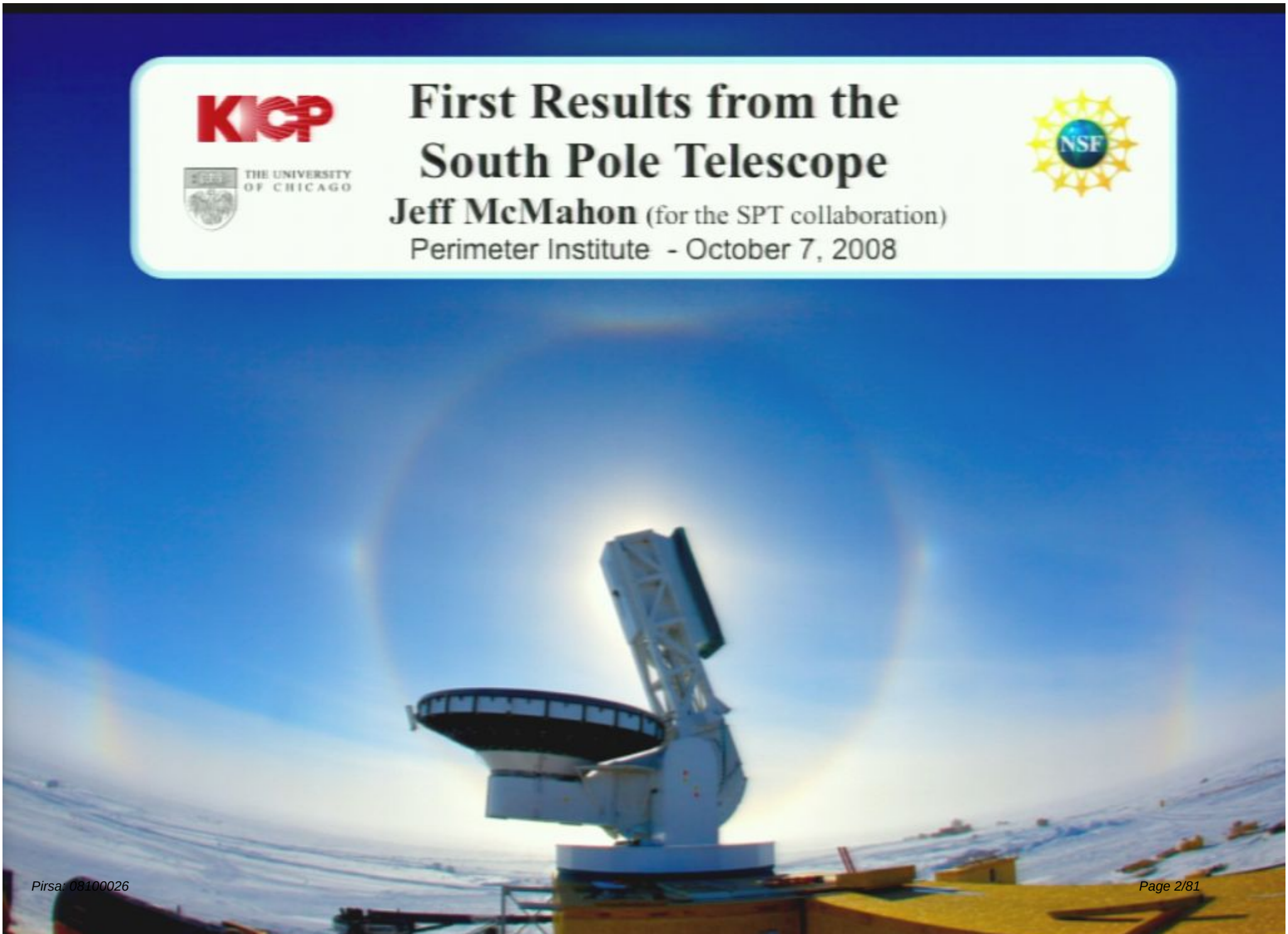
Title: First results from the South Pole Telescope (SPT)

Date: Oct 07, 2008 02:00 PM

URL: http://pirsa.org/08100026

Abstract: The South Pole Telescope (SPT) is a 10-meter submm-wave telescope optimized for large-field imaging of the cosmic microwave background (CMB) at arcminute resolution. The first key project of the SPT is a large area survey to find galaxy clusters using the Sunyaev-Zel\'dovich effect. Combined with optically determined redshifts, the survey yields will be used to place constraints on the nature of dark energy, via its effect on the growth of clusters and the geometry of the universe. Working toward this goal, the SPT has surveyed two 100 square degree fields at high sensitivity. This talk will review the status of the SPT, present some of the first SZ results, and discuss future science with this instrument.


KICP
THE UNIVERSITY OF CHICAGO
First Results from the South Pole Telescope
Jeff McMahon (for the SPT collaboration)
Perimeter Institute - October 7, 2008
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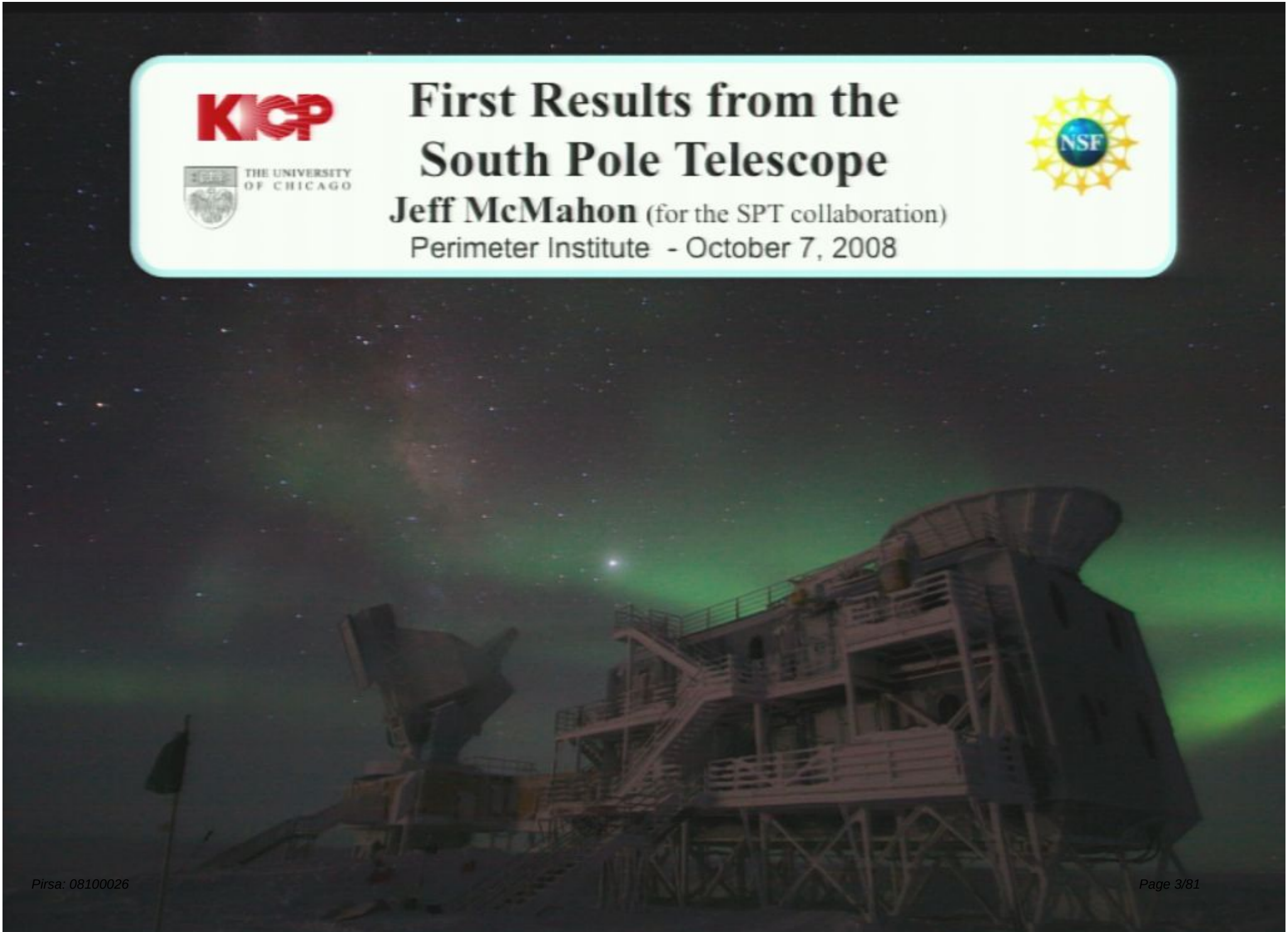
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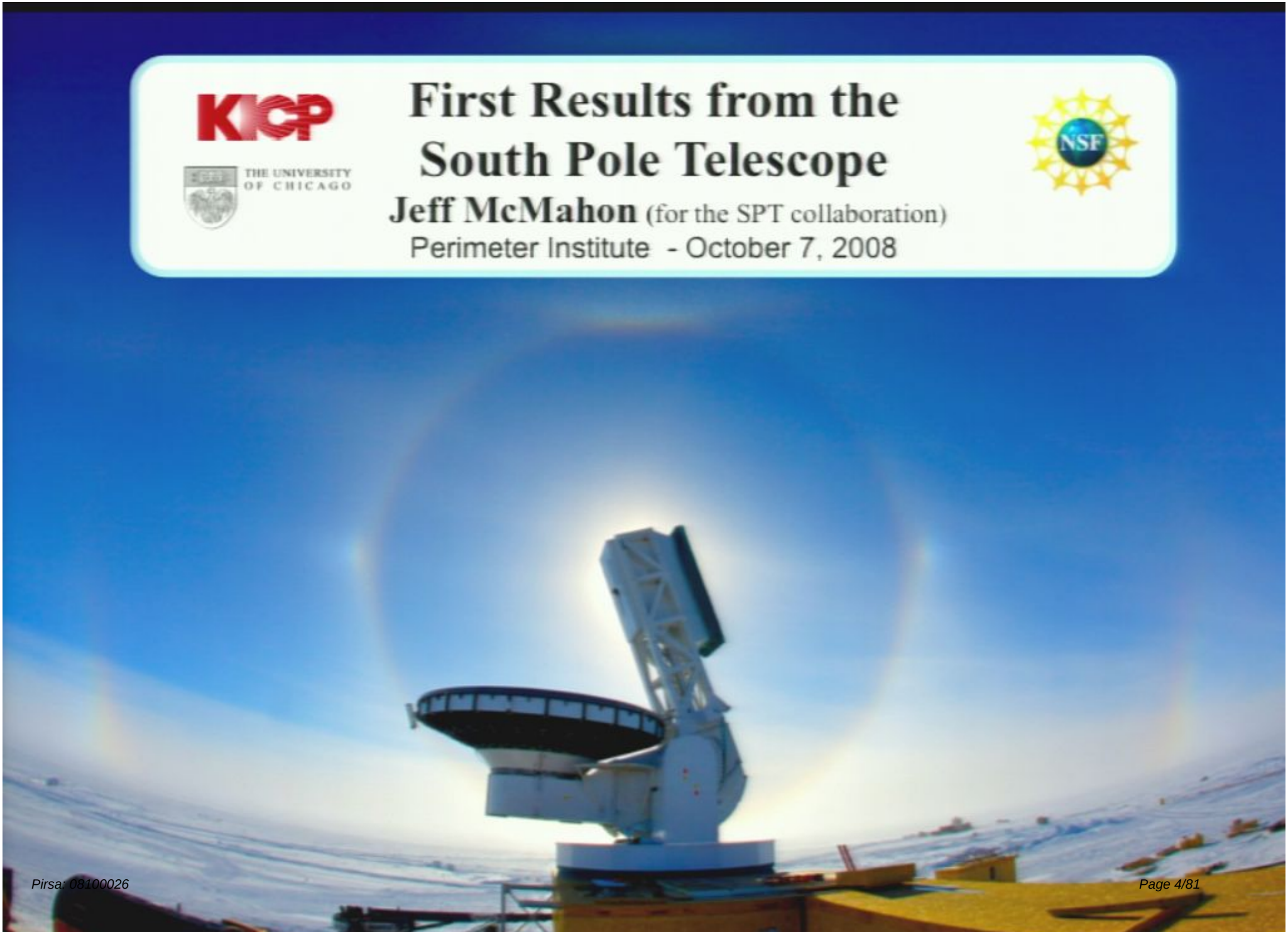
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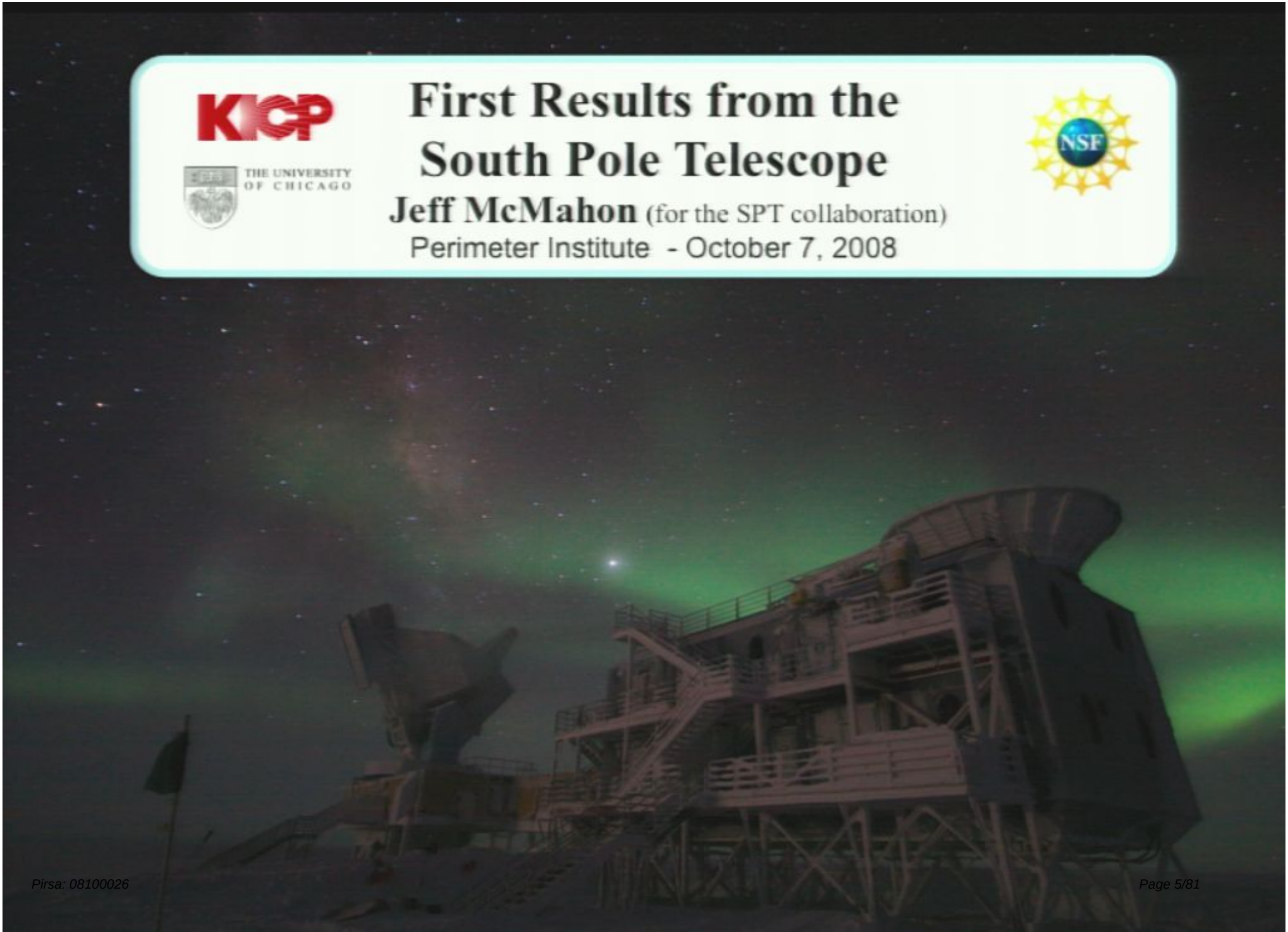
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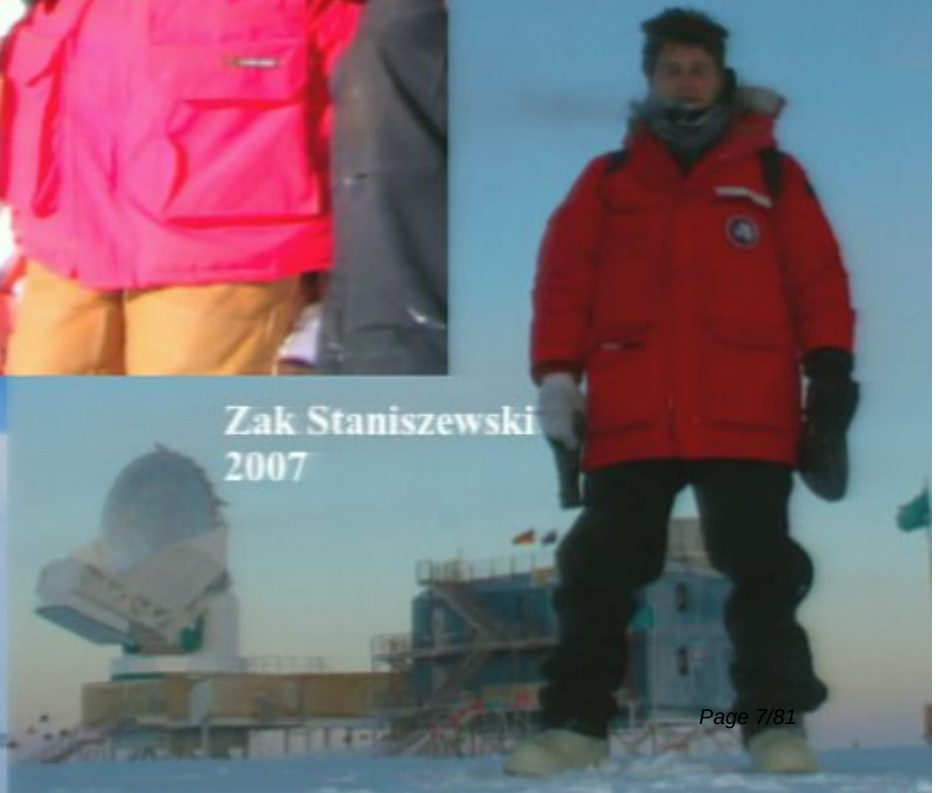
KICP
Kavli Institute
for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO
Berkeley
University of California
ASTRONOMY
UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN
Case
CASE WESTERN
RESERVE UNIVERSITY
McGill
THE UNIVERSITY OF
CHICAGO
Harvard-Smithsonian
Center for Astrophysics
CARDIFF
UNIVERSITY
PRIFYSGOL
CAERDYDD
UCDAVIS
UNIVERSITY OF CALIFORNIA
Colorado
University of Colorado at Boulder
SPT Collaboration

SPT Heroes Gallery

Keith Vanderlinde 2008

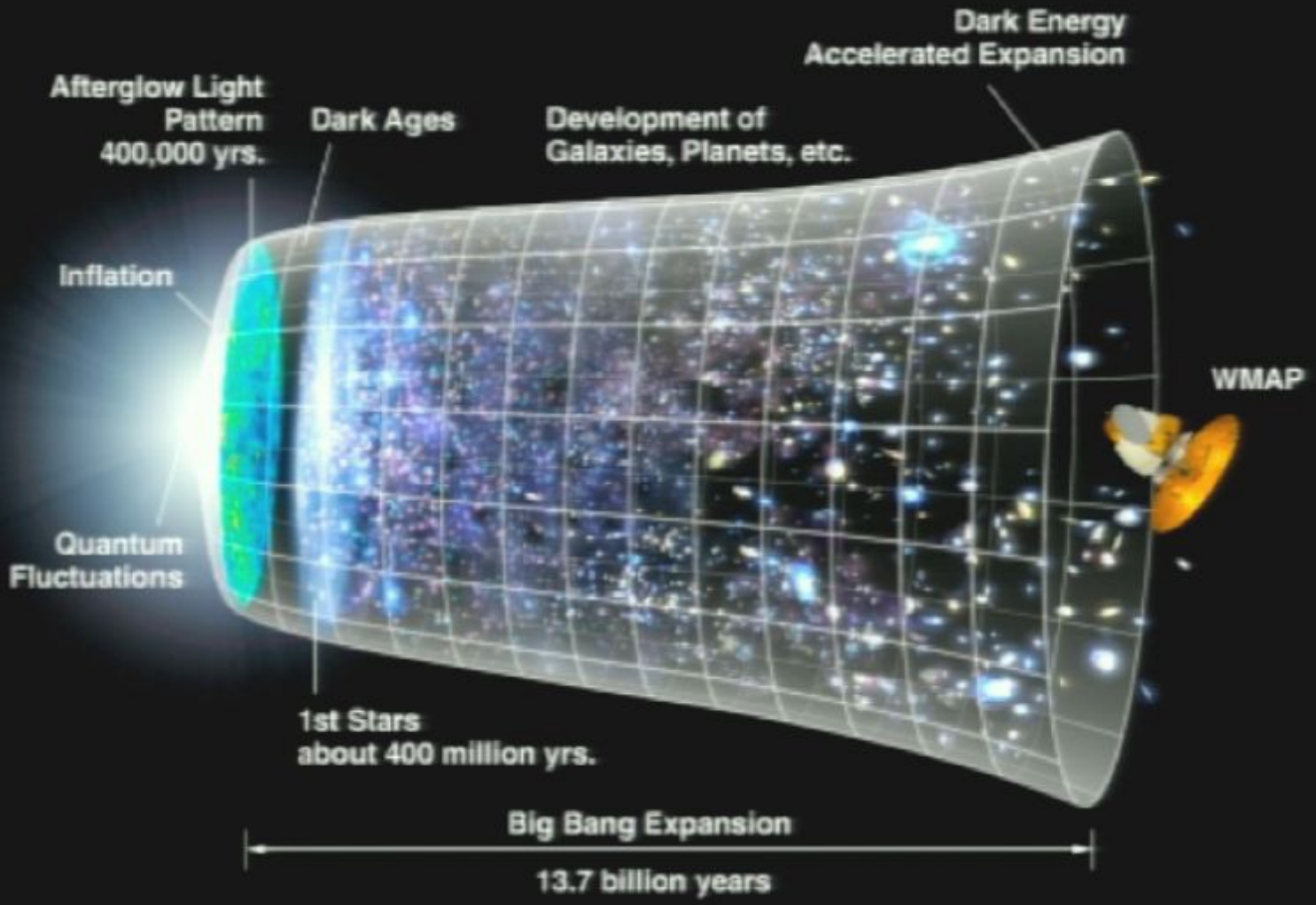
Steve Padin 2007

Dana Hrubes 2008

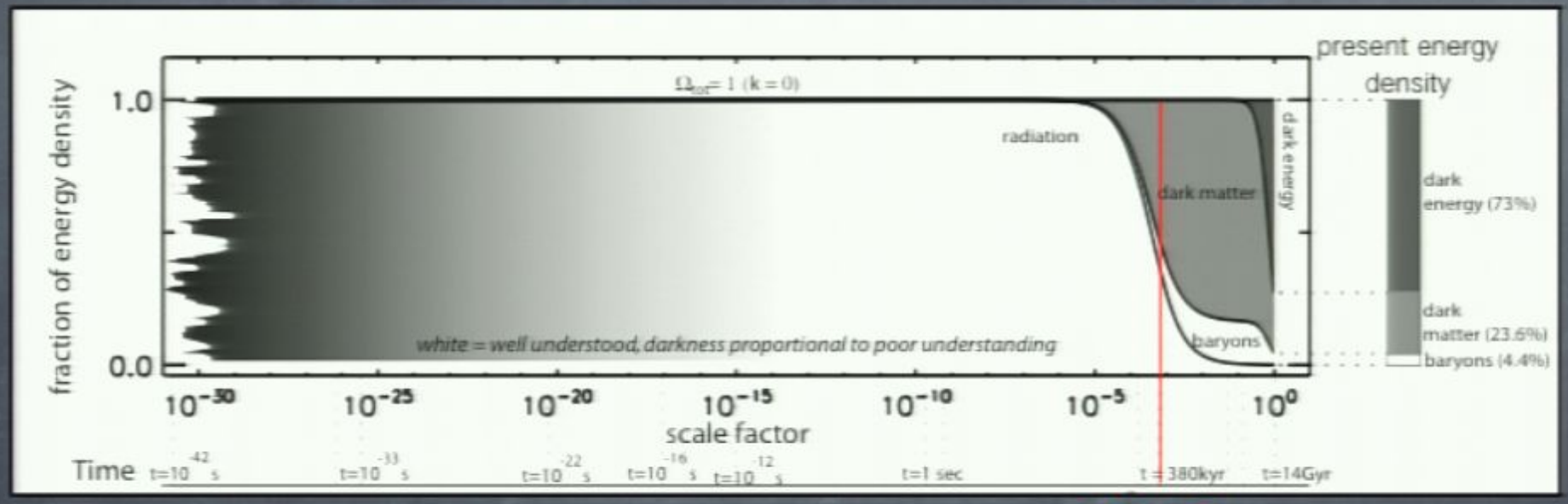


Zak Staniszewski 2007

The Cosmic Microwave Background is powerful tool for the study of Cosmology



Cosmology



CMB

- We now have a model that describes the evolution of our Universe from a hot and dense state.
- The model has some unusual features - *new physics* -
  Dark Matter, Dark Energy, and starts with a period of Inflation
- The CMB radiation we observe has interacted with intervening structure of the universe.
- The CMB also contains minute and undetected signals from the early universe

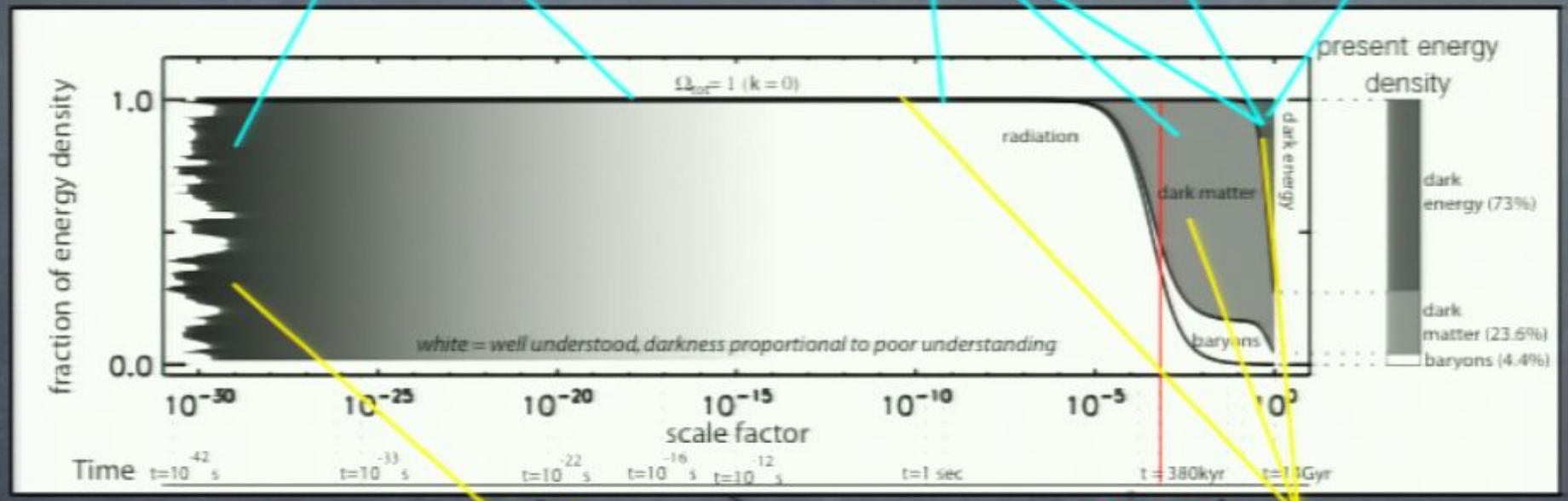
Signals Accessible with SPT

damping tail

gravitational lensing

tSZ effect

kSZ effect



Inflationary B-modes

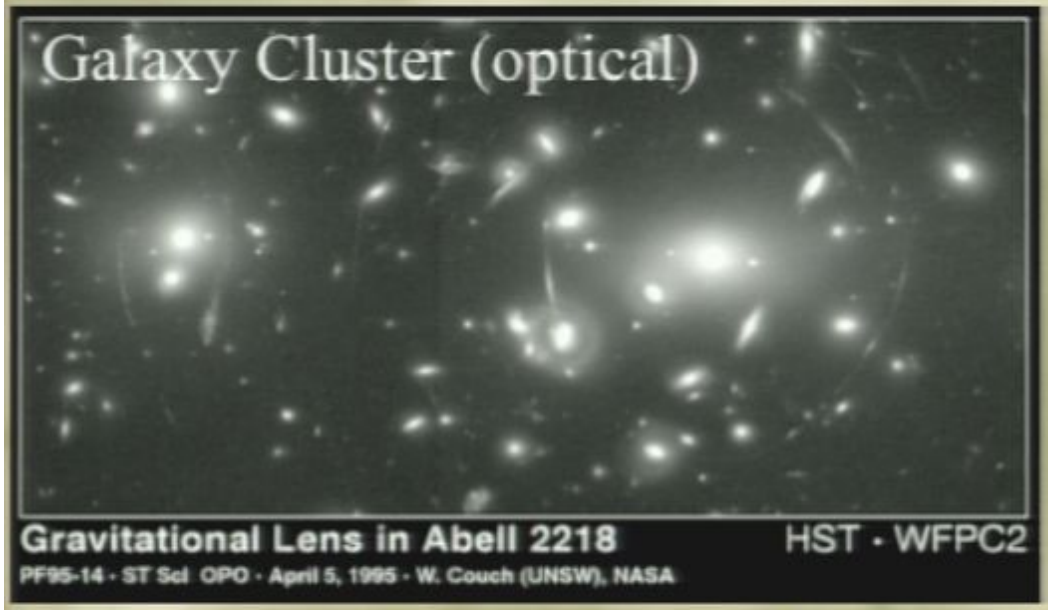
CMB

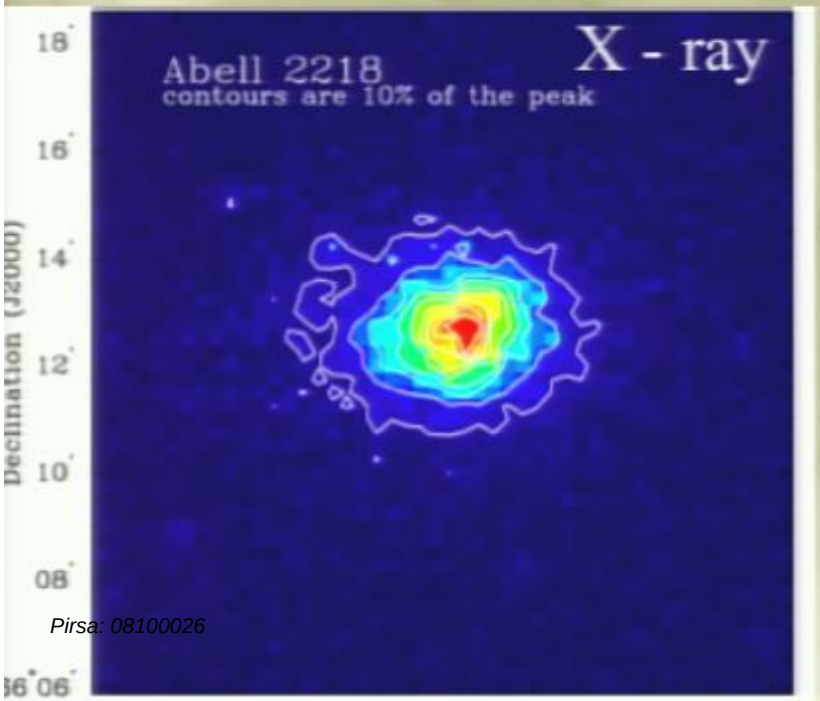
gravitational lensing

SPTsz - first key project

SPTpol - second key project

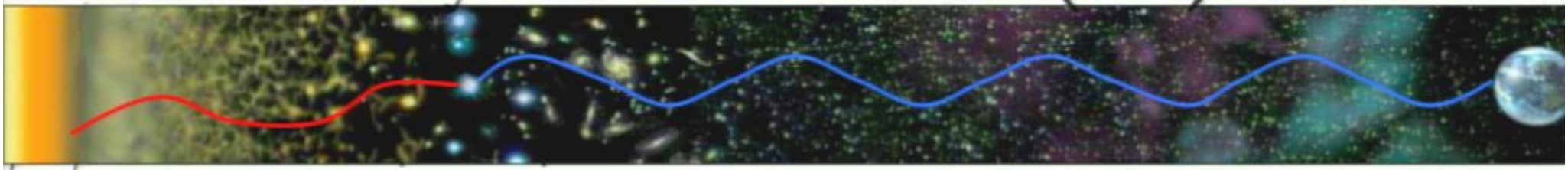
Clusters of Galaxies





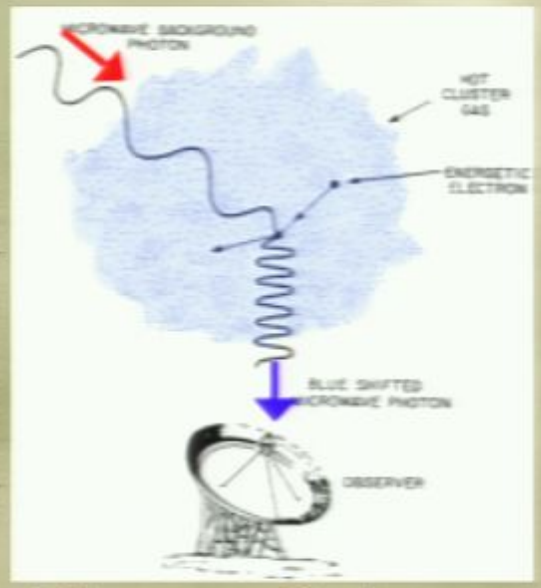
- Clusters of galaxies are the largest gravitationally viralized objects in the Universe
- 80-85% of their baryonic mass is in the form of an intra-cluster gas
- This gas is heated as it gravitational collapses into the cluster's gravitational potential well
- For massive clusters this gas can be heated to 100,000,000 Kelvin and is visible via its X-ray emission and the Sunyaev-Zel'dovich (SZ) Effect

The Sunyaev-Zel'dovich (SZ) Effect



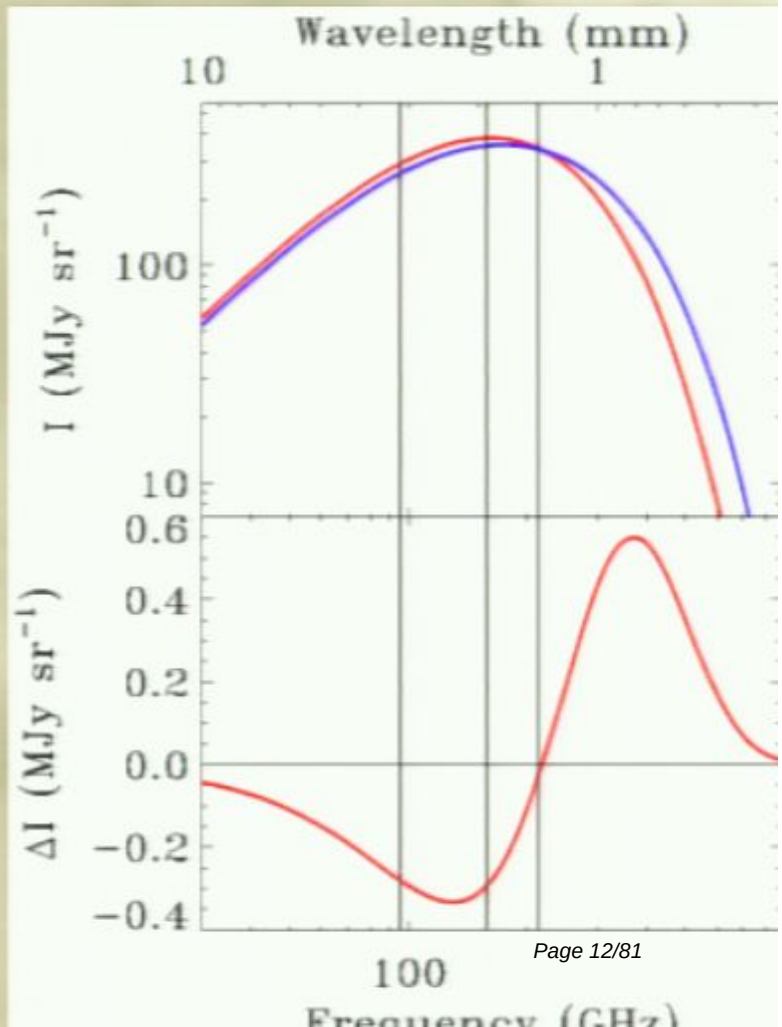
0 379,000 years

CMB photons provide a backlight for structure in the universe. Preser

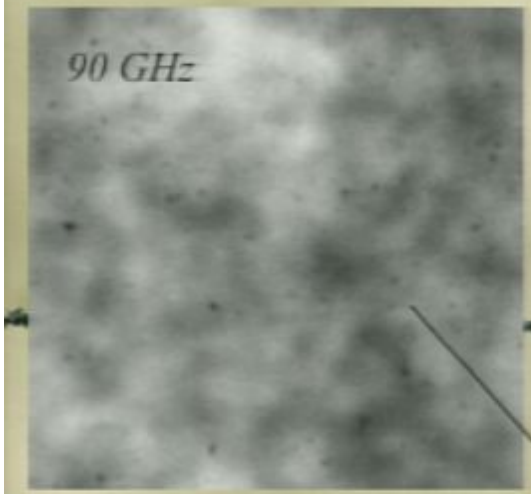


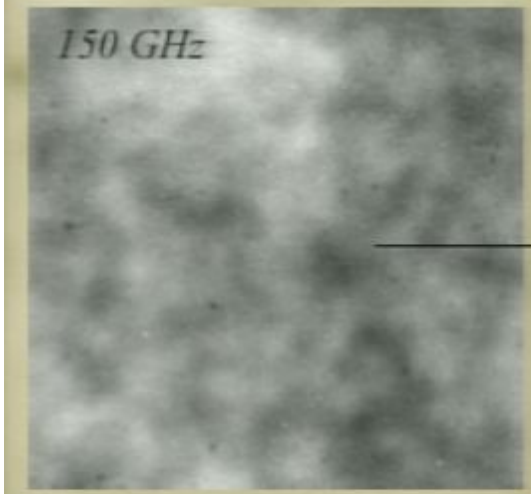
Adapted from L. Van Speybroeck

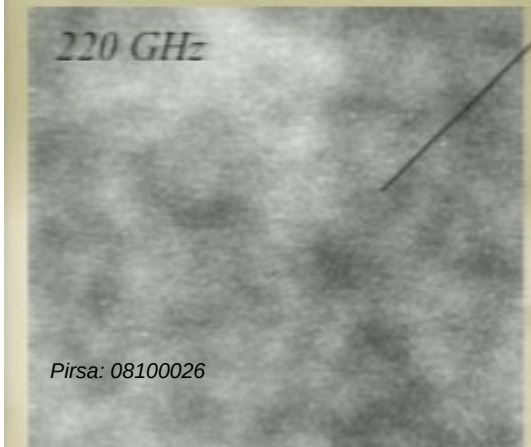
- 1-2% of Cosmic Microwave Background (CMB) photons scatter off of hot intra-cluster gas to higher energy, this is the **Sunyaev-Zel'dovich (SZ) Effect**
- SZ surface brightness is redshift independent
- Unique spectral signature
- also a kinetic effect due to motion of cluster gas wrt



Cosmology with Clusters

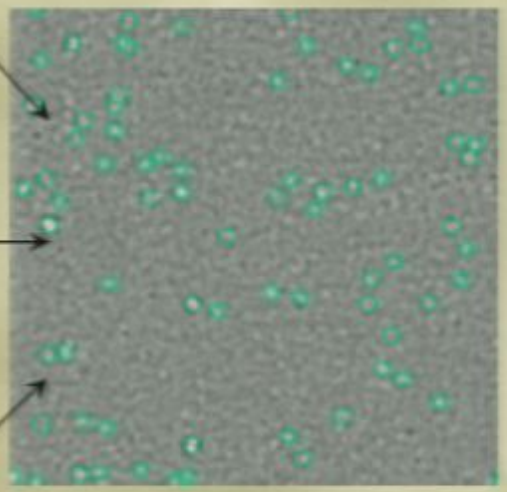






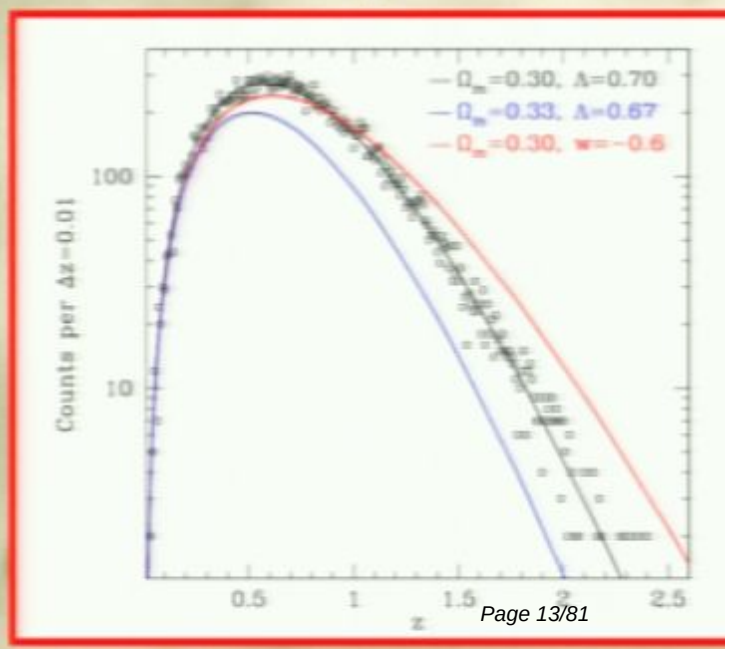
cluster finder

SZ selected catalog



(Work by Tom Crawford)

optical redshifts



G. Holder

Cosmology with Clusters of Galaxies

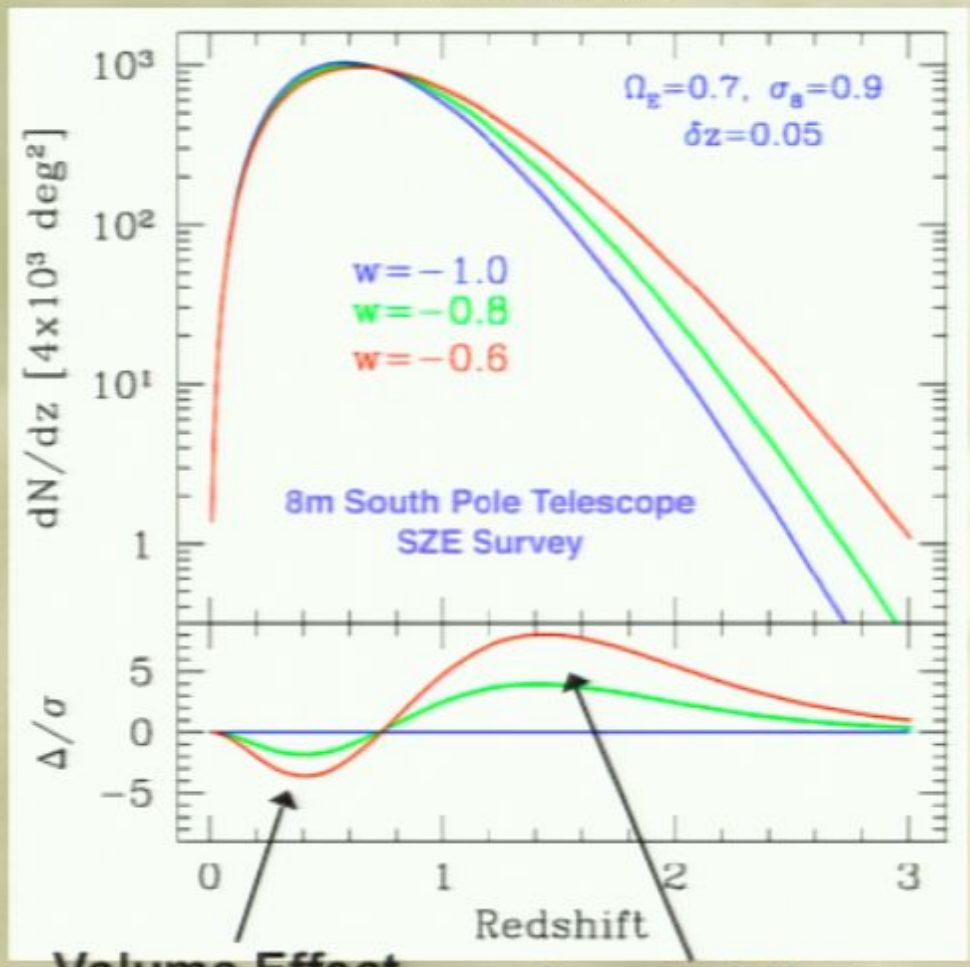
Cluster Abundance, dN/dz

$$\frac{dN}{d\Omega dz} = n(z)\frac{dV}{d\Omega dz}$$

Depends on:
Matter Power Spectrum, *P(k)*
Growth Rate of Structure, *D(z)*

Depends on:
Rate of Expansion, *H(z)*

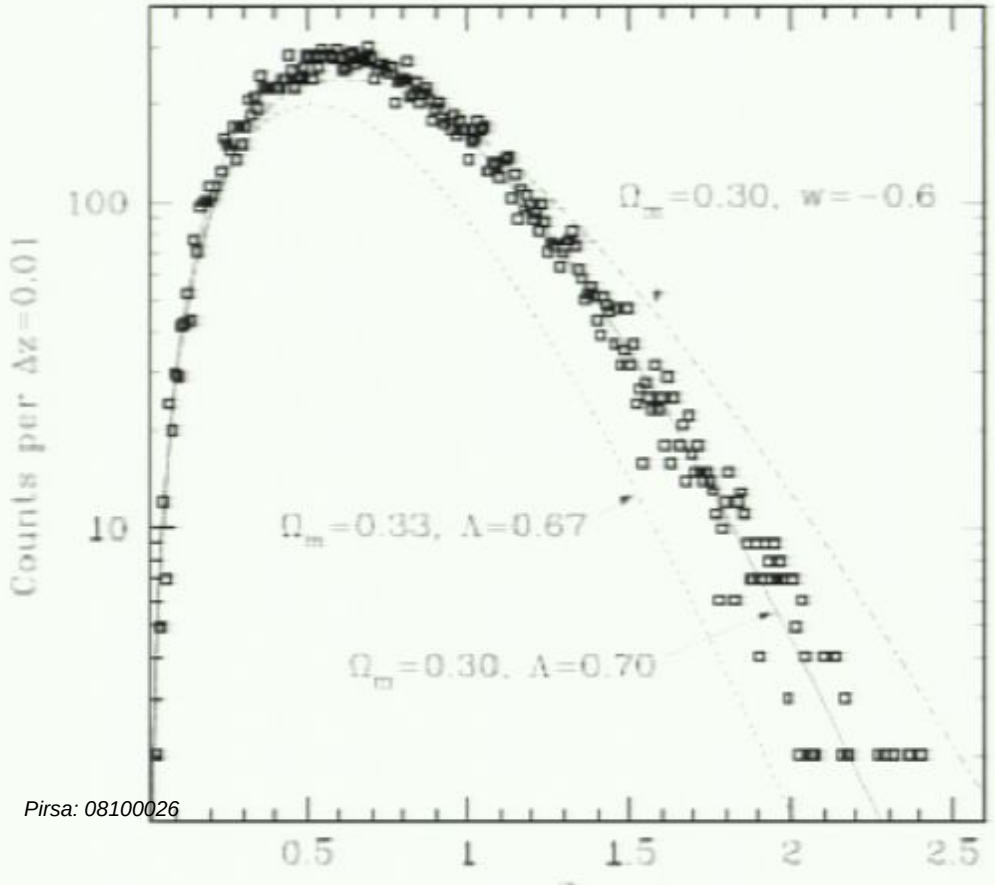
Credit: Joe Mohr

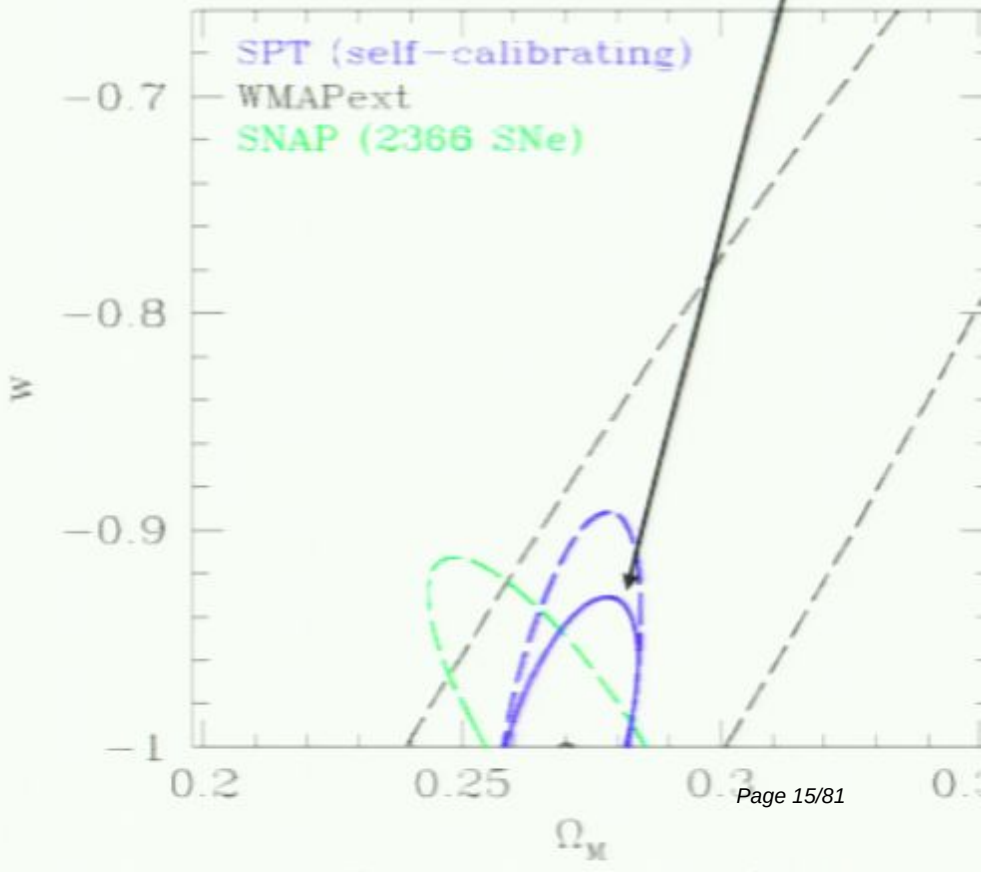


SPT Survey:

- 4000 square degrees
- 90, 150, 220 GHz
- 10μK/arcmin pixel
- Thousands of clusters
- Mass limited down to ~2x10^14 solar masses

Self-calibration plus 100 clusters with 30% mass determinations





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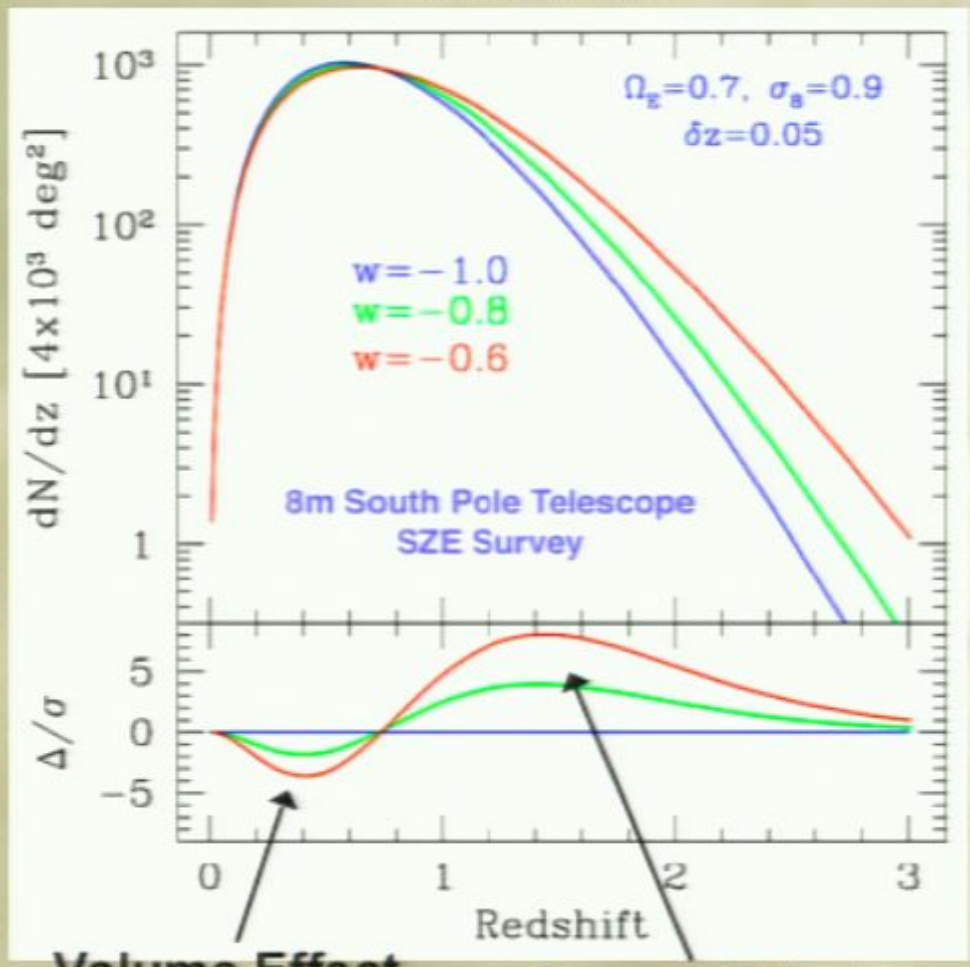

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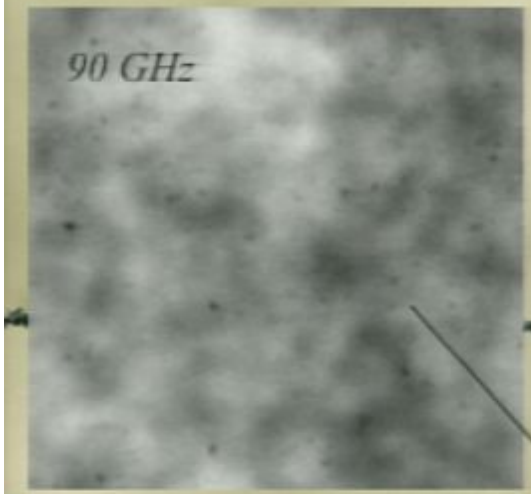

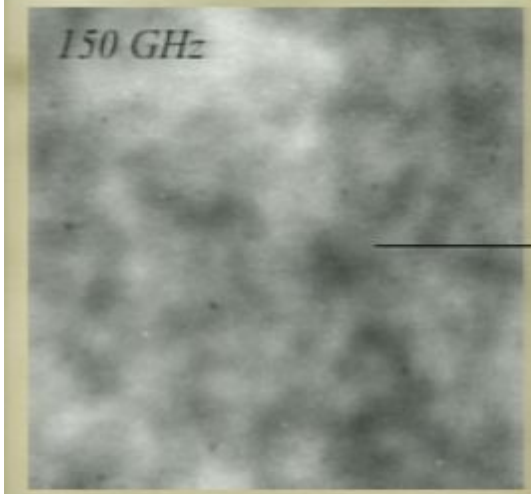

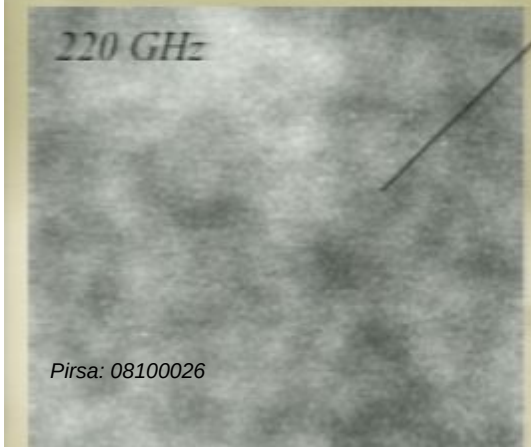

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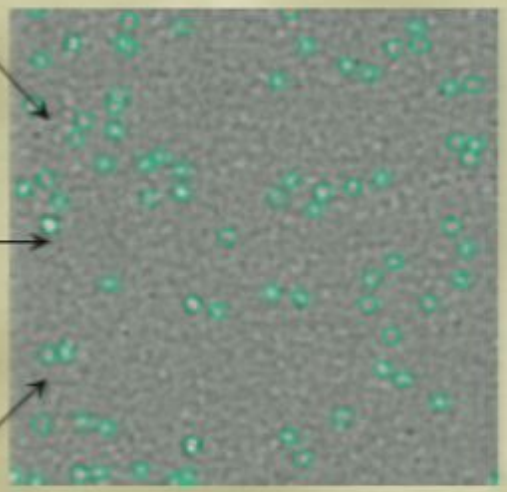

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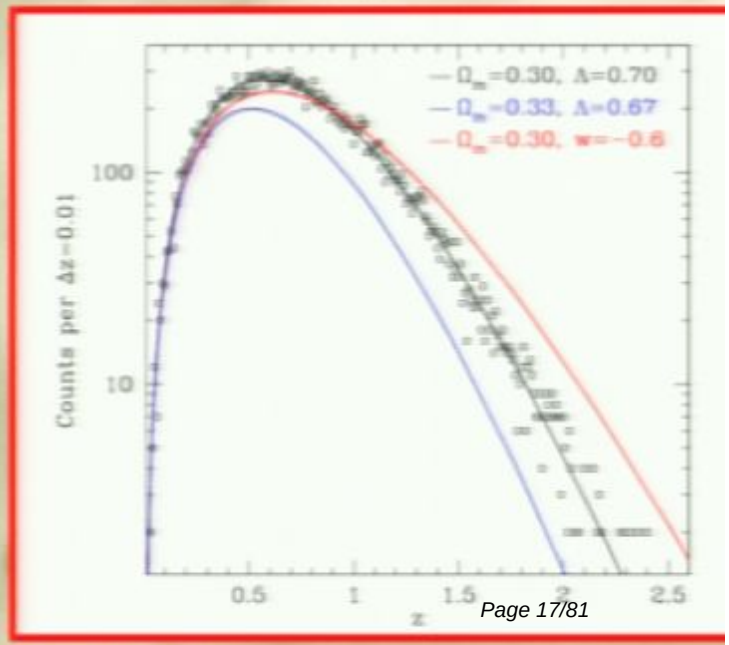

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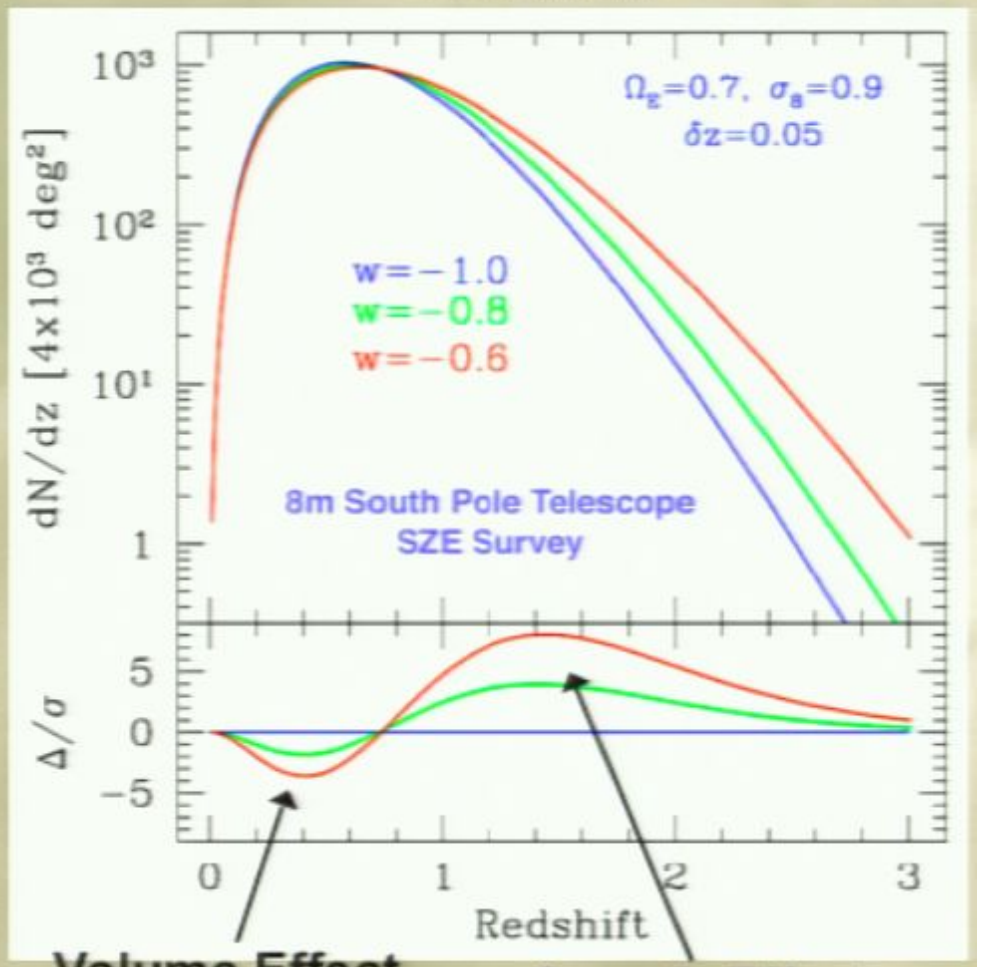

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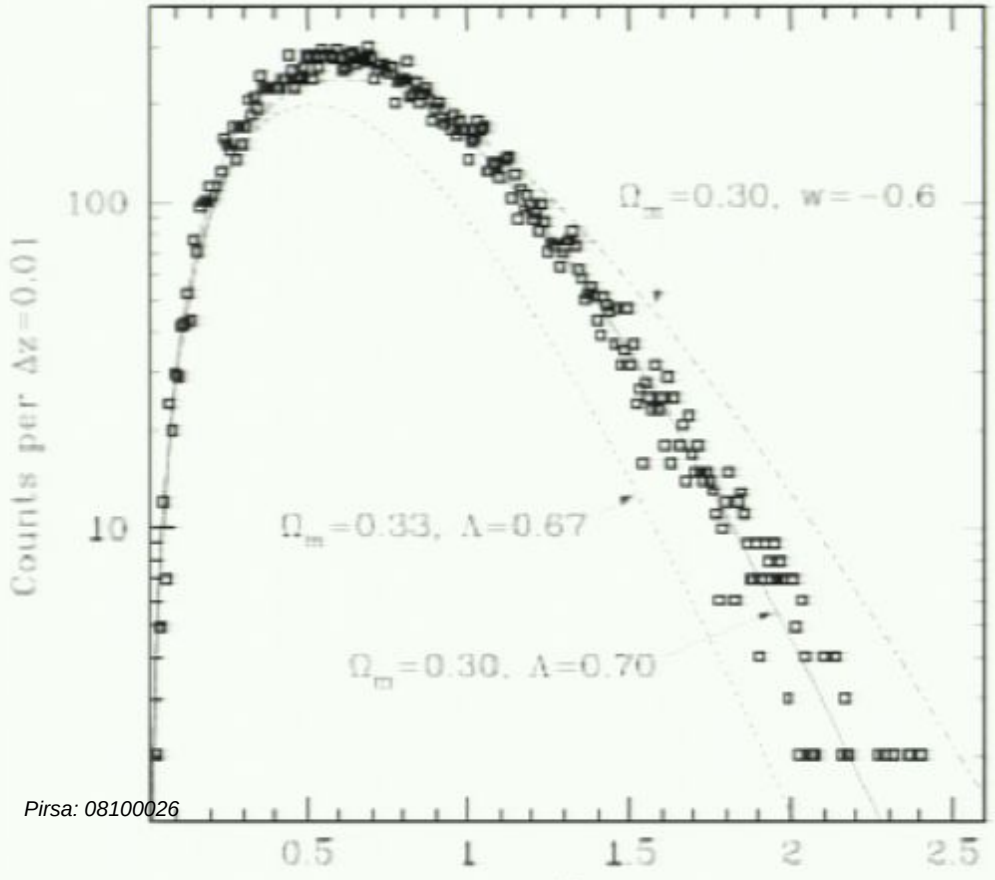

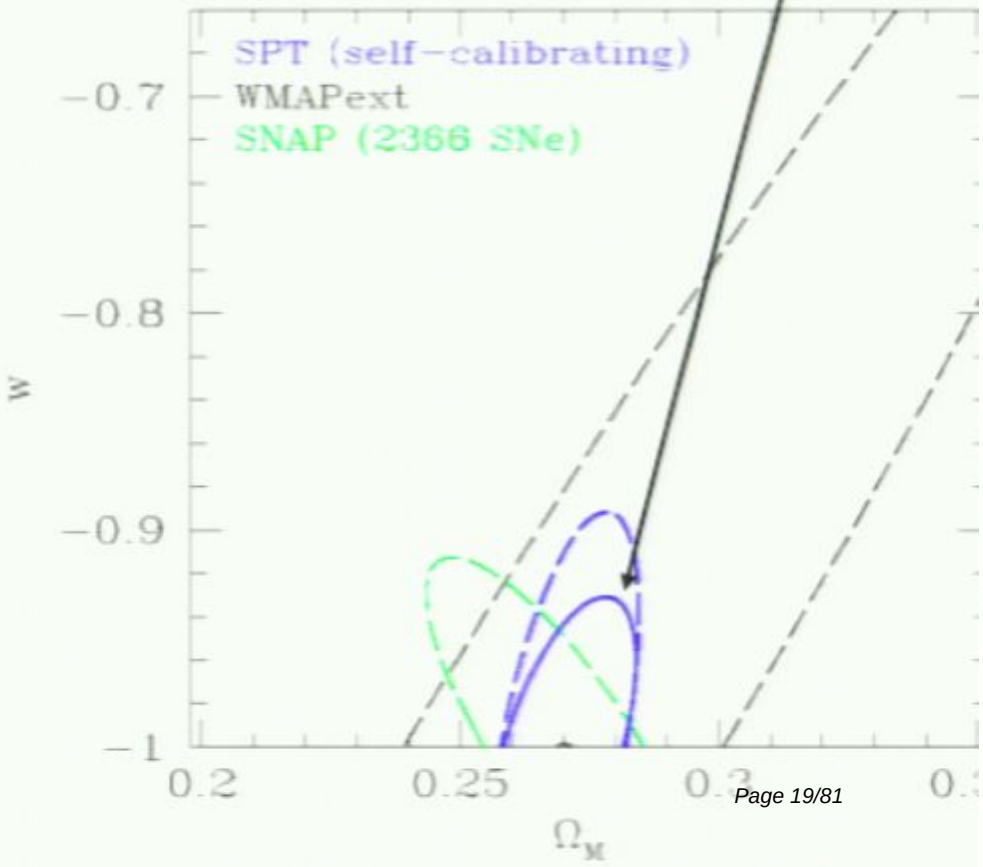

Requirements SZ cluster-finding machine

- **Resolution**
  - 1' is well-matched to typical cluster size at these redshifts
  - At 150 GHz this means you need a 8-10 meter dish

- **Mapping Speed**
  - (# of elements) / noise^2
  - At 150 GHz (from the ground), bolometers have reached photon background limit to sensitivity
  - Previous SZ/CMB instruments have on the order of tens of pixels (e.g. – ACBAR =16, QUAD = 31 pixels, ...)

Need More background limited Bolometers!!!

Meeting these requirements opens up lots of other

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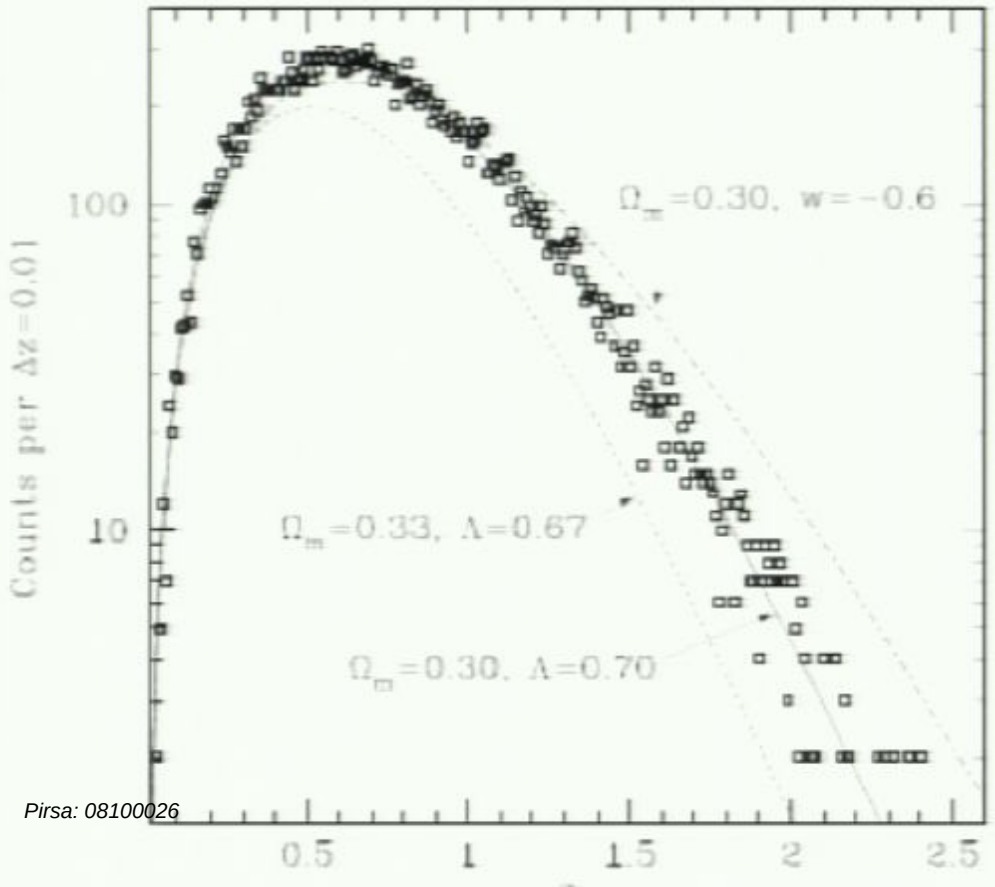

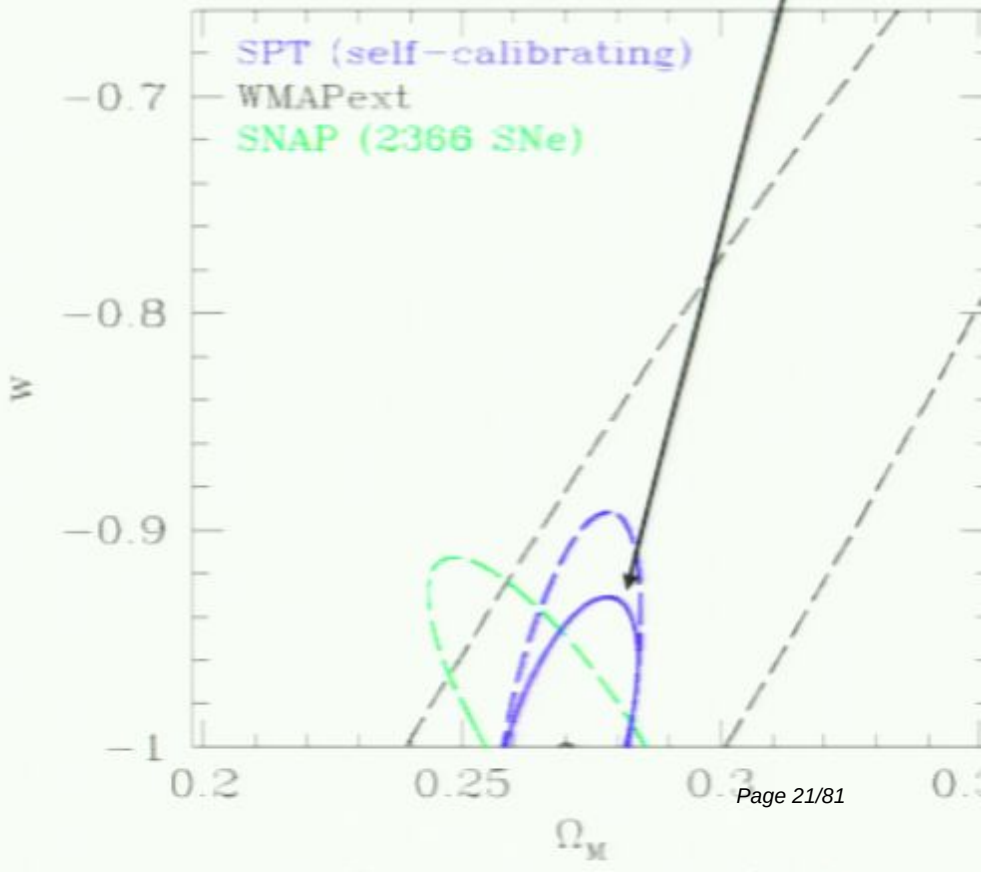

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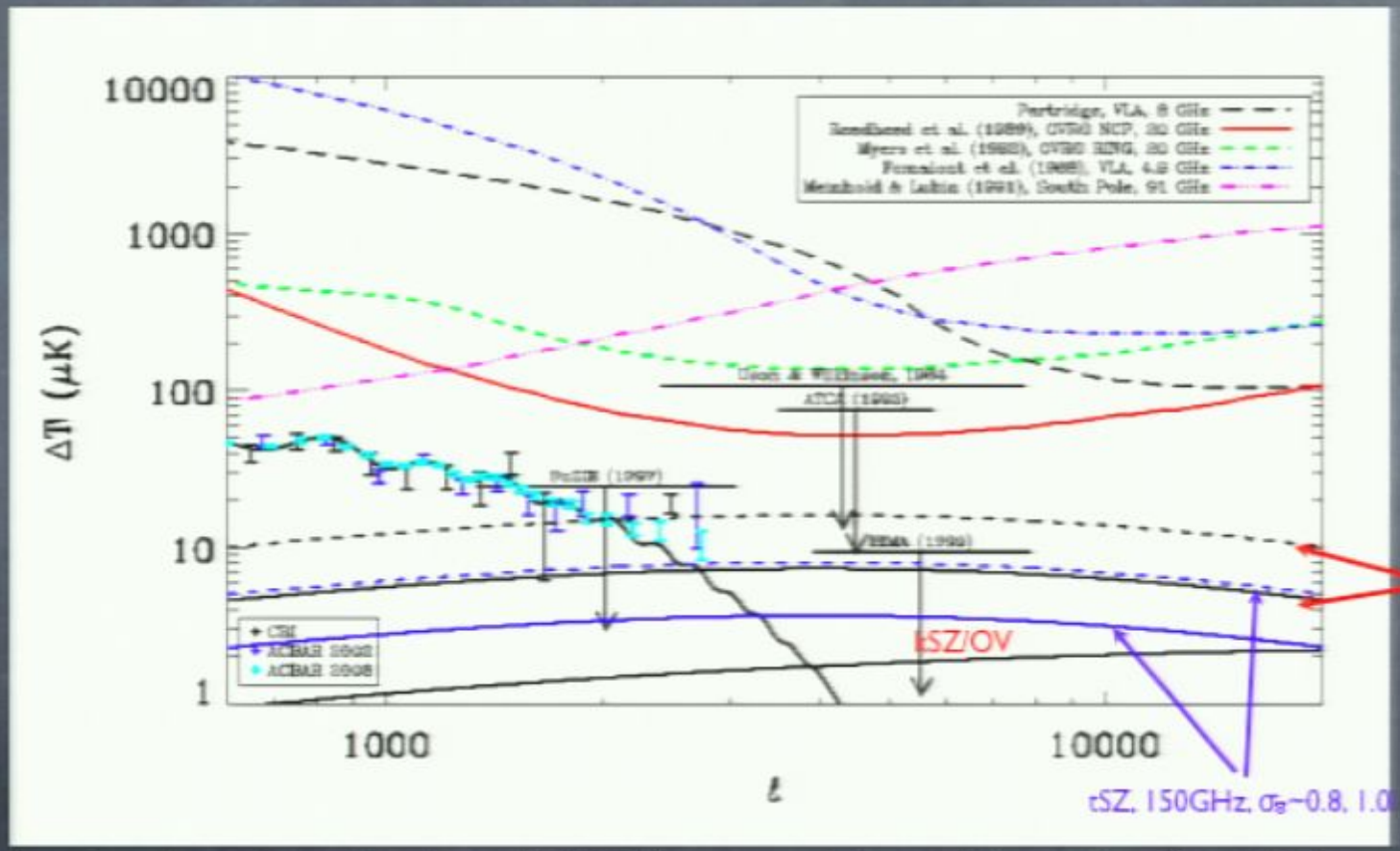
Small-Scale CMB Anisotropy



CBI points from Readhead et al. (2004)
ACBAR 2002 points from Kuo et al. (2003)
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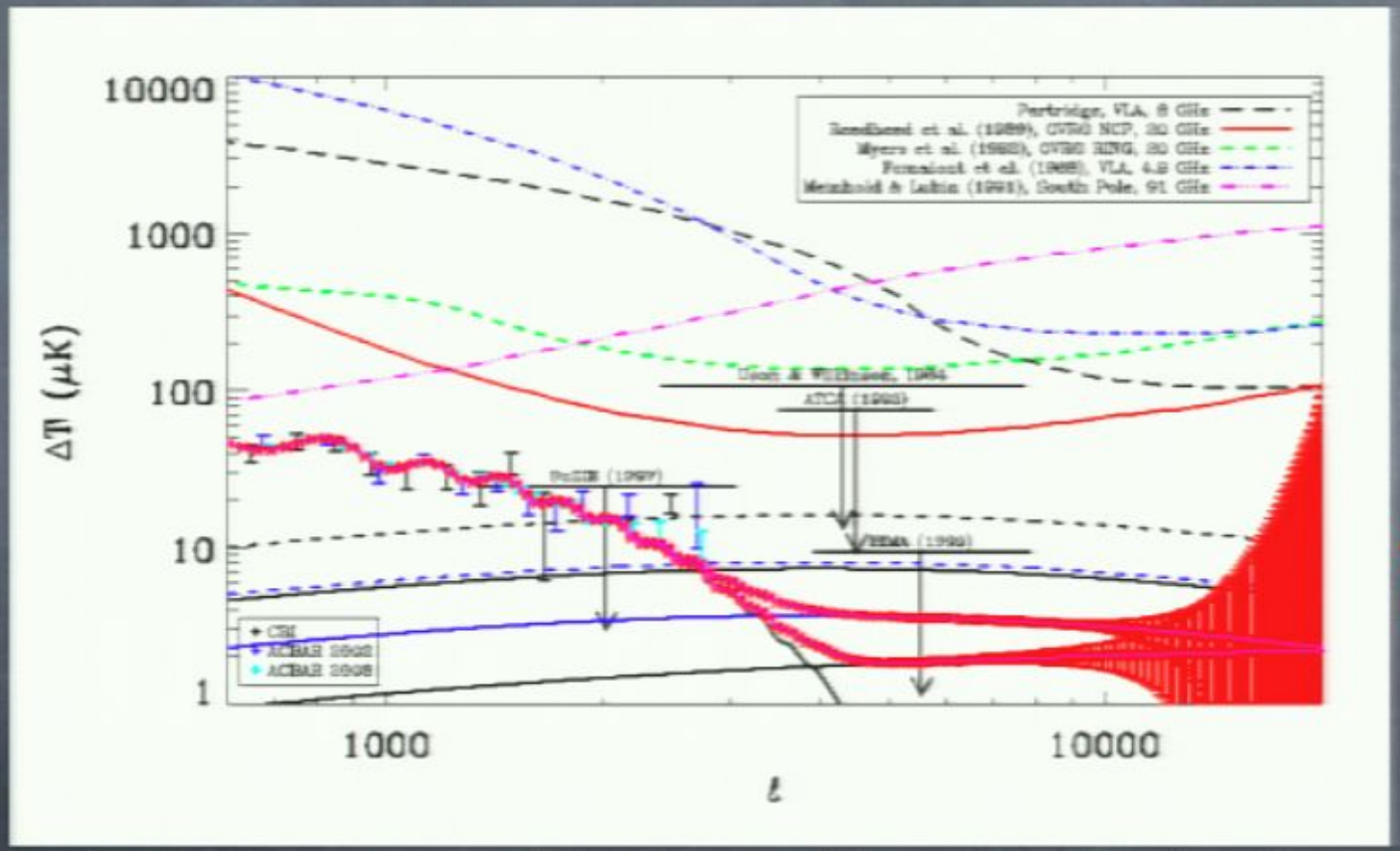
1993-1999 points from Gawiser & Silk (2000)

SPT Projection



4000 sq. deg
10uK-arcmi

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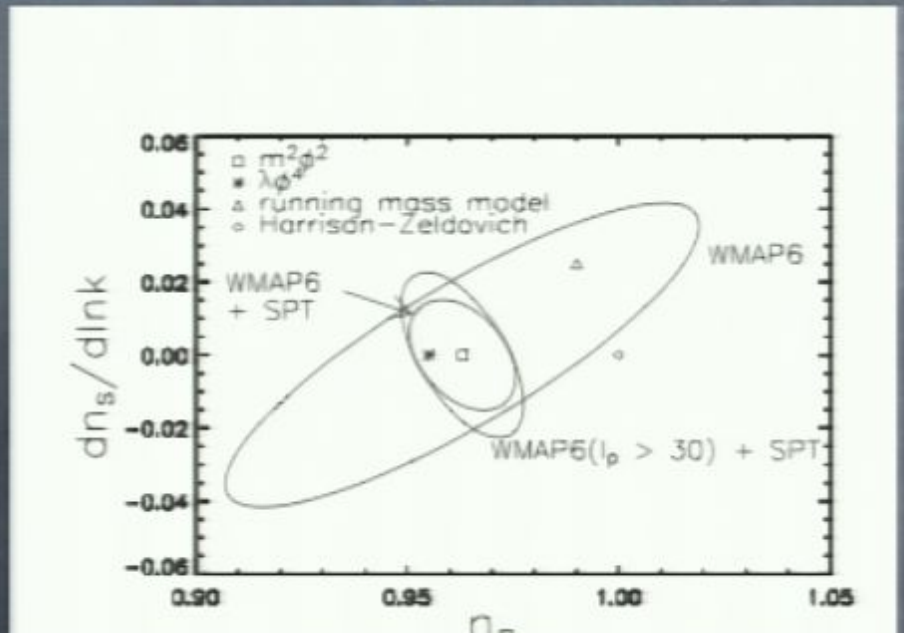
Science from Small Scale CMB

1. the damping tail.
   - Current limits on scalar spectral index degenerate with baryon density and reionization.
   - Direct high-l measurements break this.

   - Independent measure of curvature (cross-check)



More SPT Science

- Gravitation Lensing of the CMB
  - calibrate mass observable relationship
- kSZ
  - Dark Energy via pecular velocities
- Point sources
  - multi-color studies
  - AGN vs dusty galaxies
- Cluster science
  - gas emission past viral radius
  - properties vs redshift and mass

The South Pole Telescope (SPT)

Sub-millimeter Wavelength Telescope:

- 10 meter telescope (1' FWHM beam at 150 GHz)
- Off-axis Gregorian optics design
- 20 microns RMS surface accuracy
- 1 arc-second pointing
- Fast scanning (up to 4 deg/sec in azimuth)

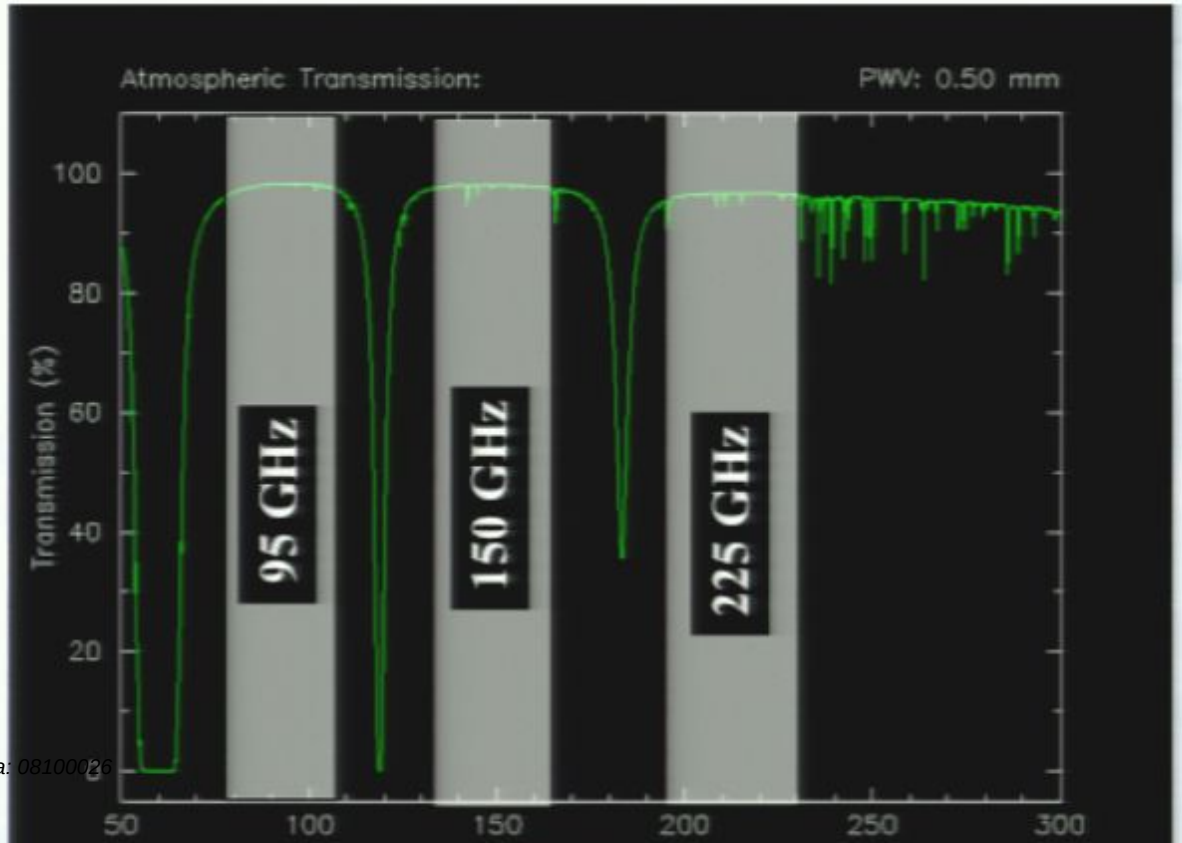
SZ receiver:

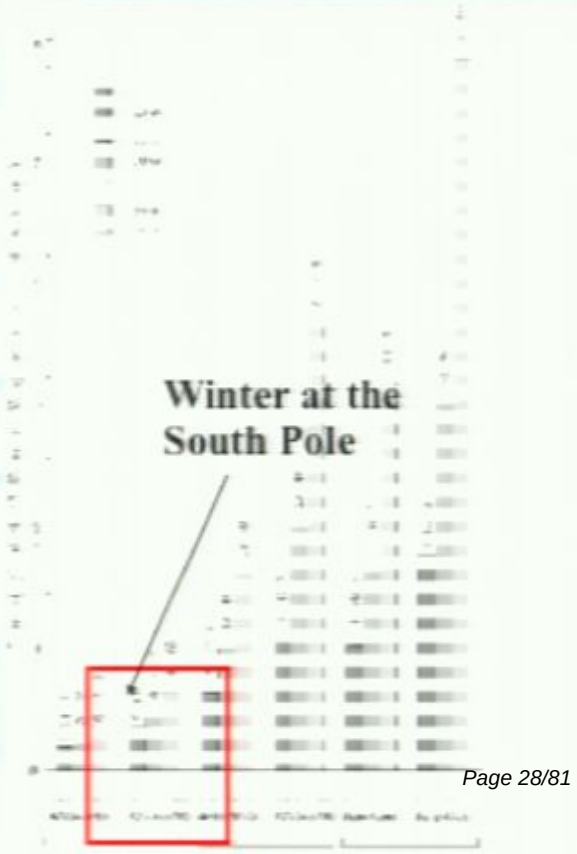
- 1 sq. deg FOV
- ~960 background limited pixels
- Observe in 3+ bands between 90-220 GHz simultaneously with a modular focal plane

Funded by NSF

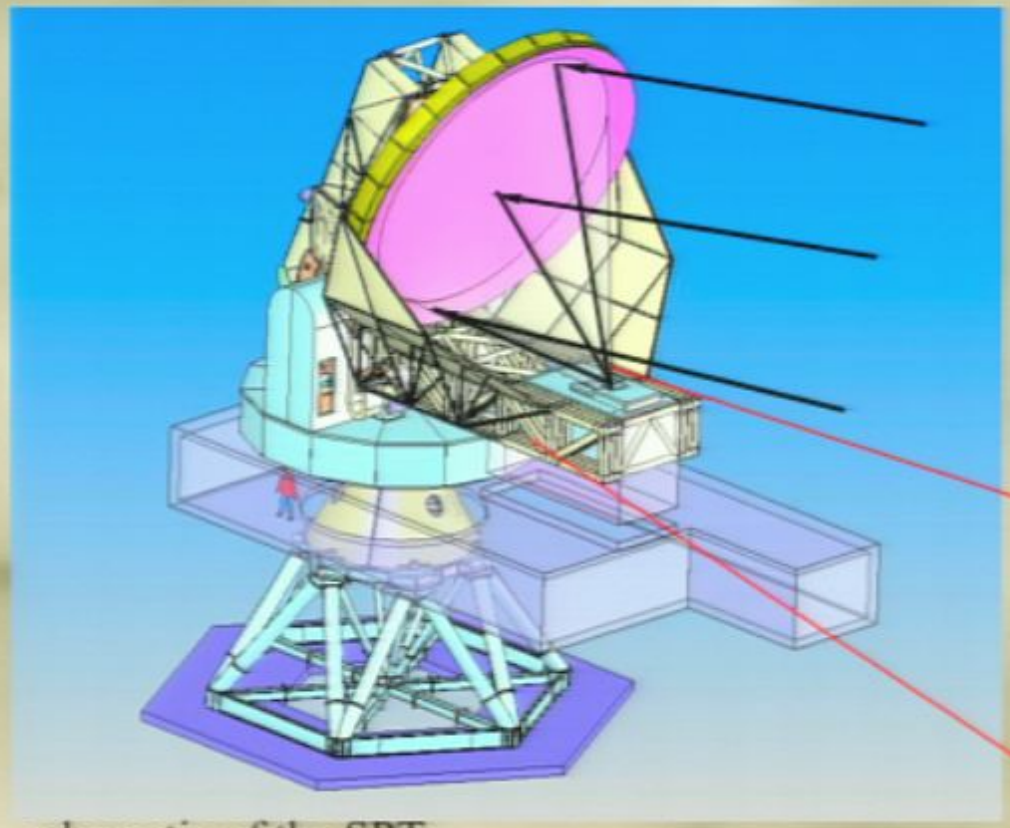
Why the South Pole?

- **High Elevation** (comparable overall transmission to Atacama)
- **Extremely Dry** (very little water vapor at -70C)
- **Stable** (no diurnal variations and low turbulence)
- **Low peak wind speed**





Telescope Design

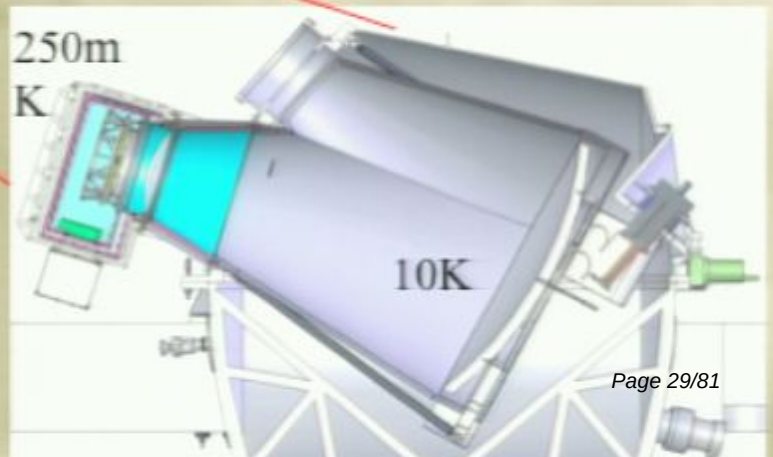


schematic of the SPT

Low noise, precision telescope

- 20 um rms surface over 10m
- arcsecond pointing
- arcmin resolution at 2 mm
- scan entire telescope
- 3 levels of shielding
  - 1 m radius on primary
  - inner moving shields
  - outer fixed shields

receiver + secondary cryostat



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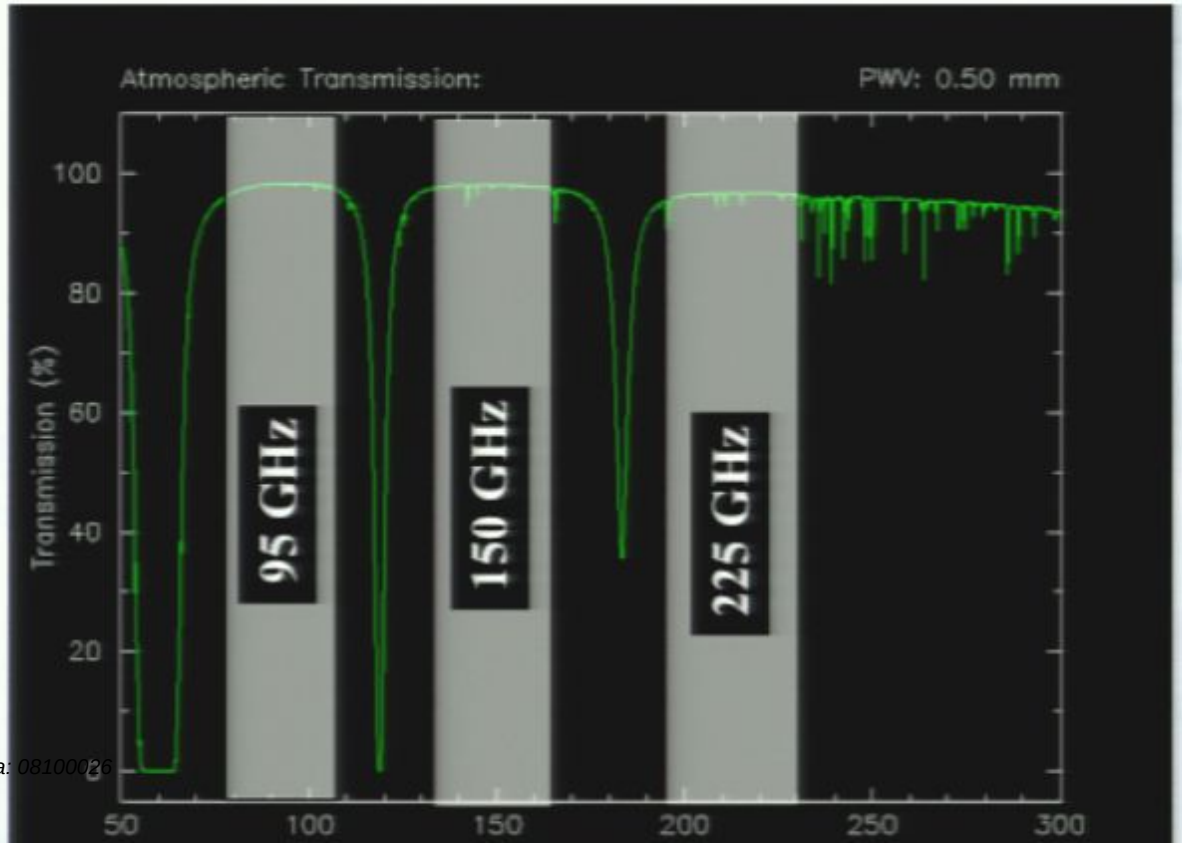

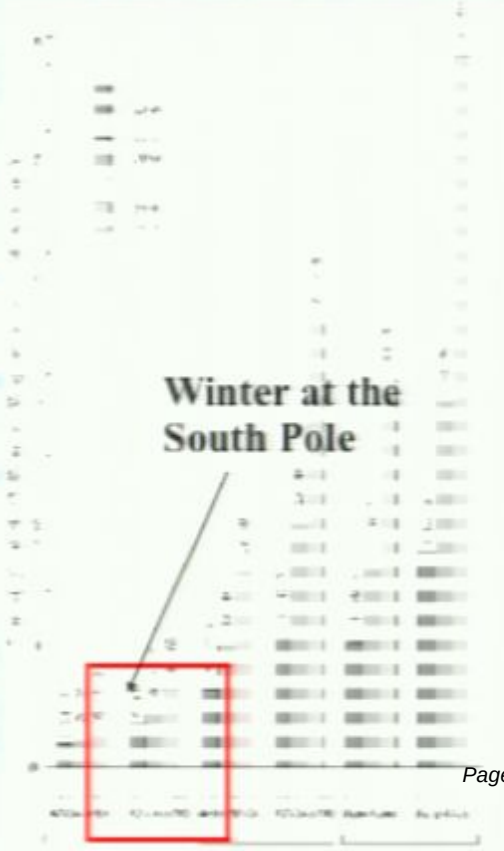

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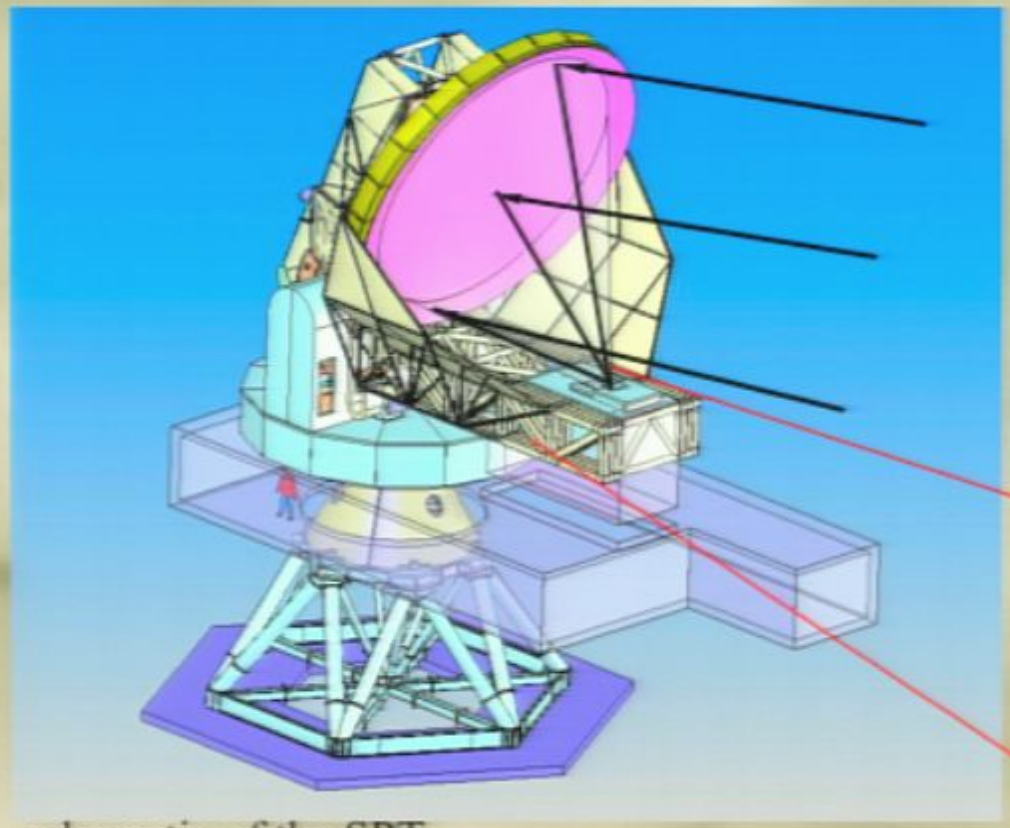

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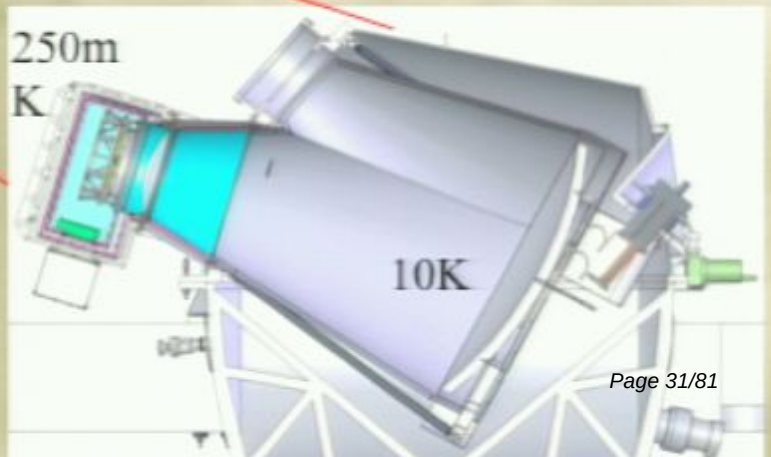
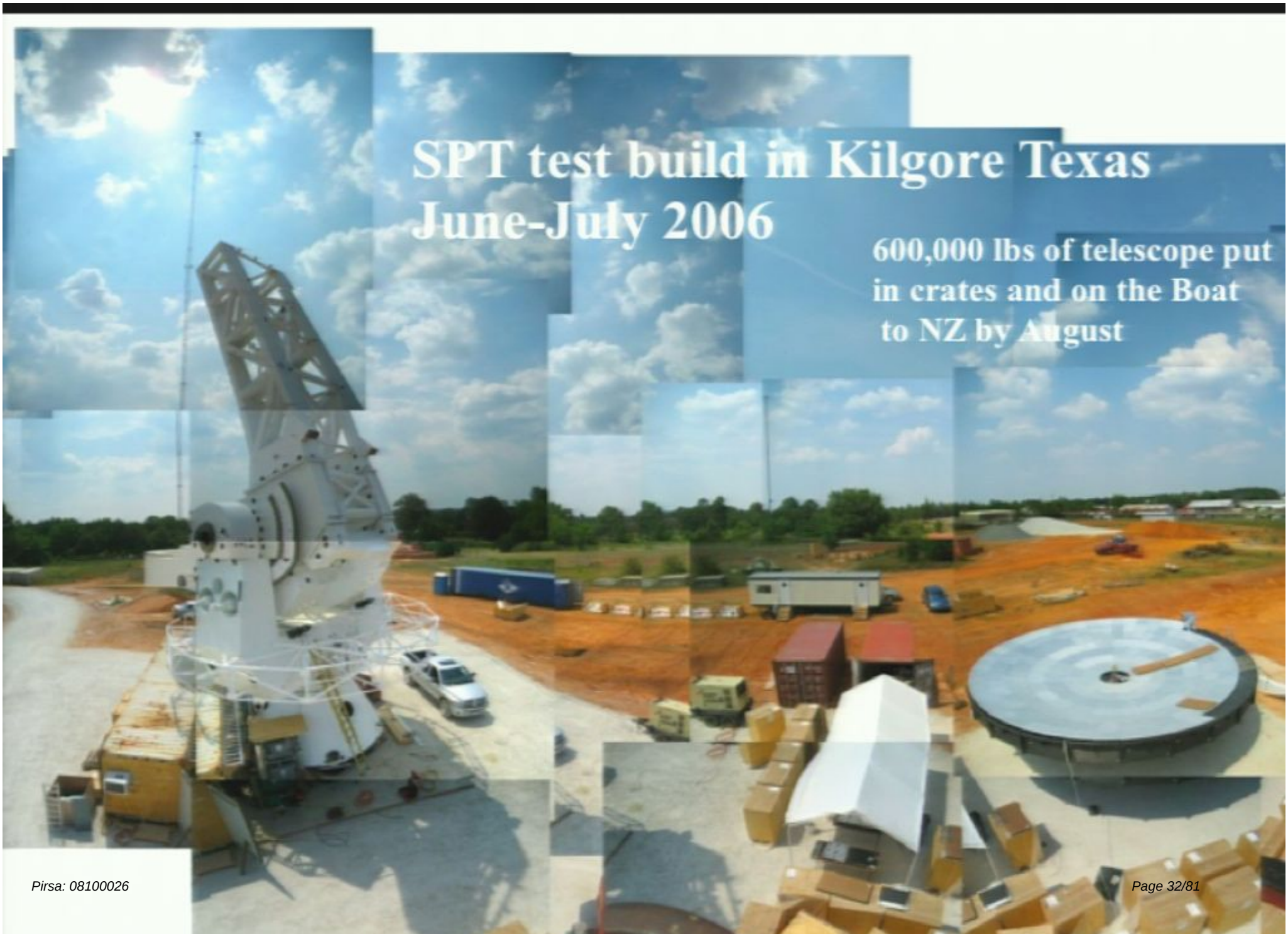
receiver + secondary cryostat




SPT test build in Kilgore Texas
June-July 2006
600,000 lbs of telescope put
in crates and on the Boat
to NZ by August


Only 16,000 lbs per LC-130
flight and 600,000 lbs of telescope.
U.S. AIR FORCE

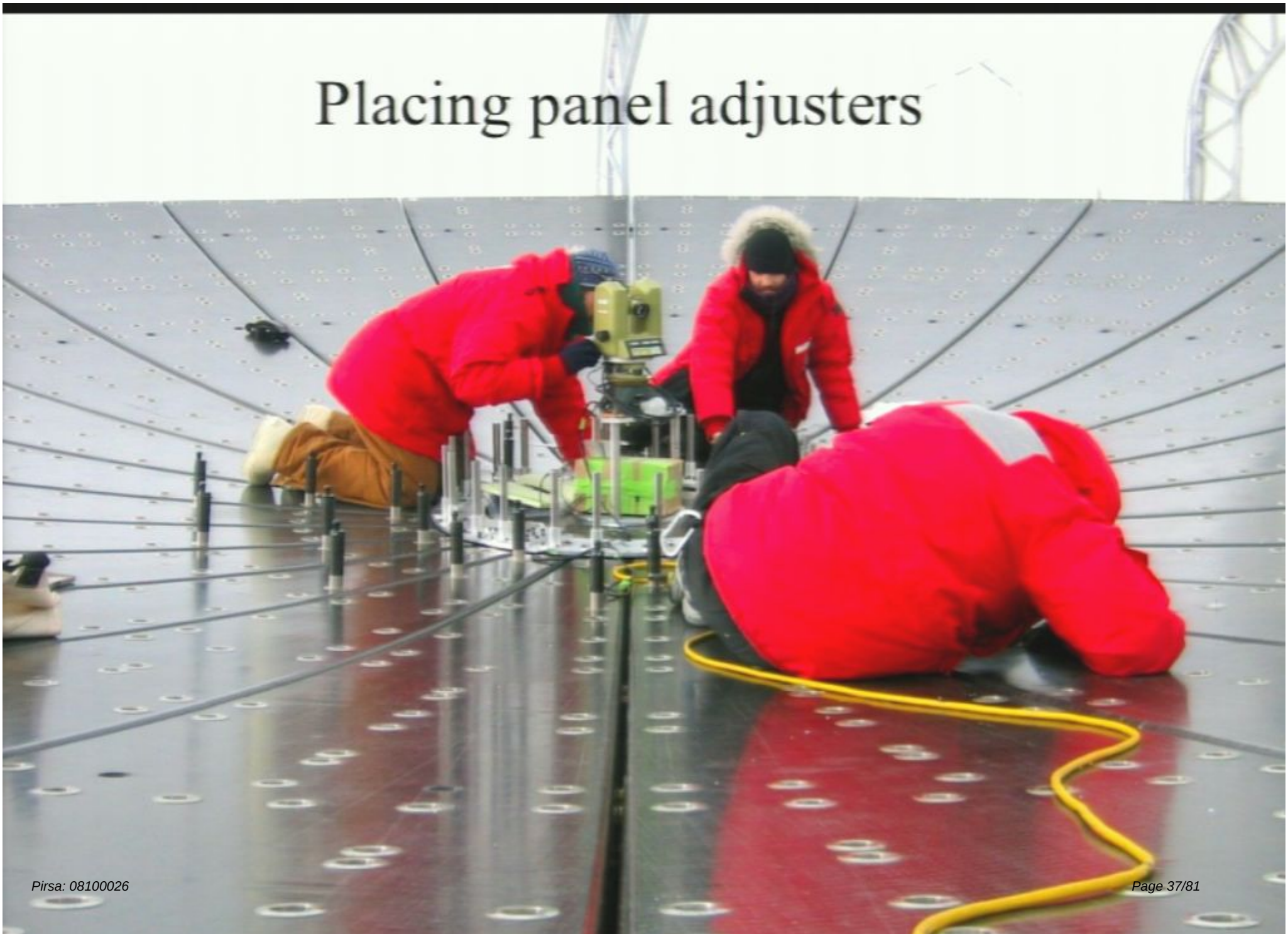

November 2006

Assembling the BUS

South Pole Transportation

- Nov 20, 2008

Placing panel adjusters



Installing reflector panels

Finished?

Wiring up Heaters

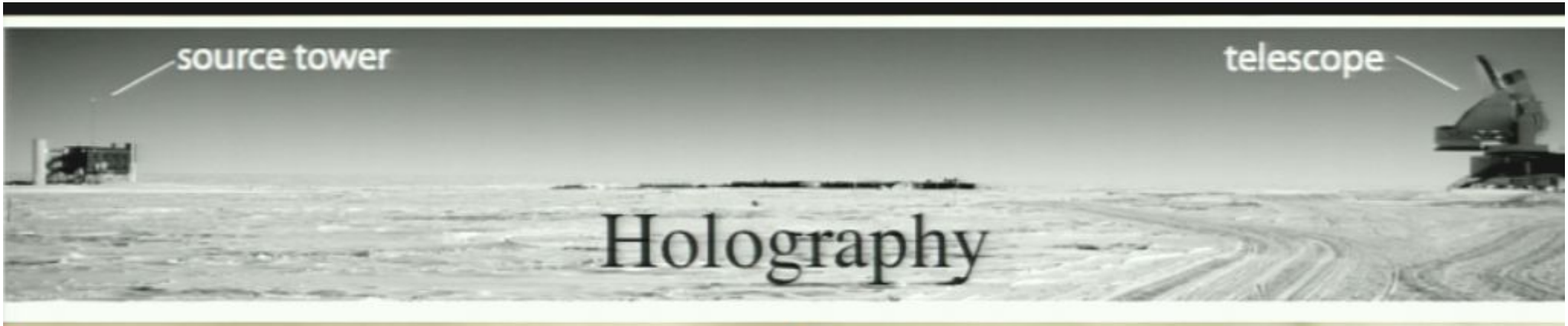
The BIG lift

precision and percussion
cosmologists pause for the
“hero” shot

cosmologists

steel-crew

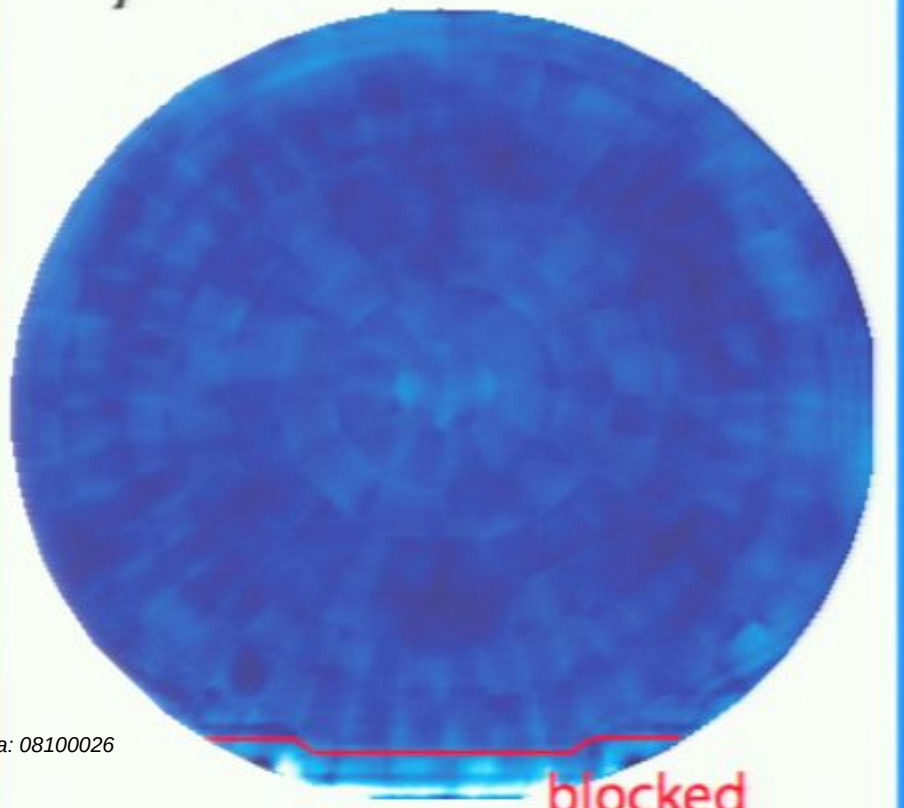
Hundreds of photographs. Thousands of screws



Holography

Primary Mirror

25 μ rms



$$f(R,u,v) = \int_{\Sigma} \frac{F(\xi,\eta)e^{-ikr}}{4\pi r}\left[\left(ik+\frac{1}{r}\right)\hat{z}\cdot\hat{r}+ik\hat{z}\cdot\hat{k}\right]d\xi d$$

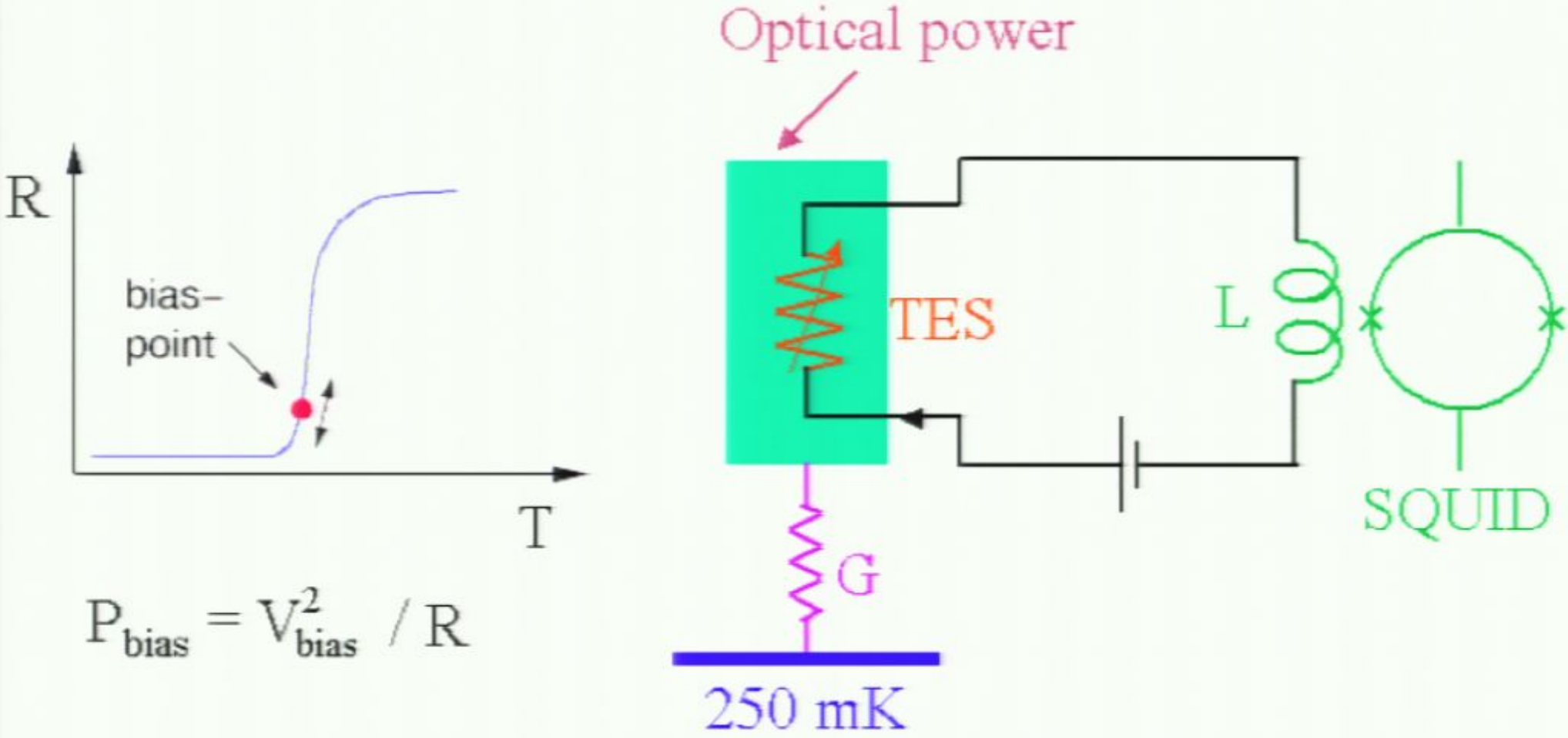
- *fields on the aperture (F) related to fields in space (f)*
  - *(fields in space = diffraction pattern)*
- *a perfect parabolic mirror has constant phase on the aperture*
- *measure f solve for F, interpret the phase(F) as errors in the mirror surface*

Austral Summer 2006-2007: camera

assembled an
commissioned
in 1.5 months

lead by UC
Berkeley

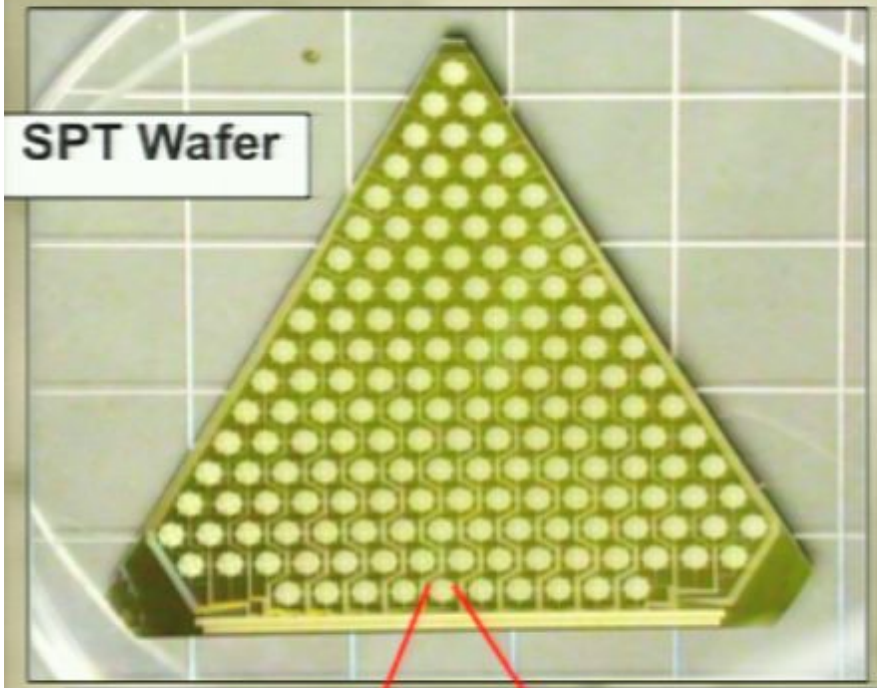
Transition-Edge Sensor (TES) Bolometers



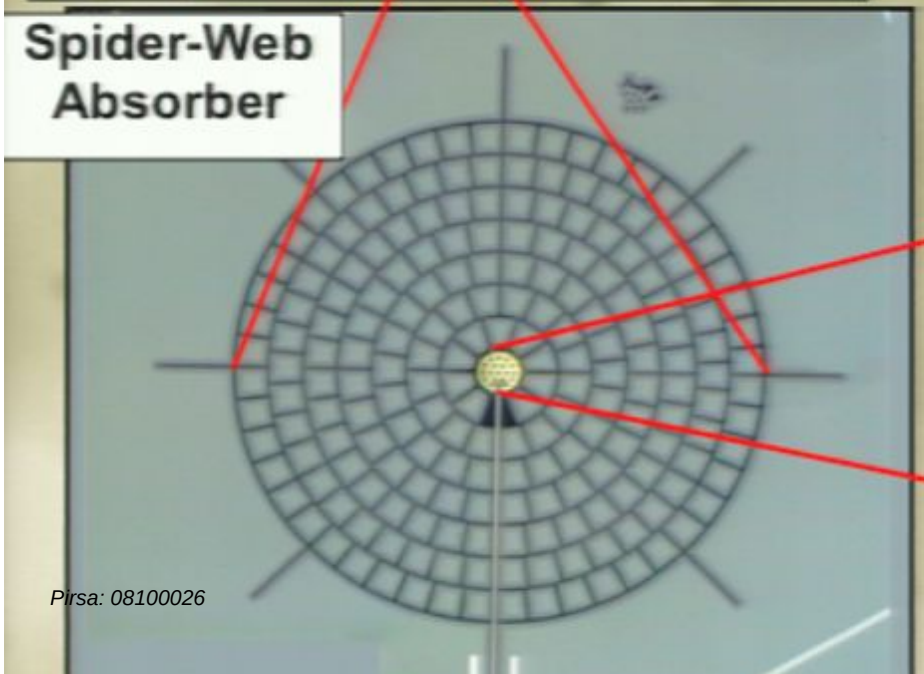
$$P_{bias} = V_{bias}^2 / R$$

$$P_{total} = P_{bias} + P_{photon} \approx \text{constant}$$

SPT Detector Wafer

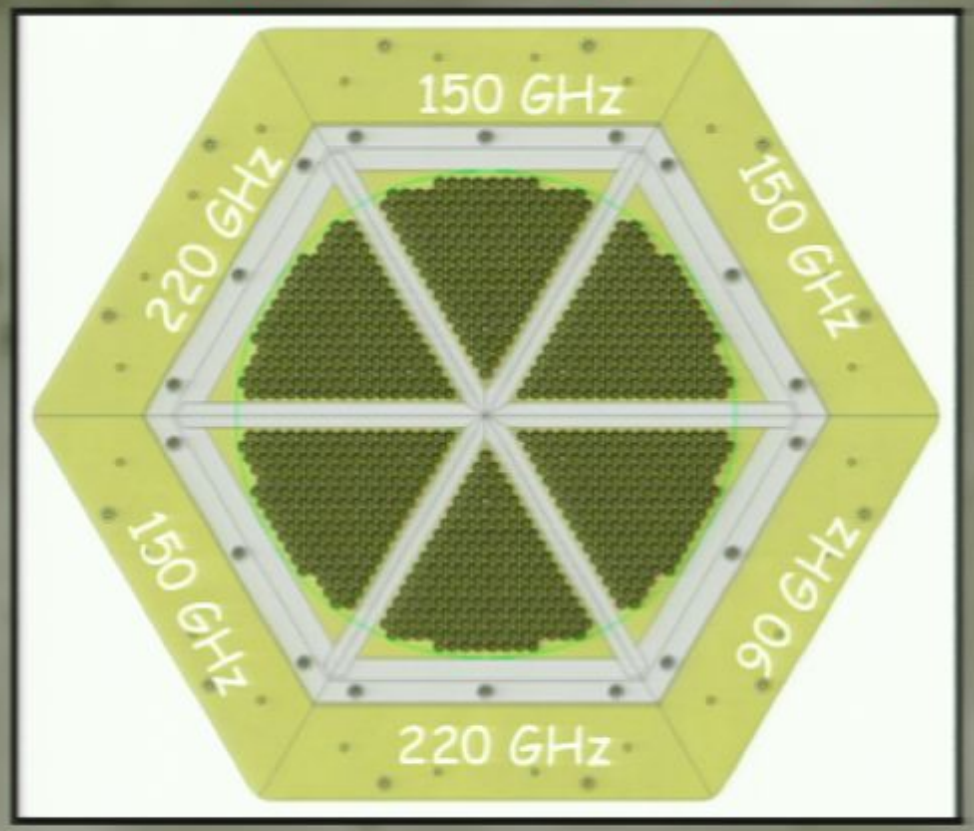


- *160 bolometers per wafer*
- *Al-Ti bi-layer Transition Edge Sensor (TES) with Tc = 0.55 K attached to spider-web shaped absorbing substrate*
- *Optical time constant of 10 ms*
- *Electrical time constant in transition of 1 ms*
- *Wafer thickness tuned to frequency bands*

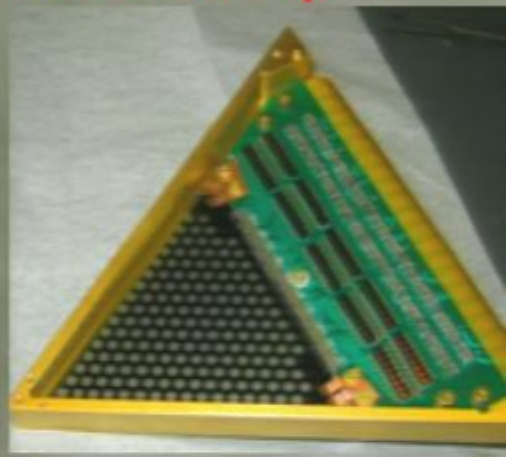


The SPT 966 pixel detector array

180 mm: ~1 degree on sky



Built at UC Berkeley



- 161 possible channels on each wedge, 8x multiplex
- Transition Edge Sensor bolometers with Tc ~500mK

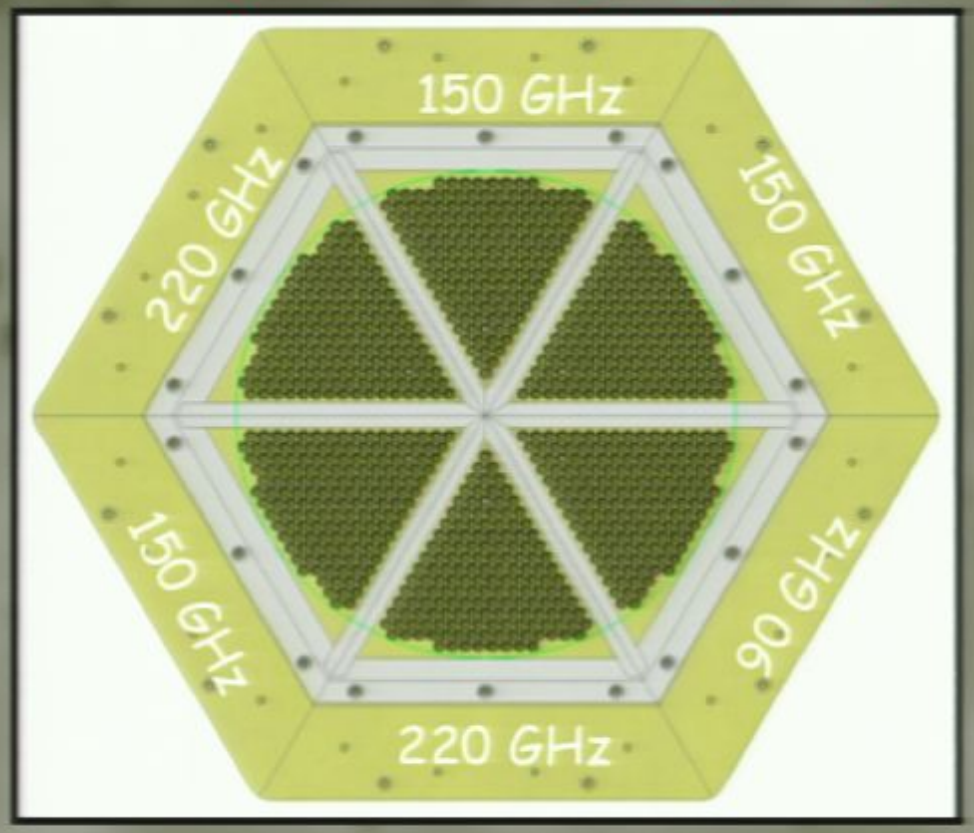
Installing Receiver and Optics Cryostats into the SPT Receiver Cabin

Don’t have to go outside!


Moving Ground Shield installed
Ready to observe!

The SPT 966 pixel detector array

180 mm: ~1 degree on sky



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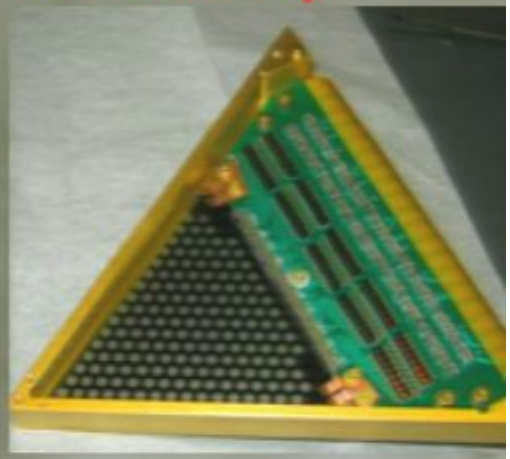

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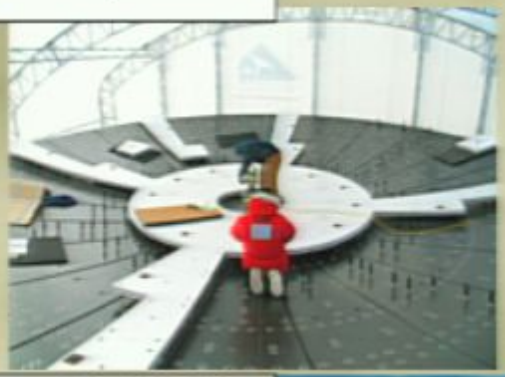
SPT 1st Year Deployment

Dec 14, 2006



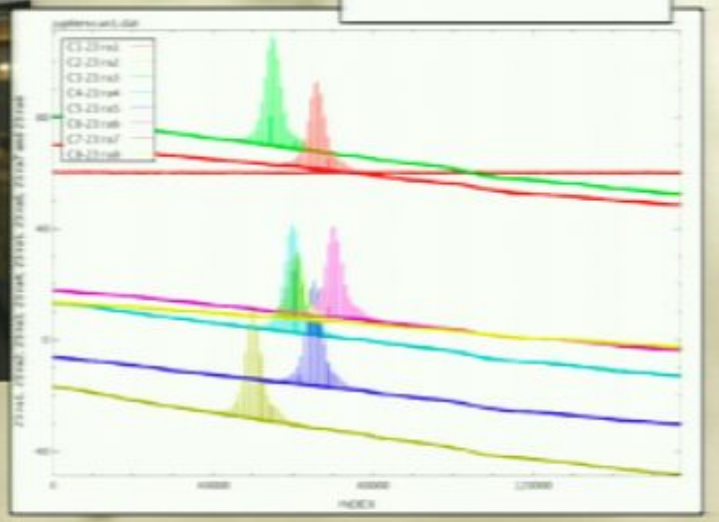
Dec 16, 2006

Jan 3, 2007

- Nov 20, 2006 Begin telescope + reflector assembly
- Jan 5, 2007 – Primary Mirror mounted on Telescope
- Jan 20, 2007 - Reflector surface aligned 40μ rms
- Feb 12, 2007 - Receiver mounted on Telescope
- Feb 16, 2007 - First Light = Scans of Jupiter
- Feb 17, 2007 - Kicked out of South Pole

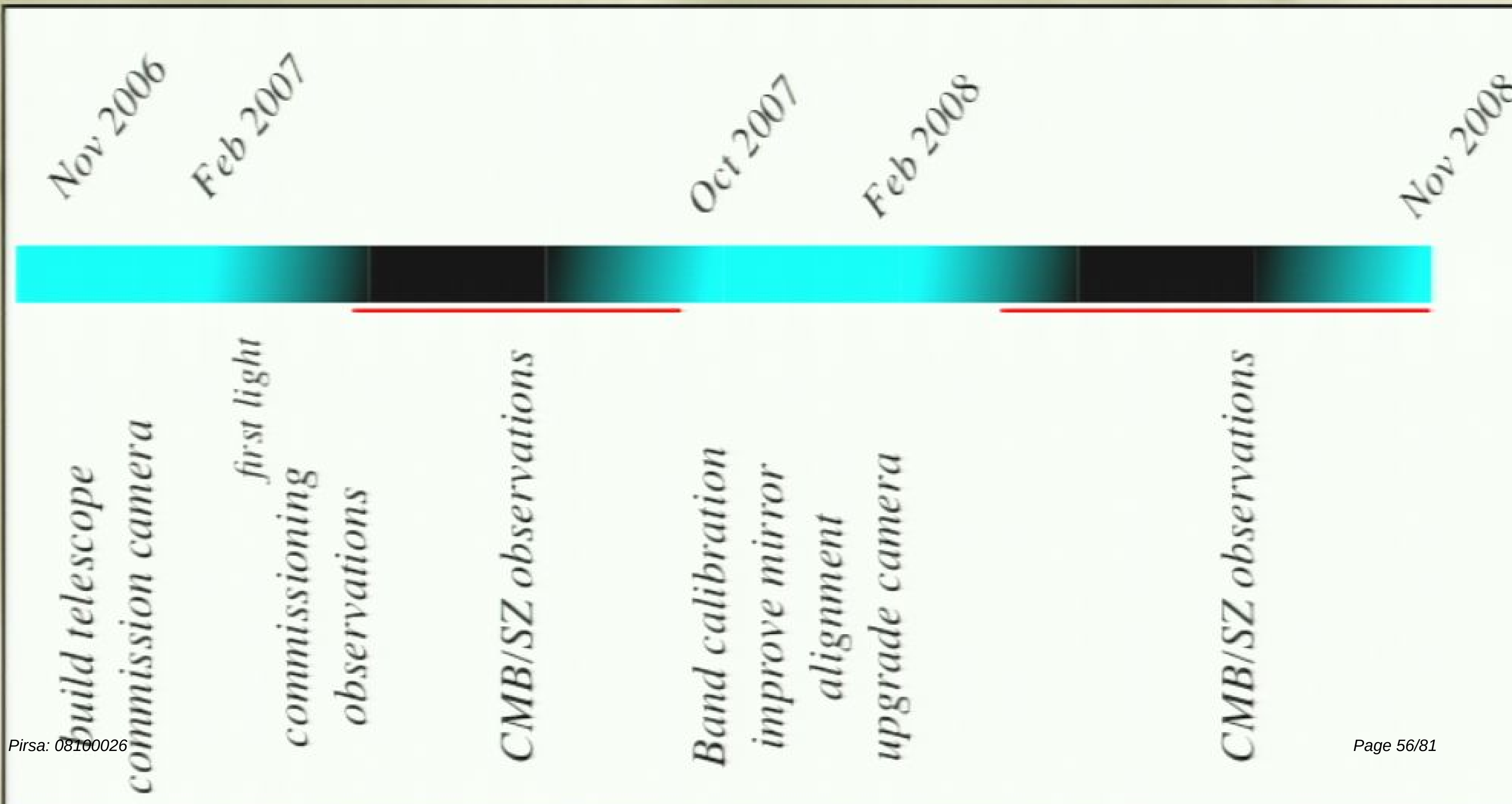
Feb 12, 2007

Feb 16, 2007



Telescope and Receiver Team 2006-2007

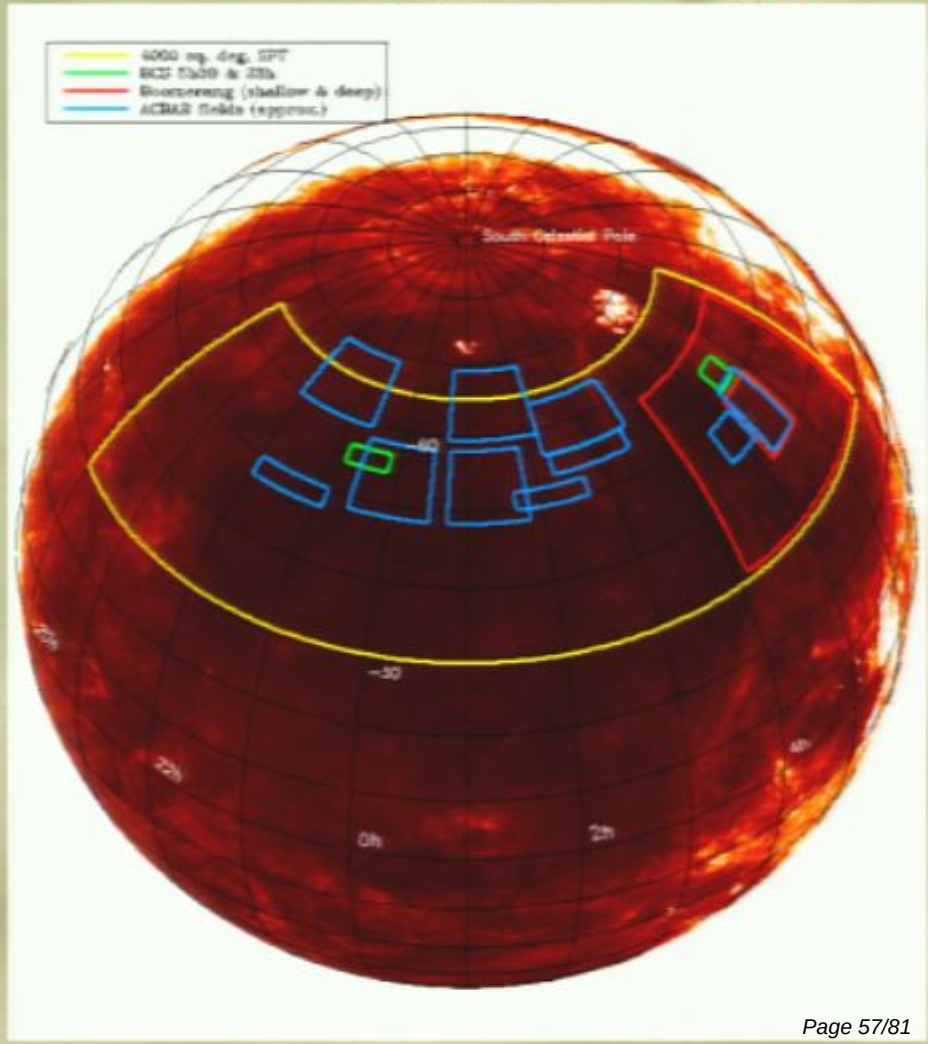
TIME LINE



Nov 2006
Feb 2007
Oct 2007
Feb 2008
Nov 2008
build telescope
commission camera
first light
commissioning
observations
CMB/SZ observations
Band calibration
improve mirror
alignment
upgrade camera
CMB/SZ observations

The Survey

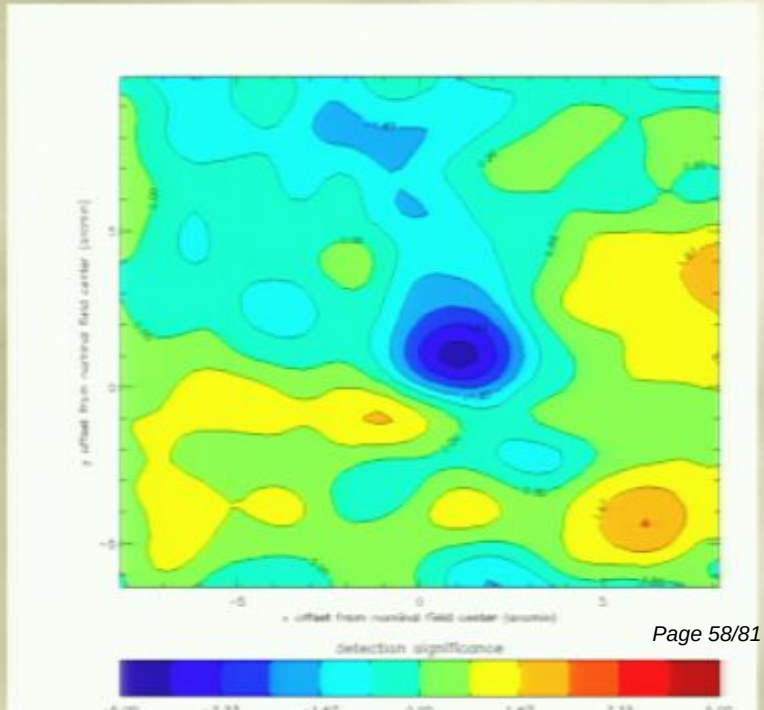
- *Limited to Southern Celestial Hemisphere.*
- *Galactic dust emission drives to 20h < RA < 7h.*
- *Atmospheric emission drives to observing elevations > 30deg.*
- *Leaves us ~4000 contiguous square degrees*



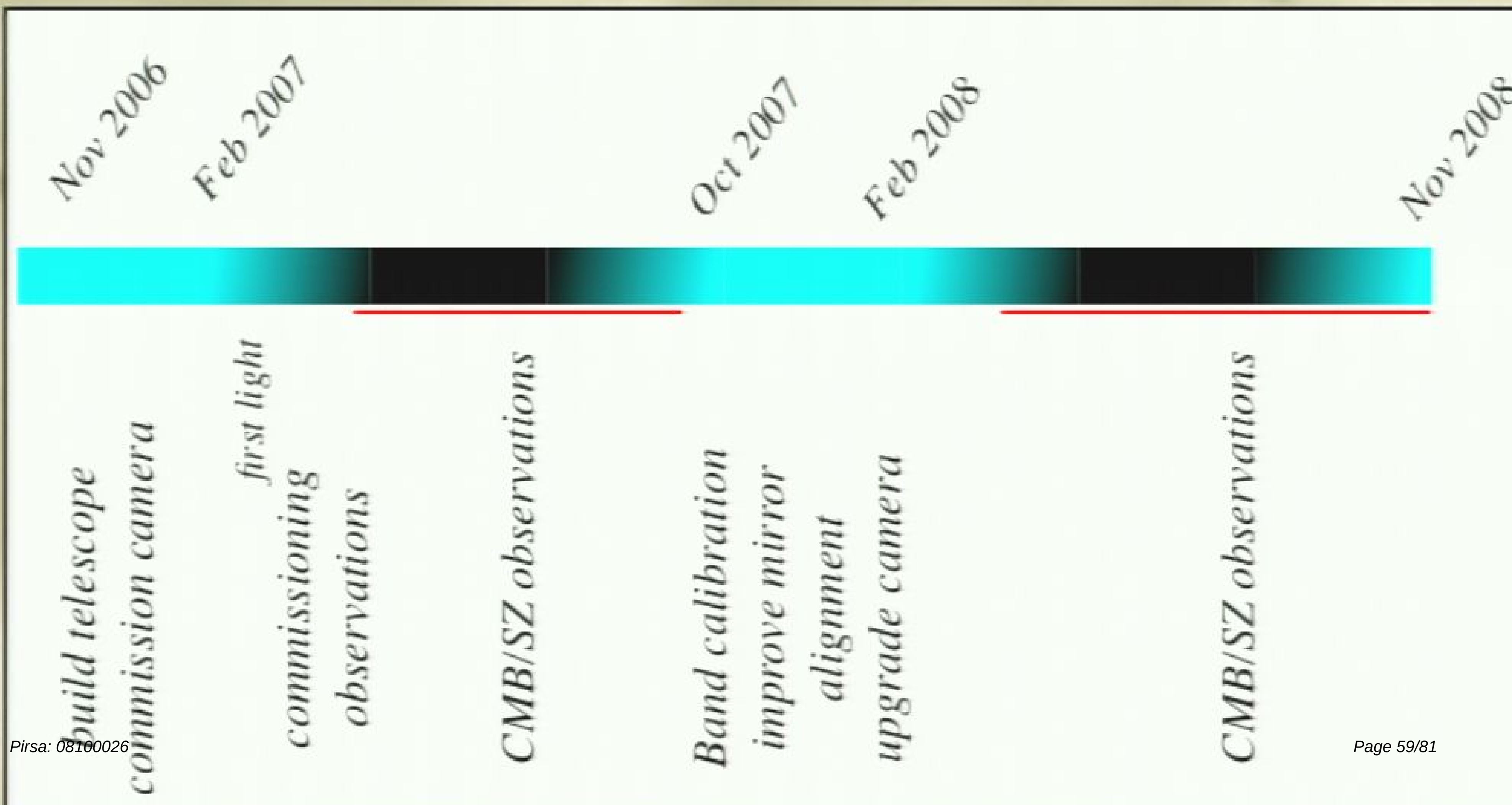
2007 Performance

- 1st year (mostly engineering)
  - 60 sq. degrees in BCS 5hr
    - 40 μK/arcmin
  - 5 sq. degrees inside previous region
    - 15 μK /arcmin
- 90 and 150 GHz channels working well
- noise slightly higher than expected, (but still better than anything previous)

•First SPT SZ measurement cluster AS1063
•Map uses both 95 and 150 GHz data
•5 sigma detection in 1 hour



TIME LINE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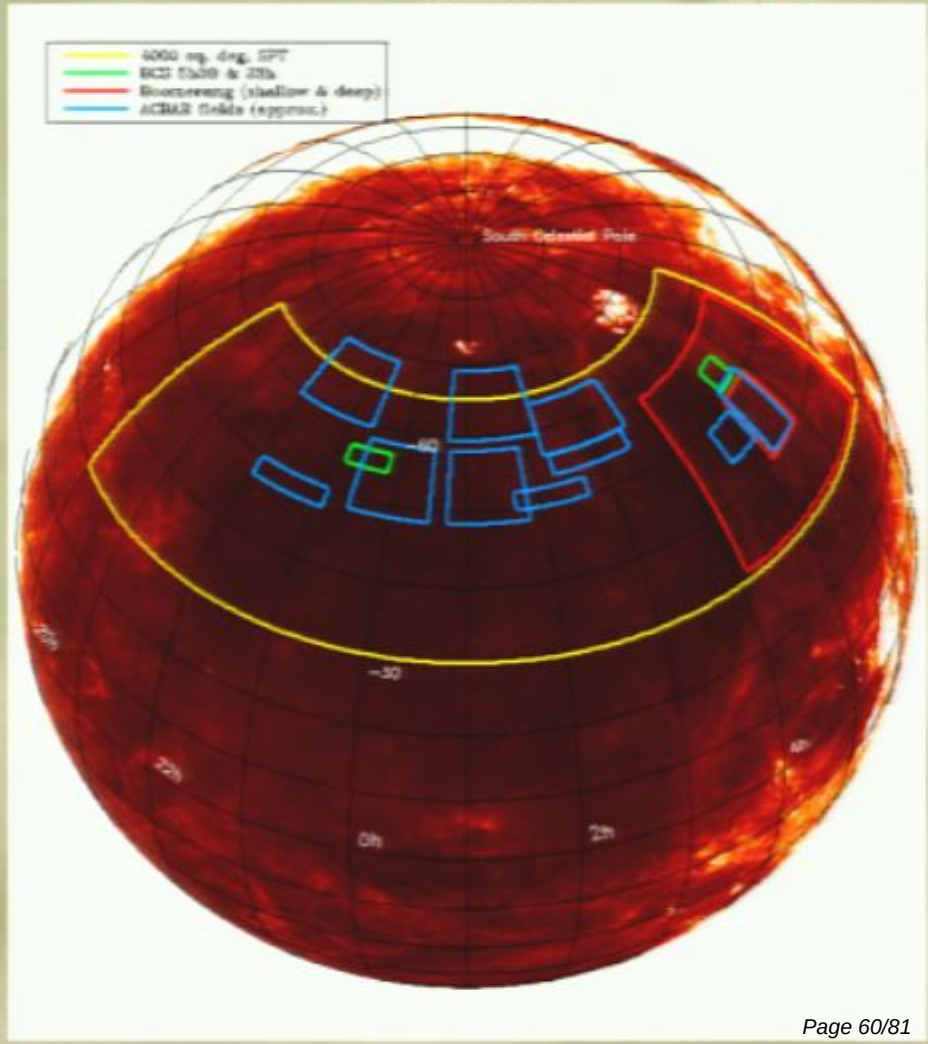

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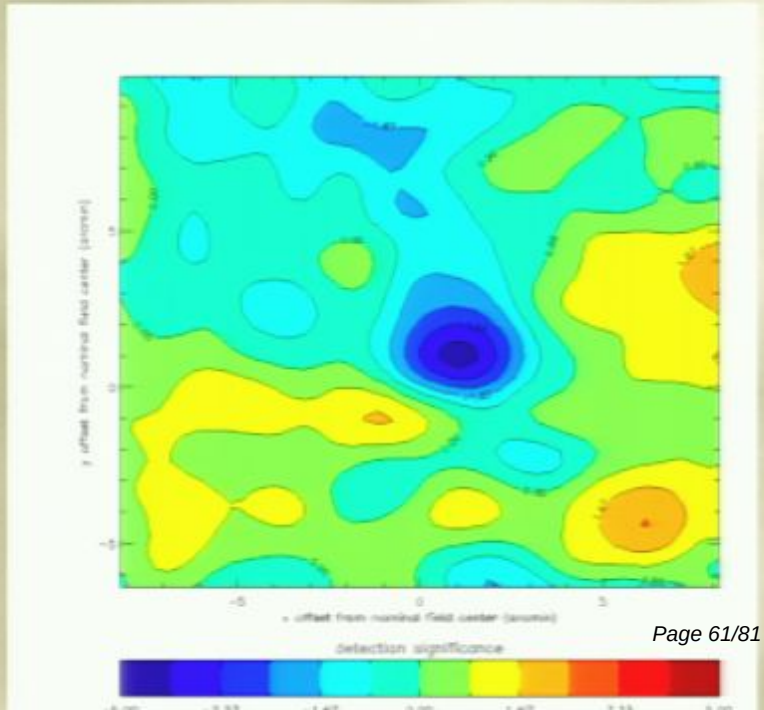


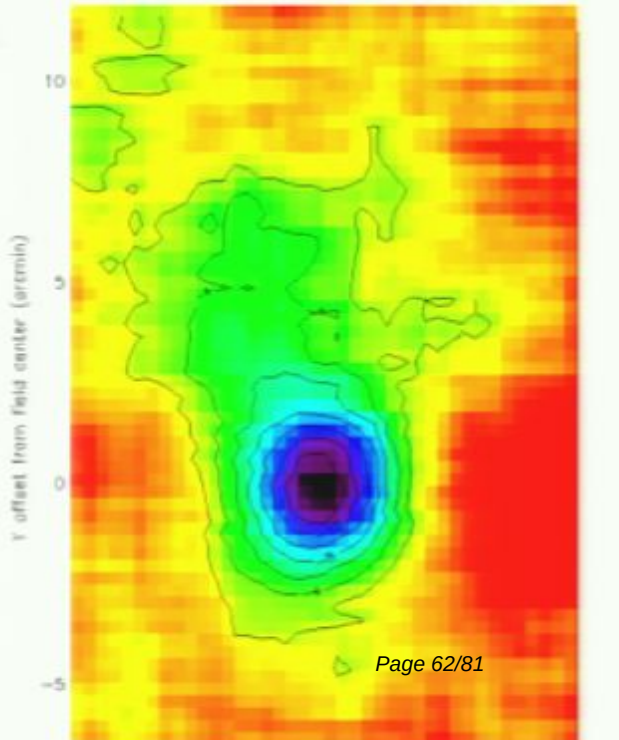
Upgrades before 2008

- *2007-2008 summer*
  - *Improved primary mirror to 20 μm rms*
  - *Improved camera sensitivity*
    - *150 GHz (~500 uK /rt(HZ) cmb) w/ 350 detectors!*
    - *220 GHz (~700 uK /rt(Hz) cmb) w/ 200 detectors!*
- *Improved cryogenics*
  - *dewar cold ~36 hours at a time*

•First SZ measurement of 2nd observing season, cluster AS1063

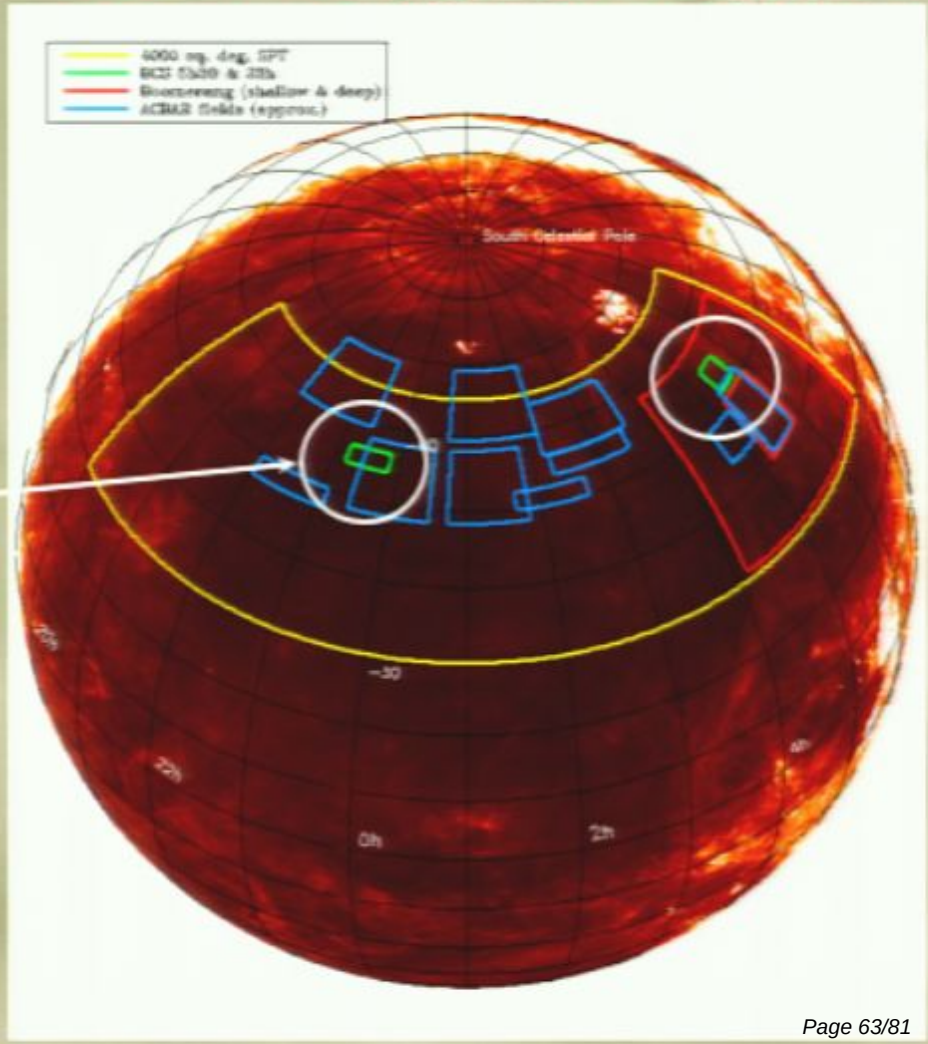
•Map uses only 150 GHz data, 321 detectors, 40 minute observation

•16 sigma detection (contours are eve
2 sigma



The 2008 Survey

- *Expected survey duration: Now - September, 2011.*
- *Currently going deep on 100 sq. degrees (RA=5h30, dec=-55)*
- *150GHz depth in both 100-sq.-deg. field ~15uK.*
- *220GHz depth in 100-sq.-deg. field ~40uK.*



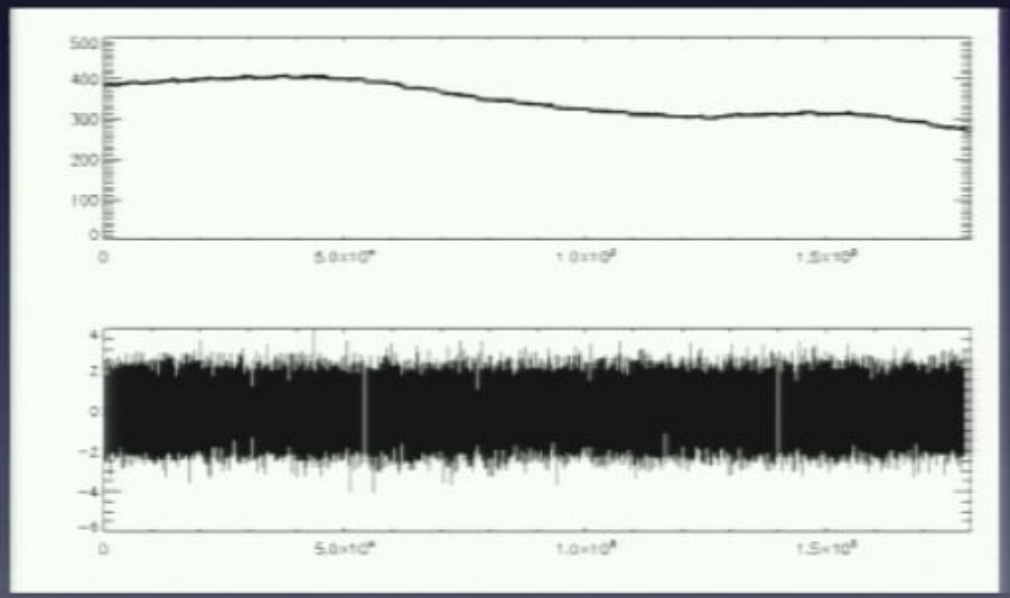
Analysis of Survey Data

- It is simple*
  - Time streams to maps
  - maps to cluster candidates

* completely understanding 'simple' things requires great care

Data processing

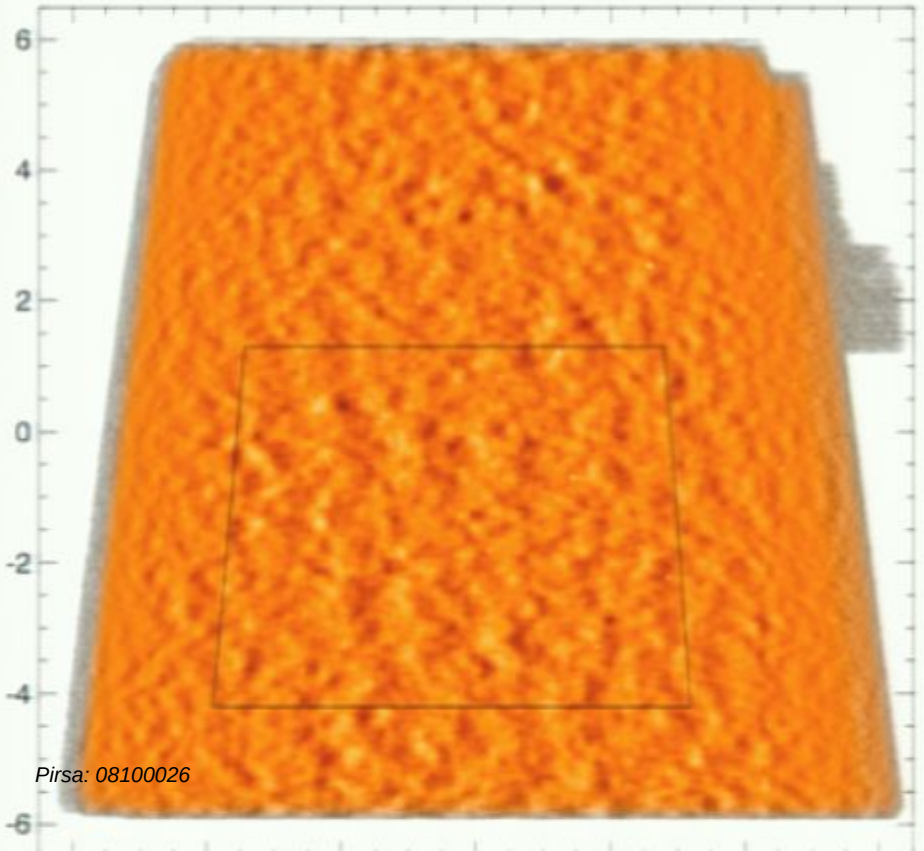
- Undo detector time response.
- De-spike.
- Fourier-domain filtering.
- Remove long-timescale drifts.



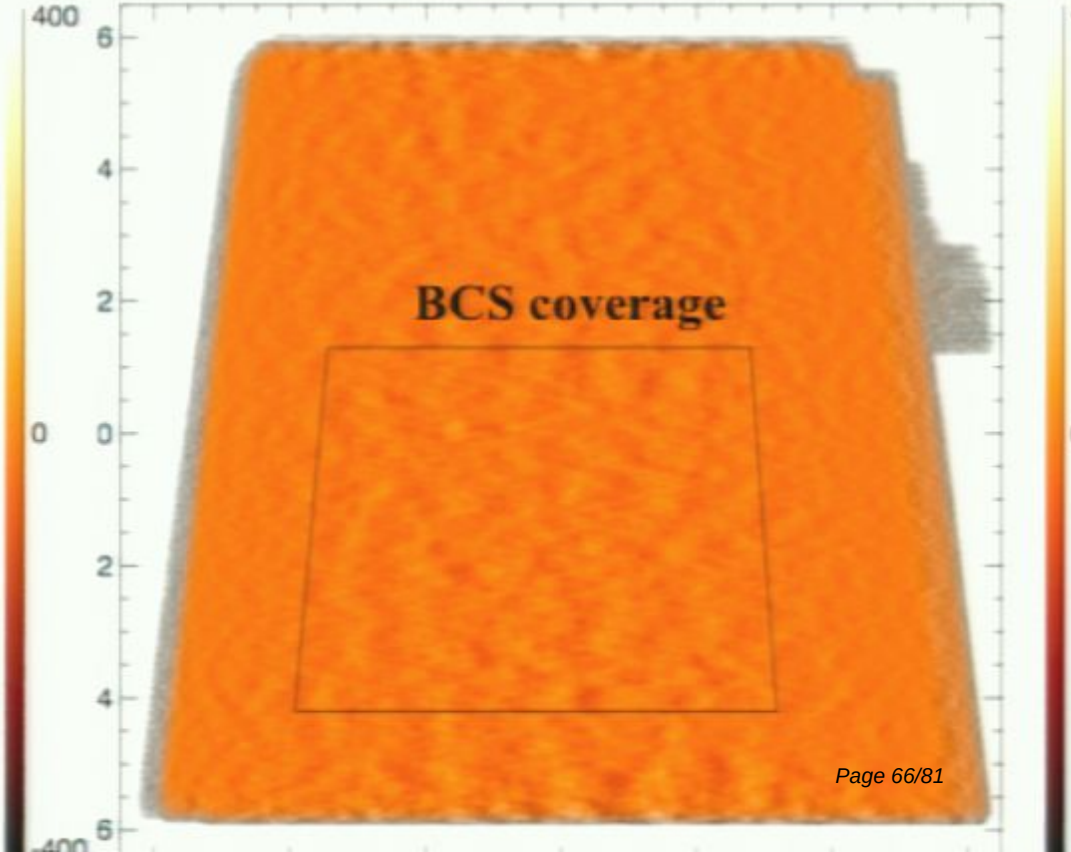
First Survey Field RA~ 23 Hours

- Mapped with interleaved azimuth raster scans
- ~800 hours of observation
- 100 deg^2 ~17 uK/arcmin pixel
- 60 deg^2 overlap with BCS

150 GHz L+R map



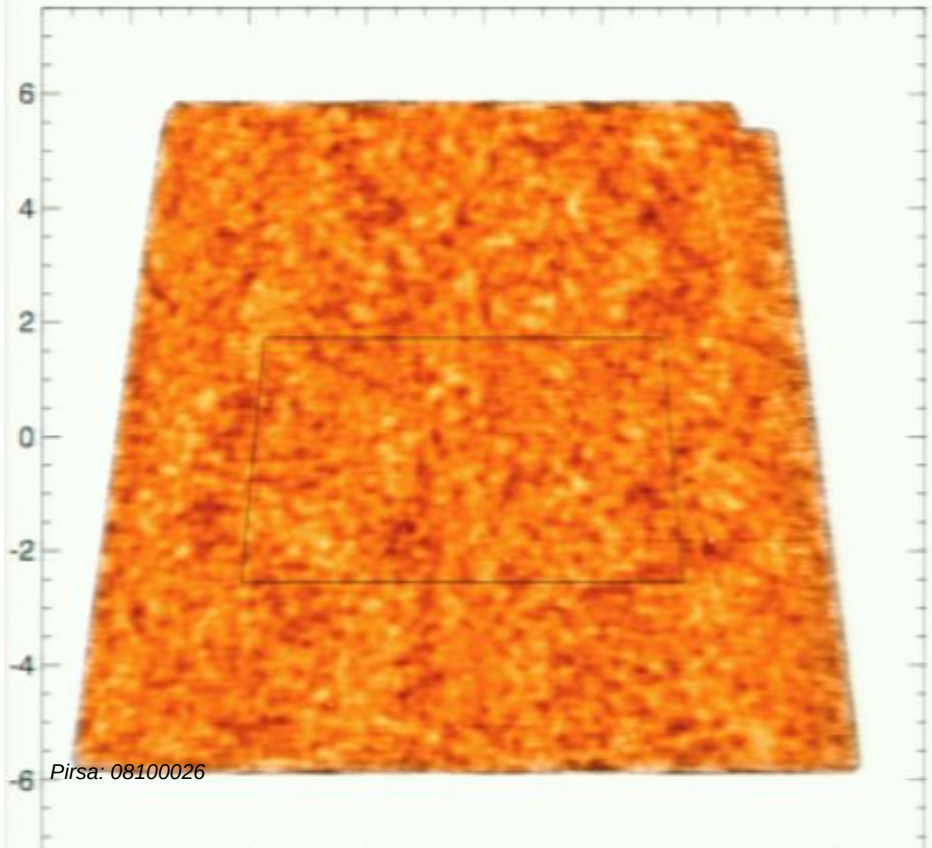
150 GHz L-R map



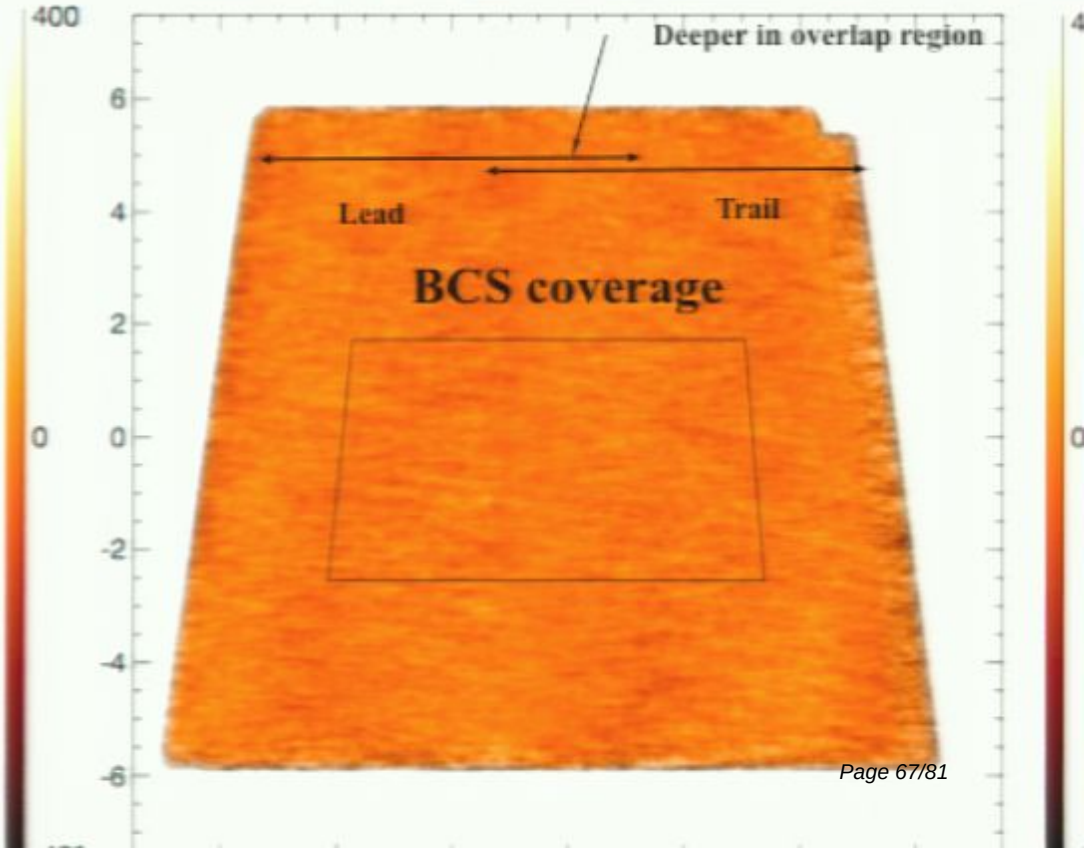
Second Survey Field RA~ 5 Hours

- Mapped with alternating Lead/Trail azimuth raster scans
- ~1000 hours of observation (so far)
- 100 deg^2 ~15 uK/arcmin pixel
- 40 deg^2 overlap with BCS

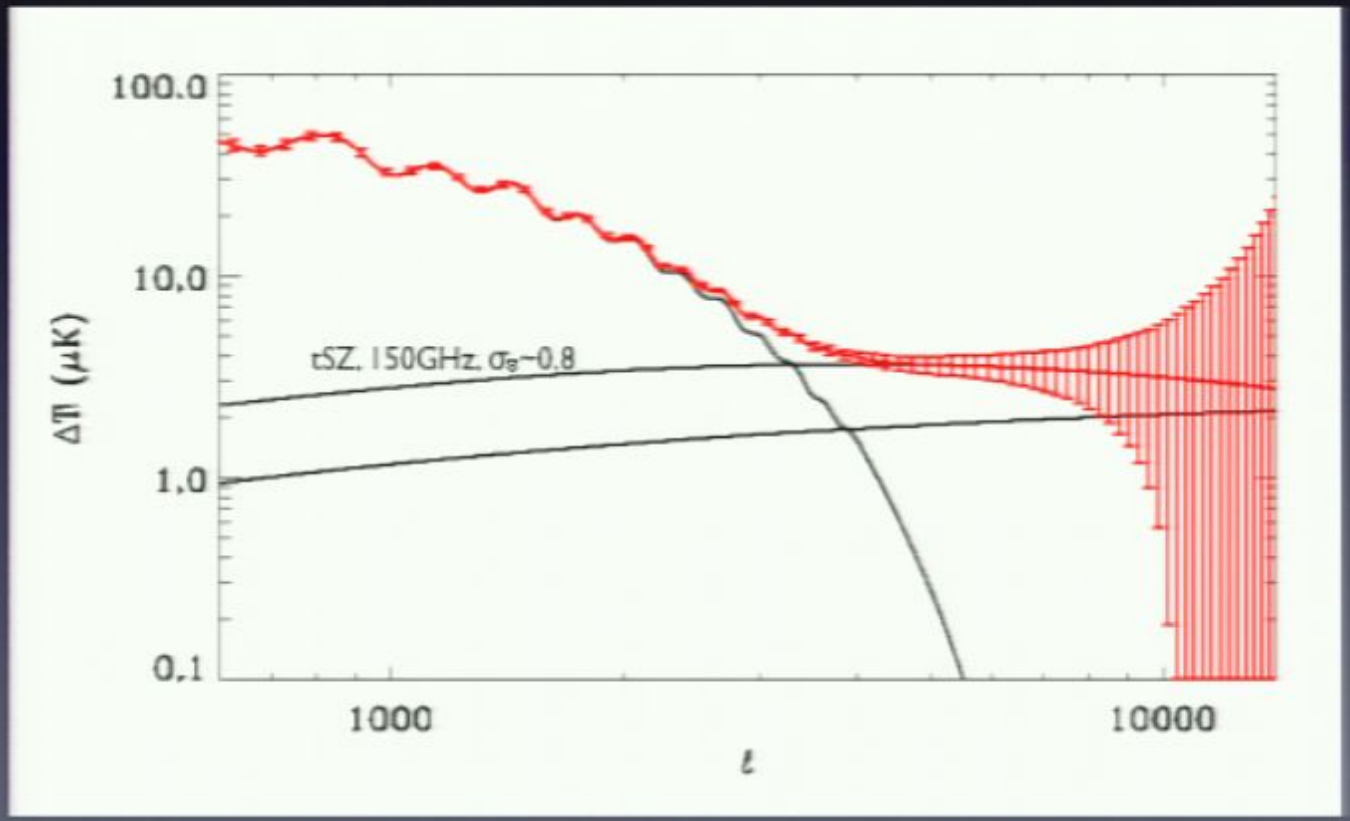
150 GHz L+R map



150 GHz L-R map



Power spectrum forecast for 100 square degrees



working to understand noise, calibration, point sources, ...

Identifying SZ Clusters in the SPT maps

CMB & PS dominate the maps (clusters buried in the mix)

Apply matched filter to maximize S/N on clusters.

Matched filters 101

Linear filter designed to maximize the S/N of a known source given a noise model.

For noise covariance matrix N, and signal template S, the matched filter is:

$$\psi = \frac{S^T N^{-1}}{\sqrt{S^T N^{-1} S}}$$

N would include the CMB, foregrounds (dusty IR galaxies, radio), instrumental and atmospheric noise.

For SPT: S is assumed to be a β-model, Nagai profile, or Gaussian.

Melin et al., 200

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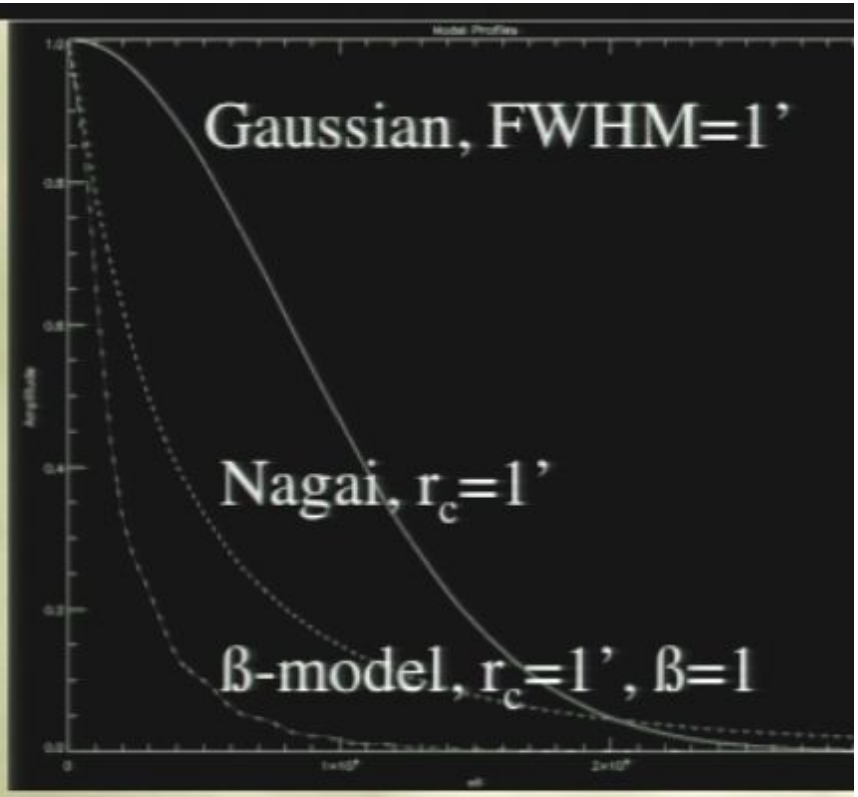
Signal template:
Cluster models

- Start with ß-model, modified NFW profile, or Gaussian.



- Convolve with estimate of filtering + beam convolution on a delta function

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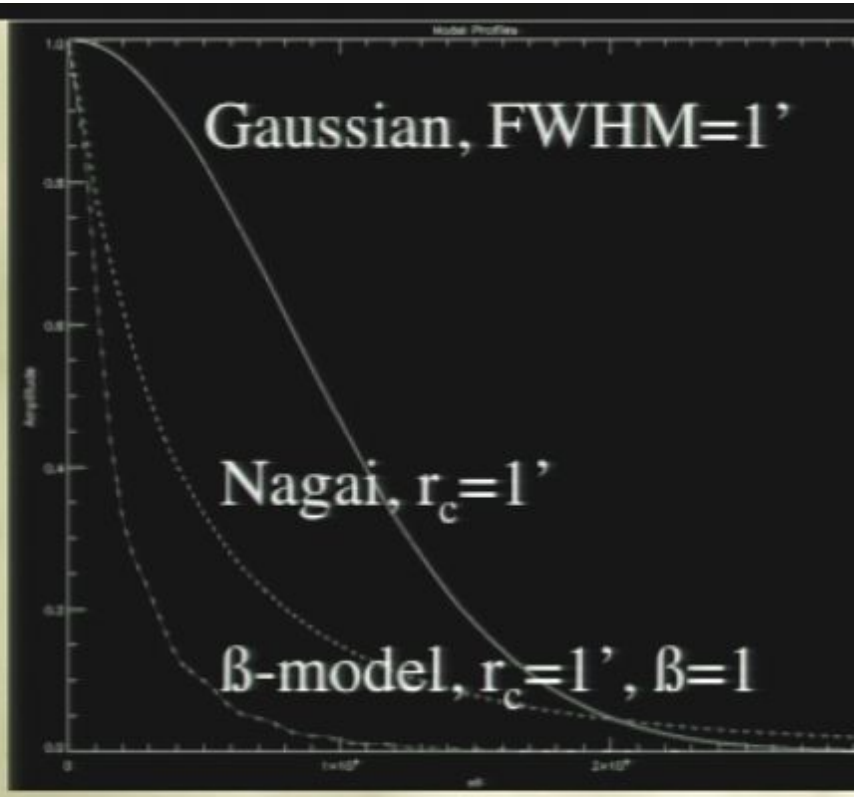

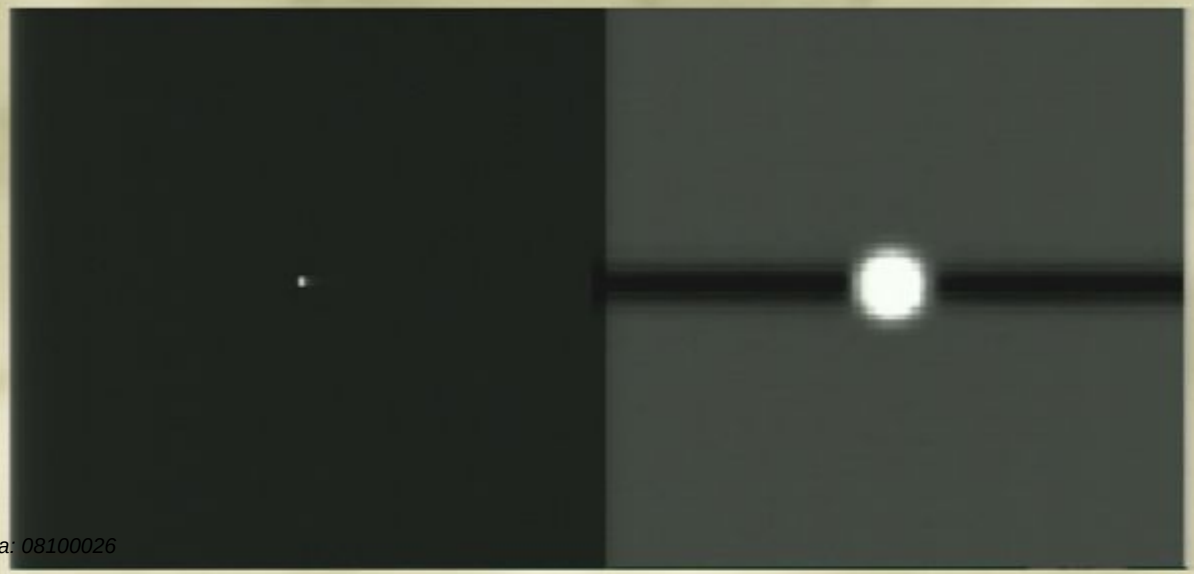

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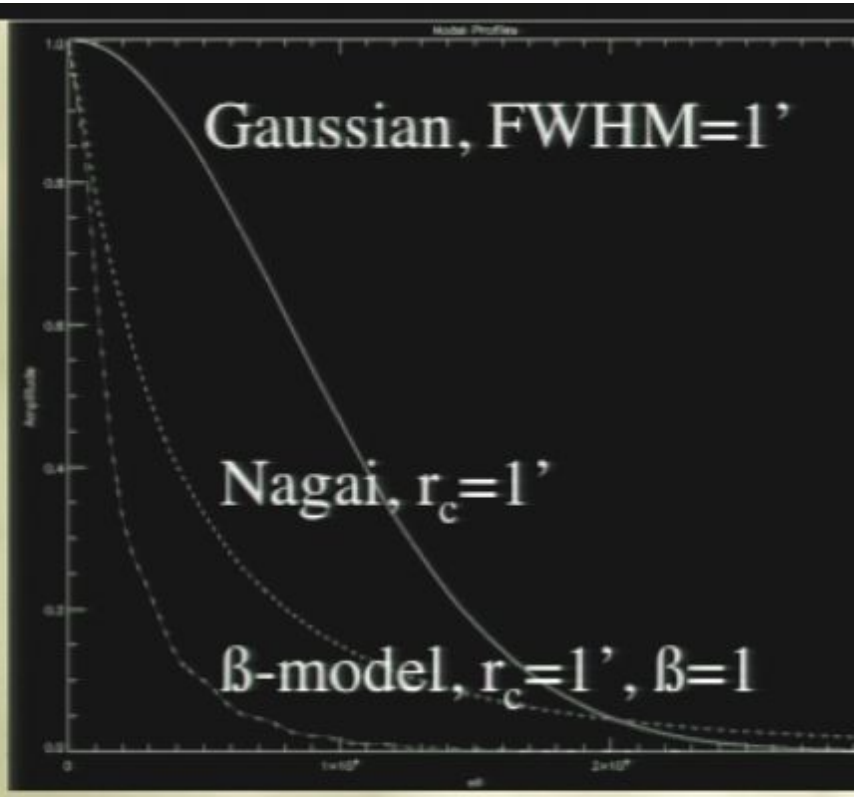
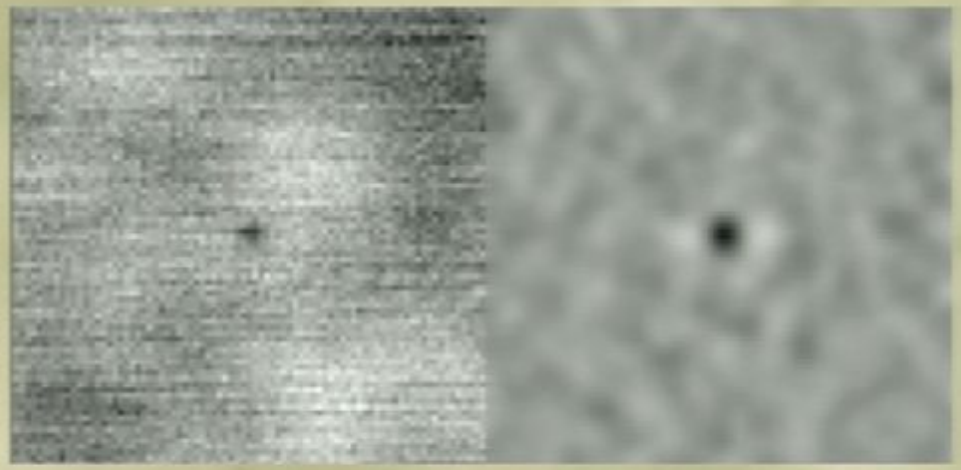


- Convolve with estimate of filtering + beam convolution on a delta function

Raw *Filtered*



40'

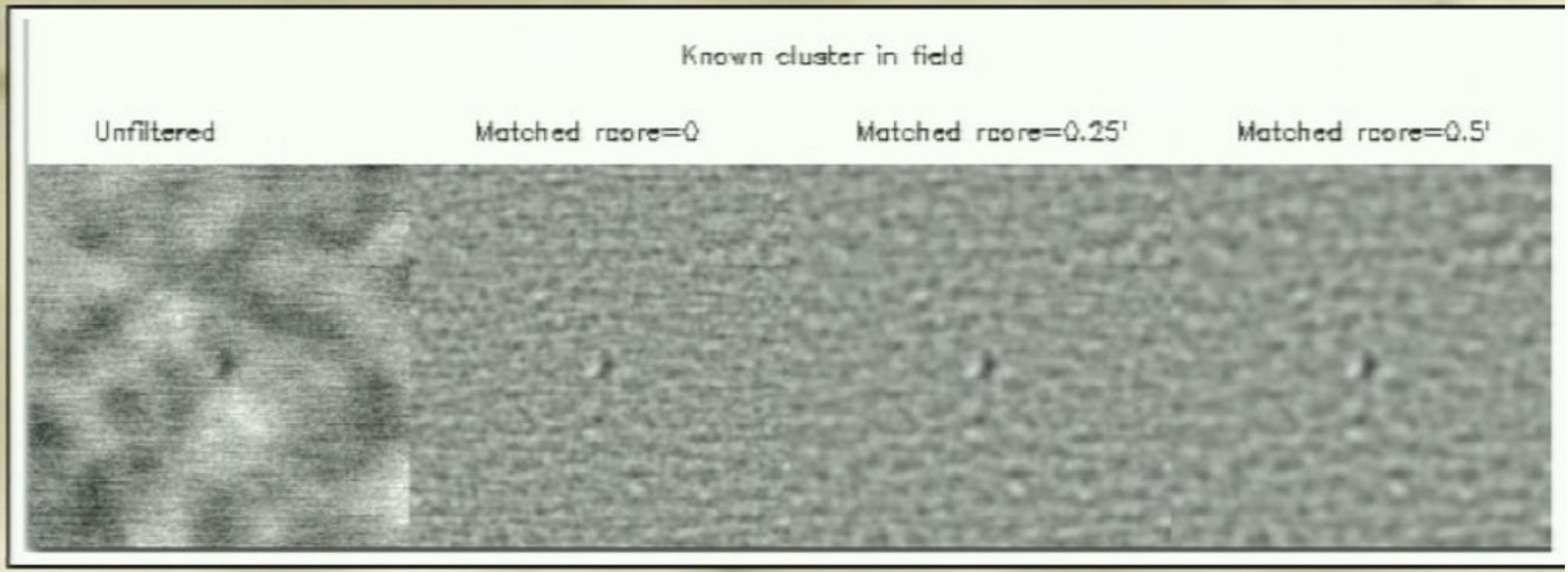
12 σ

8 σ

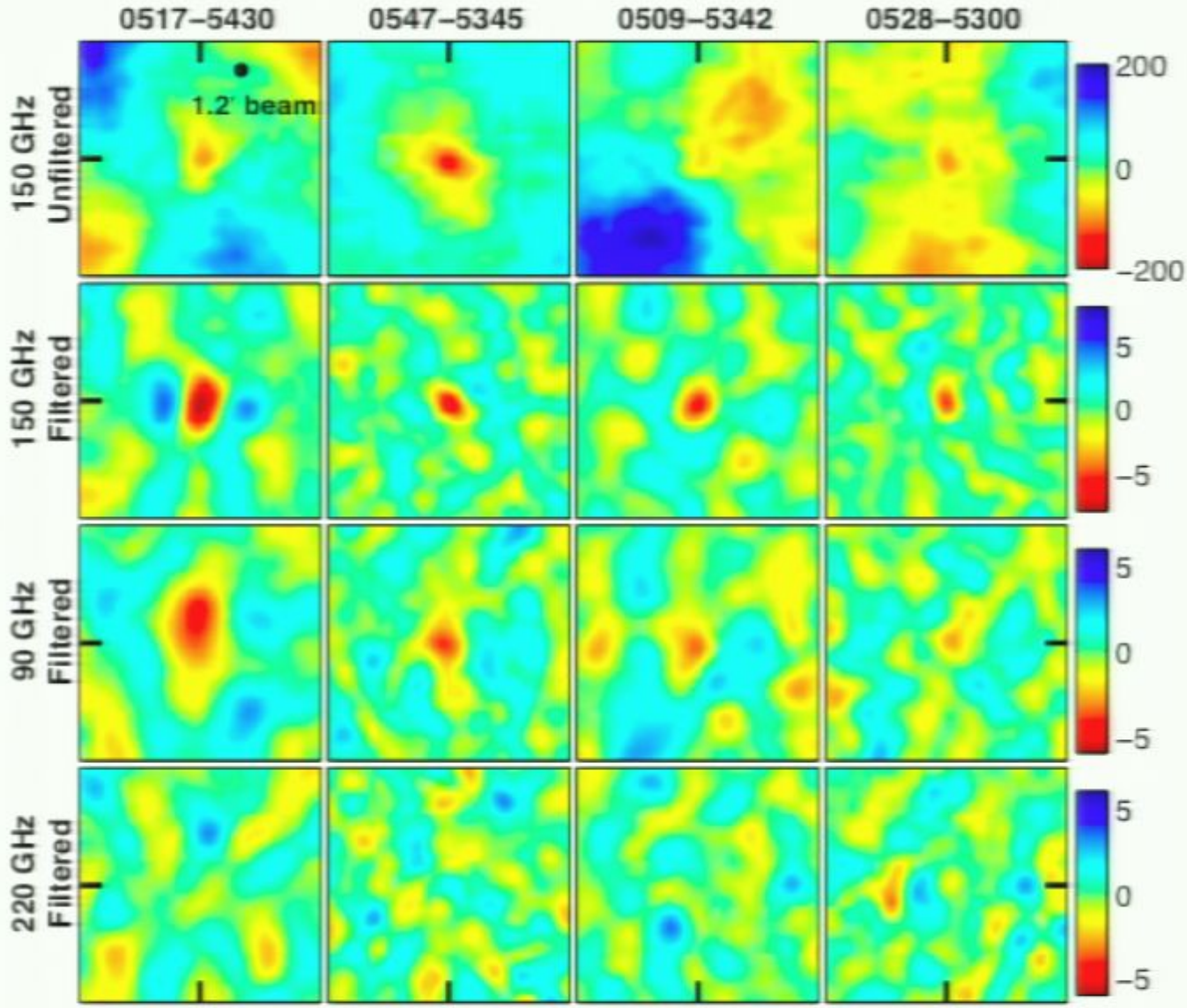
Template for matched filter was a β-model:

$r_c = 1'$, $\beta = 1$

results don’t depend much on details.



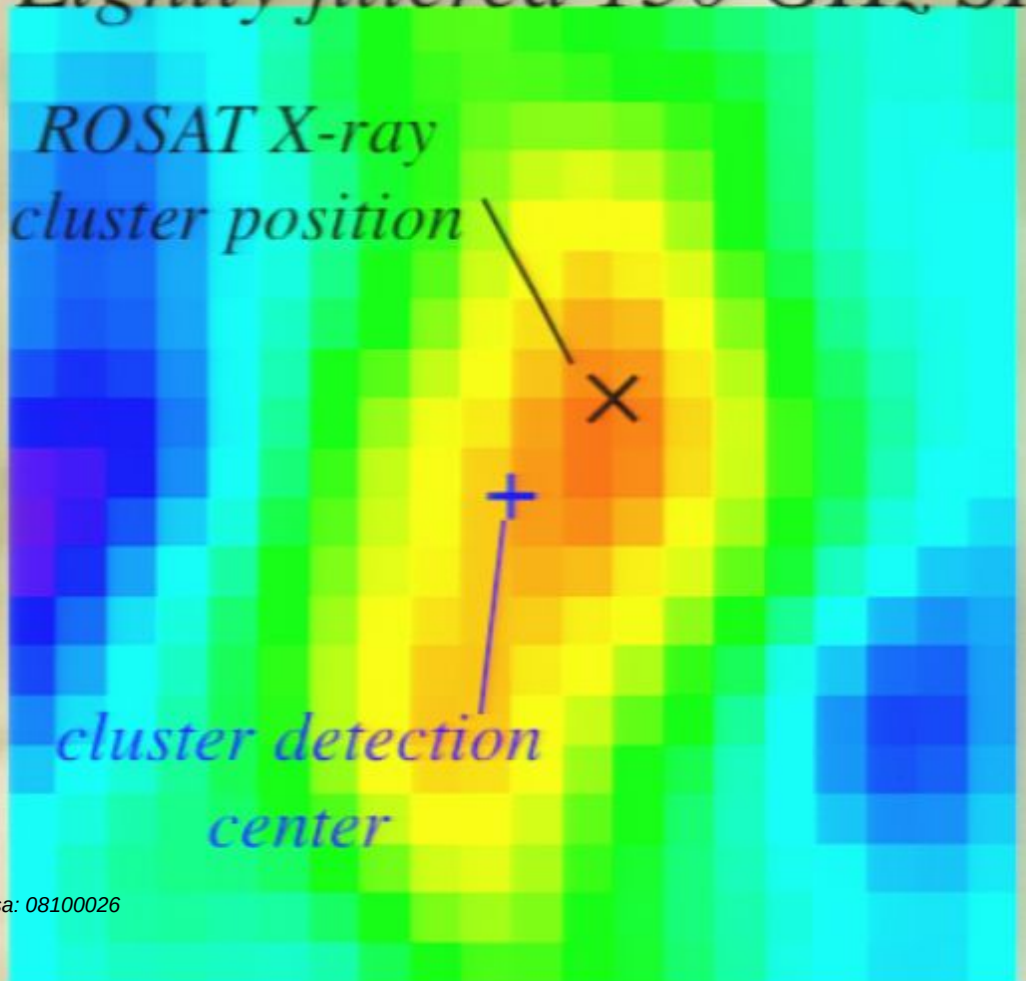
SZ selected clusters!



first SPT science results: see Staniszewski et al

SPT 0517 5430

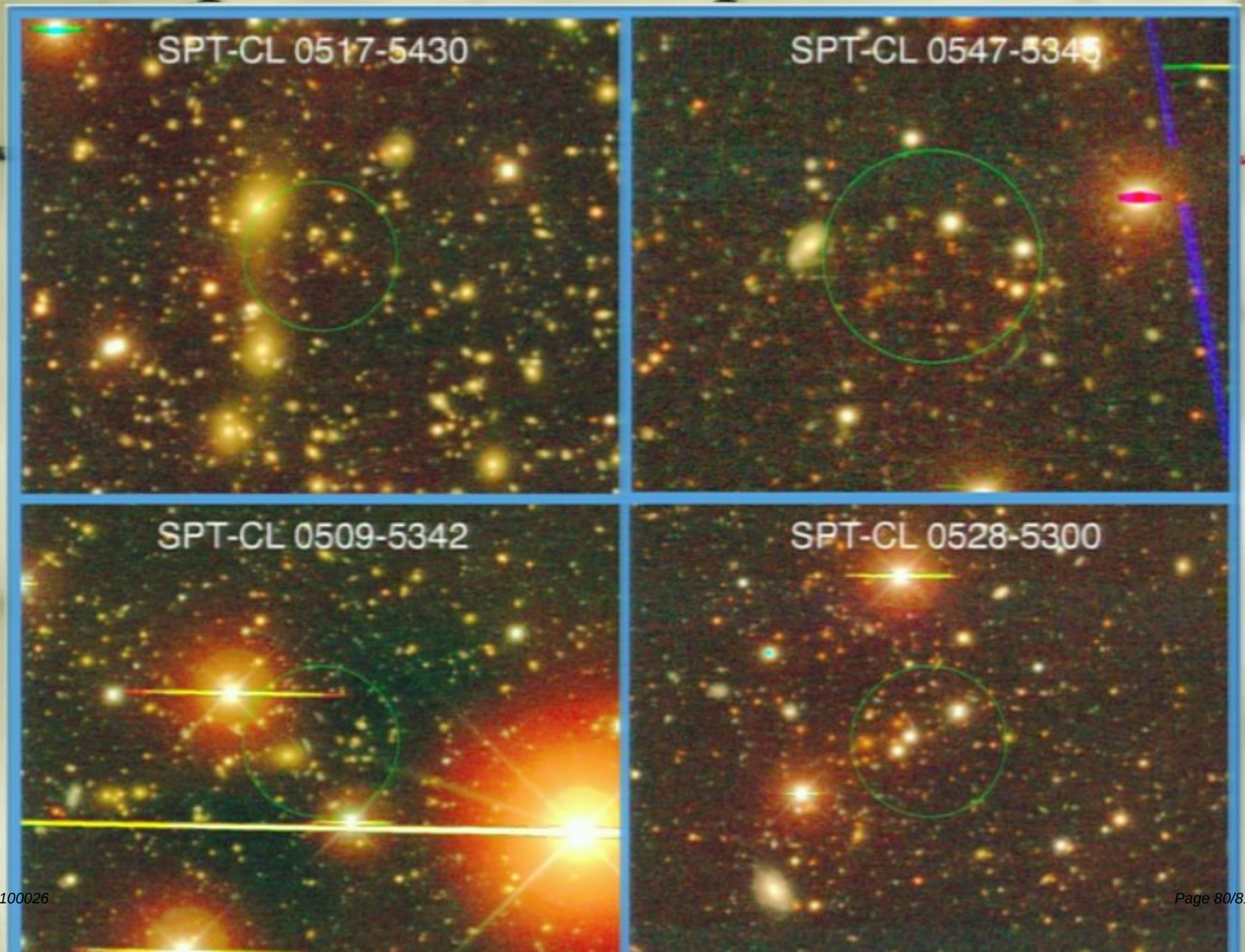
Lightly filtered 150 GHz SPT map



brightest detection = known cluster

very encouraging

Optical followup with BCS



Conclusions

- The South Pole Telescope is an exciting tool for Cosmology
  - Dark energy (tSz, kSz)
  - Inflation (damping tail)

- SPT has data
  - nearing the end of our second observing season
  - completed 2 100 sq. deg fields overlapping with BCS
  - **detected clusters using the SZ effect!**
  - analysis underway for SZ and CMB signals