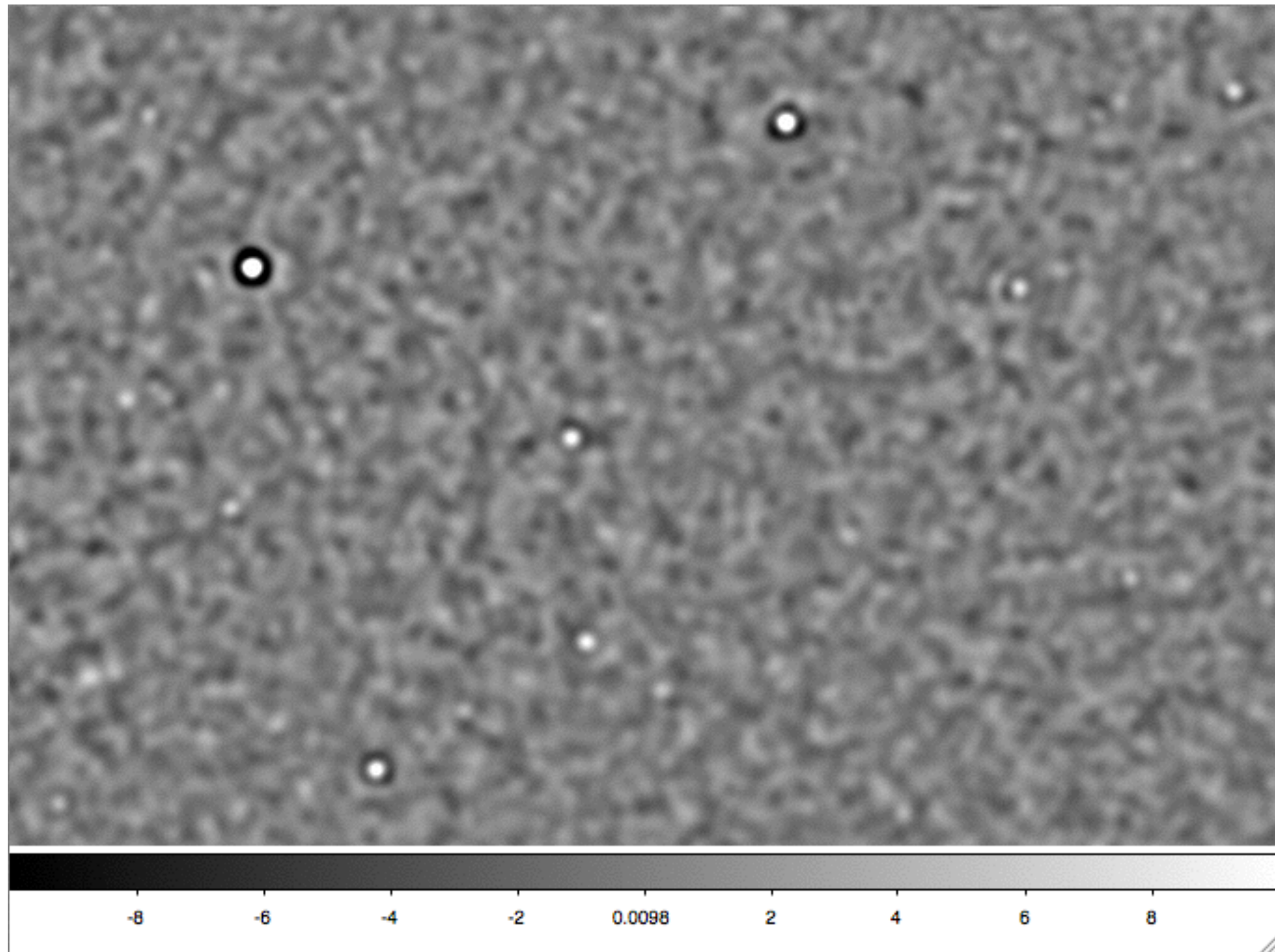
Simulated data



XMM field (Intensity) Raw



XMM field (Intensity) Filtered



FIN