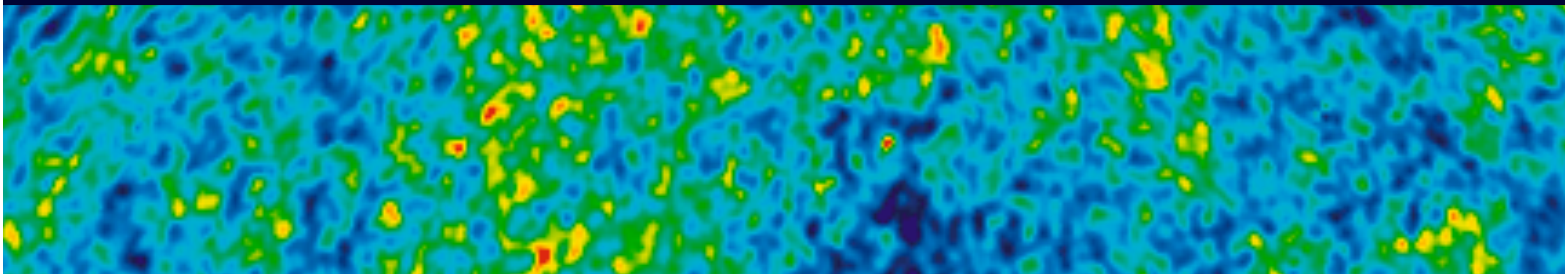
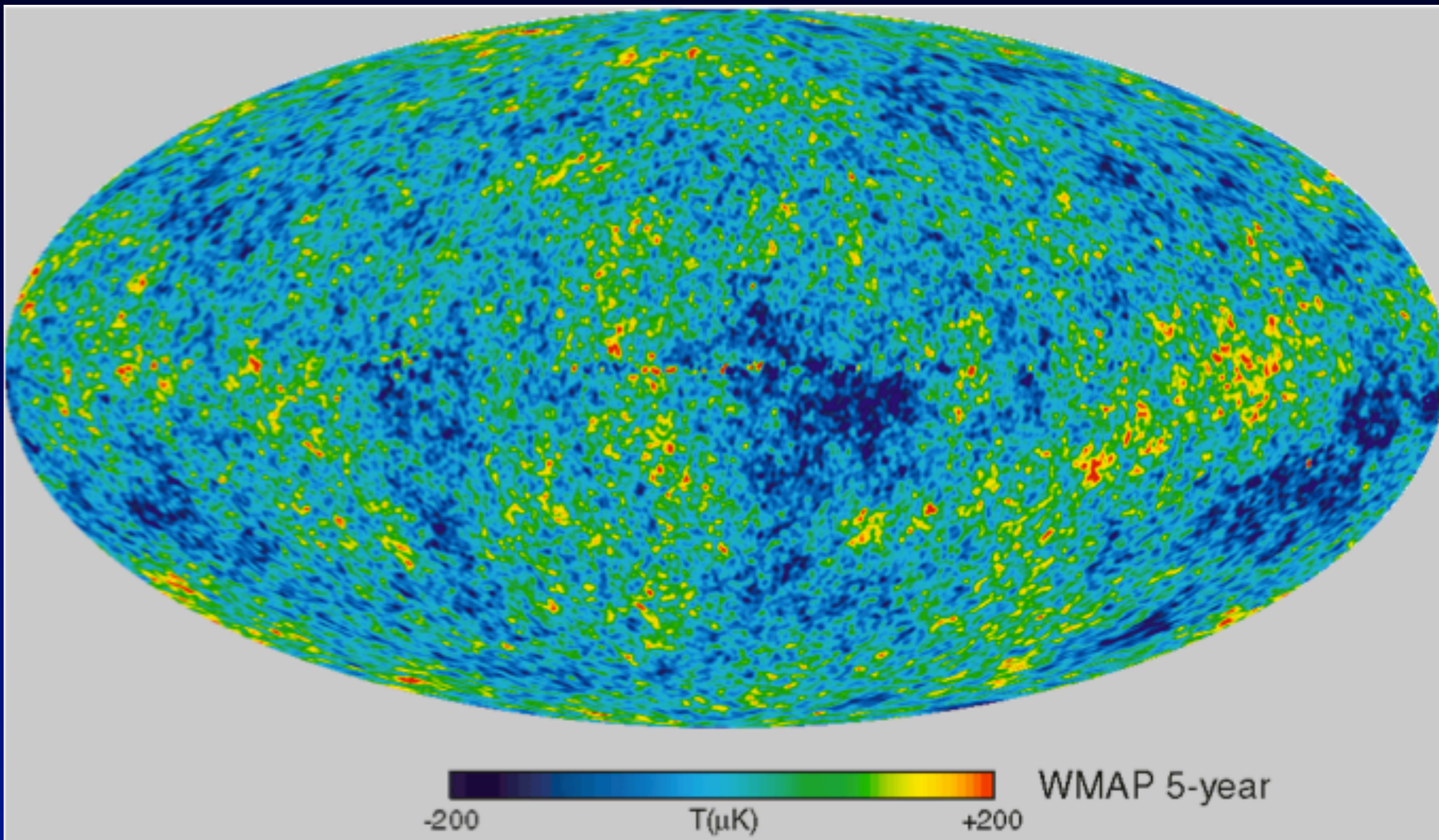
COSMOLOGY FROM THE CMB AT ARCMINUTE SCALES: FIRST RESULTS FROM THE ATACAMA COSMOLOGY TELESCOPE



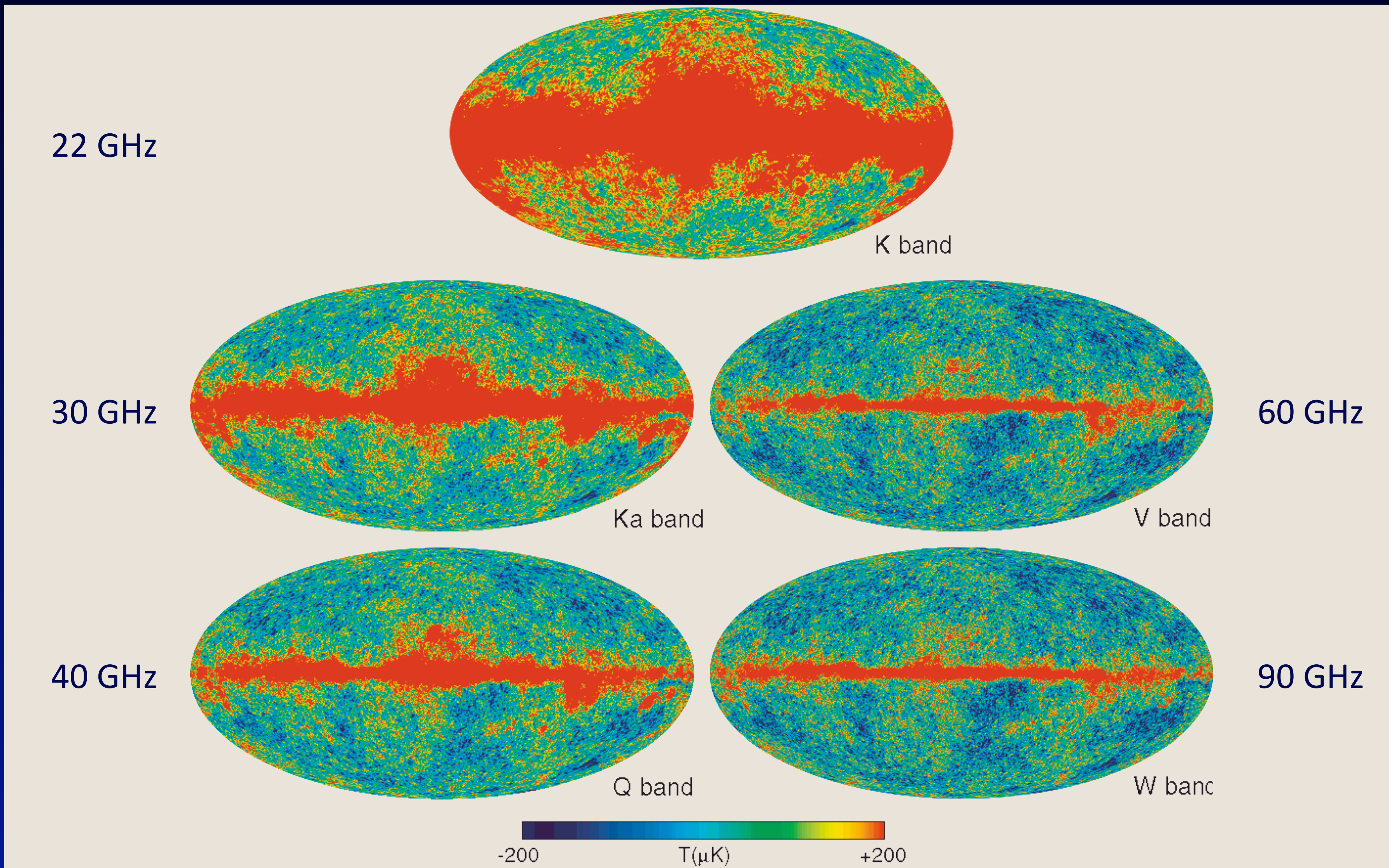
CEA Saclay Particle Physics Group Seminar

Joe Fowler
Princeton University
April 8, 2010

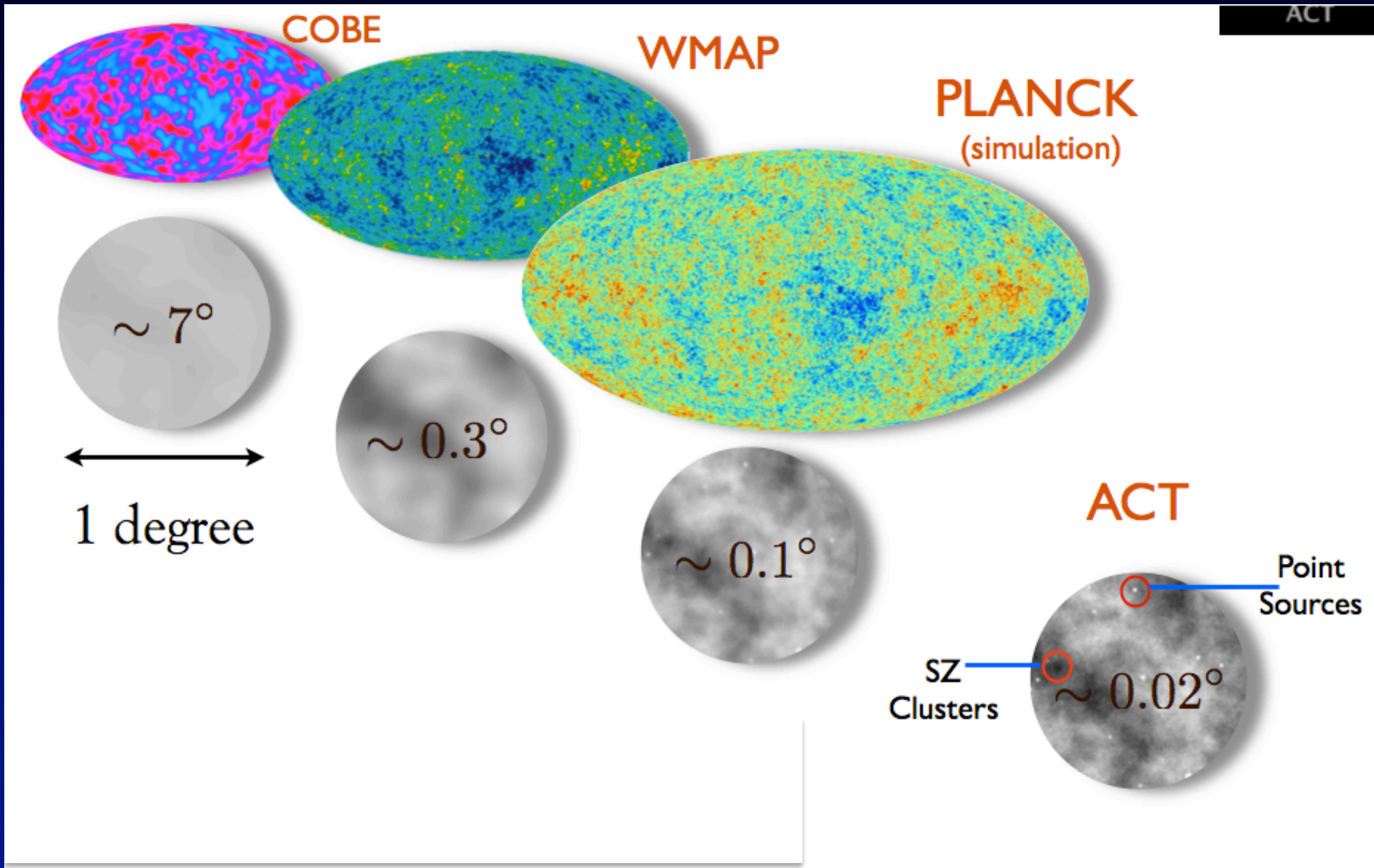
Cosmic Microwave Background Anisotropies



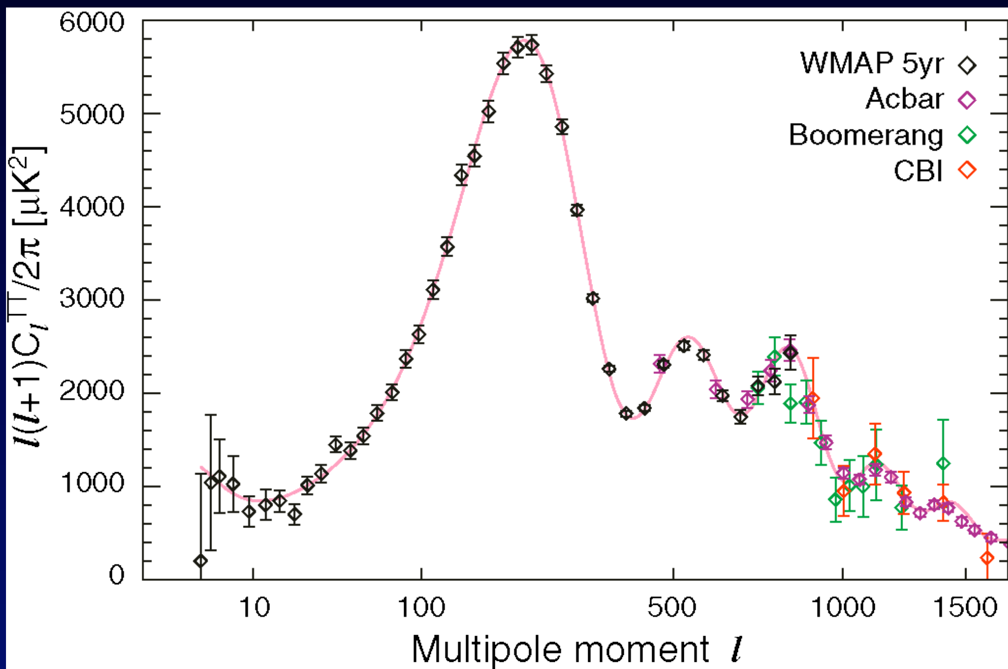
THE REAL MICROWAVE SKY

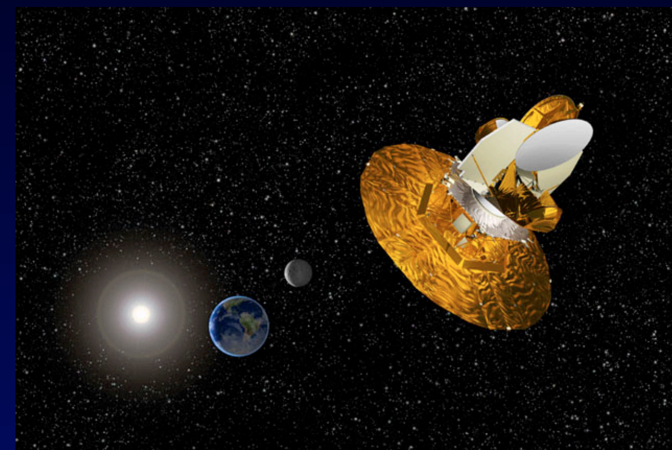


NEW SCIENCE FROM LARGE MILLIMETER TELESCOPES



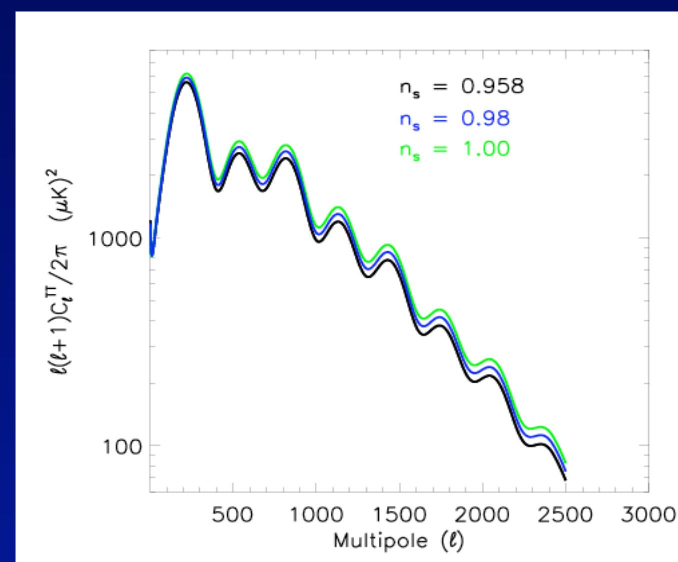
CMB ANISOTROPY POWER SPECTRUM



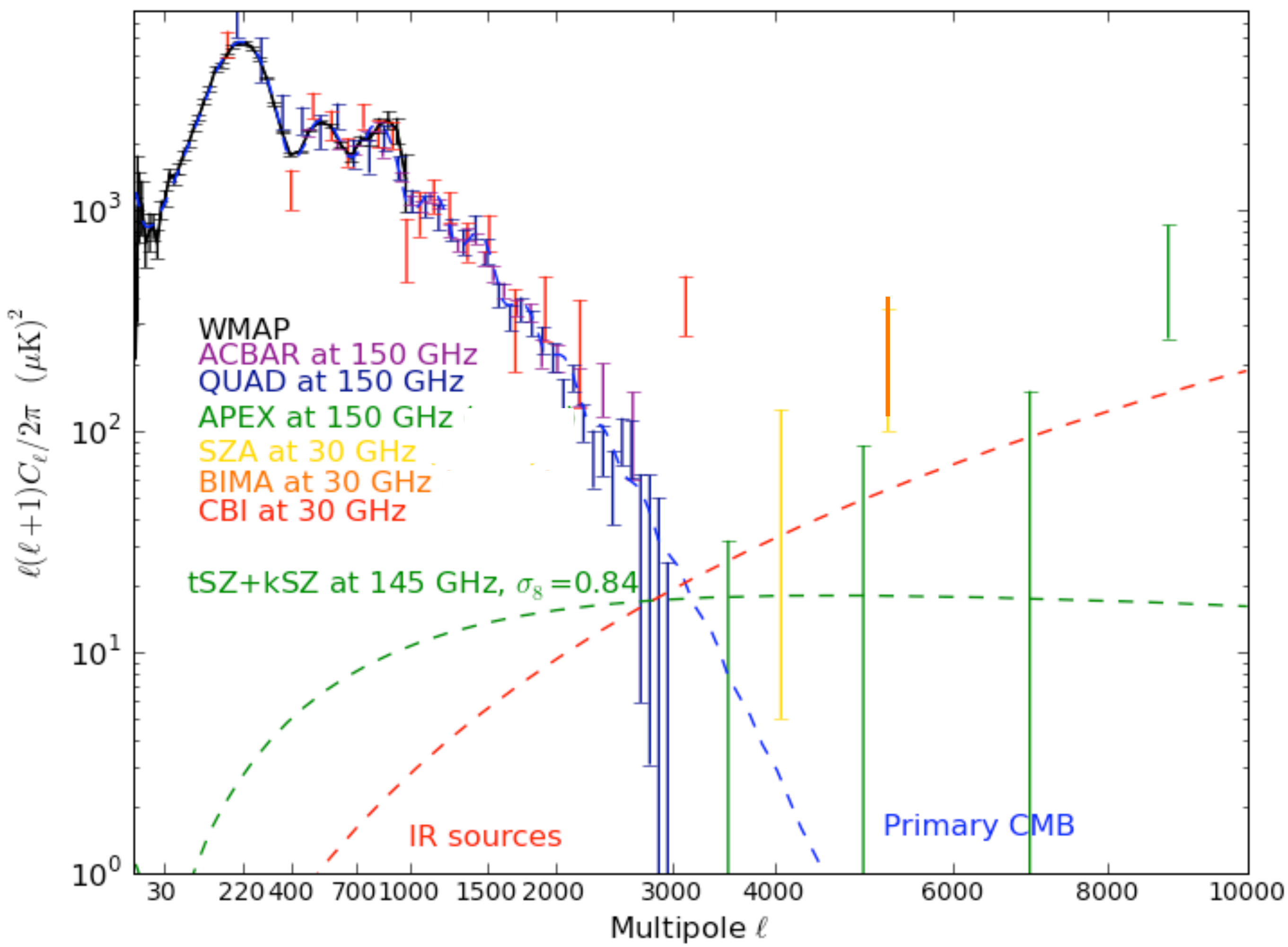


Measurements to date mainly observe effects imprinted in the first 1 Myr, the “primary anisotropy”.

- (Single-field) inflation governs the spectral tilt n_s



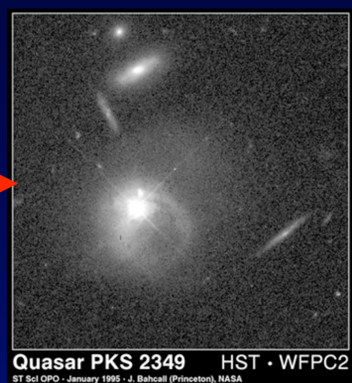
~~Current~~ Recent State of the CMB Power Spectrum

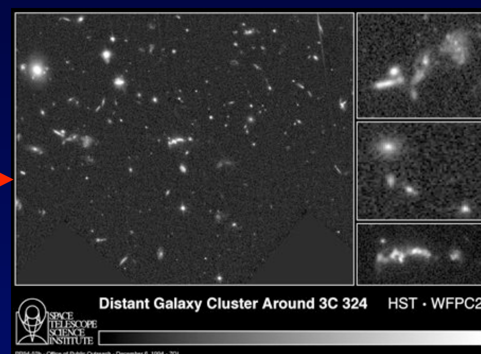


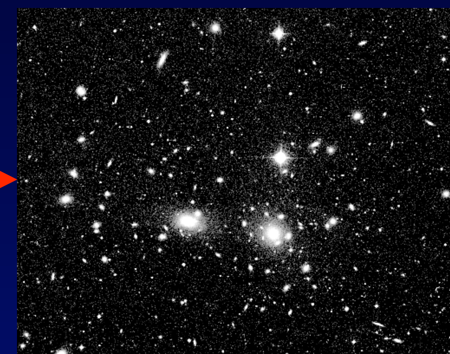
SECONDARY ANISOTROPIES IN THE CMB

"Secondary" = all effects later than the z=1089 last scattering surface.

Secondary anisotropies also contain information beyond the power spectrum.





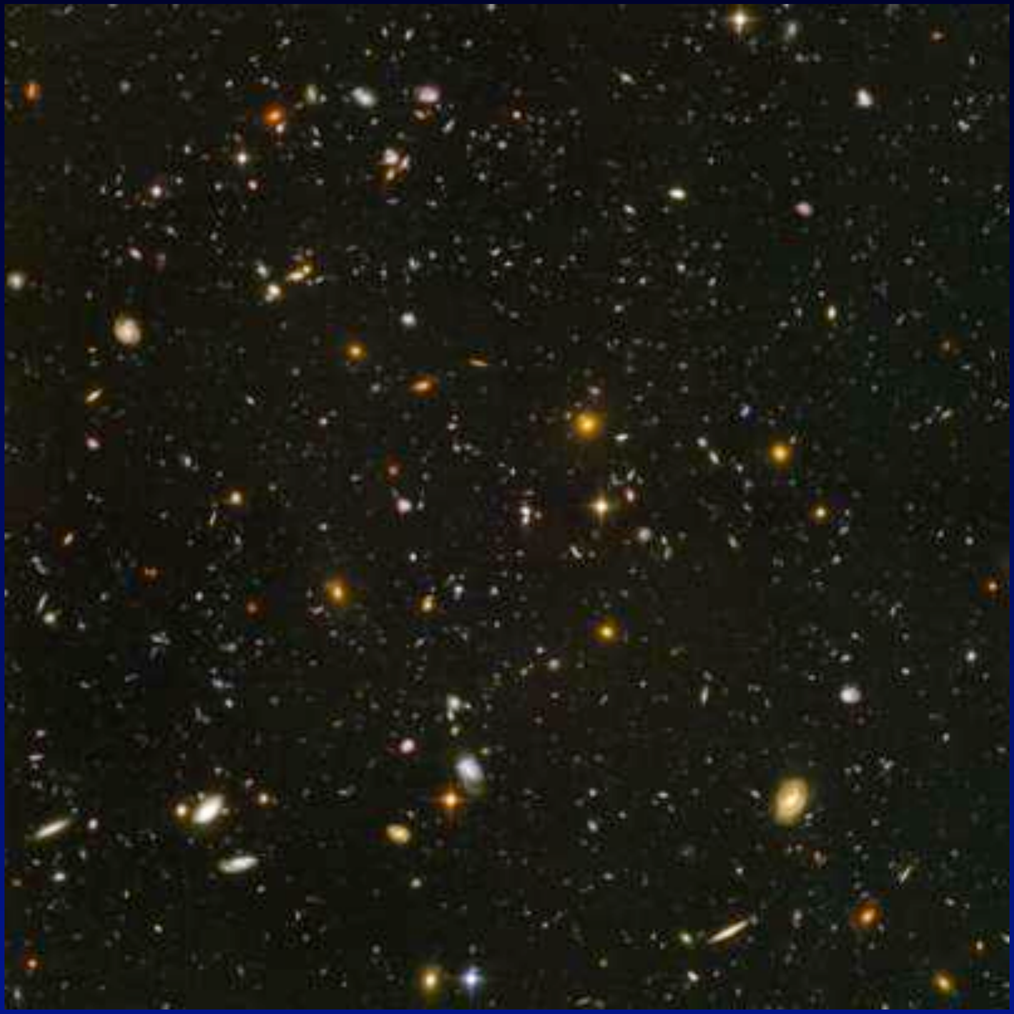


Using the CMB as a backlight—study structure as it was forming.

Structure formation → Dark Energy

Primary CMB	OV / Diffuse SZ	CMB Lensing	Cluster Surveys	
z = 1500	z = 6—7	z = 1—2	z <1	now

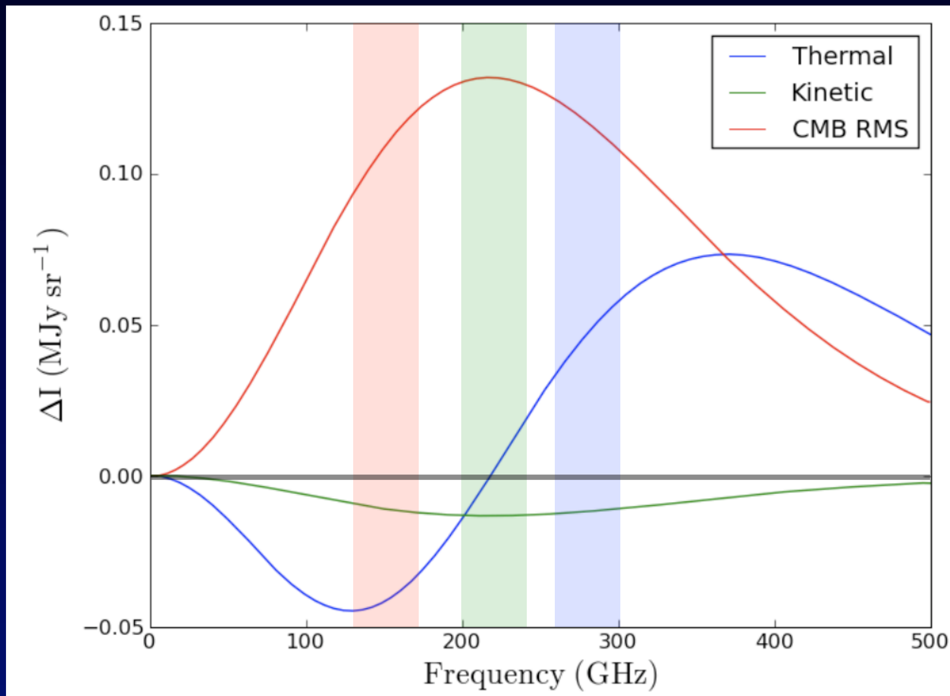
GALAXY CLUSTERS TRACE COSMIC STRUCTURE FORMATION



Hubble Ultra-deep field

Cluster: Abell 2667

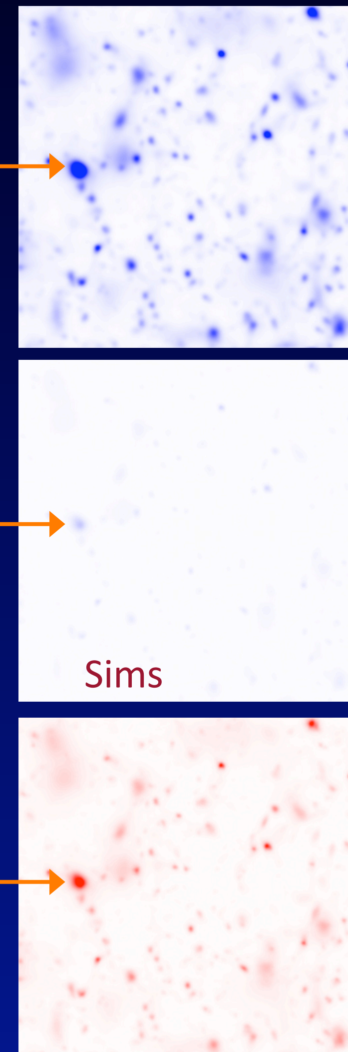
Sunyaev-Zel'dovich Effect (1970): Signature of Massive Clusters



145 GHz decrement

220 GHz null

270 GHz increment



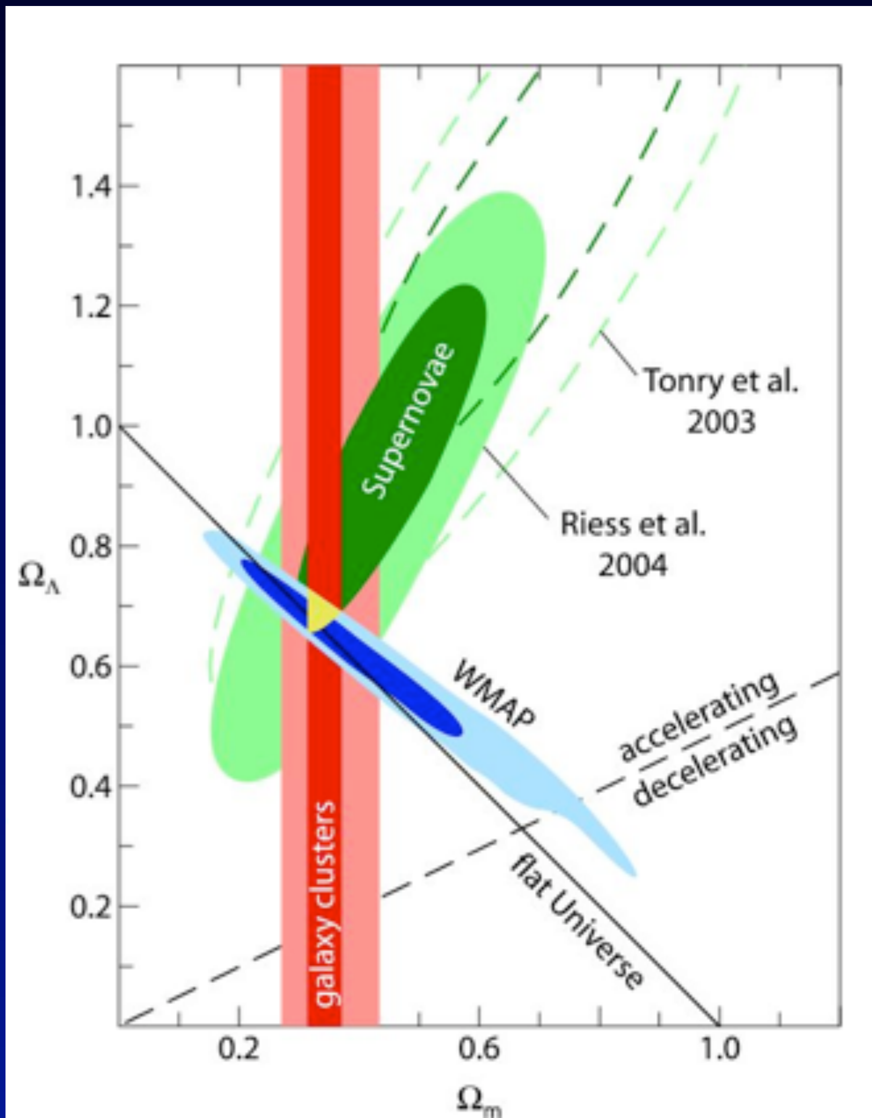
Elastic Compton $e\gamma \rightarrow e\gamma$ from hot electron ICM

A *z-independent* signal!

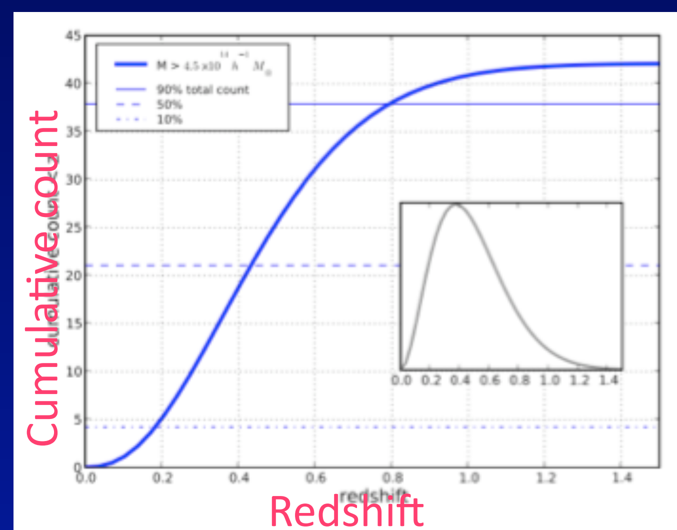
Traces integral of n_e rather than n_e^2.

Once *z* measured in optical: a history of the formation of large structures.
Need *coordinated observations.*

WHY SURVEY FOR CLUSTERS WITH THE CMB?



- Clusters are (exponentially) sensitive to growth of structure in the universe.
- Constrain the cosmological model and the evolution of Ω_Λ.
- SZ effect is independent of *z*.
- Integrated Compton *y* is tightly correlated with cluster mass.

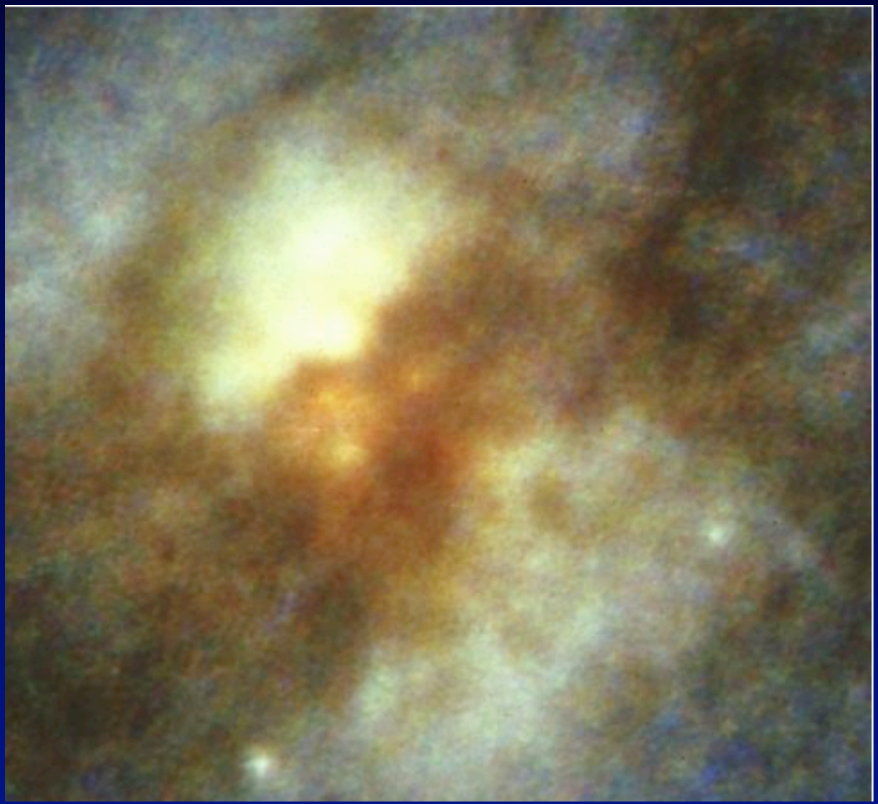


EXTRAGALACTIC FOREGROUNDS

Flat-spectrum radio galaxies

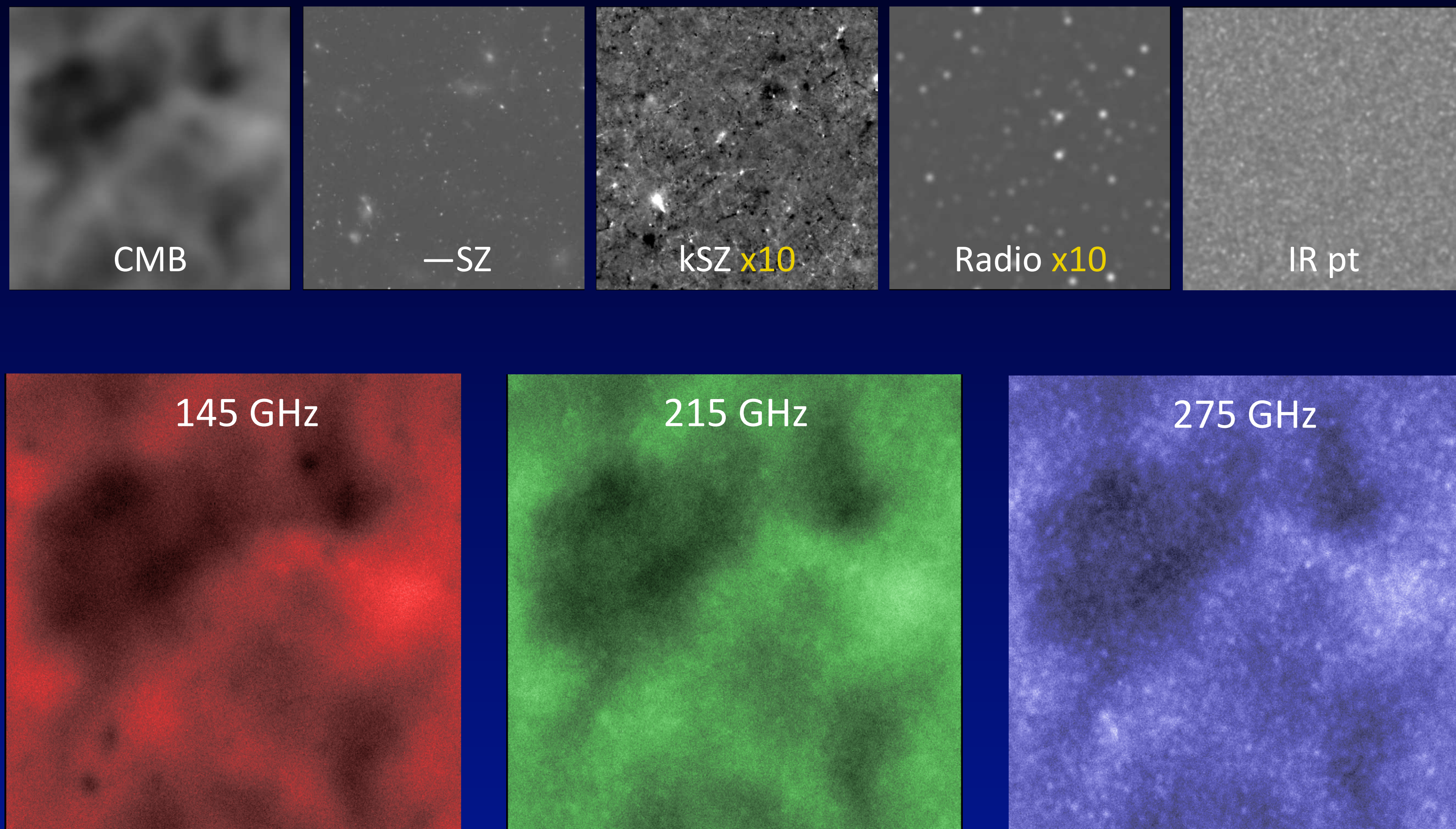
Centaurus A
(optical, submm, X-ray composite)

Dusty starburst galaxies



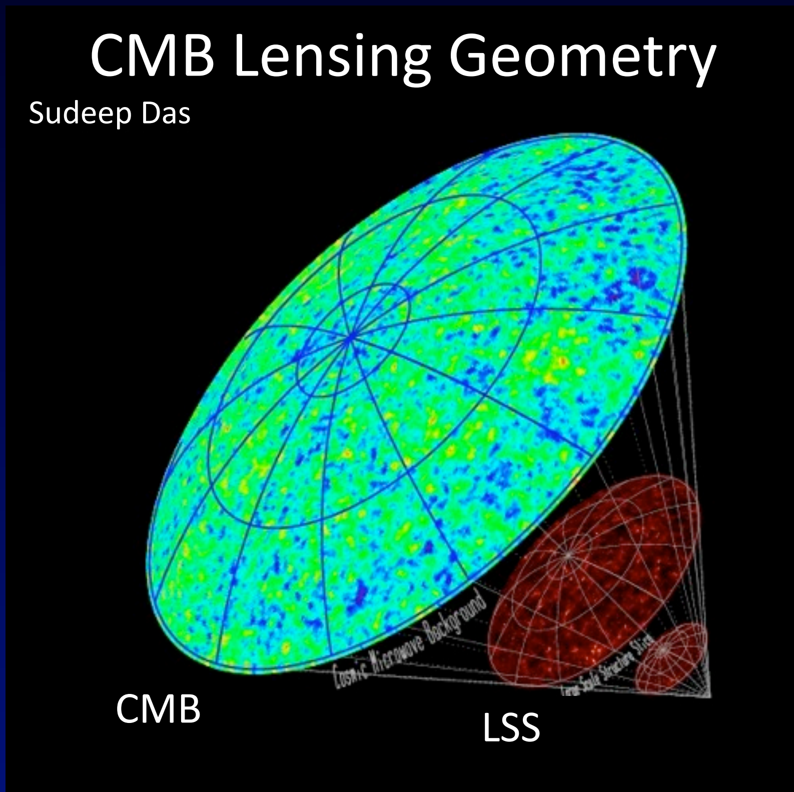
Arp 220
Visible (HST)

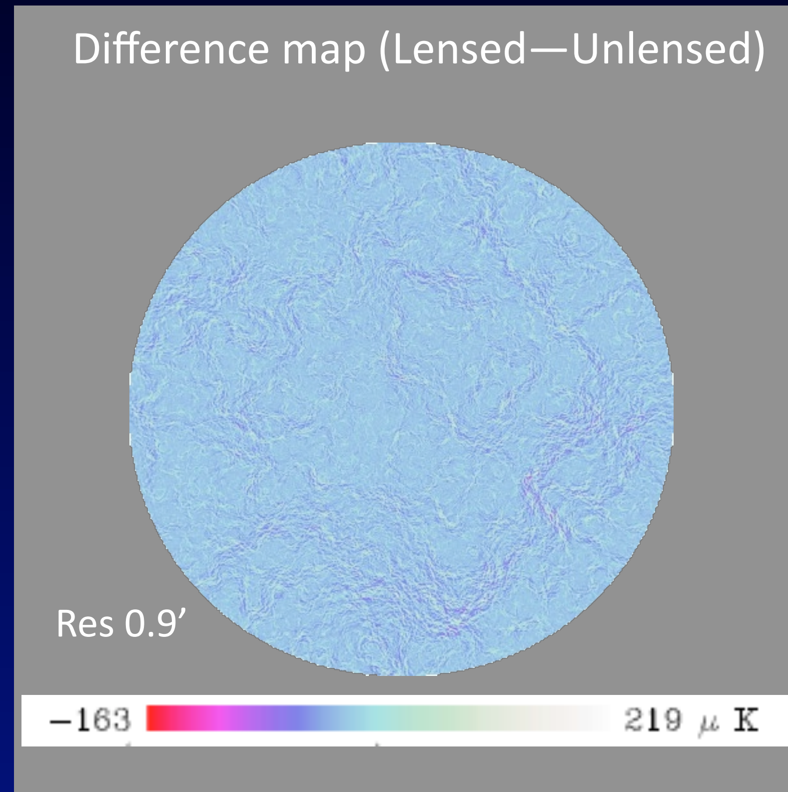
The Millimeter-wave Sky at ACT Frequencies



Simulations : Sehgal et al, arxiv:0908.0540

LENSING OF THE CMB (NOT THERE YET…)





Typical 3' shift, but convergence spectrum peaks at ℓ = 50: large & small scales coupled!

More on recovery : Das, Hajian & Spergel 2008

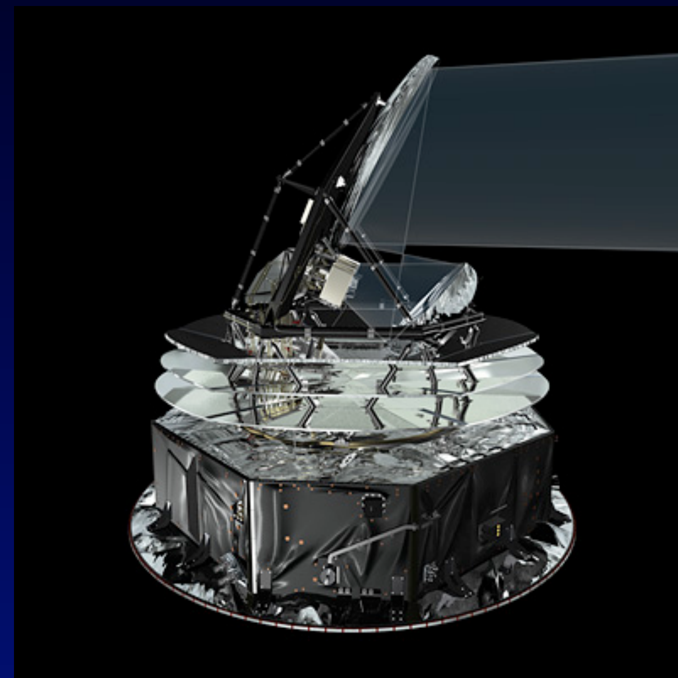
ACT SCIENCE GOALS

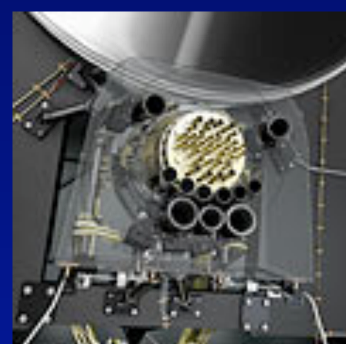
1. Constrain Inflationary Potential through n_s
2. Constrain σ_8 Through tSZ Power Spectrum, Cluster Counts, CMB Lensing
3. Produce Mass-Selected tSZ Cluster Catalog
4. Probe Galaxy Cluster Pressure Profiles
5. Measure CMB Lensing Convergence and Correlate Lensing Convergence with LSS
6. Characterize Flat Spectrum Radio and Sub-mm Galaxies
7. Search for Missing Baryons through kSZ

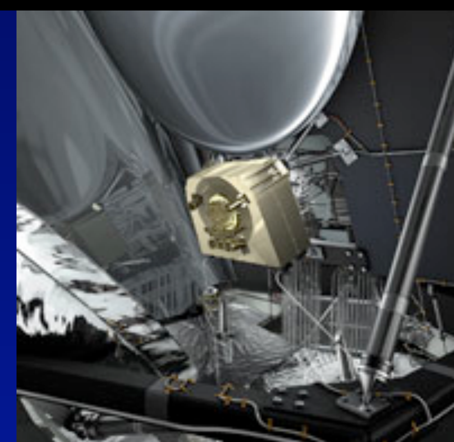
High-Resolution Millimeter Observations are Underway

Shown here:

- South Pole Telescope
- APEX-SZ
- BLAST
- Planck
- SZA







The Atacama Cosmology Telescope Team

ACT with Unfinished Ground Screen

D. Swetz at the site with ACT Receiver

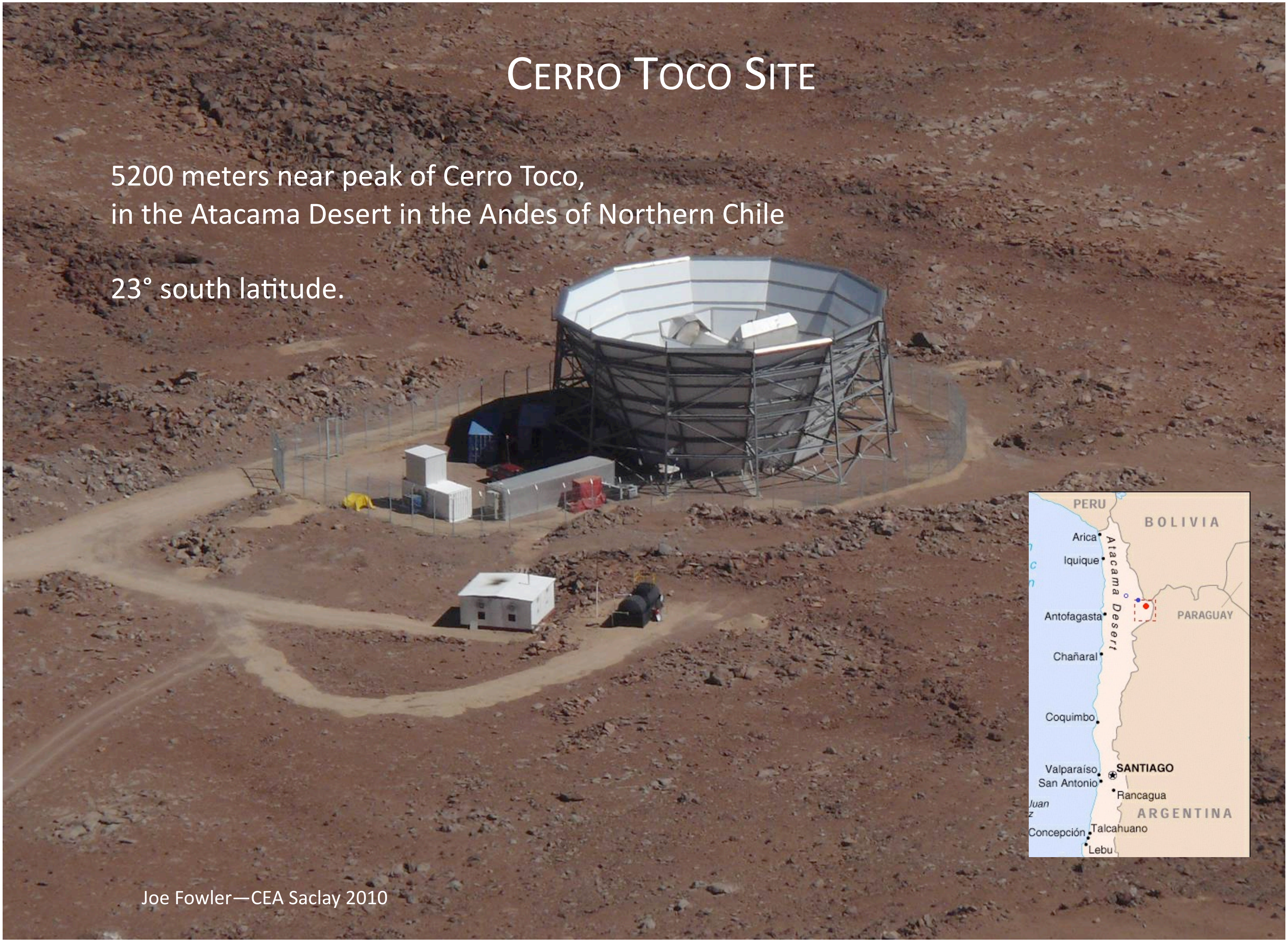
With collaborators now at:

- Cardiff University (UK)
- Columbia University (USA)
- Harvard/Smithsonian CfA (USA)
- Haverford College (USA)
- INAOE (Mexico)
- LLNL (USA)
- MPI Garching (Germany)
- NASA/GSFC (USA)
- NIST (USA)
- Oxford University (UK)
- Pontificía Universidad Católica (Chile)
- Princeton University (USA)
- Rutgers University (USA)
- Stanford University (USA)
- University of Barcelona (Spain)
- University of British Columbia (Canada)
- University of Chicago (USA)
- U. of KwaZulu-Natal (South Africa)
- University of Massachusetts (USA)
- University of Miami (USA)
- University of Pennsylvania (USA)
- University of Pittsburgh (USA)
- University of Rome (Italy)
- University of Toronto (Canada)
- University of Tokyo/IPMU (Japan)
- West Chester University (USA)

Cerro Toco Site

5200 meters near peak of Cerro Toco,
in the Atacama Desert in the Andes of Northern Chile

23° south latitude.

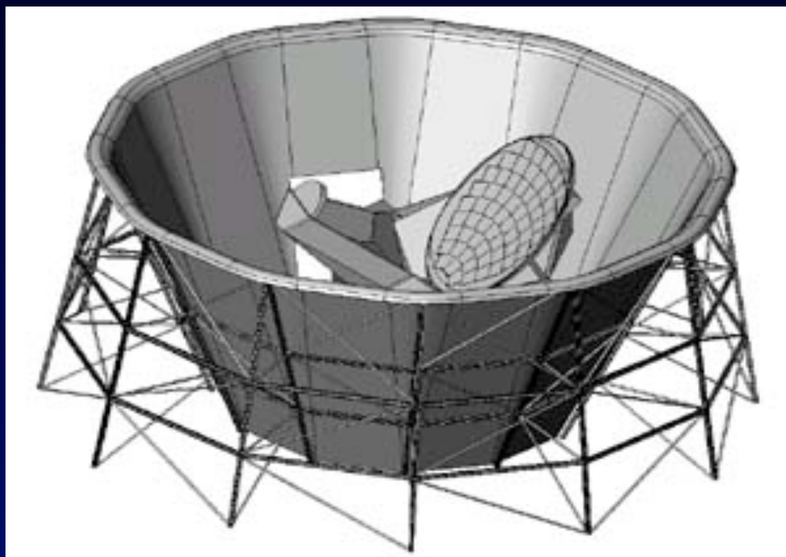


Joe Fowler—CEA Saclay 2010

INSTALLATION: EARLY 2007



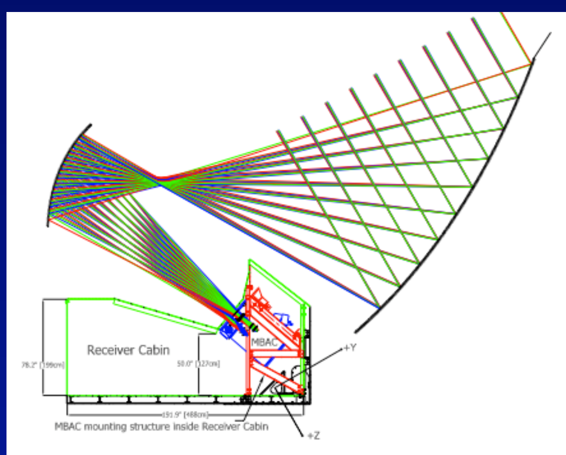
TELESCOPE



Some constraints:

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

Roughly an aplanatic Gregorian.



Measuring the 71 facets of 6 m primary

25-30 µm rms surface accuracy

CRYOSTAT

Cylindrical, axis aimed at secondary

No consumable liquid cryogens

Pulse Tube Coolers:

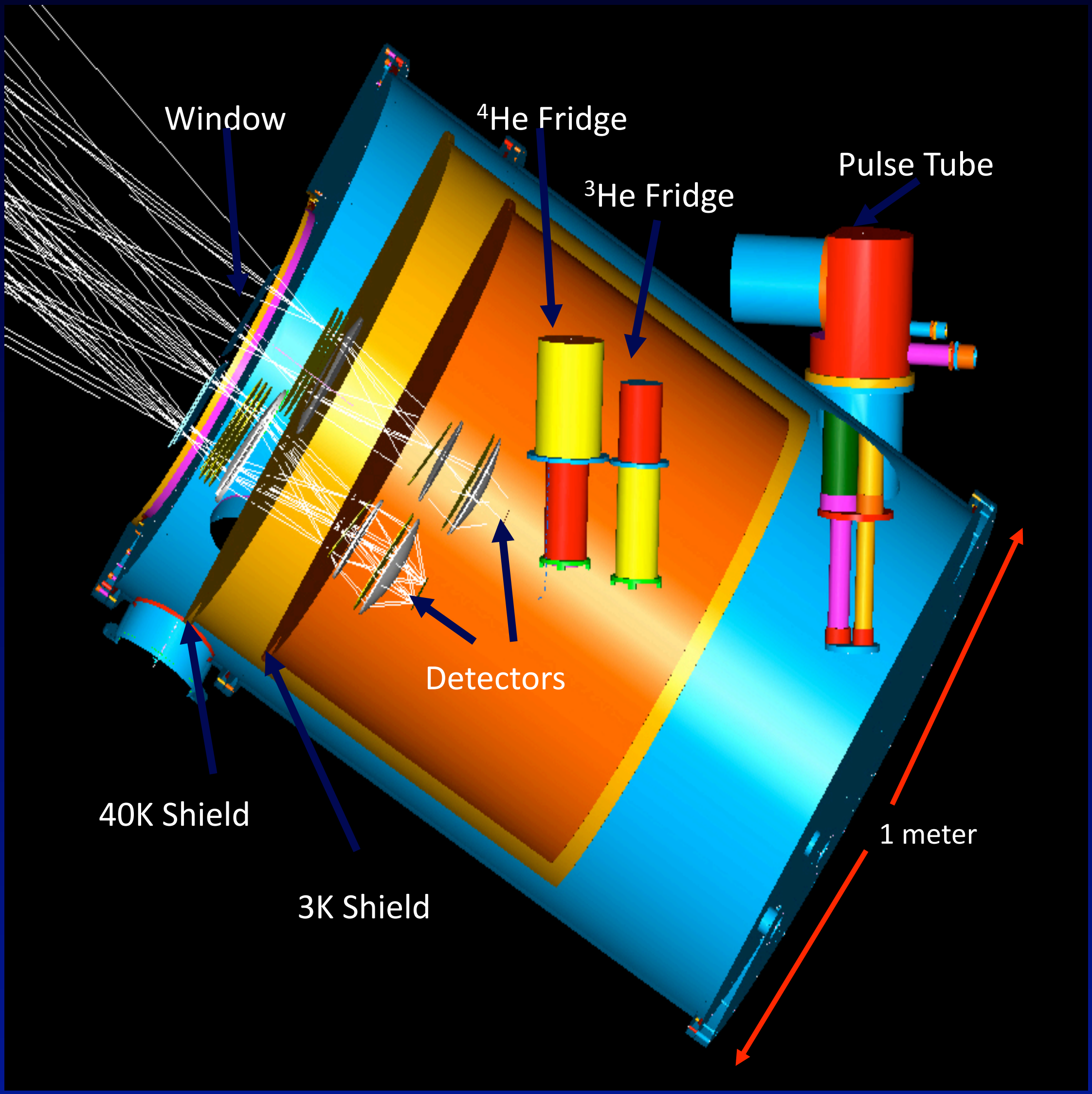
- 1^{st} stage: 30W @ 40K
- 2^{nd} stage: 0.2W @ 3K

^{4}He+^{3}He sorption fridges

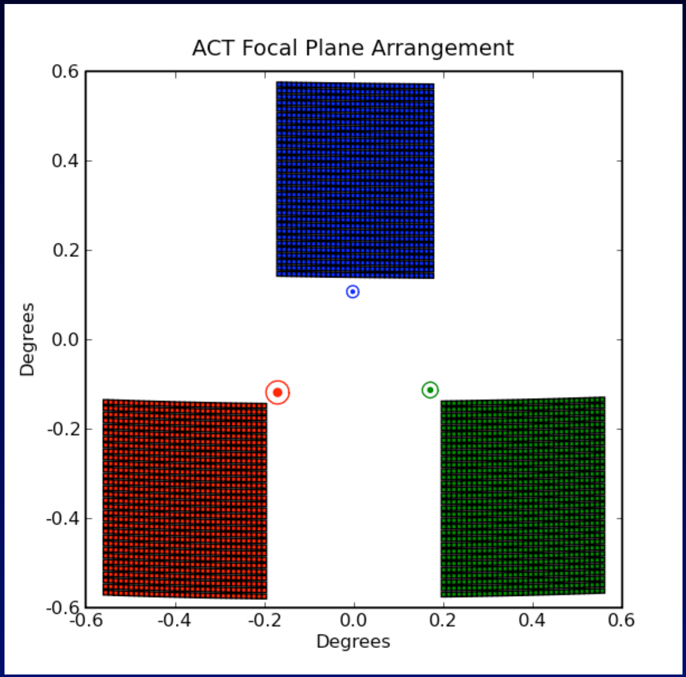
- 270 mK
- Cold all night

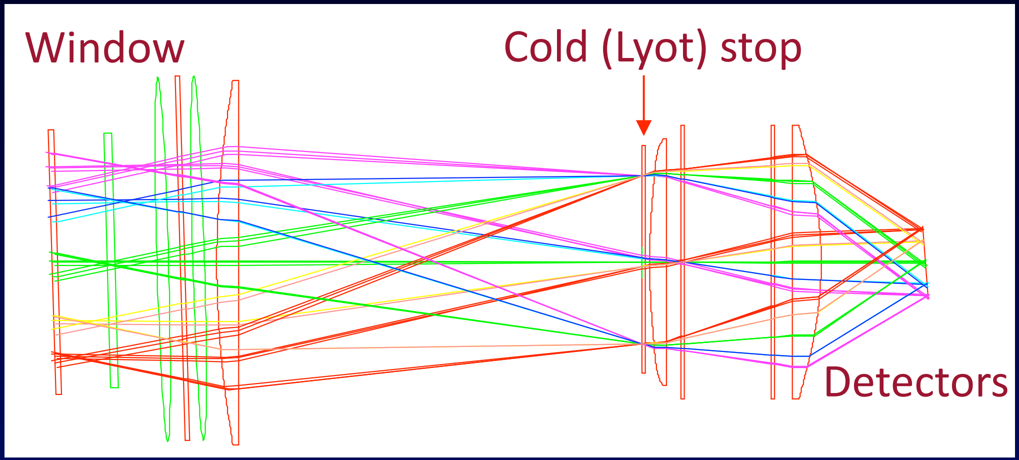
Cold silicon lenses reimage sky

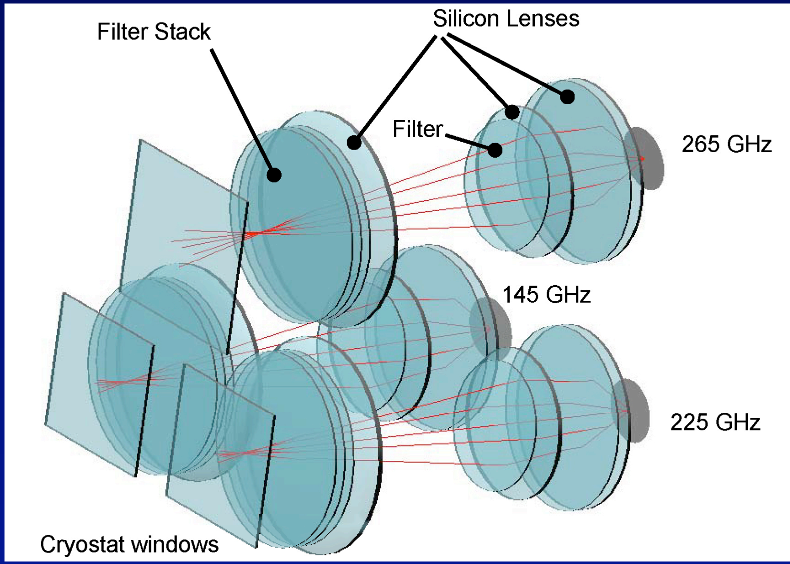
145, 215, 280 GHz filters (Cardiff)



Cryostat and Cold Silicon Optics

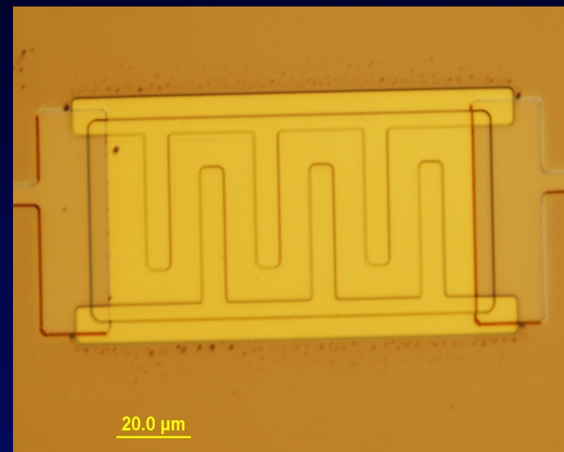






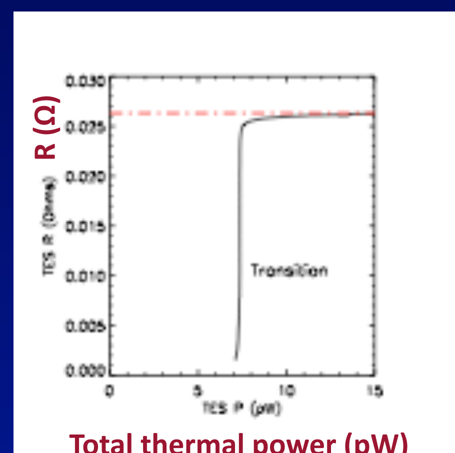
TRANSITION EDGE SENSOR BOLOMETERS (GSFC)

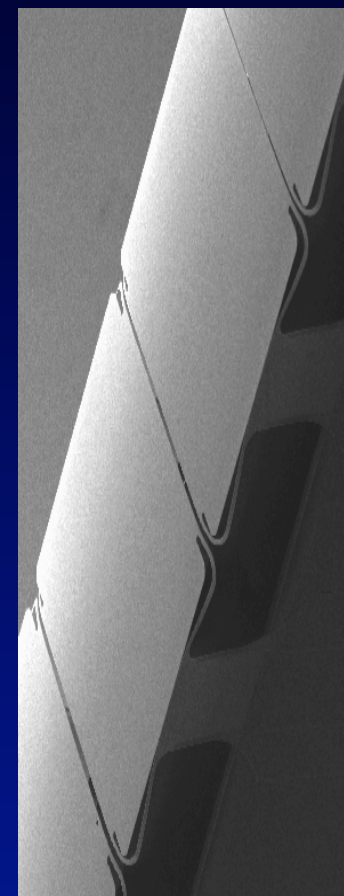
One absorber (Si) with TES



One TES (Au+Mb)

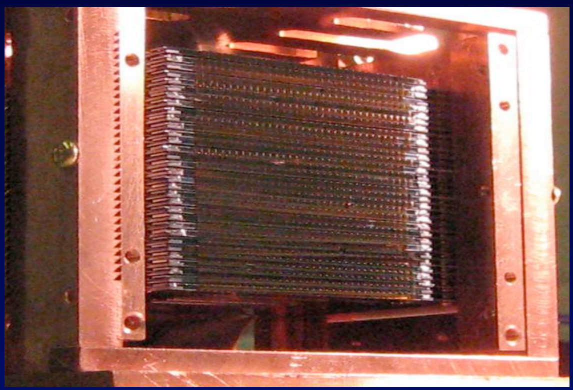
- 1 mm square absorber (silicon with implant)
- No feed horns
- Pop-up geometry; build focal plane one “column” at a time (32 columns of 1 x 32)
- Transition edge sensor (TES) held on transition at T_c=0.45 K



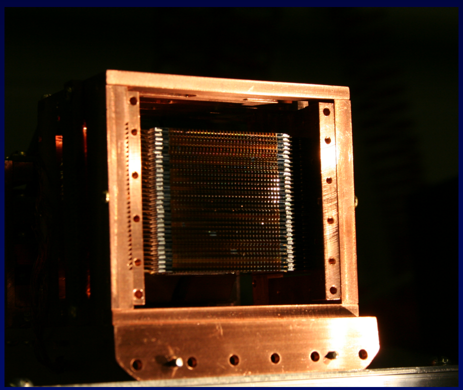


Three TES Arrays: 3072 detectors

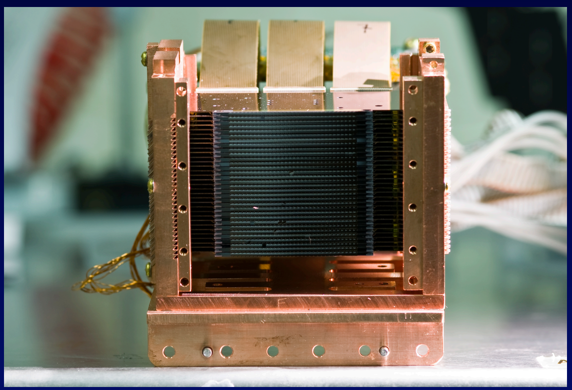
2007: 1000 x 150 GHz
2008: 1000 x (150 & 220 & 280 GHz)



150 GHz



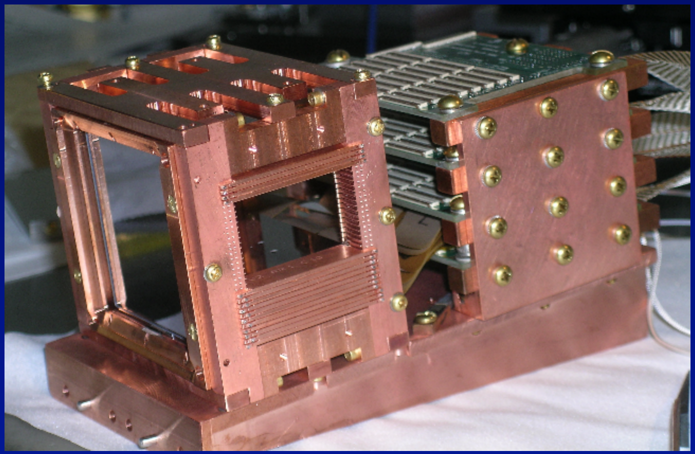
220 GHz

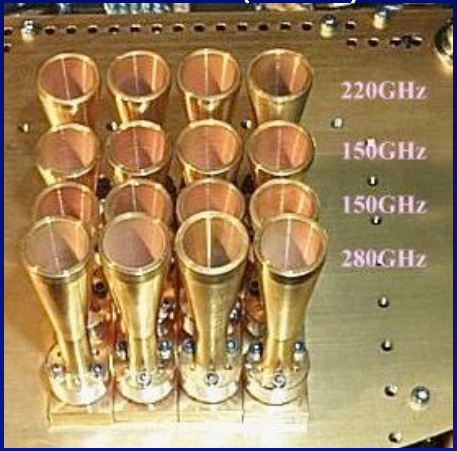


280 GHz

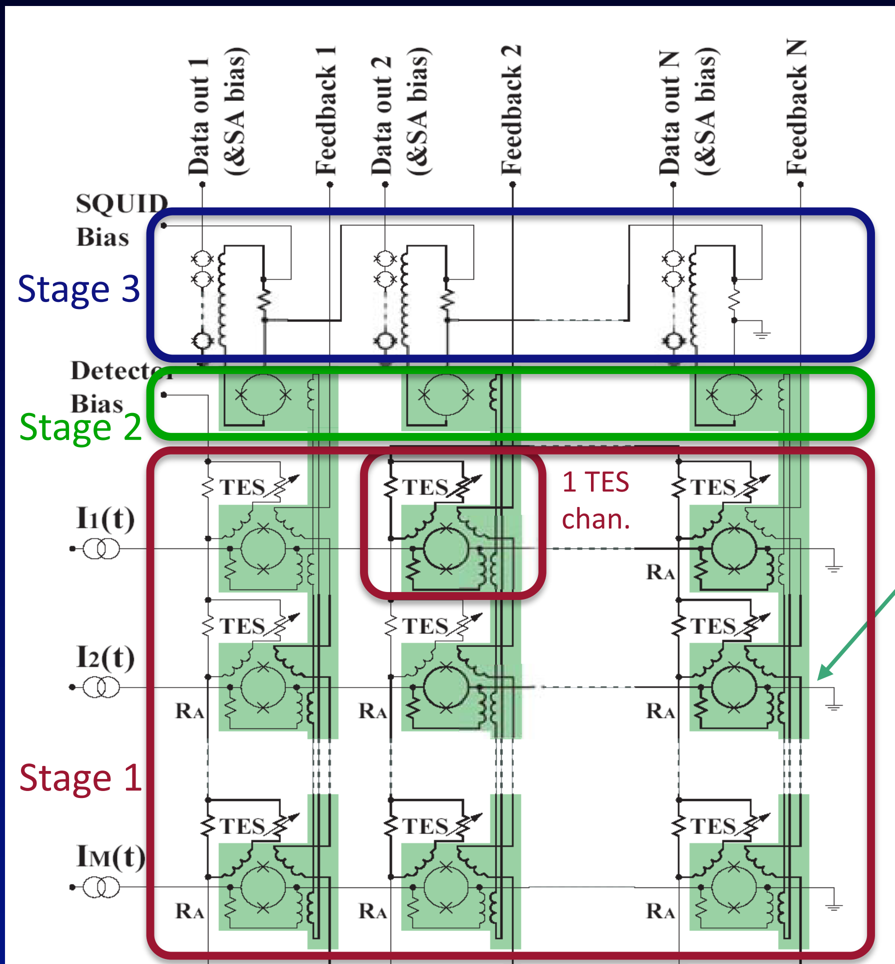
ACBAR (2005)

High-ρ silicon “coupling layer” is mounted some ~50 μm above absorbers.





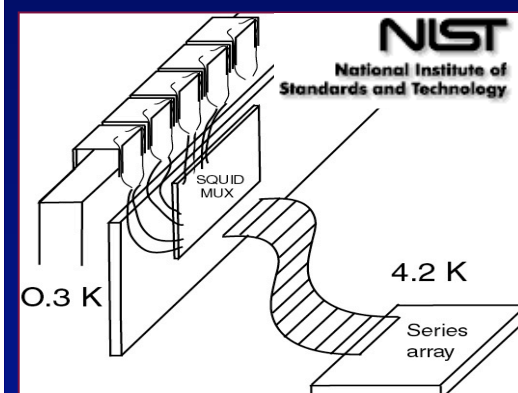
Time-Domain Multiplexing with SQUIDs (NIST)



Figures Courtesy of NIST/Boulder

- 3 stages of SQUIDs
- Feed 1st SQUID output current into a 2nd SQUID many-to-one.
- Turn on only one of the many at a time.
- 2 µs on, 64 µs off.
- Cycle the 33 inputs before L/R time.

Green parts = One MUX chip per TES column.

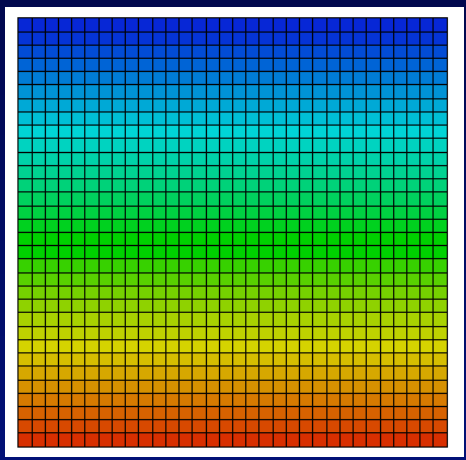


Multi Channel Electronics

Observing Strategy

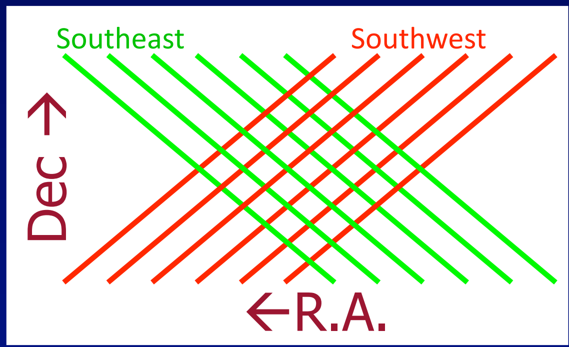
Observe [20:30-09:00 local] =

- Scan ~5° range each 10 sec
- Southeast (or NE) for ½ night
- Southwest (or NW) afterwards
- 10 minutes for a planet most nights



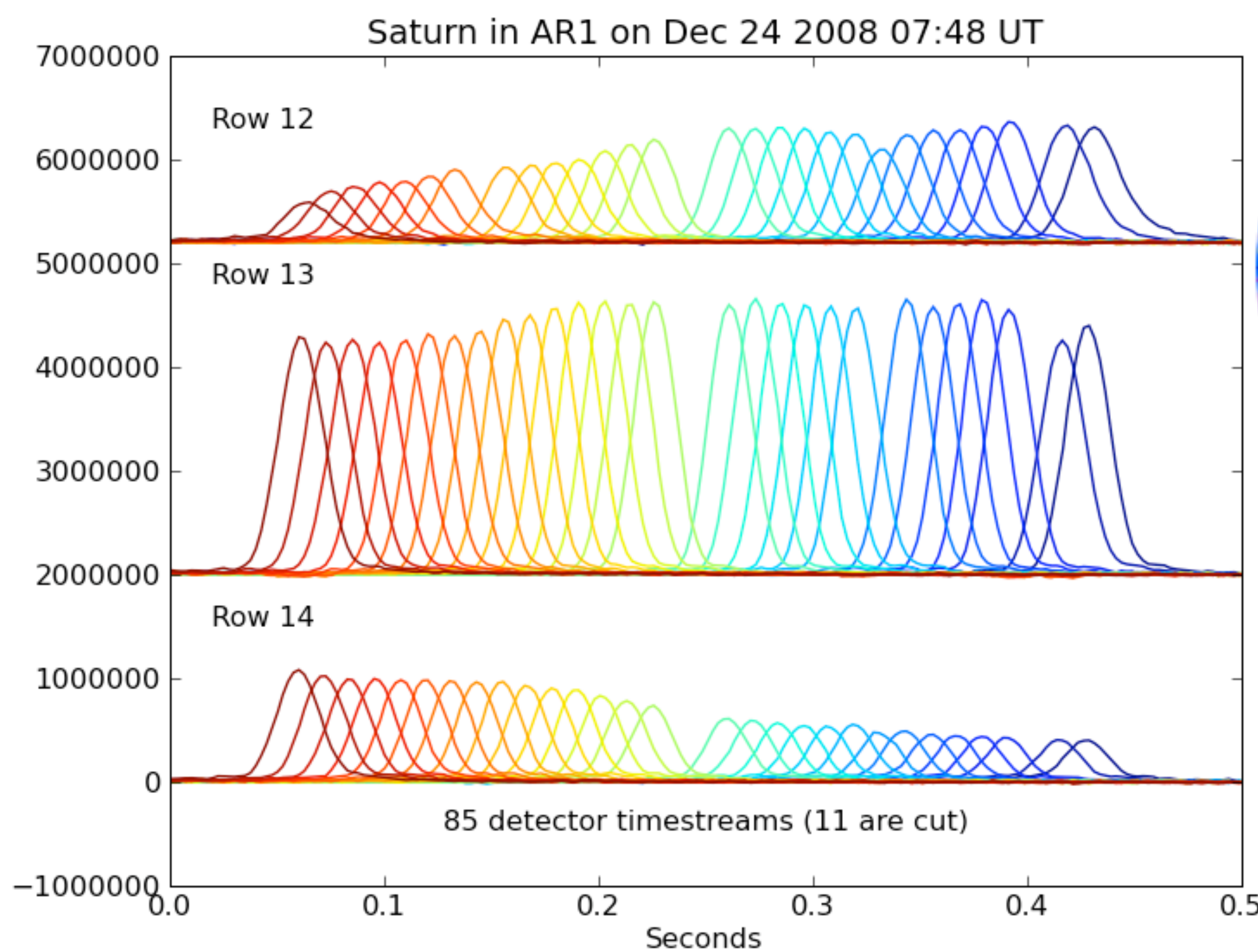
Atmosphere causes gradient on the sky ~60-100 mK

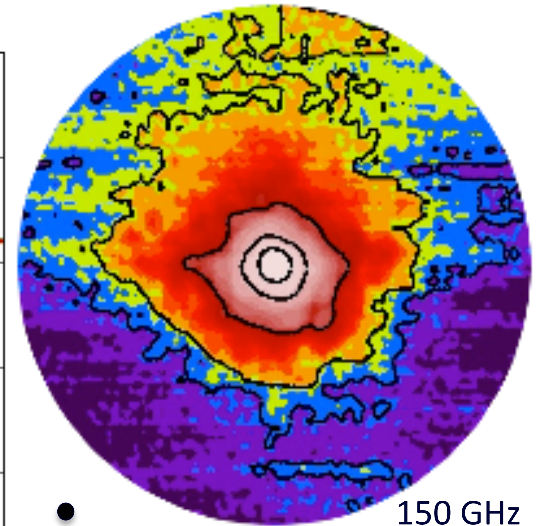
ACT approach: Scan at constant elevation

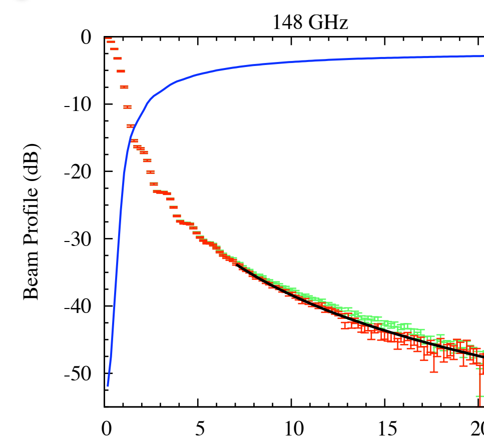


Each spot observed in 2 distinct stripes: before and after meridian crossing

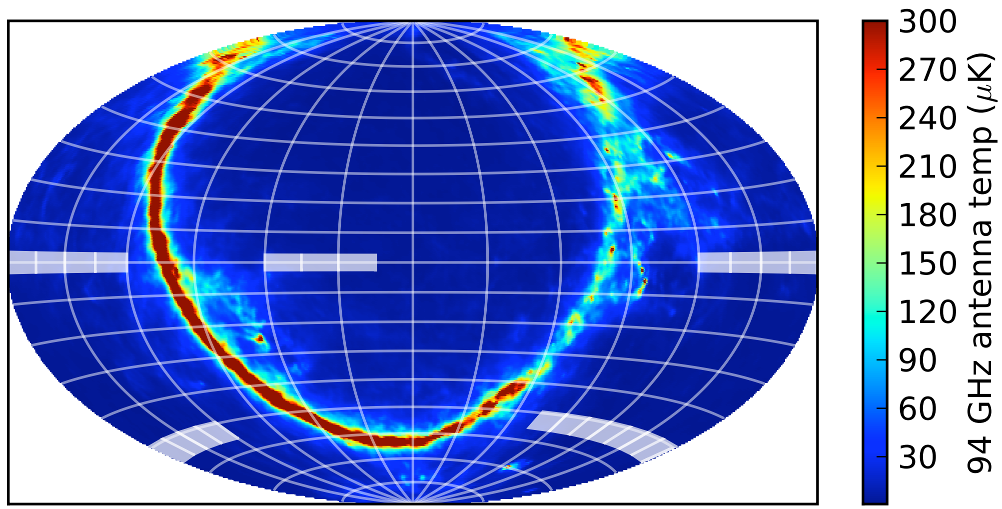
ONE-HALF SECOND SCANNING ACROSS SATURN



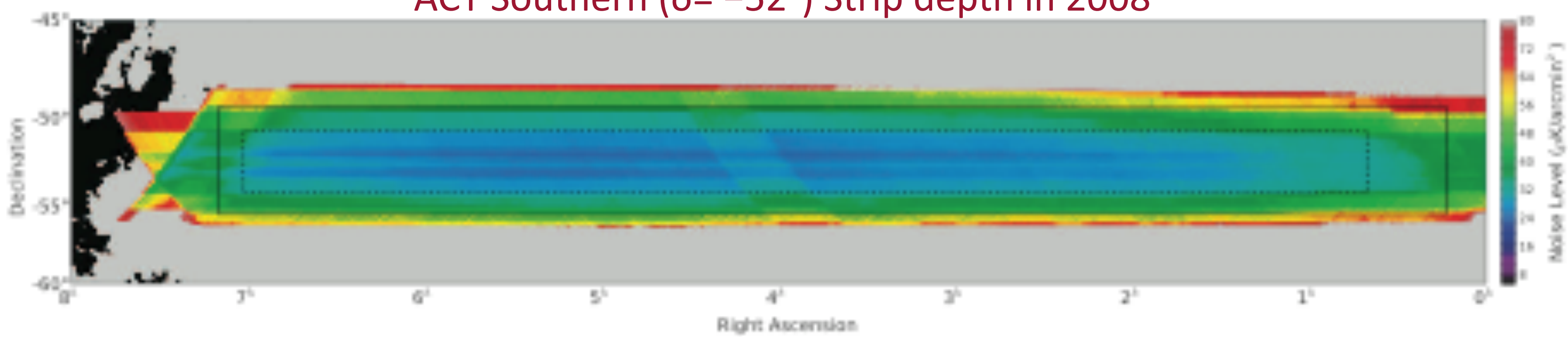




Observed Regions



ACT Southern (δ= −52°) Strip depth in 2008

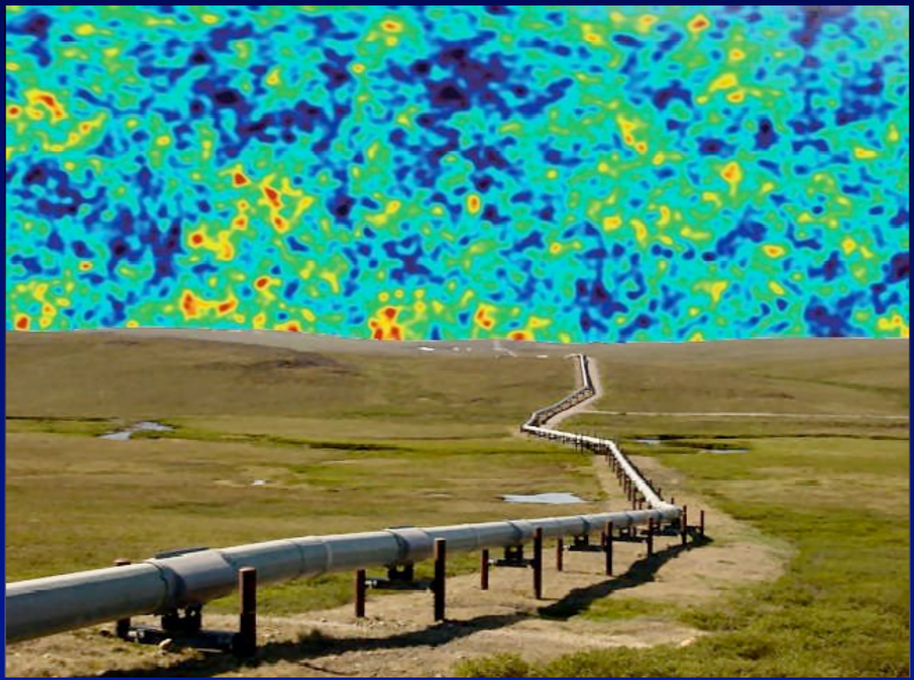


Noise level (0-80 μK color scale) Black=Galactic dust region

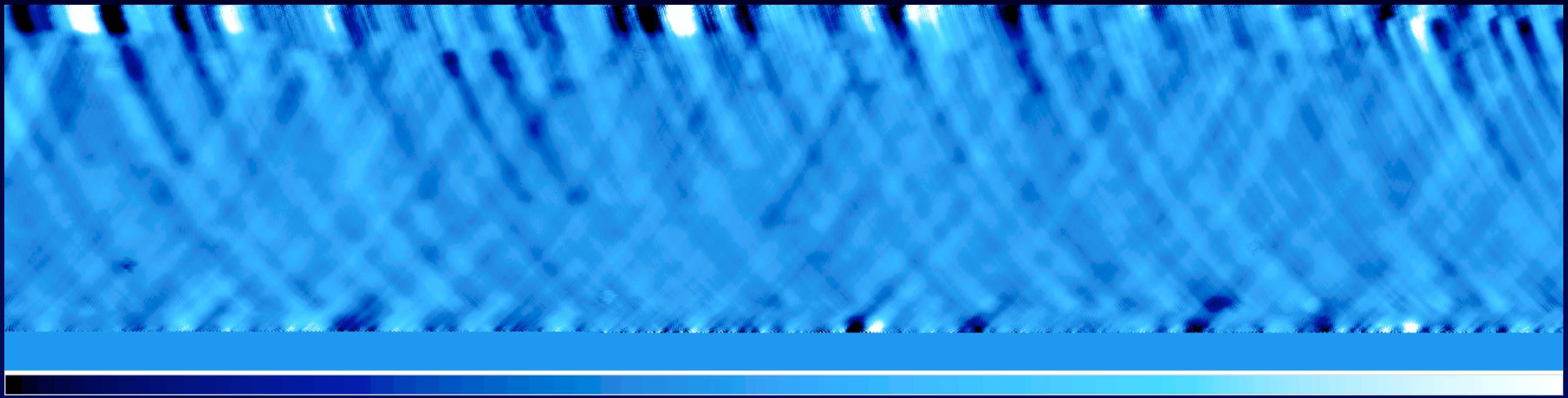
ACT RAW DATA SET

- The data are the stage1 SQUID feedback values, causally filtered by a DSP to prevent aliasing above f_{Nyq}=200 Hz.

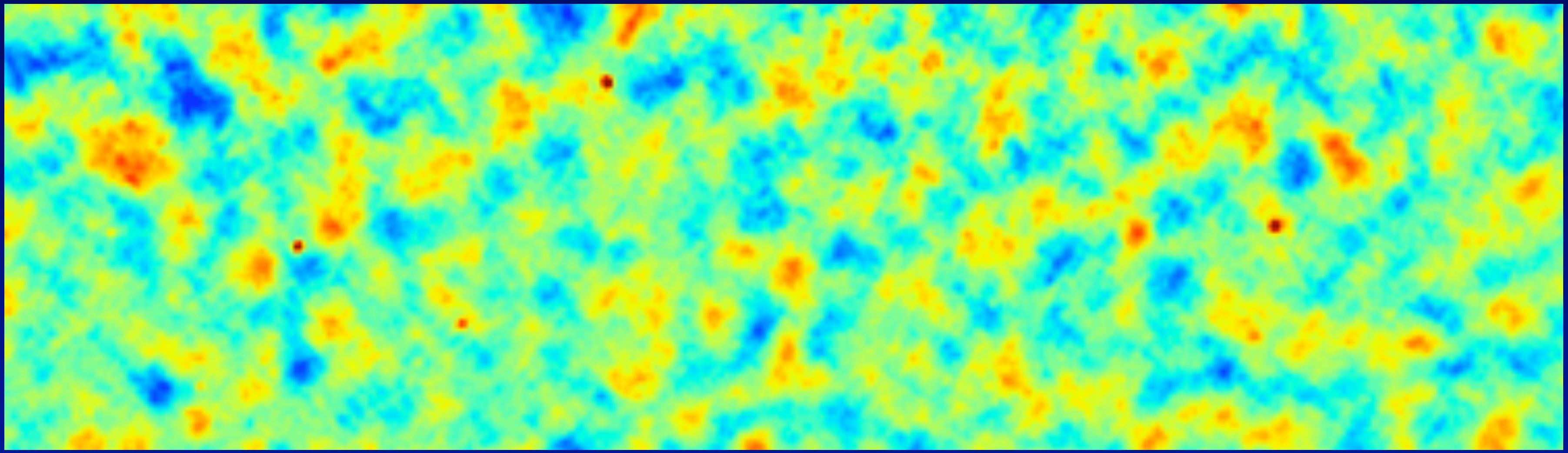
- 3 arrays * (32x32 detectors) * (400 Hz samples) * (4 bytes each) →
  19 GB raw data per hour! (6 GB with lossless compression)
- Over 2 TB per month for a single copy of raw data.
- Transport protocol: HDOA



Straightforward Mapping is not Enough



The simplest kind of map produces stripes parallel to the scan(s)
…. So how do you get from there to here?



Maximum Likelihood Maps

Mapmaking equation:

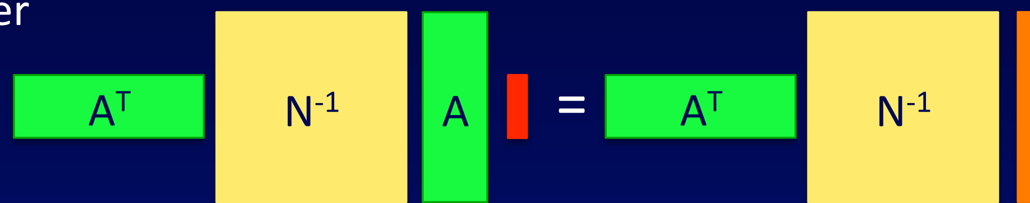
$$A^T N^{-1} A\, m = A^T N^{-1} d$$

d = raw data set (>10×10^9 per array per night)

m = desired map (30×10^6 per array)

N = noise covariance between data

A = pointing matrix



If N were diagonal, this would be an $O(n)$ process:

$N^{-1} d$ would be the weighted data set

$A^T N^{-1} d$ would map the weighted data set

$A^T N^{-1} A$ would be the total weight per map pixel

→ Generalizes the idea of weighted means

But N is not diagonal!

1. Detectors have non-white noise
2. Any mech/elec coupling in camera
3. ATMOSPHERE

ACT APPROACH TO THE MAPPING PROBLEM

Our goal: converge to a maximum likelihood map.

Mapmaking equation:

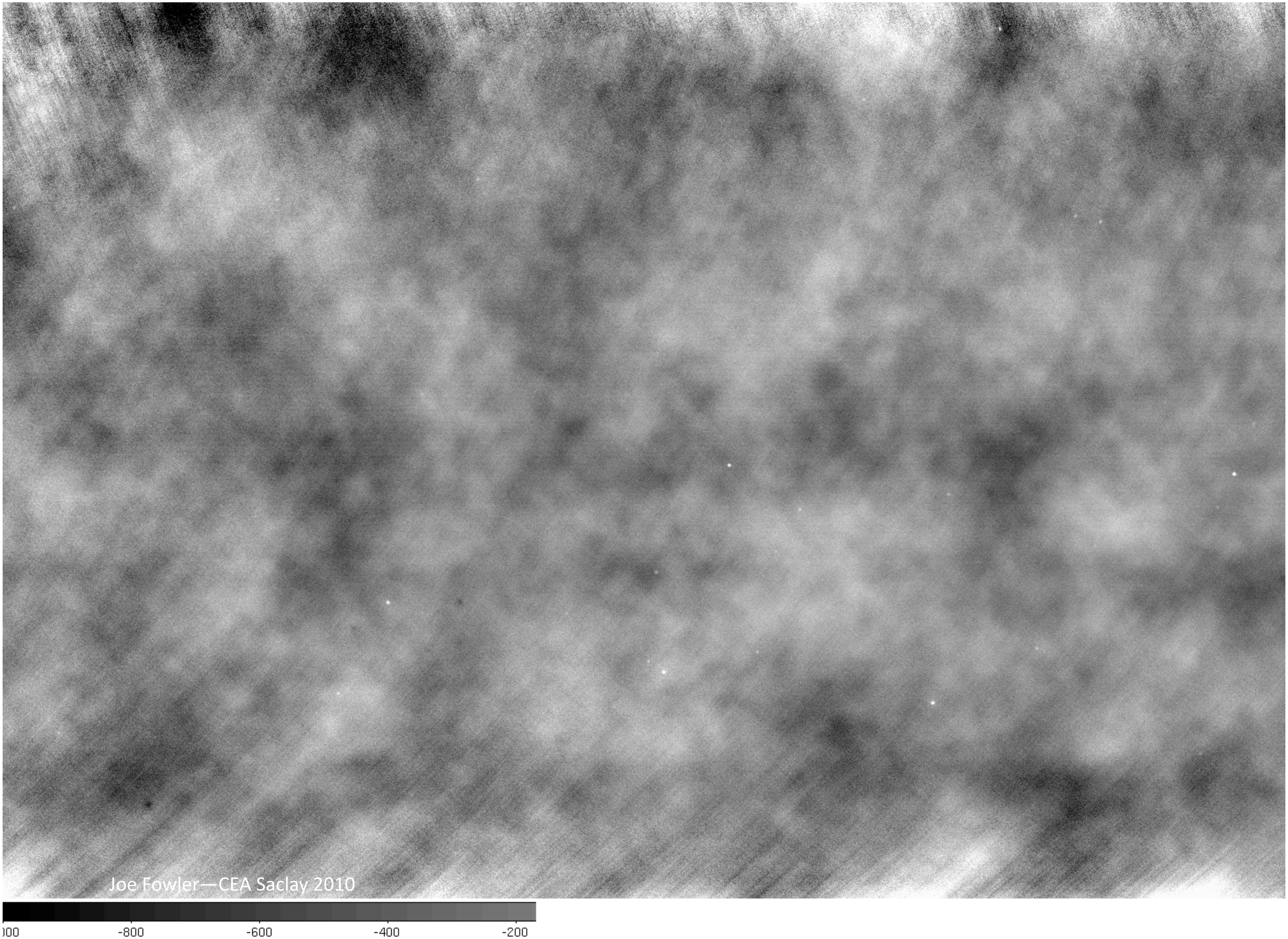
$$A^T N^{-1} A\, m = A^T N^{-1} d$$

How to approximate *m* without losing information?

- Work on N in Fourier space
- Pre-conditioned Conjugate Gradient solver
- Find/remove noisy modes (common mode+others).
- Recover low-ℓ sky modes iteratively.

Final calibration to WMAP maps is underway. It follows:

- Pointing
- Time constants
- DAC→pW
- Flat field
- Atmosphere loss
- Load-dependent correction
- Beam
- Uranus and Saturn amplitudes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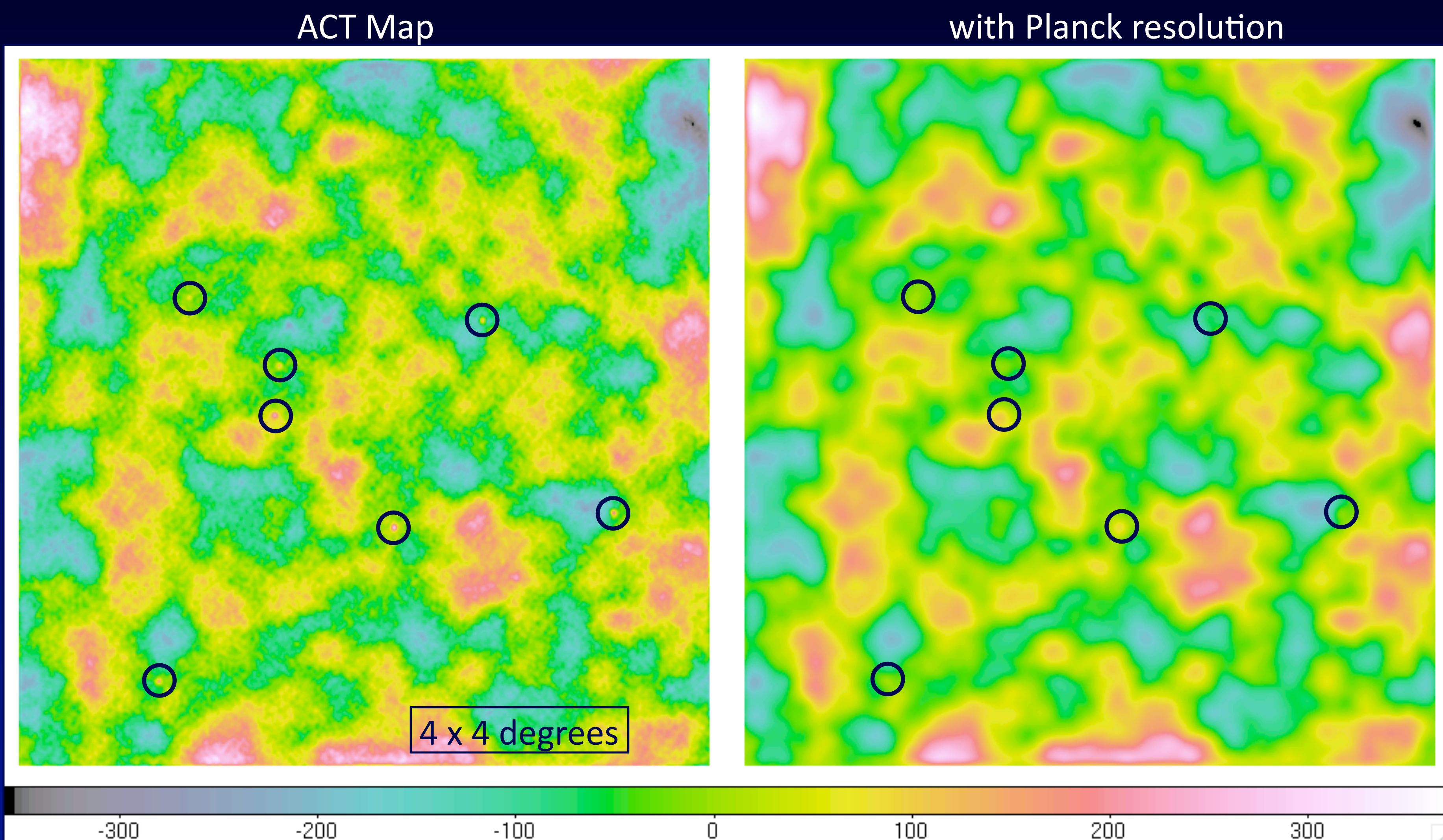
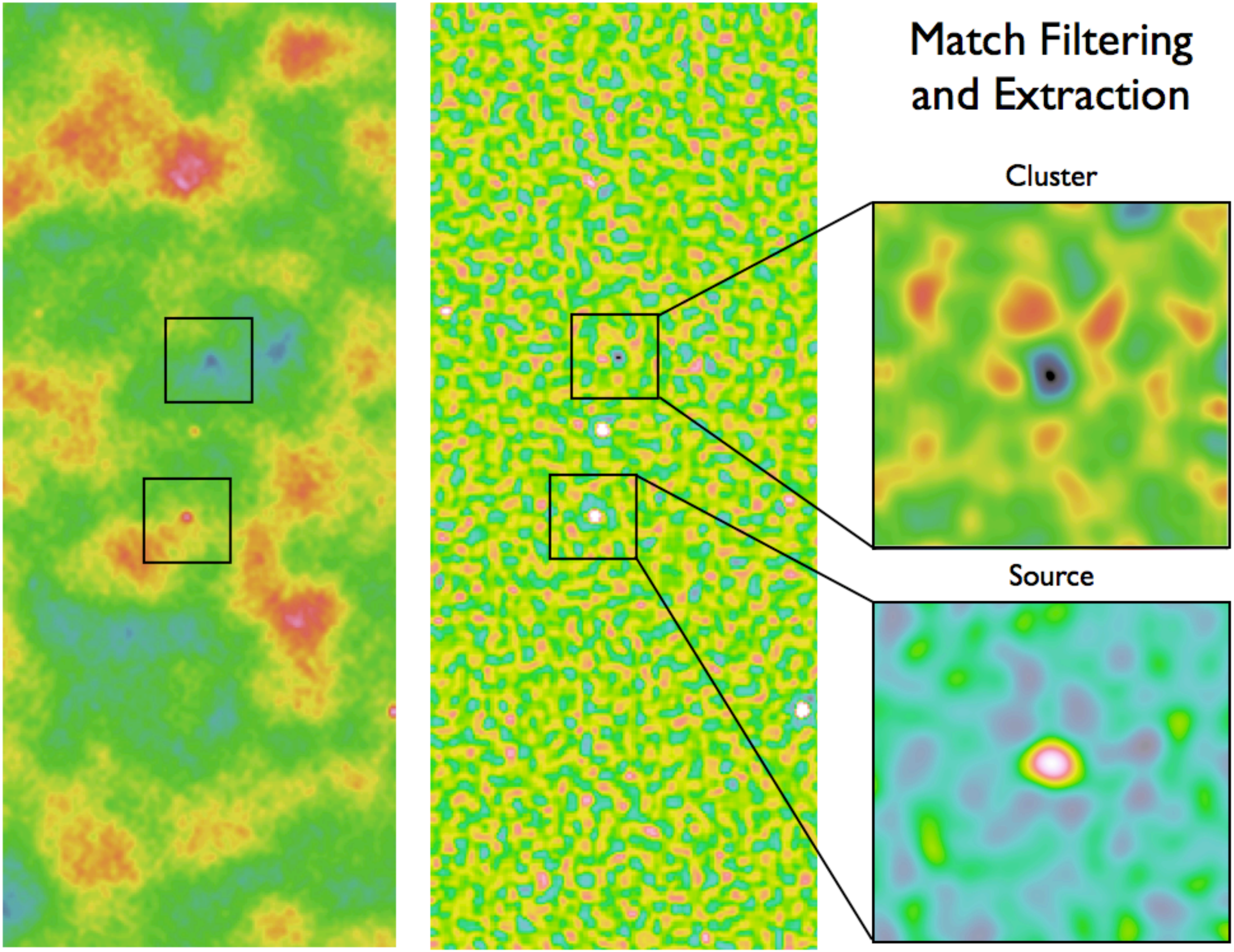
)00
-800
-600
-400
-200

DISCOVERING CLUSTERS AND POINT SOURCES



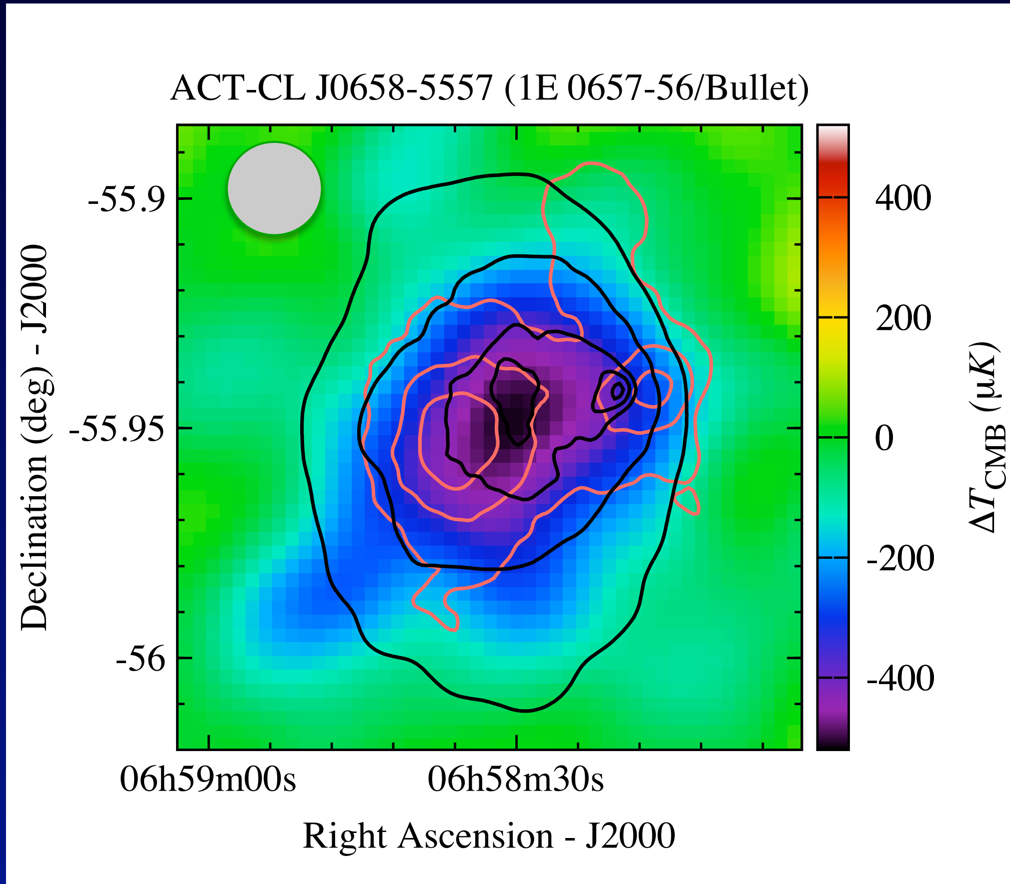
Match Filtering and Extraction



BULLET CLUSTER (1E 0657-56)

Color: ACT 145 GHz map
Black contours: Chandra 0.5-2 keV
Orange contours: dark matter
Gray disk: ACT filtered beam (2.4')

Composite Credit:
X-ray: NASA/CXC/CfA/M. Markevitch et al;
Lensing Map: NASA/STScI; ESO WFI; Magellan/Arizona/D. Clowe et al
Optical: NASA/STScI; Magellan/Arizona/D.Clowe et al.

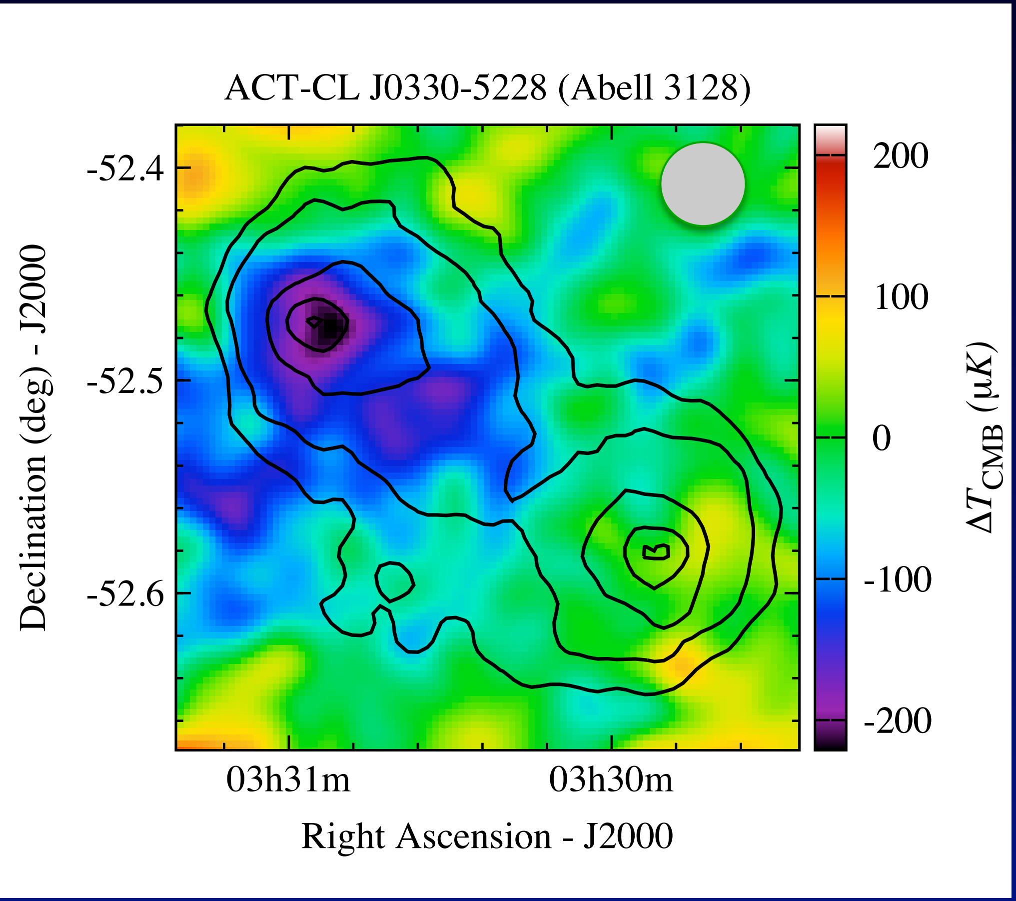


Abell 3128

NE: separate cluster $z = 0.44$.
X-ray: 5 keV

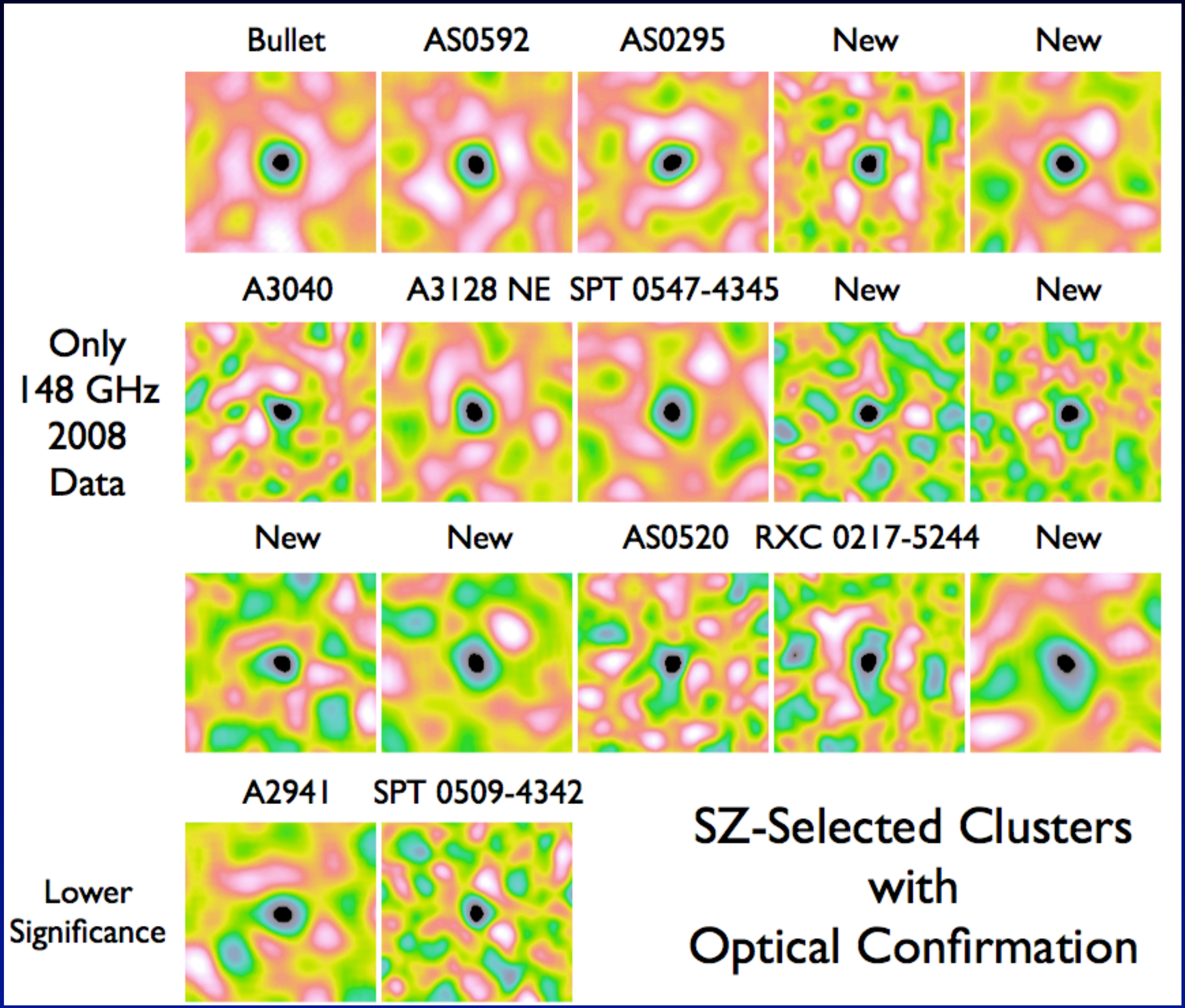
Contours: XMM-Newton
100 ks (mosaic)
Color: ACT 145 GHz map

Nice illustration of the redshift-independence of SZ



SW: Horologium-Reticulum supercluster at $z = 0.06$.
X-ray: 3 keV.

15 Clusters Found in Blind Survey

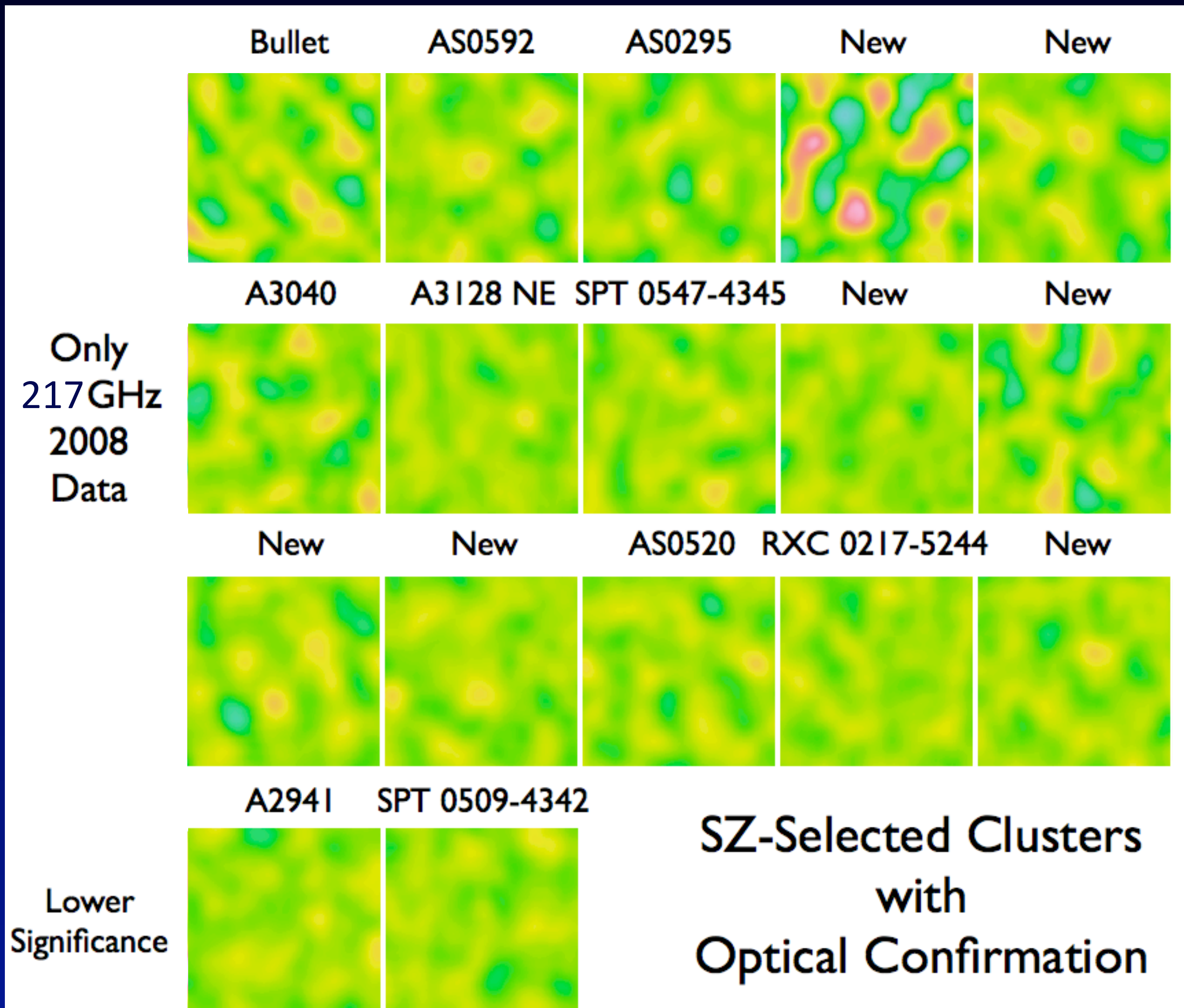


7 of 15 are new.

5 others never before seen in SZ.

Redshifts to known:
- 0.295 Bullet
- 0.222 AS0592
- 0.301 AS0295
- 0.167 A3040
- 0.440 A3128 NE
- 0.88 SPT 0547
- 0.295 AS0520
- 0.343 RXC
- 0.118 A2941
- 0.45 SPT 0509

Same 15 Clusters at 217 GHz



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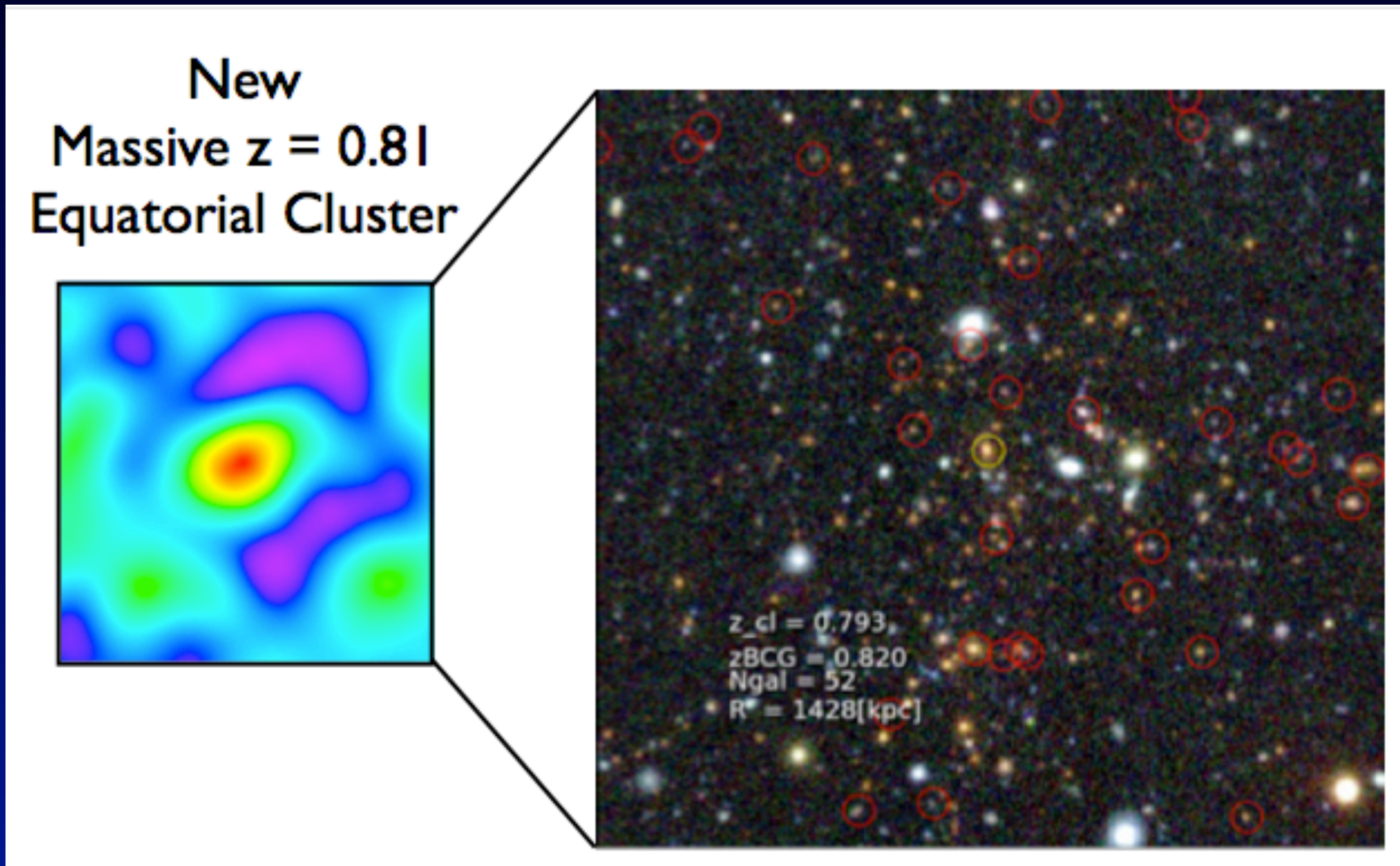
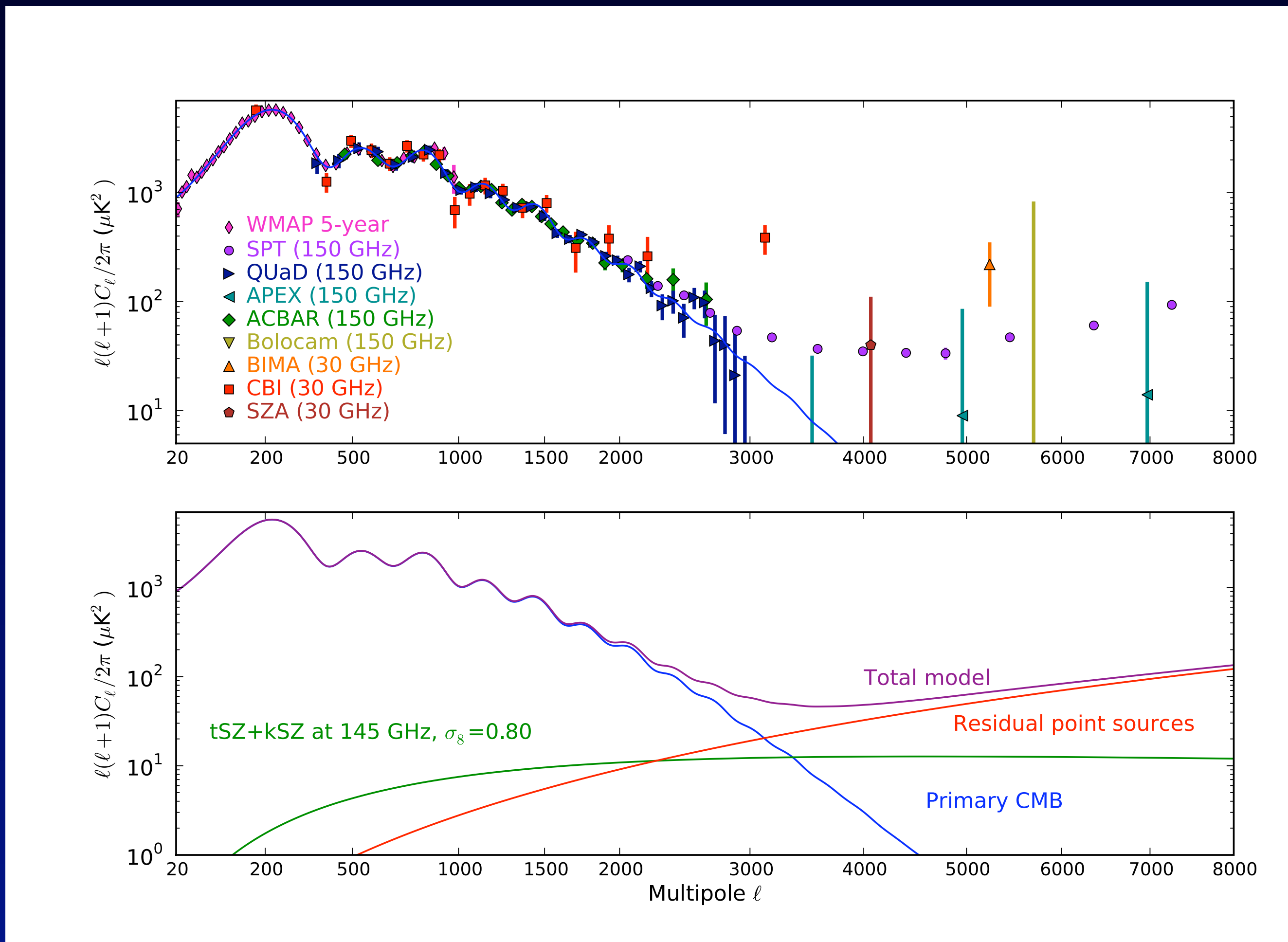
- 0.88 SPT 0547
- 0.295 AS0520
- 0.343 RXC
- 0.118 A2941
- 0.45 SPT 0509

Optical Follow-up is Underway



Power Spectrum: Current Goal

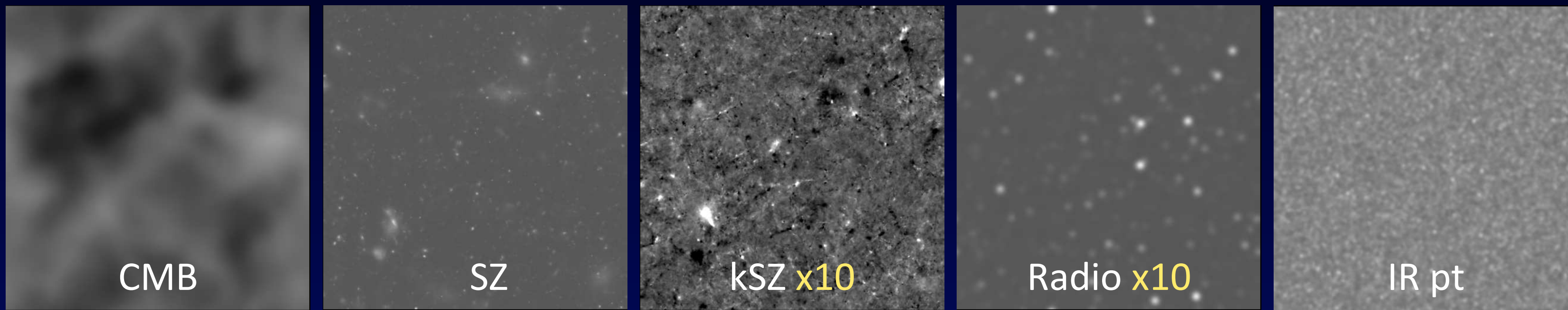


ACT aims to estimate the “total model” spectrum from 1000-8000.

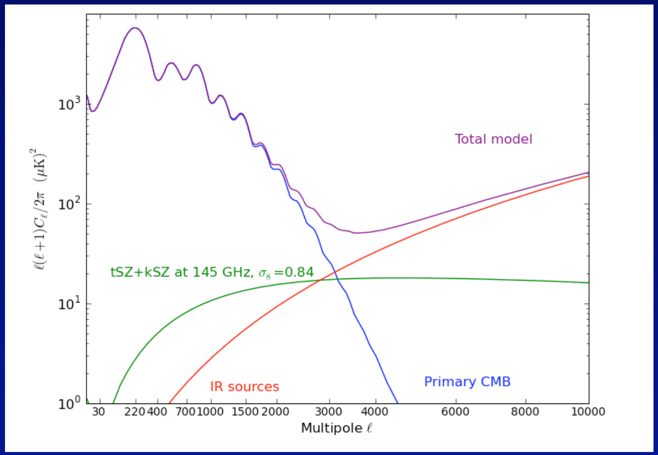
1. Inflation ℓ<3000
2. Total SZ
3. Dusty galaxies

With 220, 280 GHz, start to distinguish items 1, 2, 3.

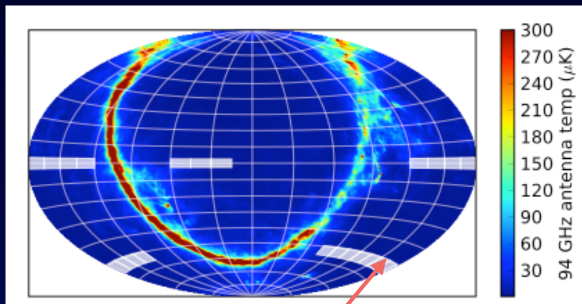
Power Spectrum Challenges



- Foregrounds include SZ clusters, radio galaxies, star-forming galaxies.
- Mapmaking: difficult to recover large-scale power.
- Source masks spread out power in the spectrum.
- Maps have edges.
- Partial correlation in source locations.



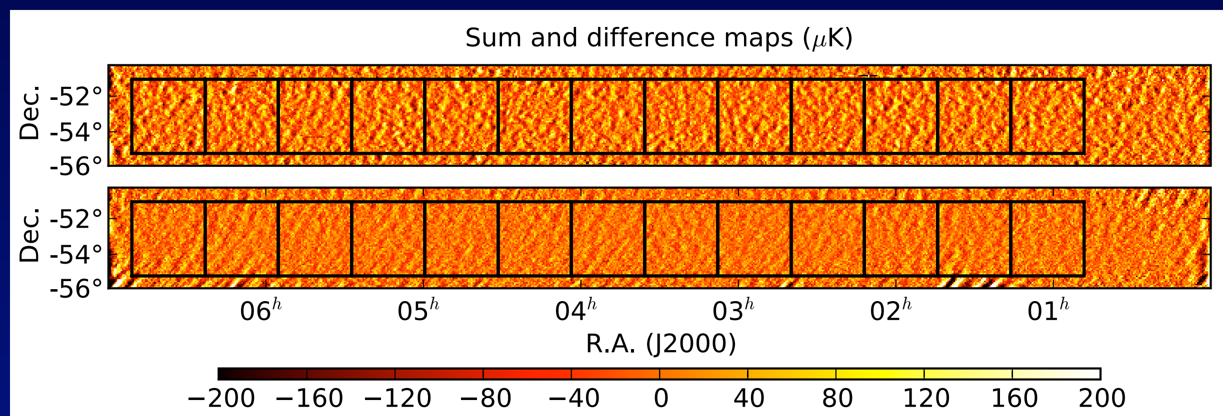
ACT Southern Field at 150 GHz

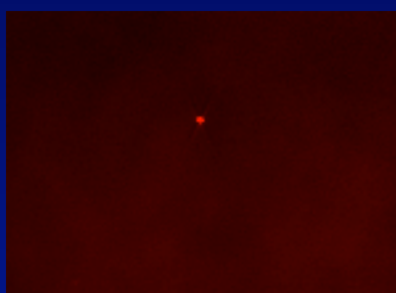


Top: full data set (filtered to remove ℓ<300 power)
Bottom: difference between halves of data

Separate maps into 13 patches of equal size, (nearly) equal weight.
4.2° × 4.2° squares → spectral resolution of 360°/4.2° ≈ 86

This analysis:
- 228 deg^2
- RA 1^h to 7^h,
- δ –55° to –51°,
- a low-dust area south of the Galactic plane.





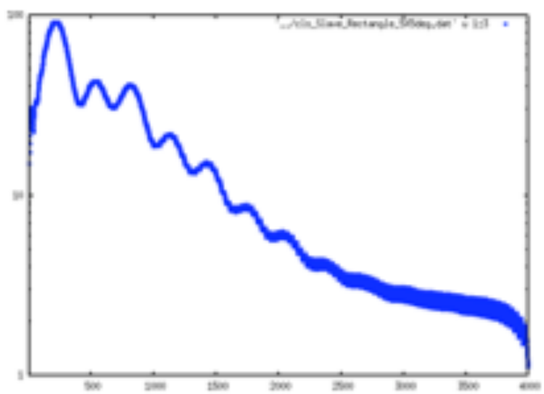
First, mask out 108 bright sources (105 are radio-identified)

Current data set: 2008 (Aug-Dec) at 150 GHz only. Not yet included:
- 2007 and 2009 data (1+7 months)
- 220 or 280 GHz data

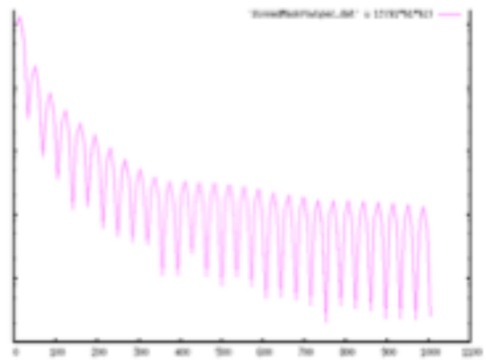
Mask Effects on the Spectrum

Observed Map = Mask * True map

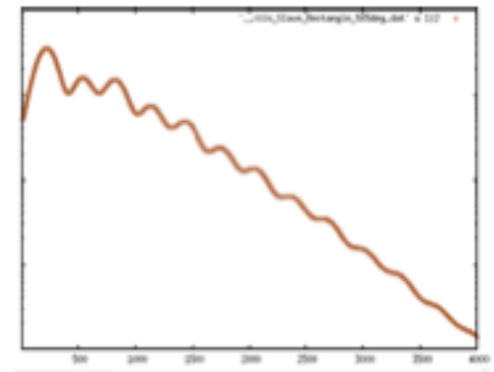
Observed FFT = FT(Mask) ⊗ FT(map)



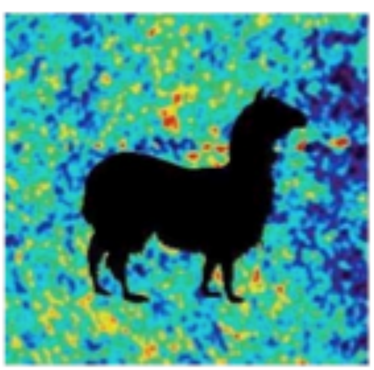
=



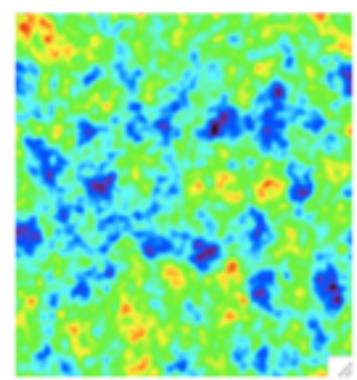
⊗



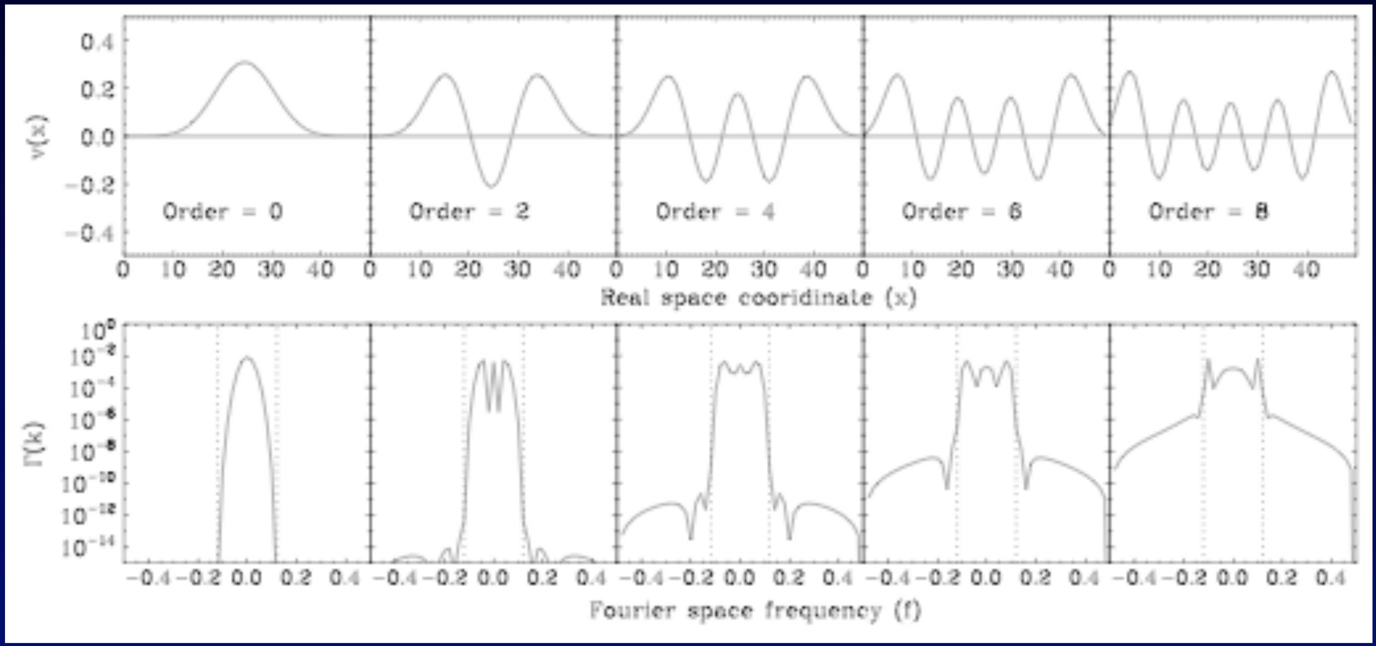
The inverse operation can be applied, but it increases high-k error bars.



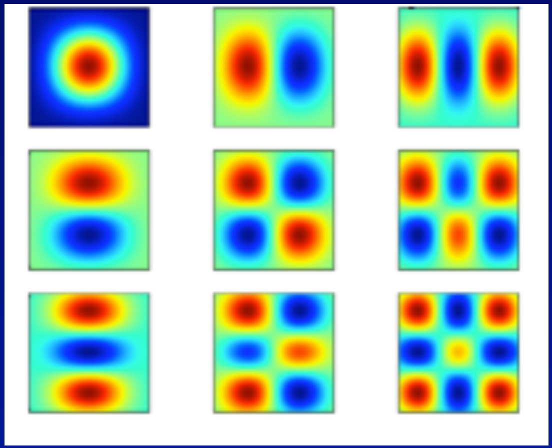
⊗ ()$^{-1}$ =



MULTI-TAPER METHOD TO MINIMIZE LEAKAGE

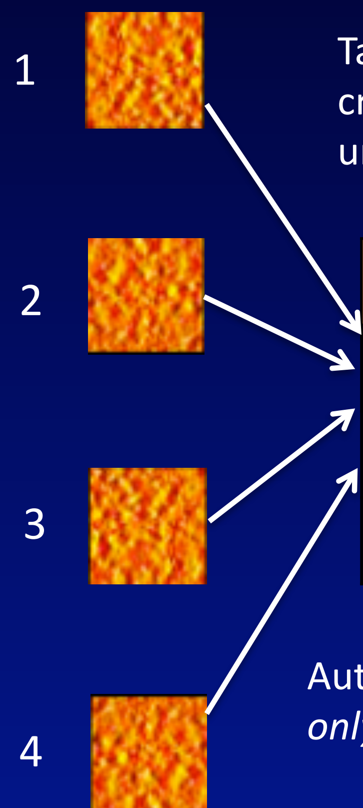


- Use the DPSS (above) in 2D (right)
- Multiple tapers to extract most info
- Prewhiten map to reduce ill effects of remaining leakage



Data are split into four parts for cross-spectra

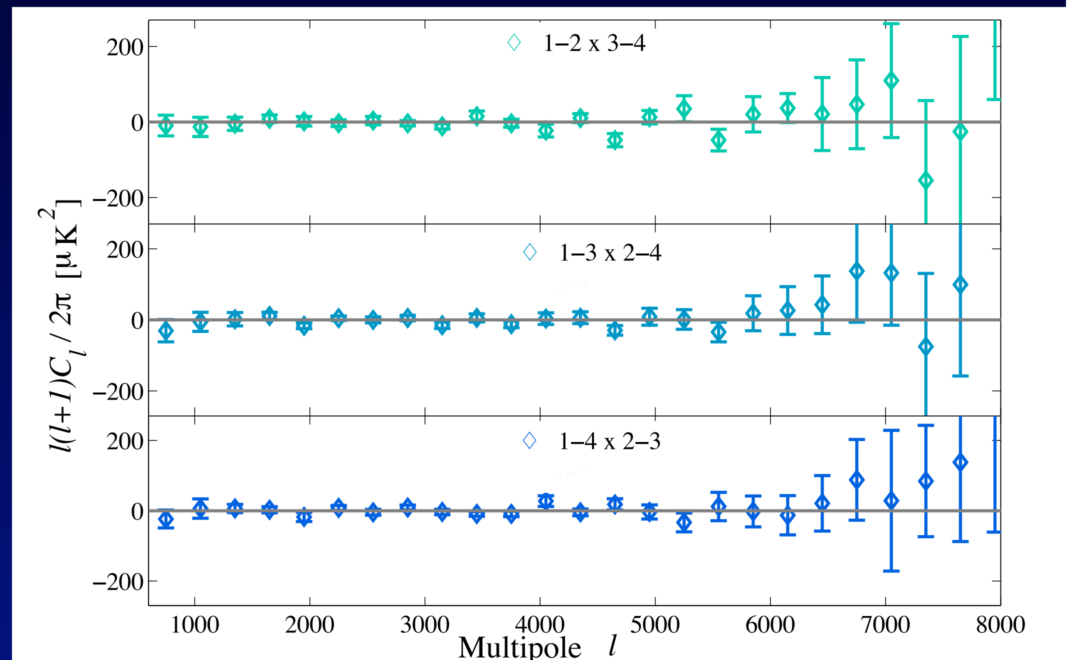
Region mapped
4x with ¼ of data:



Take all possible cross-products for unbiased spectra

11	12	13	14
21	22	23	24
31	32	33	34
41	42	43	44

Auto-spectra are used *only* to estimate noise



Splitting data into 4 also offers strong null tests.

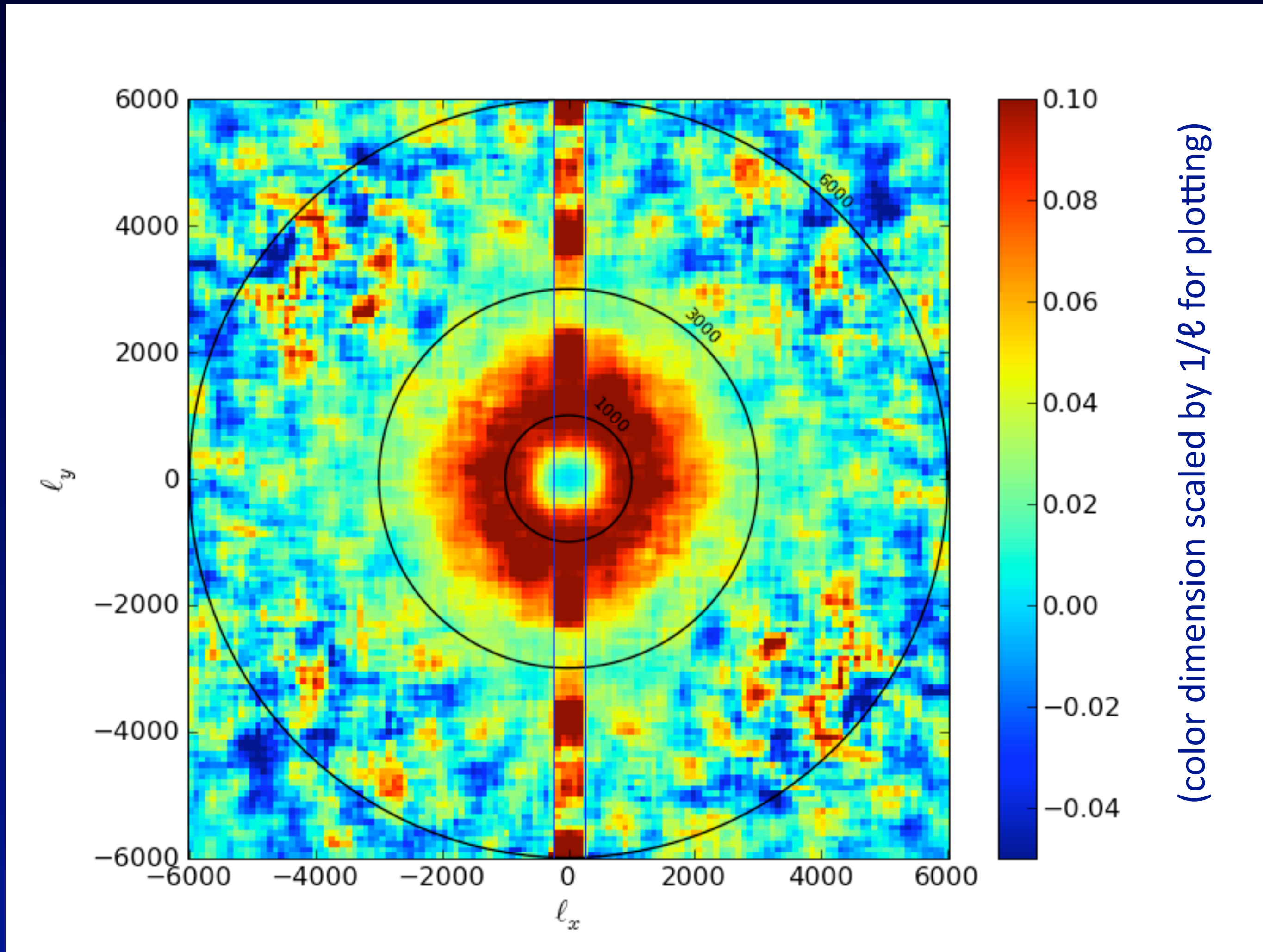
TWO-DIMENSIONAL POWER SPECTRUM

Multi-taper method with N_{res}=3 gives resolution of ~250 in ℓ

The entire data set, averaged over all 13 patches just for visualizing:

Narrow band of problems in $|\ell_x|<250$ due to stable scan-synchronous pickup.

Expedient: mask in ℓ-space.

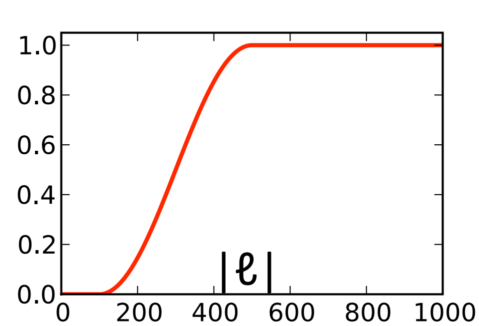


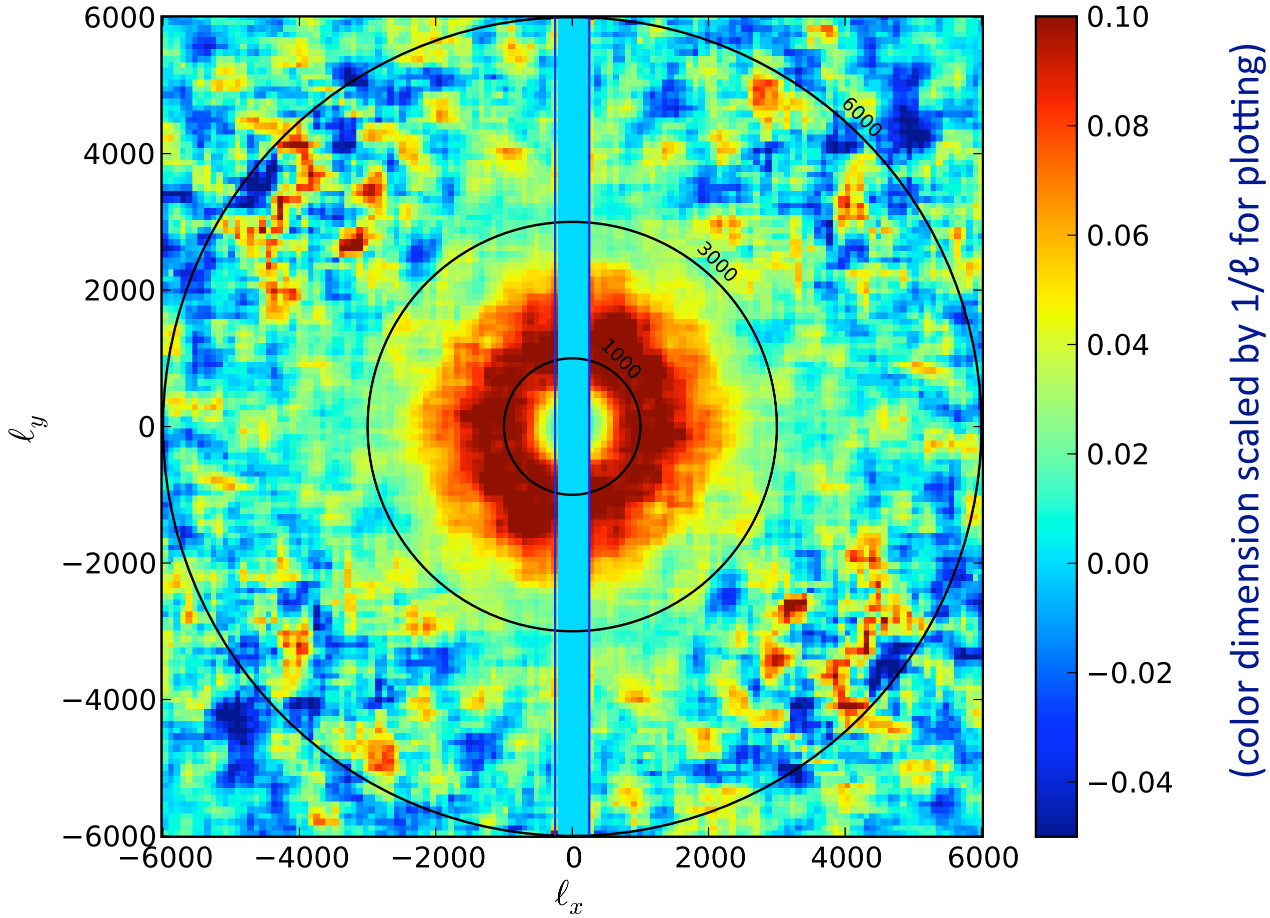
Two-dimensional power spectrum (masked)

Isotropy test in 2d ℓ-space:

- Noise: no
- Mean: yes

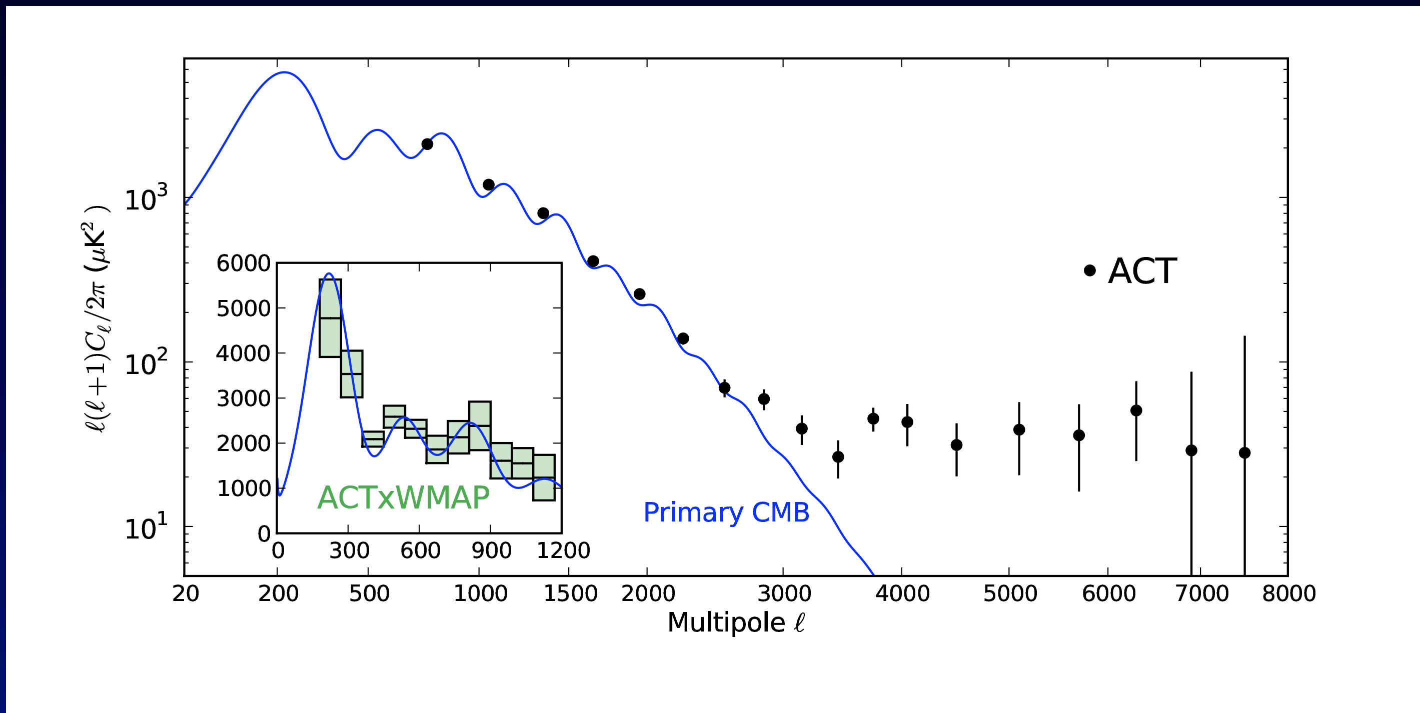
Filtered out lowest angular frequencies, |ℓ|<300:





Next step: annular averaging → 1d spectrum

ACT 150 GHz POWER SPECTRUM

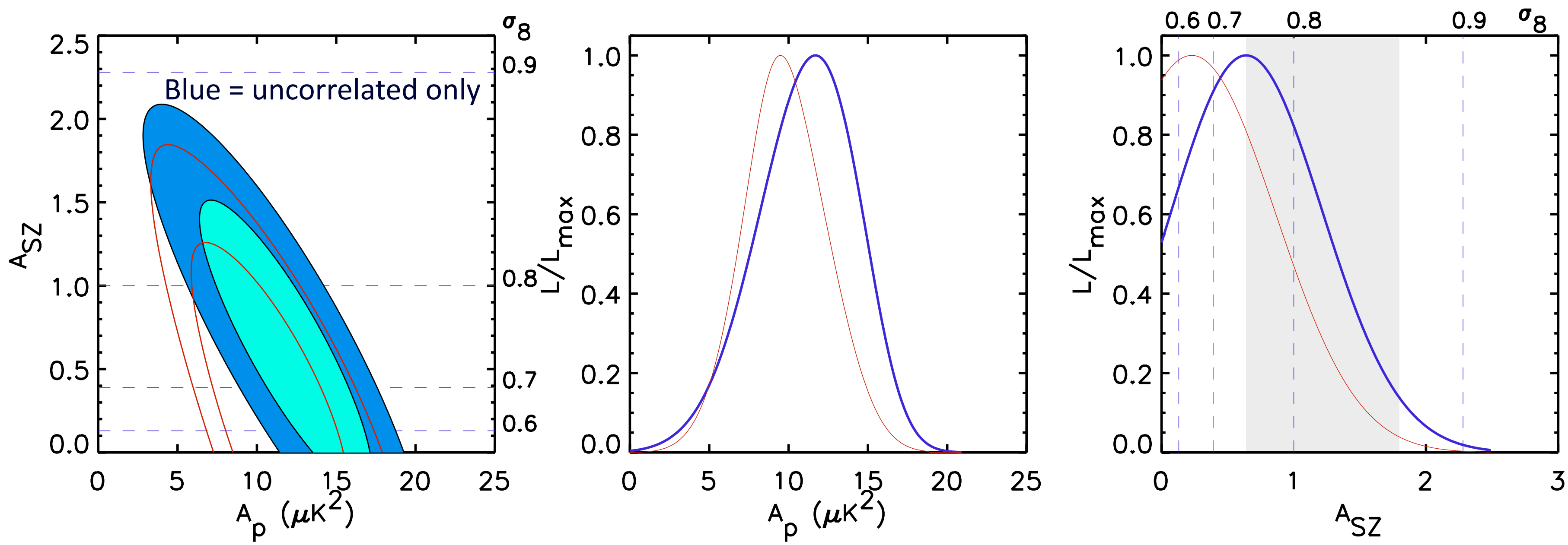


Cross-power with WMAP agrees with WMAP spectrum!

UNCERTAINTIES

- Analytic model for statistical errors
- Calibration to Uranus: 6% systematic from T_U (WMAP7 improves—and changes—this)
- Calibration to WMAP most promising for future work: expect 3% or better.

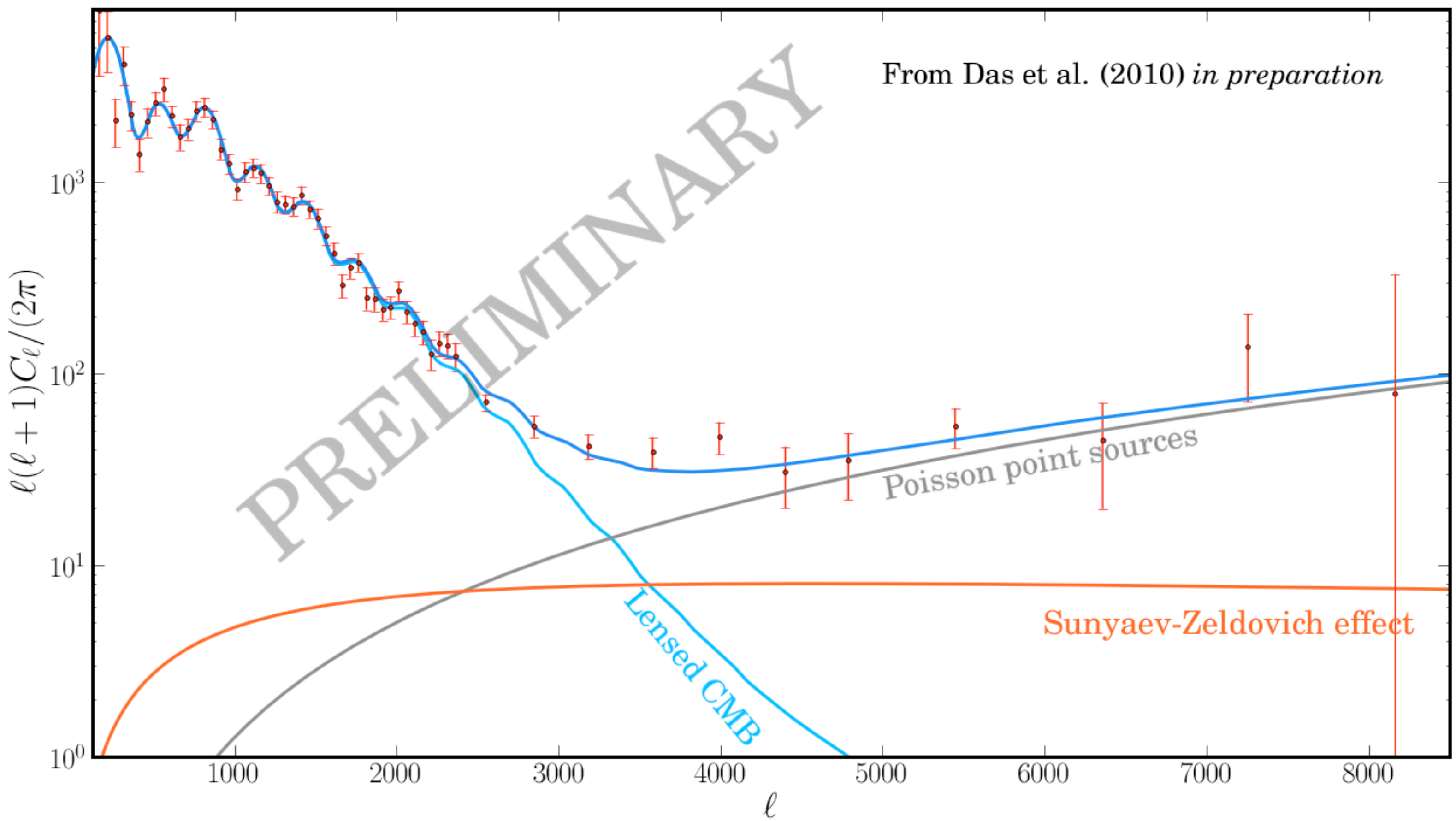
Parameters Fit to ACT Power Spectrum



A_{SZ} < 1.63 x (the power expected from a σ_8=0.80 model) even if all sources are Poisson.

While model-dependent, this requires σ_8<0.86.
(consistent with SPT; low for WMAP5 cosmology)

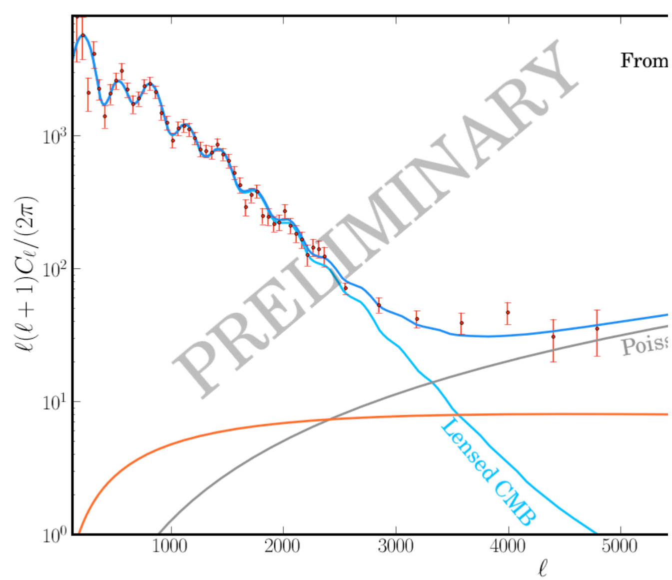
Power Spectrum at Lower Multipoles

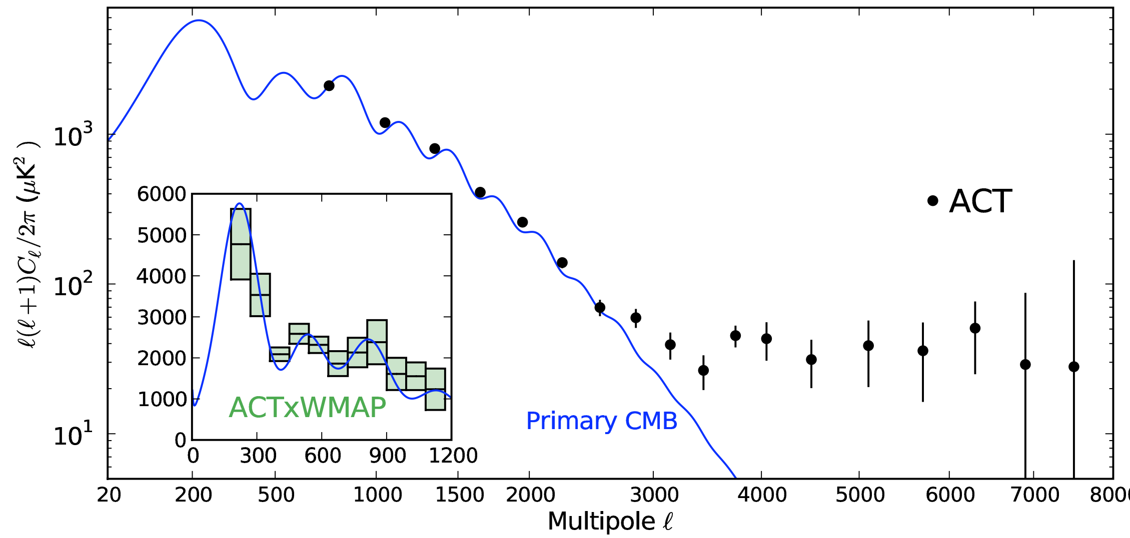


ACT Power Spectrum Conclusions

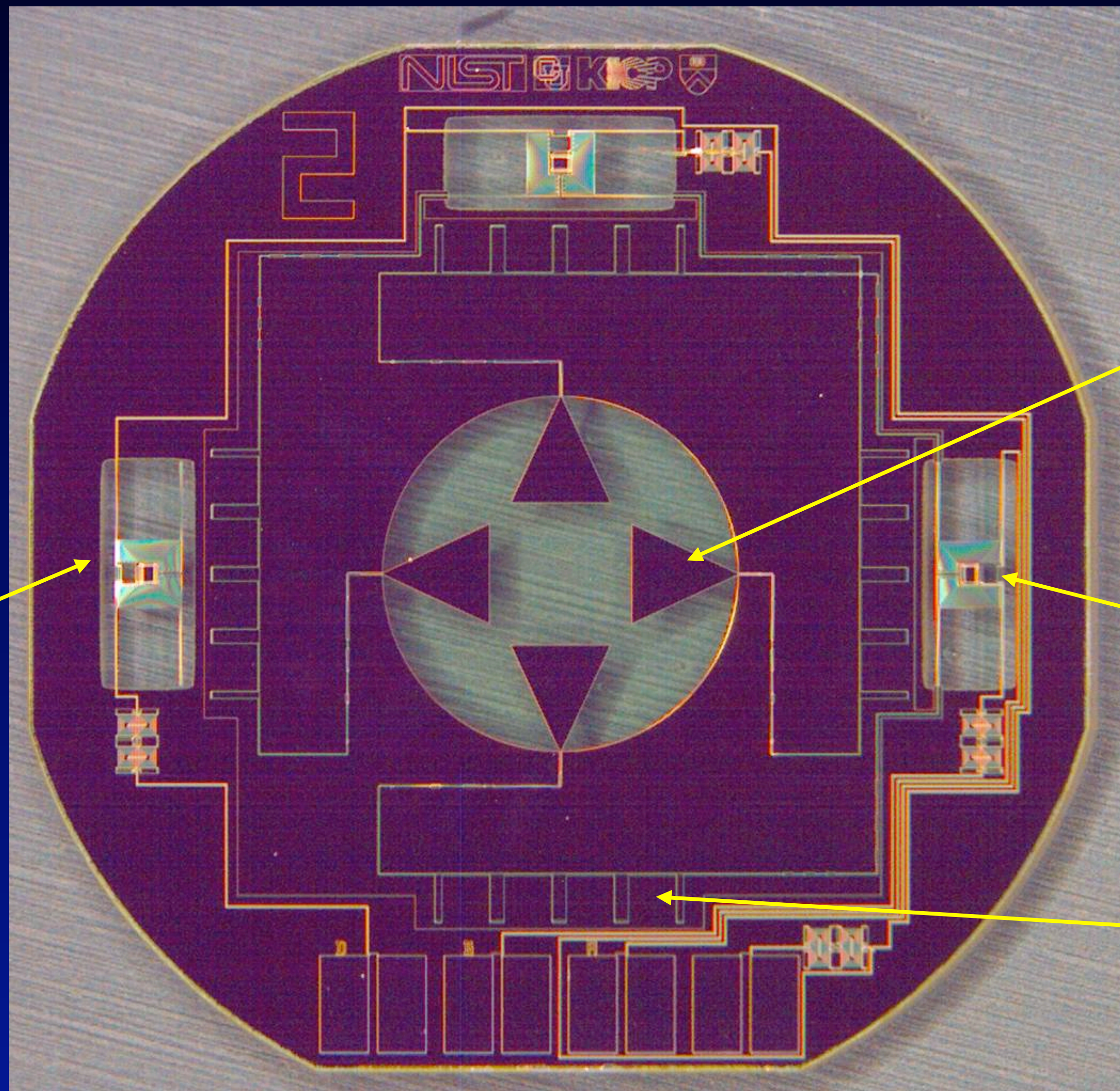
With improved spectral resolution, we see ℓ=500 acoustic peak and higher.

1. Agrees with WMAP at low: gets ℓ ~400 to 6000 with one instrument.
2. Agrees with SPT spectrum (Dec 2009).
3. Consistent with known source information.
4. Upper limit on amount of SZ effect so far.
5. If interpreted as a σ_8, it's less than 0.86 (95%CL).
6. Promise for much improvement with (a) more data and (b) 220 GHz maps.





Next Steps: 150 GHz CMB Polarimeter (NIST)



“Dark TES”

OMT

One TES

Bandpass filter in microstrip

Bond pads

ACTPOL: AN ACT UPGRADE (2012+)

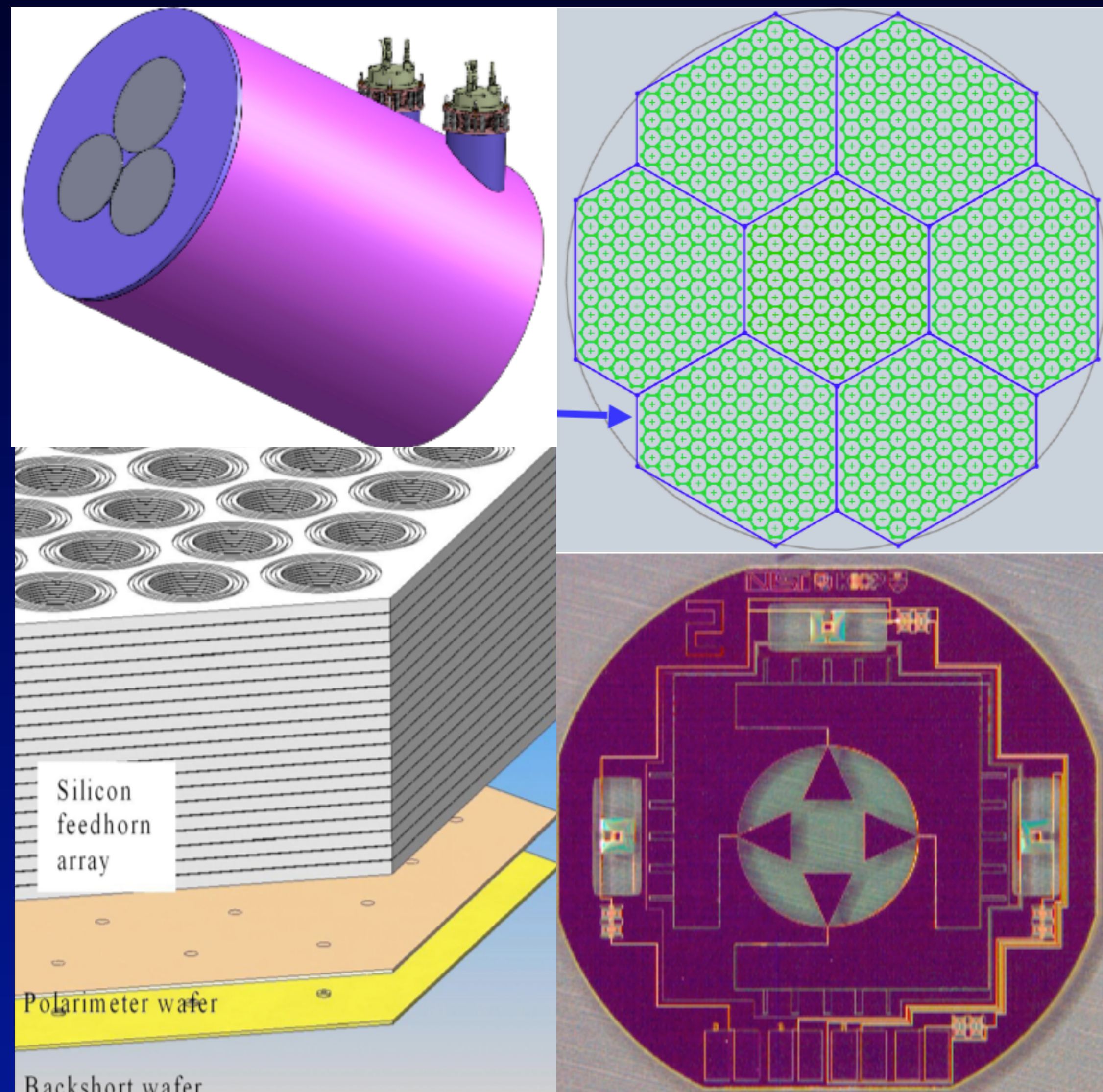
Instrument

- A 150/220 GHz camera for ACT
- Silicon lenses
- 640 feed horns+PSBs per array
- Band filter on chip
- TES sensors
- Time-domain MUXed SQUIDs

Science

- More sensitive SZ survey
- Spectrum at high-*l* constrains n_s
- EE spectrum
- Lensing deflection field (matter at z~2) sensitive to neutrino masses
- Many cross-correlations

Currently proposed to US NSF



Atacama B-Mode Search (under construction)

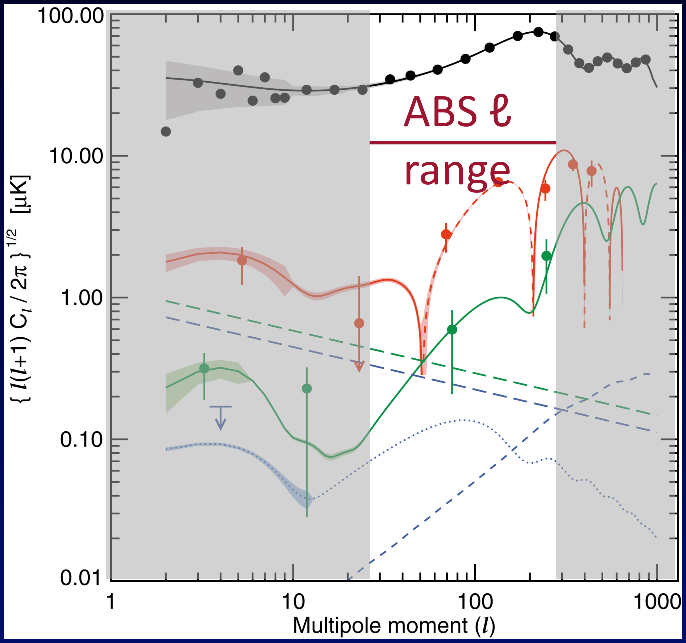
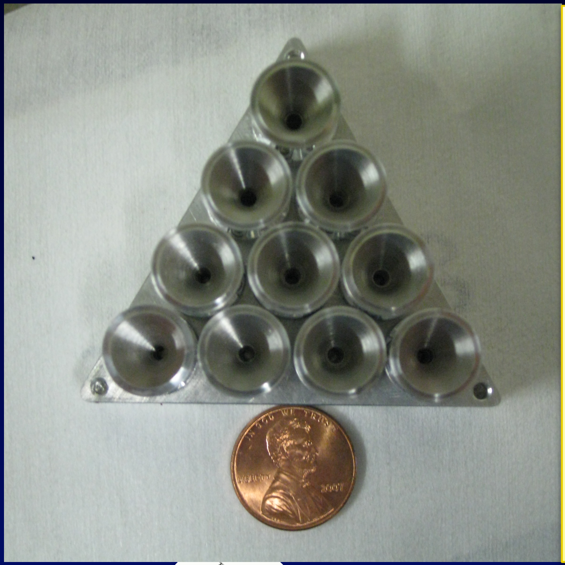
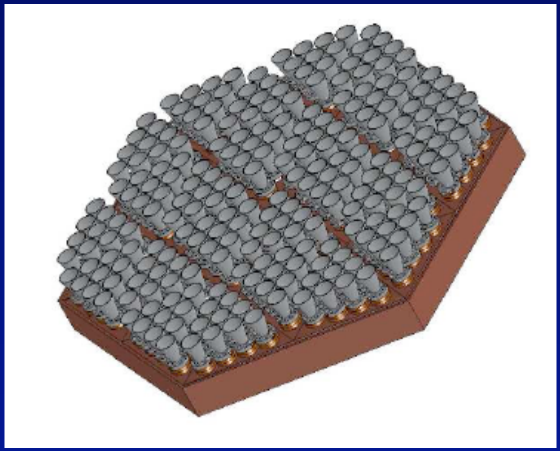
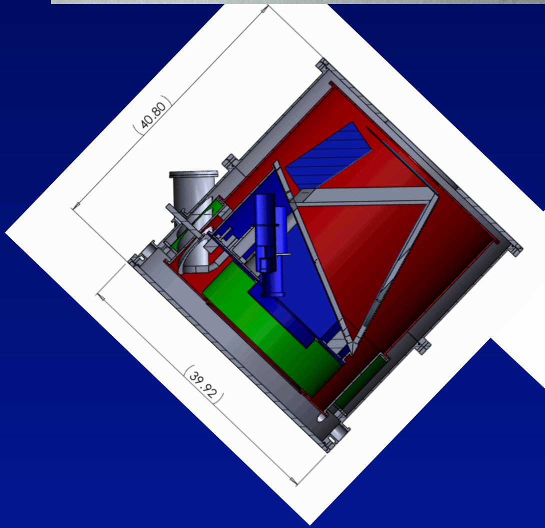


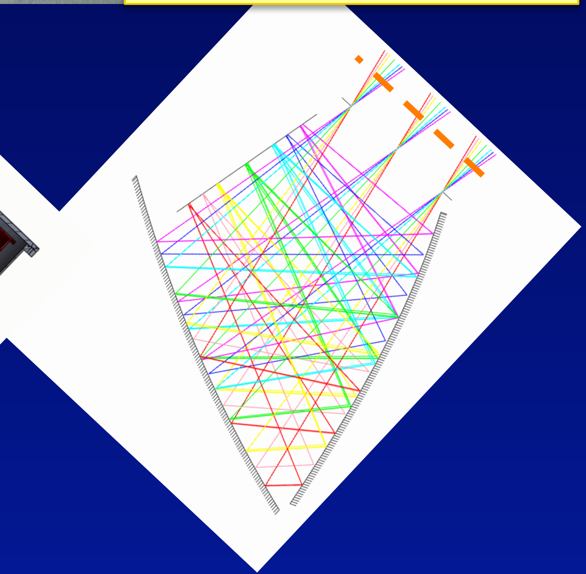
Image: NASA/WMAP science team

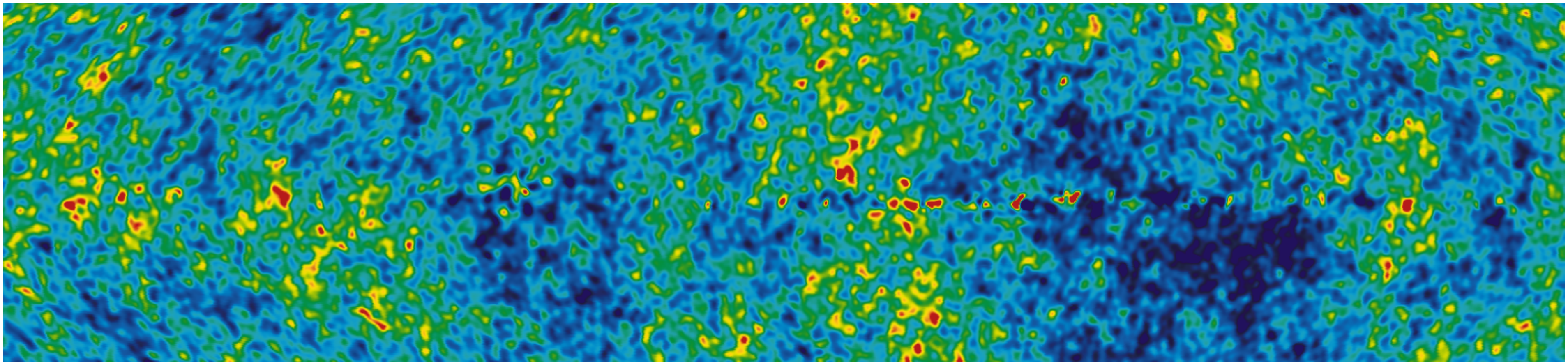


- Focal plane array of NIST polarization-sensitive TES
- 240 machined Al feeds
- Cryogenic crossed-Dragone mirrors
- Feeds and on-chip filters define a band ~150 GHz
- Rotating half-wave plate outside cryostat
- 0.6° (FWHM) beams, 20° overall field of view
- Compact telescope



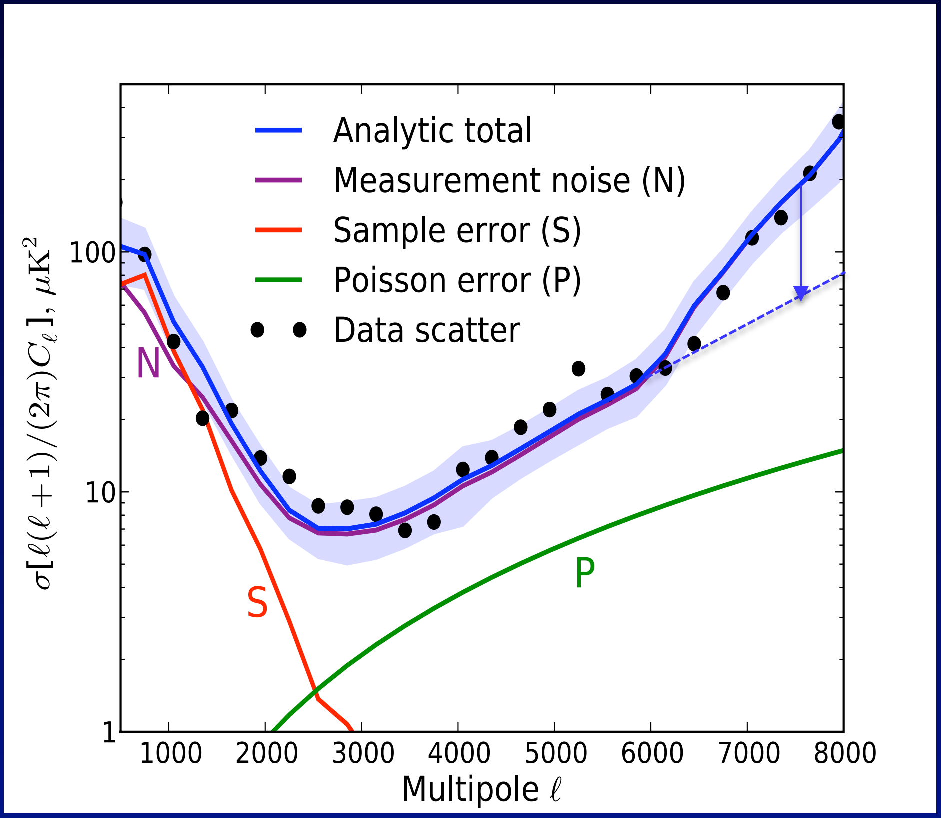


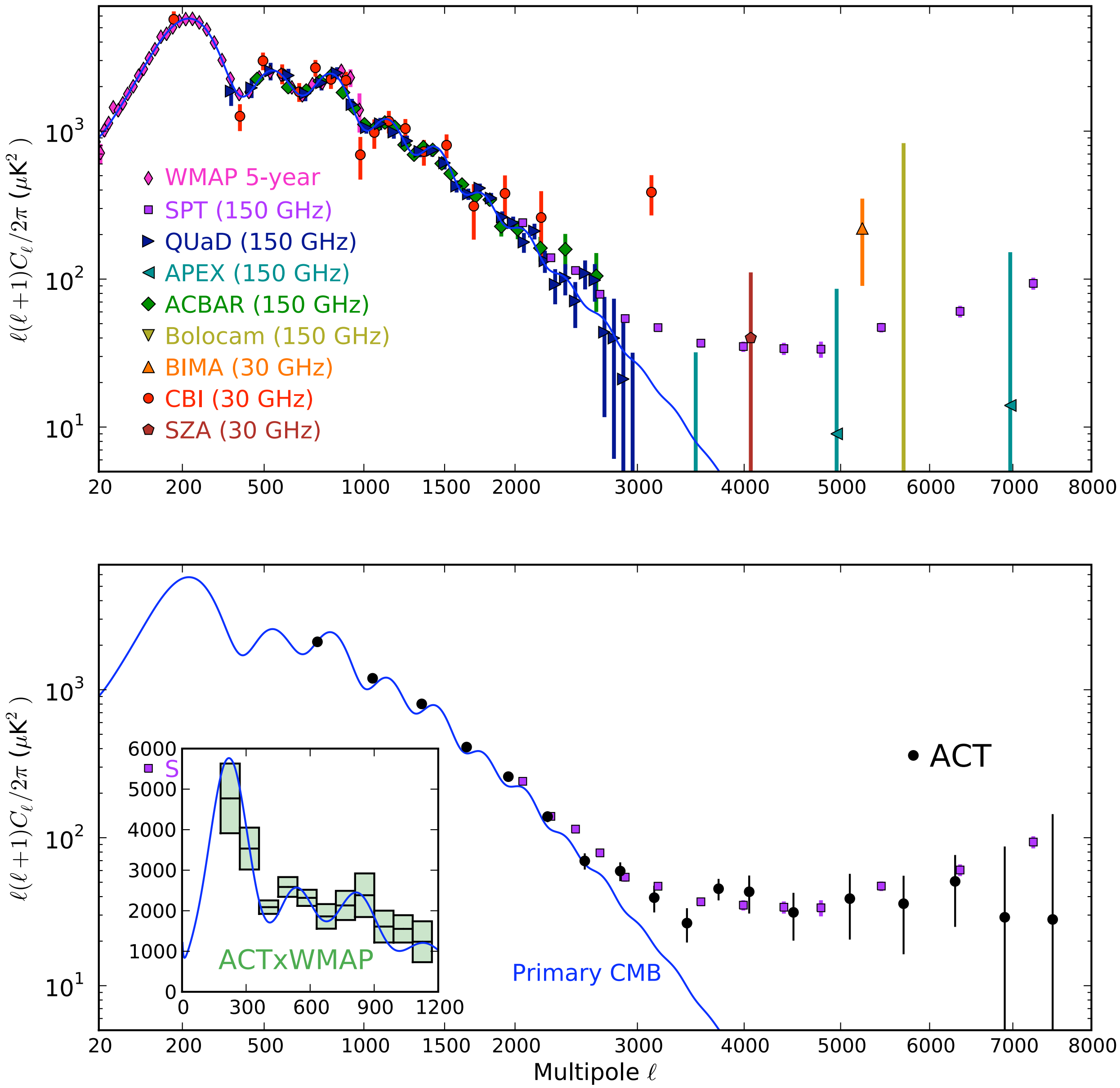





ACT

POWER SPECTRUM ERRORS: ANALYTIC VERSUS SCATTER





WMAP 5-year
SPT (150 GHz)
QUaD (150 GHz)
APEX (150 GHz)
ACBAR (150 GHz)
Bolocam (150 GHz)
BIMA (30 GHz)
CBI (30 GHz)
SZA (30 GHz)
$\ell(\ell+1)C_\ell/2\pi\ (\mu K^2)$
ACT
ACTxWMAP
Primary CMB
Multipole ℓ