Galaxy Clusters and Sunyaev-Zel'dovich Effect Measurements

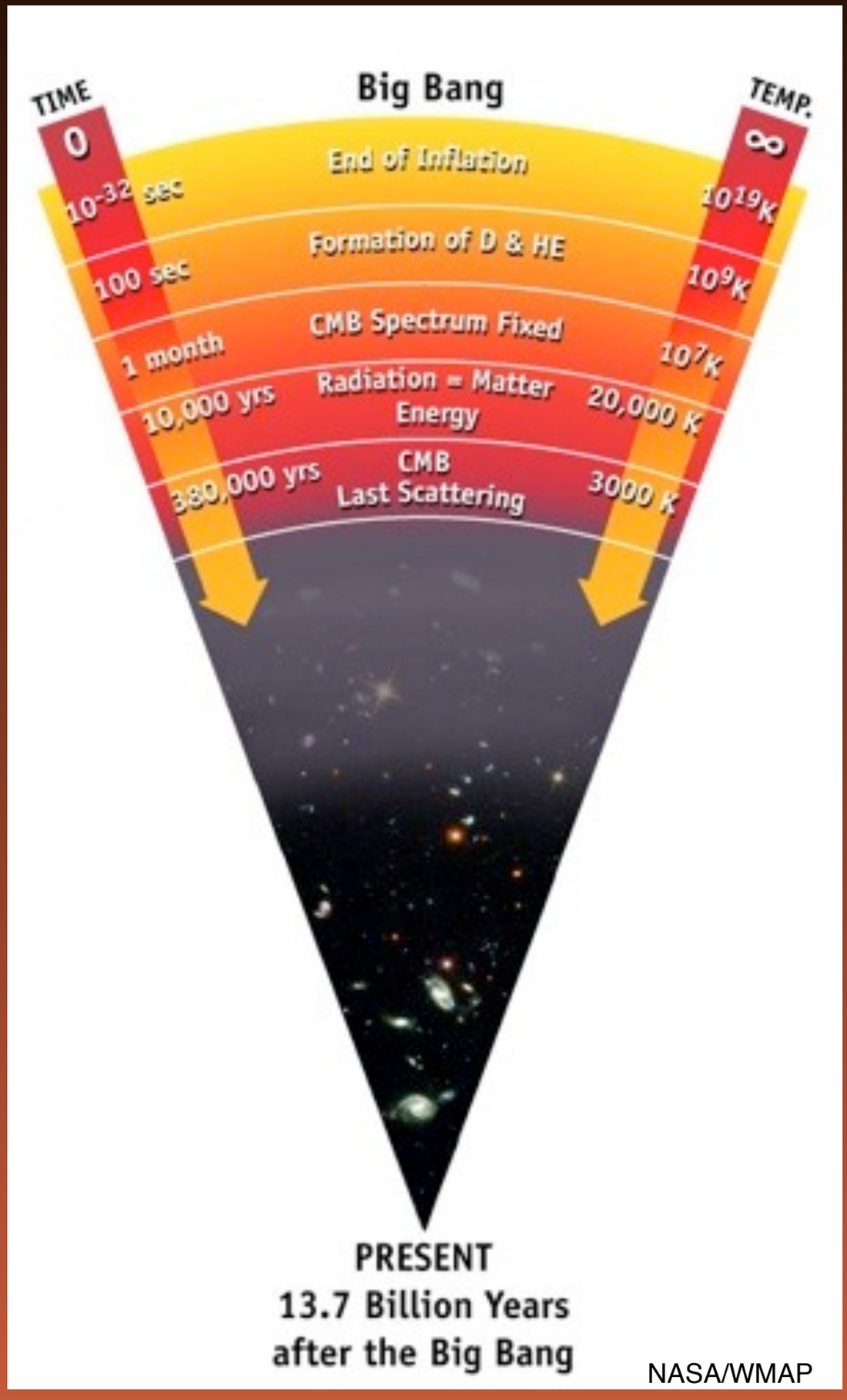
John Carlstrom
University of Chicago

Its been an exciting decade for cosmology

We now have a model that describes the evolution of our Universe from a hot and dense state.

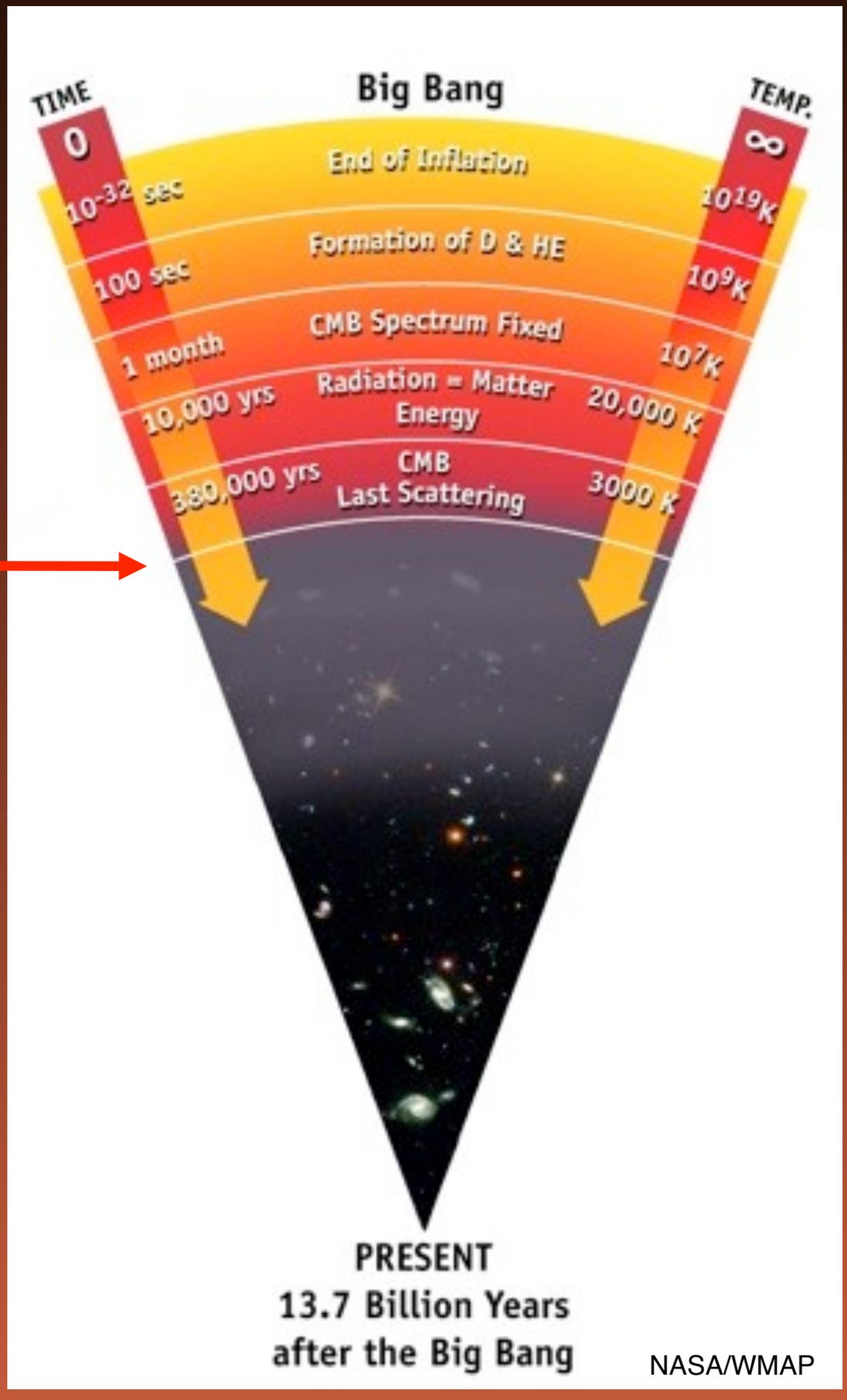
We are able to make precise predictions and test them with powerful new experiments.

The model has some unusual features - new physics - Dark Matter, Dark Energy, and starts with a period of Inflation

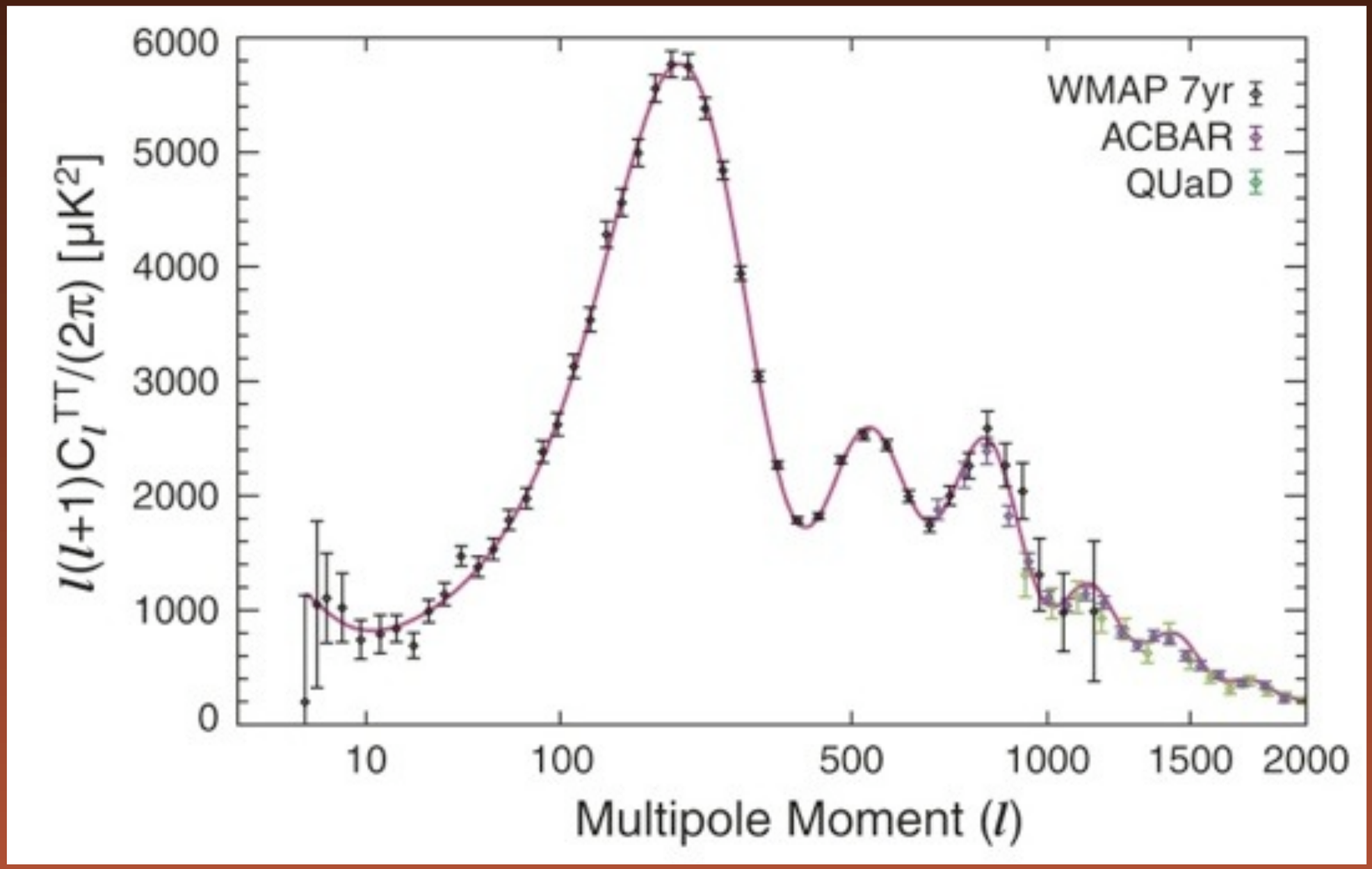


Much of the model has been determined from measurements of the Cosmic Microwave Background (CMB) radiation

RMS measurements of the CMB provide a snapshot of the infant universe as it was 14 billion yr ago.



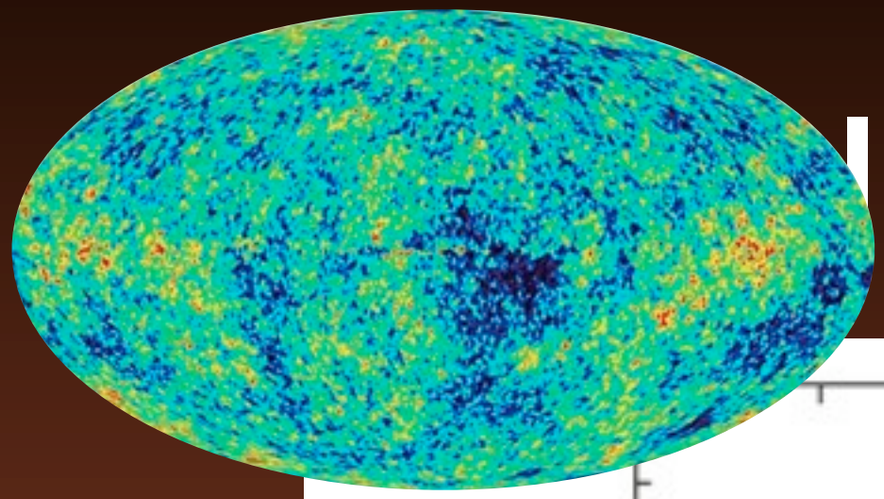
Incredible progress

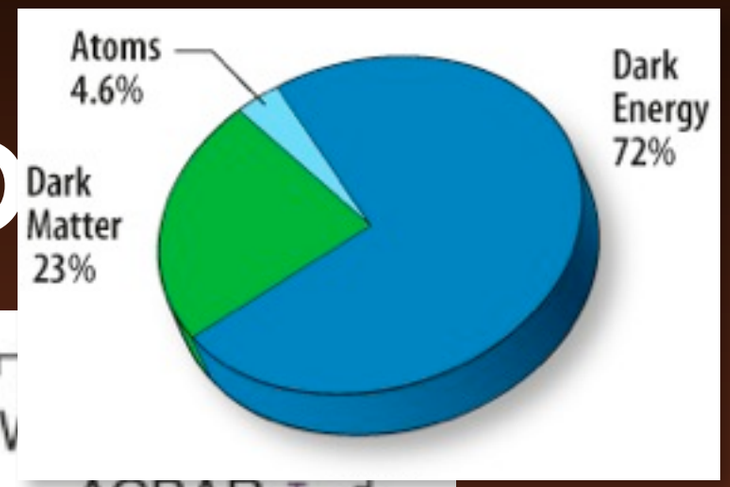


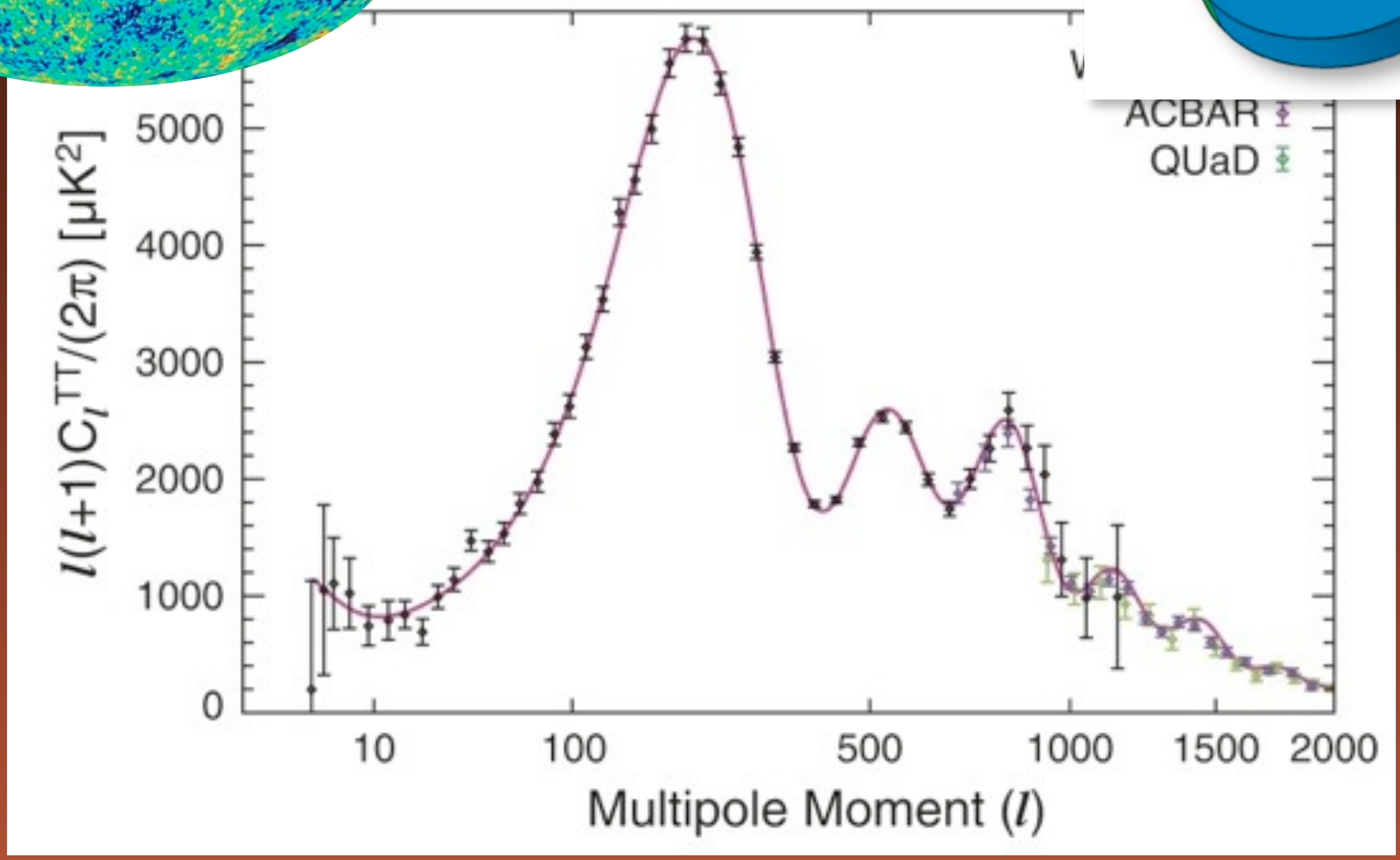
Line is fit to a flat ΛCDM cosmology model with just six parameters: $\Omega_b h^2$, $\Omega_m h^2$, A_s, τ, n_s, Ω_Λ

Komatsu et al., arXiv:1001:4538; Larson et al., arXiv:1001.4635

Incredible p







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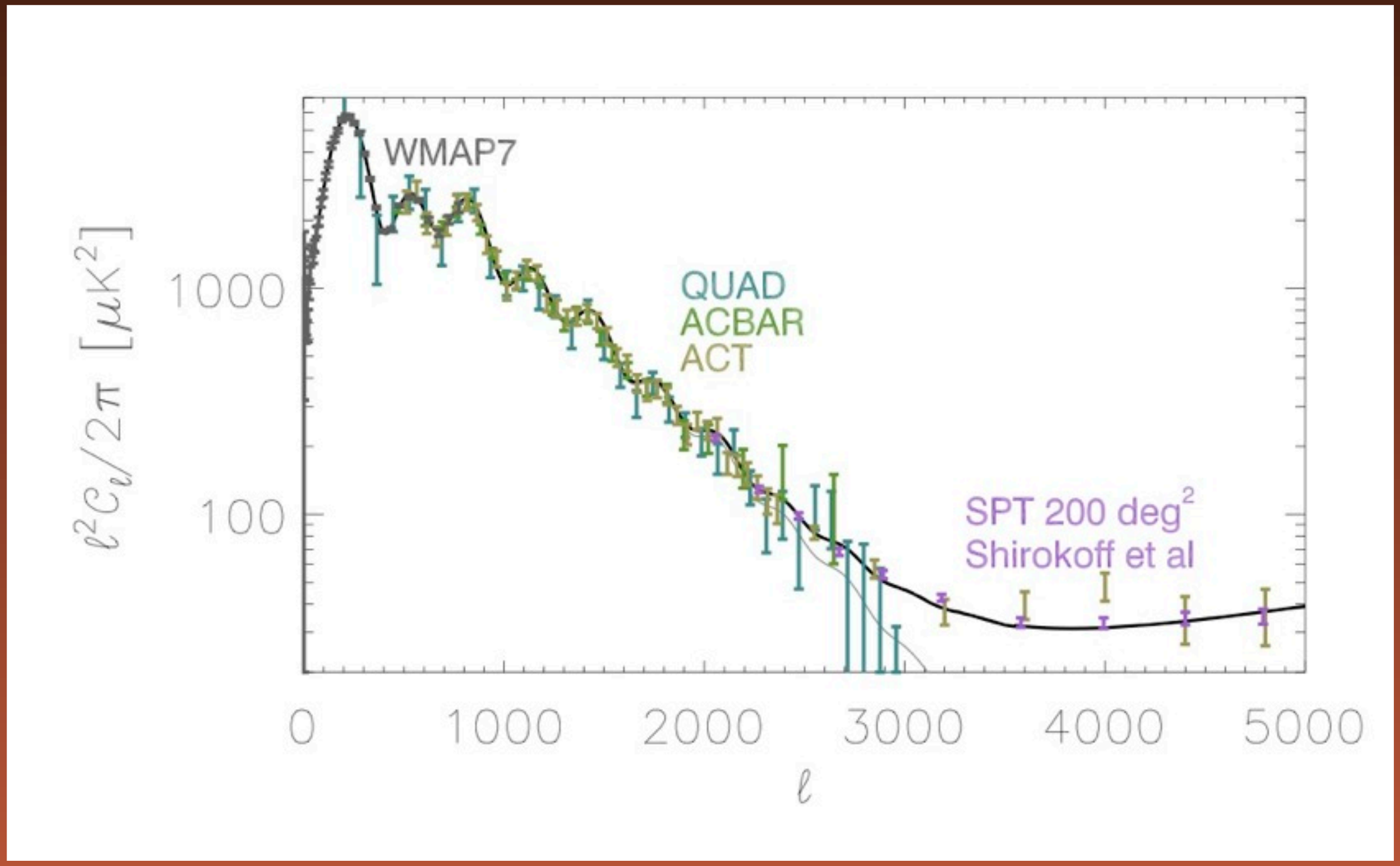
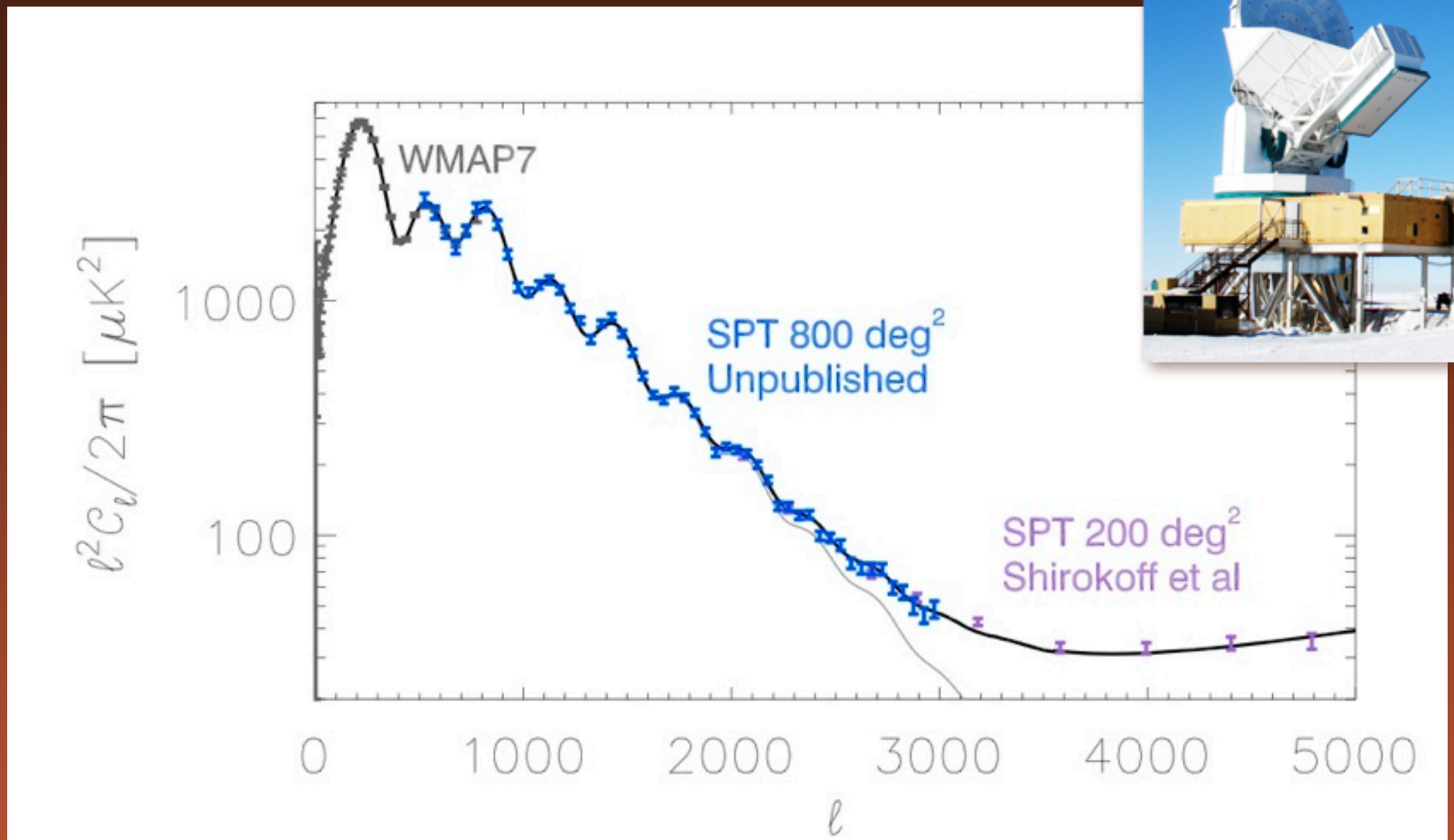
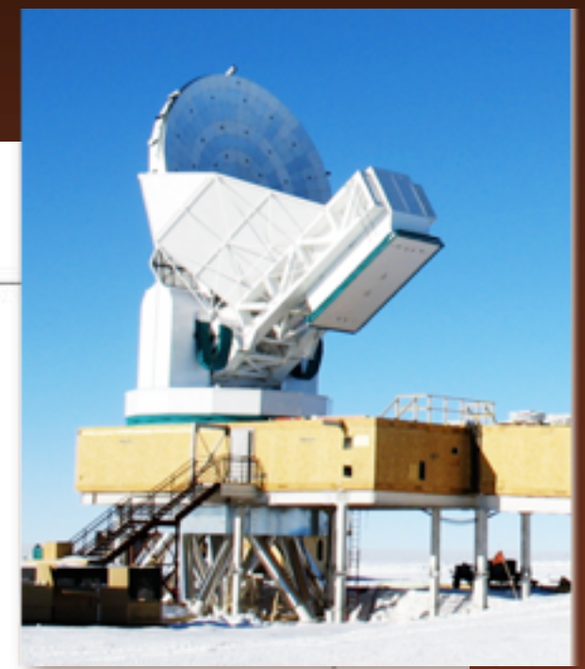
Fine angular scale anisotropy: detection of secondary CMB anisotropy



Sneak preview of newest SPT results:





Ryan Keisler Ph.D. thesis Nov 1, 2010

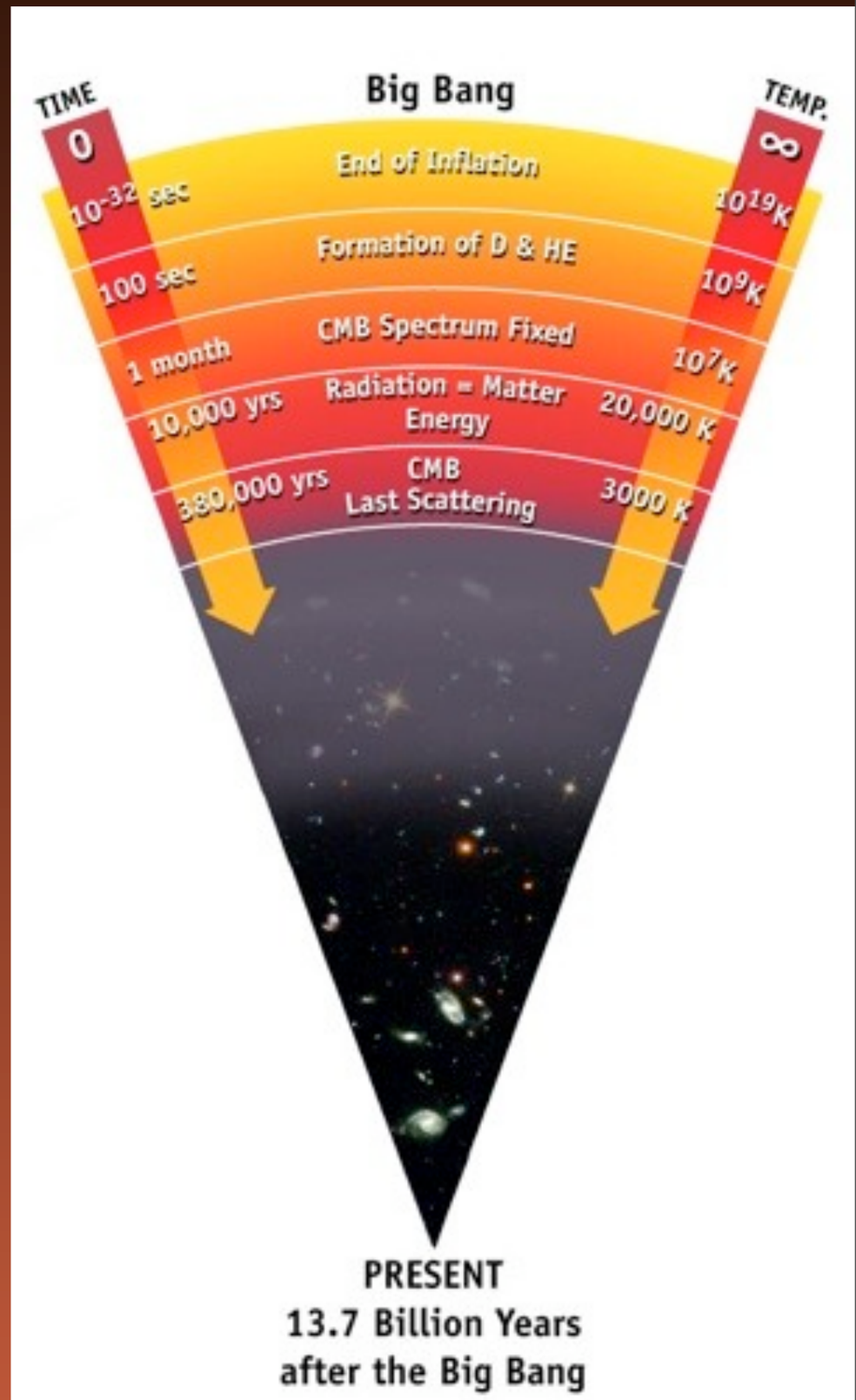
What's next?

There is wealth of information to extract from the CMB

- From the distribution of the intrinsic temperature variations across the sky.

- From polarization patterns imprinted by gravitational waves generated in the first instants of the universe.

- From small scale distortions to the CMB as it passes through the universe. Evolution of the universe.



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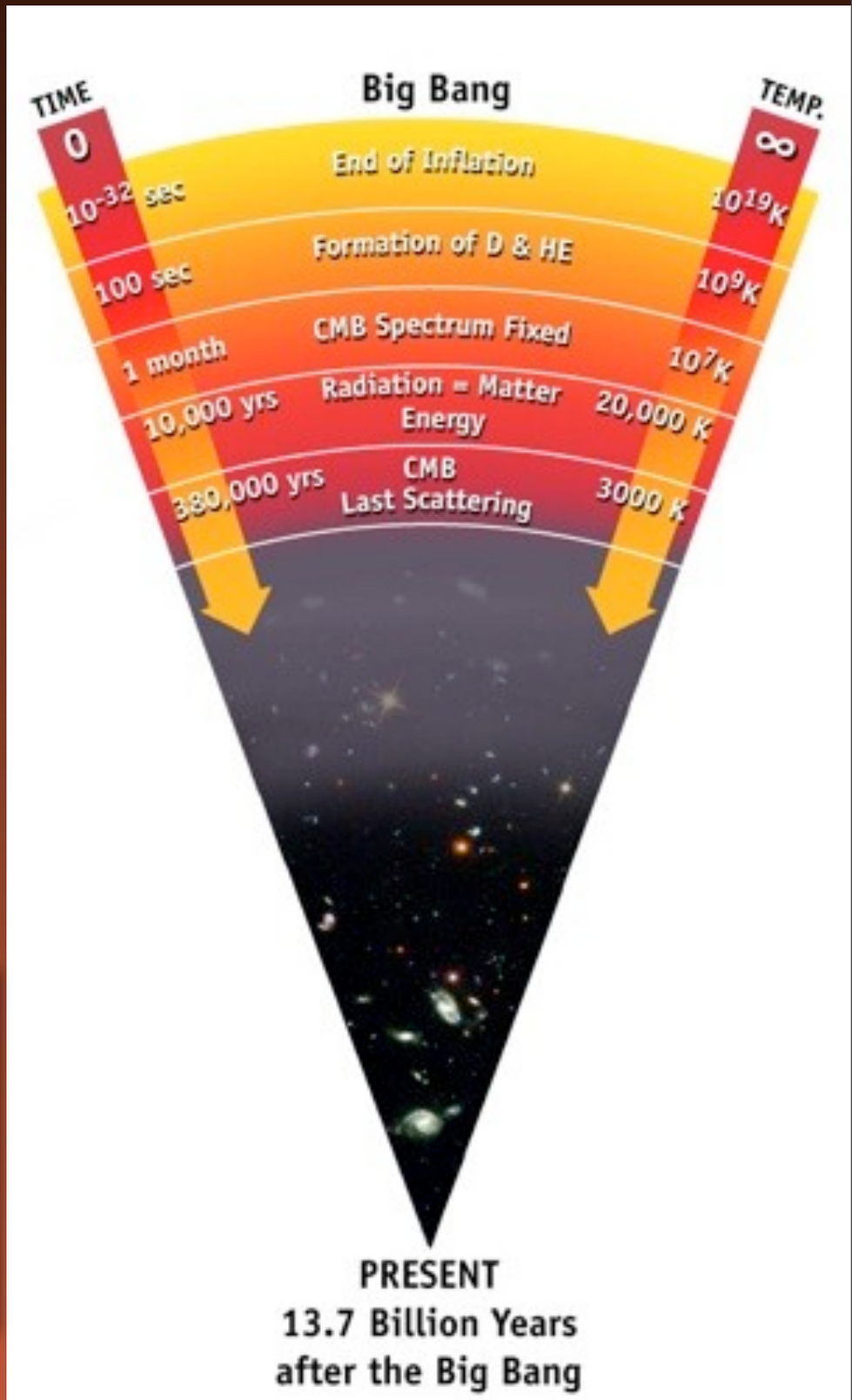
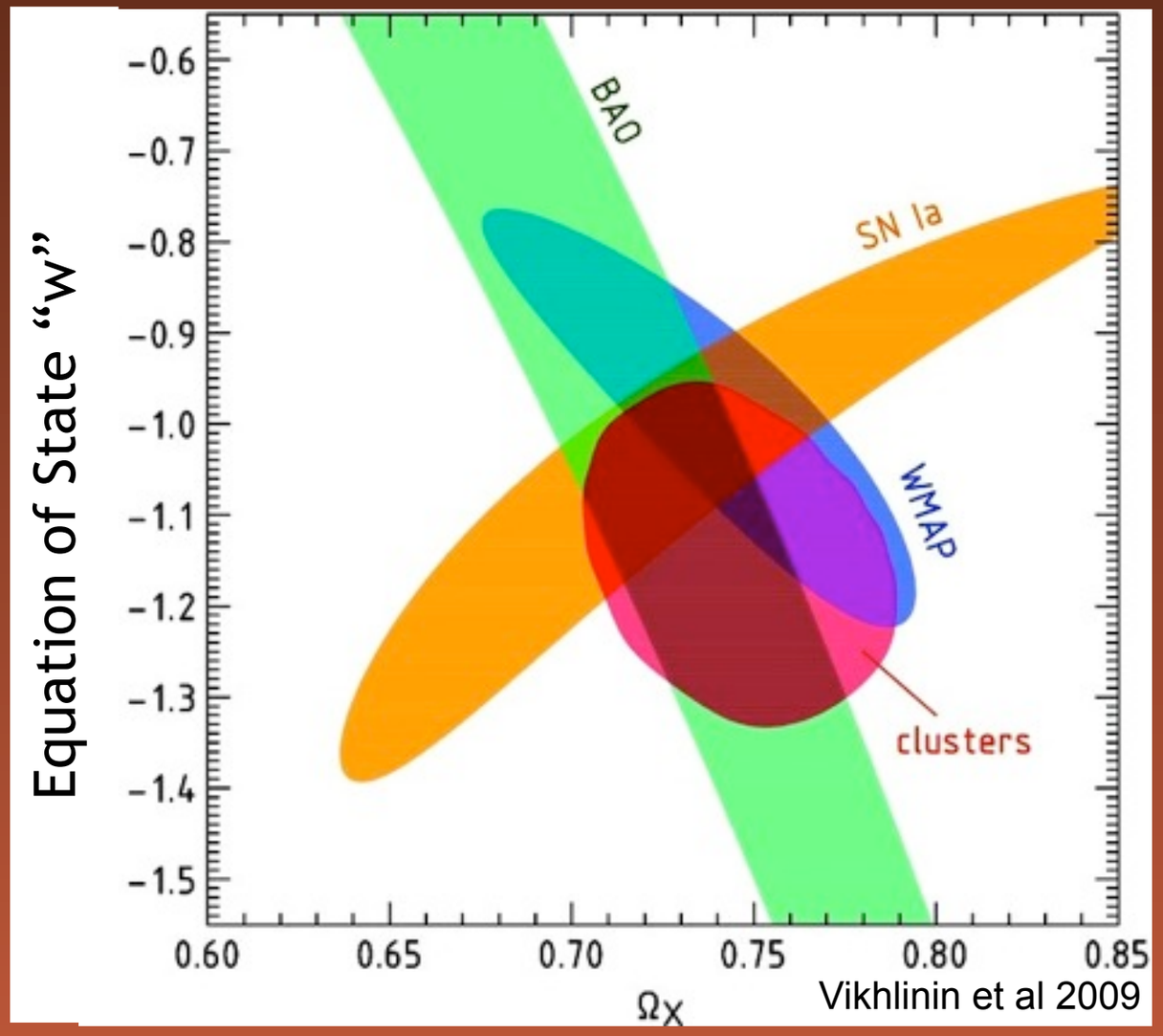
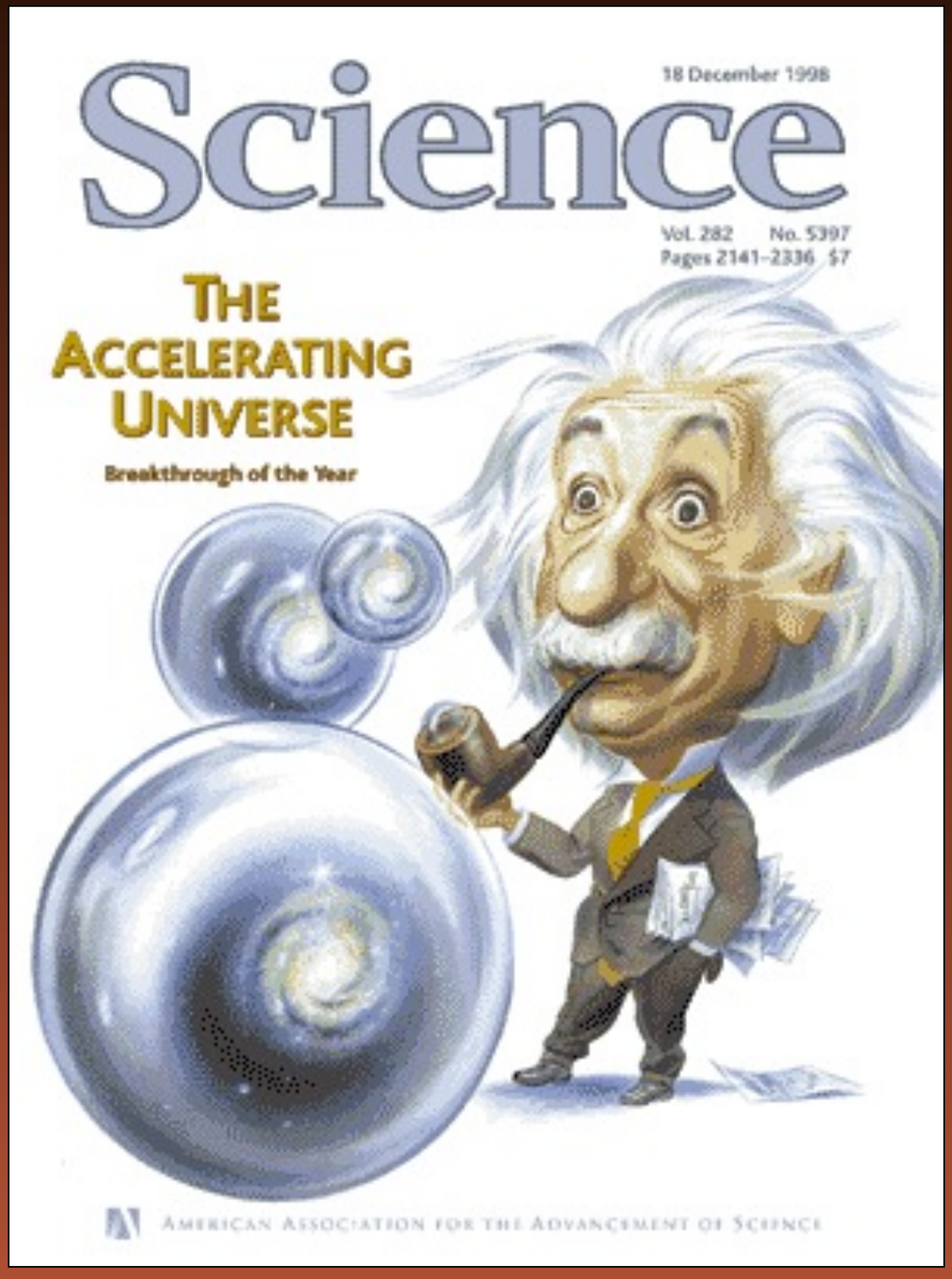


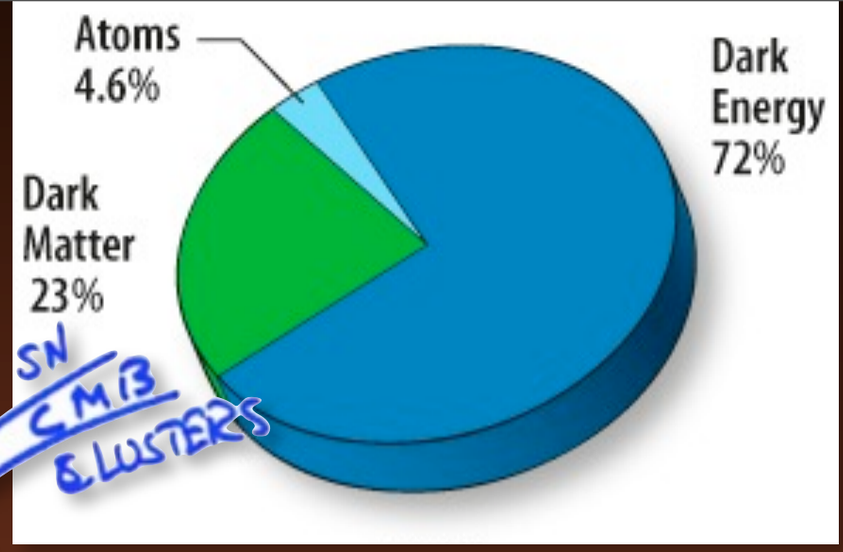
We live in a universe dominated by dark energy

SNe Ia + CMB + Cluster evolution + Large Scale Structure



... but what is dark energy ?





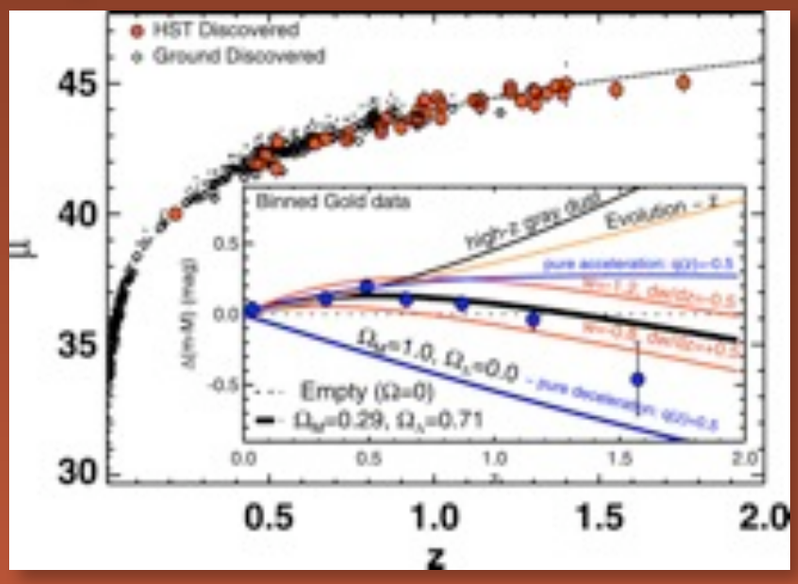
DARK ENERGY

$d_A(z)$
$d_L(z)$ GEOM.

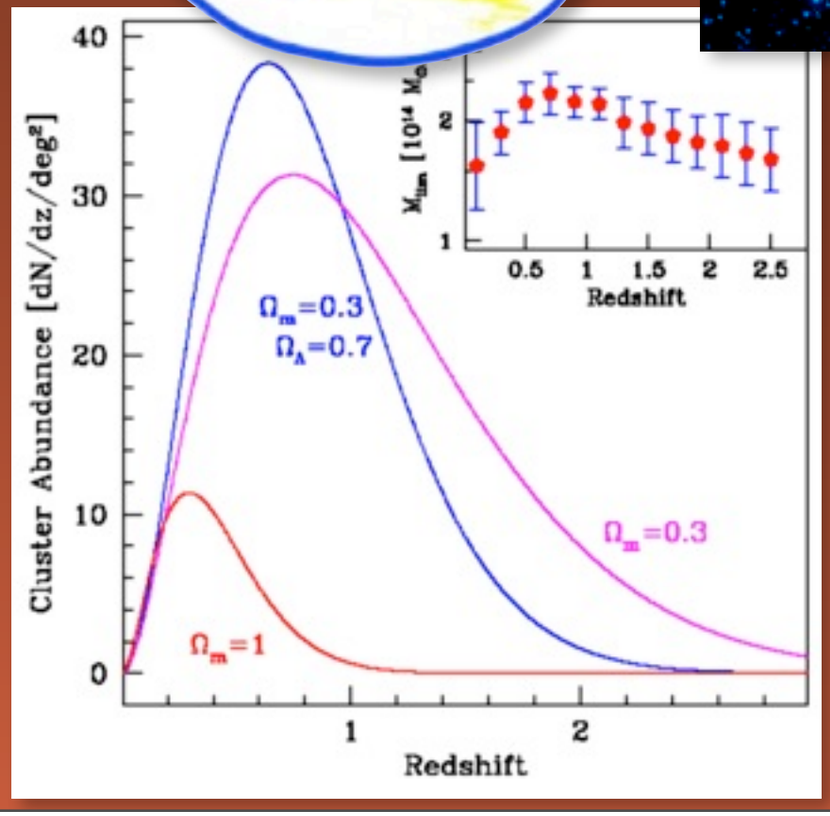
$\frac{\delta\rho}{\rho}(z)$ GROWTH

Galaxy Clusters

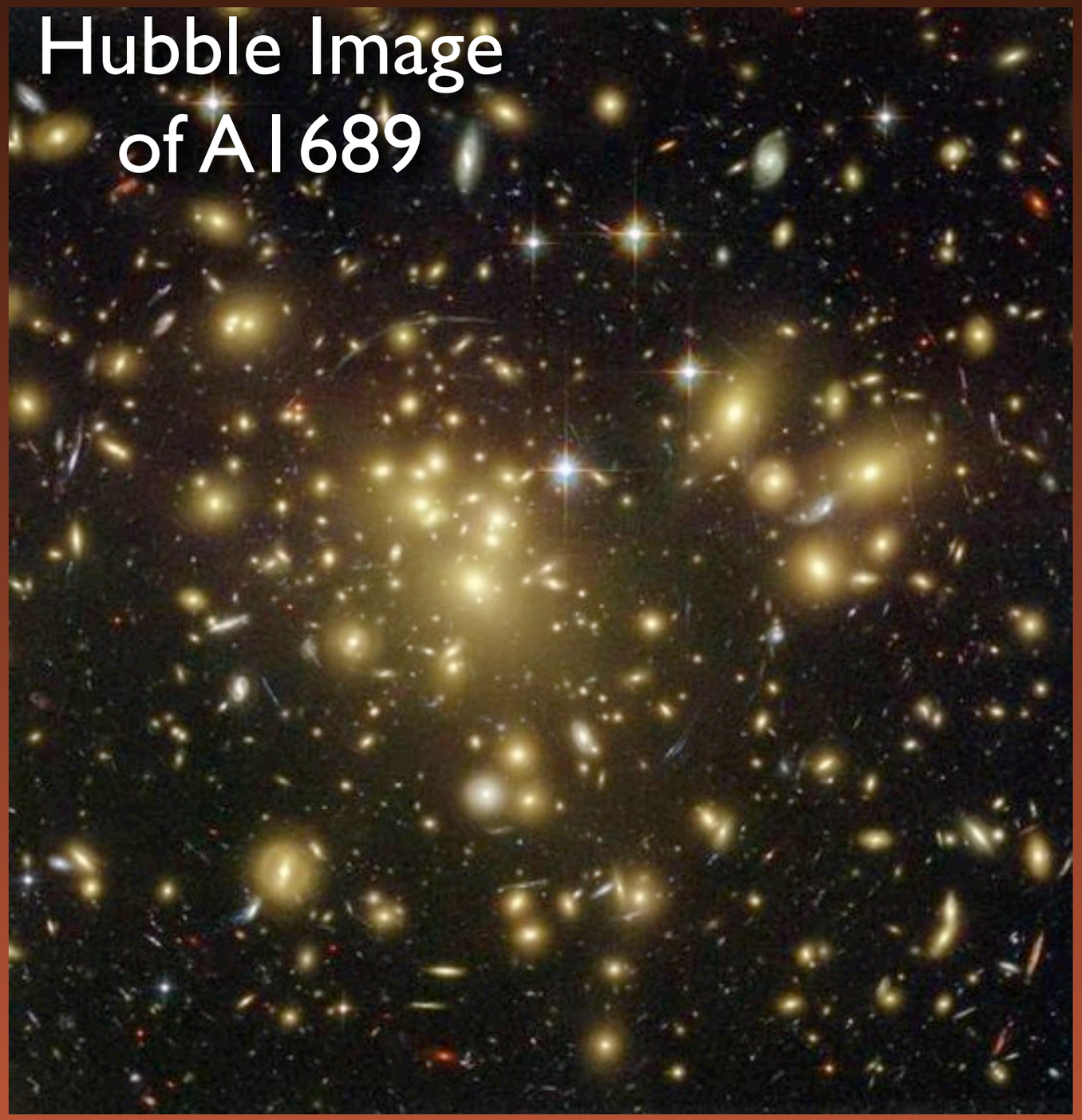
Supernovae



Riess et al 2007



Clusters of Galaxies



- Clusters are the largest virialized object in universe (and therefore very rare!)

- Their formation traces the growth of structure through history of the universe.

Clusters are mostly hot gas (and dark matter)

- Massive clusters are ~10^{15} $M_\odot$

- ~85% of the baryonic matter is in the form of a hot gas

- As gas collapses, it becomes gravitationally virialized and heats up to ~10^8 K (or 8 keV)

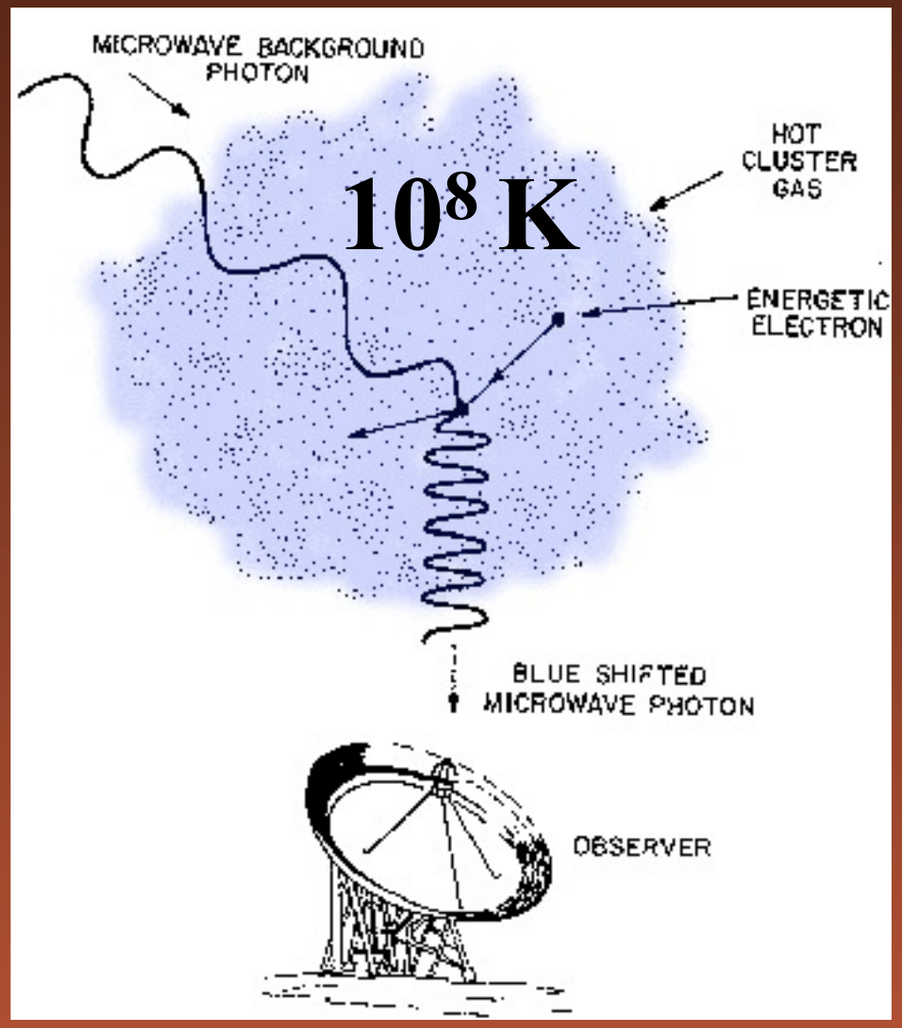
Sunyaev-Zel'dovich (SZ) Effect

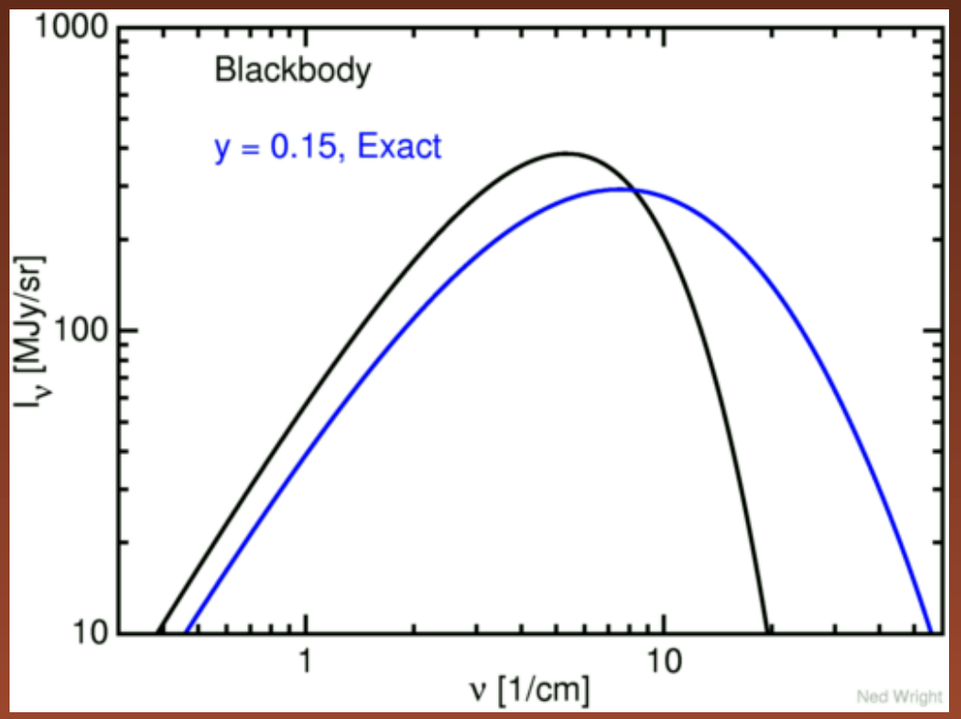
CMB photons provide a backlight for structure in the universe.

~1% of CMB photons traversing a massive galaxy cluster scatter.

Thermal SZ effect (tSZ) spectral "y" distortion due to inverse Compton scattering.

Kinetic SZ effect (kSZ) due to cluster moving with respect to the CMB





from Ned Wright

Surface brightness of the SZ effect is independent of redshift!

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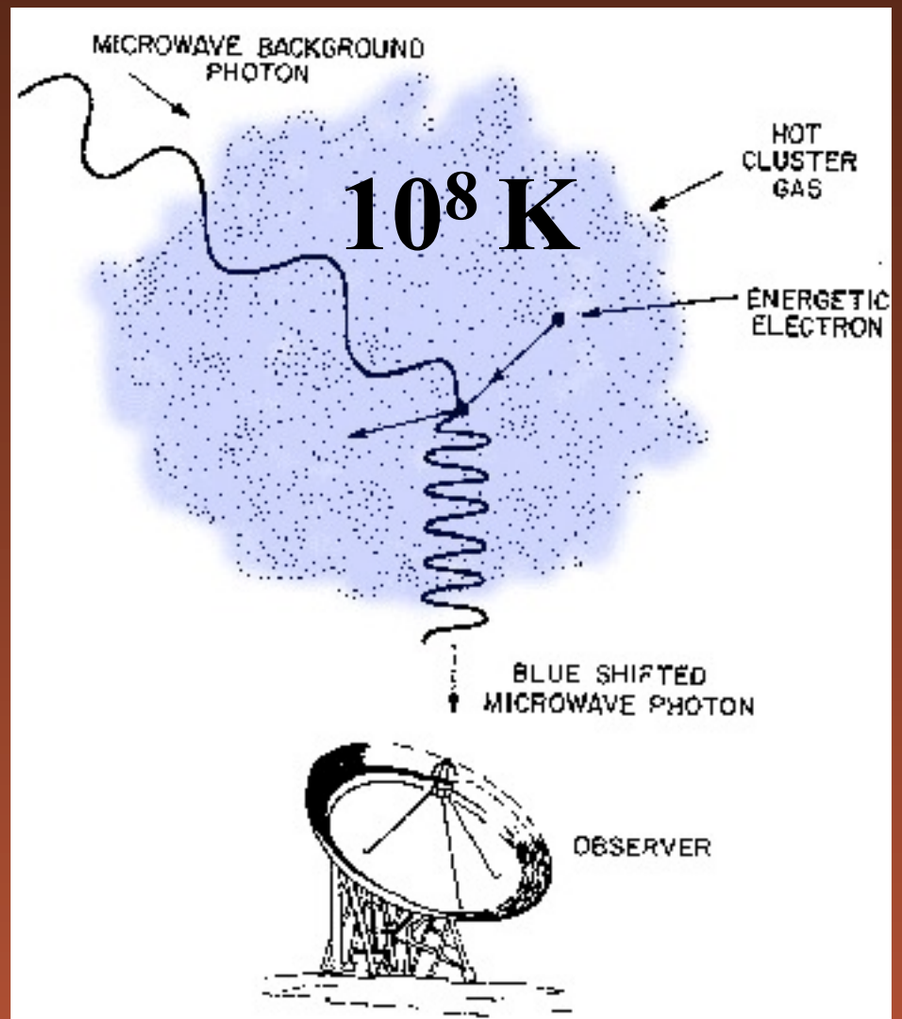

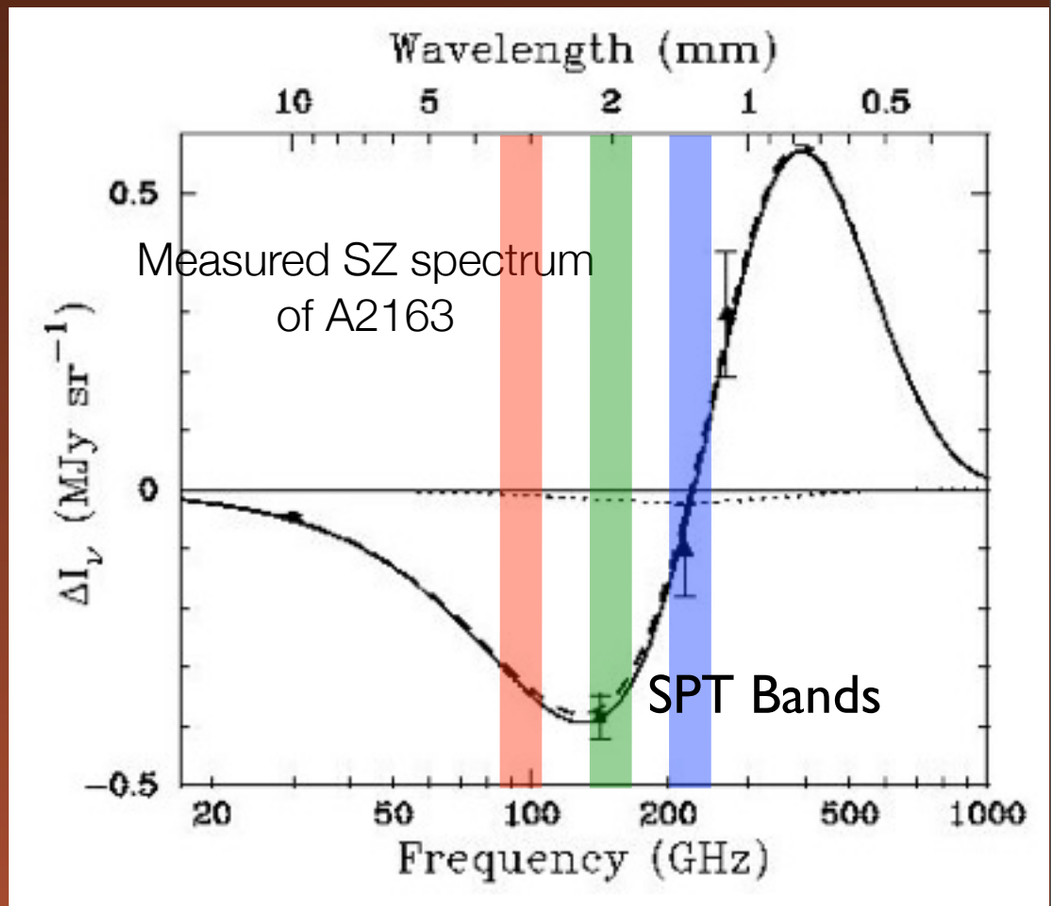

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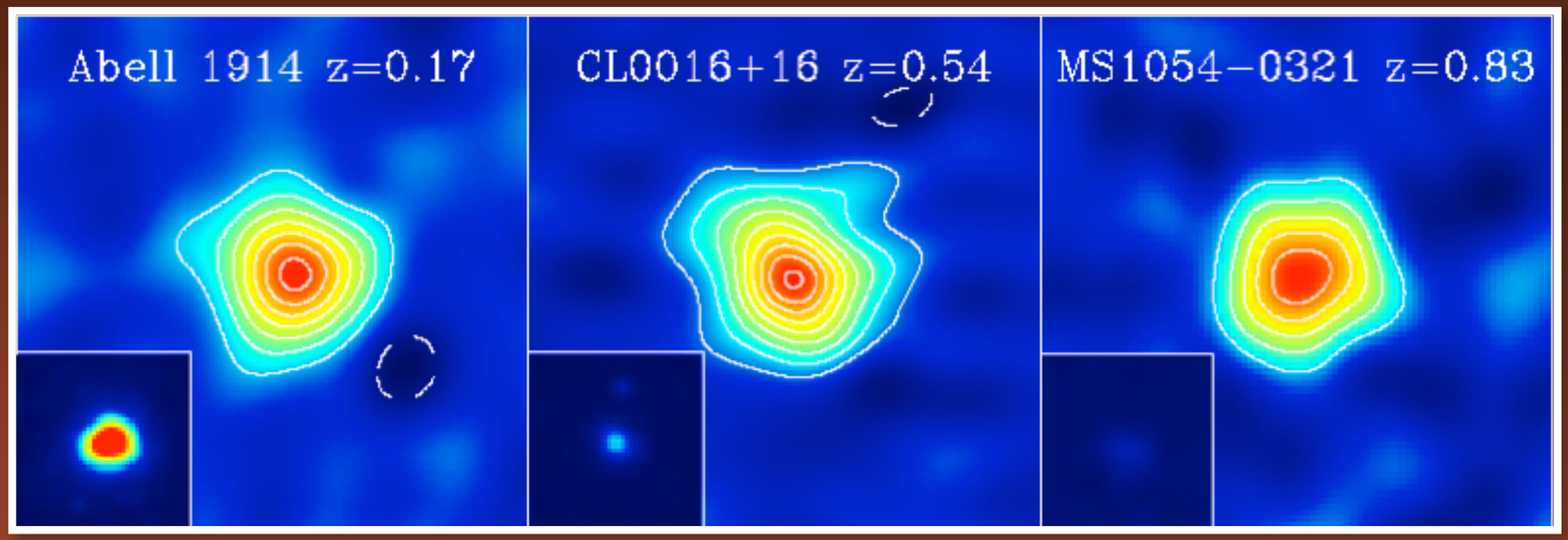
SZ Effect Surveys

Exploit SZ redshift independence to probe structure formation and to provide a mass limited cluster sample.



Credit: Mohr & Carlstrom

Same range of X-ray surface brightness and SZ decrement in all three panels.

$$\text{SZ flux} : \mathbf{S} \propto \frac{\mathbf{1}}{\mathbf{d_A(z)^2}} \int \mathbf{n_e T_e dV}$$

Proportional to the total thermal energy of cluster, so should be excellent measure of mass.

Constraining Dark Energy with Cluster counts

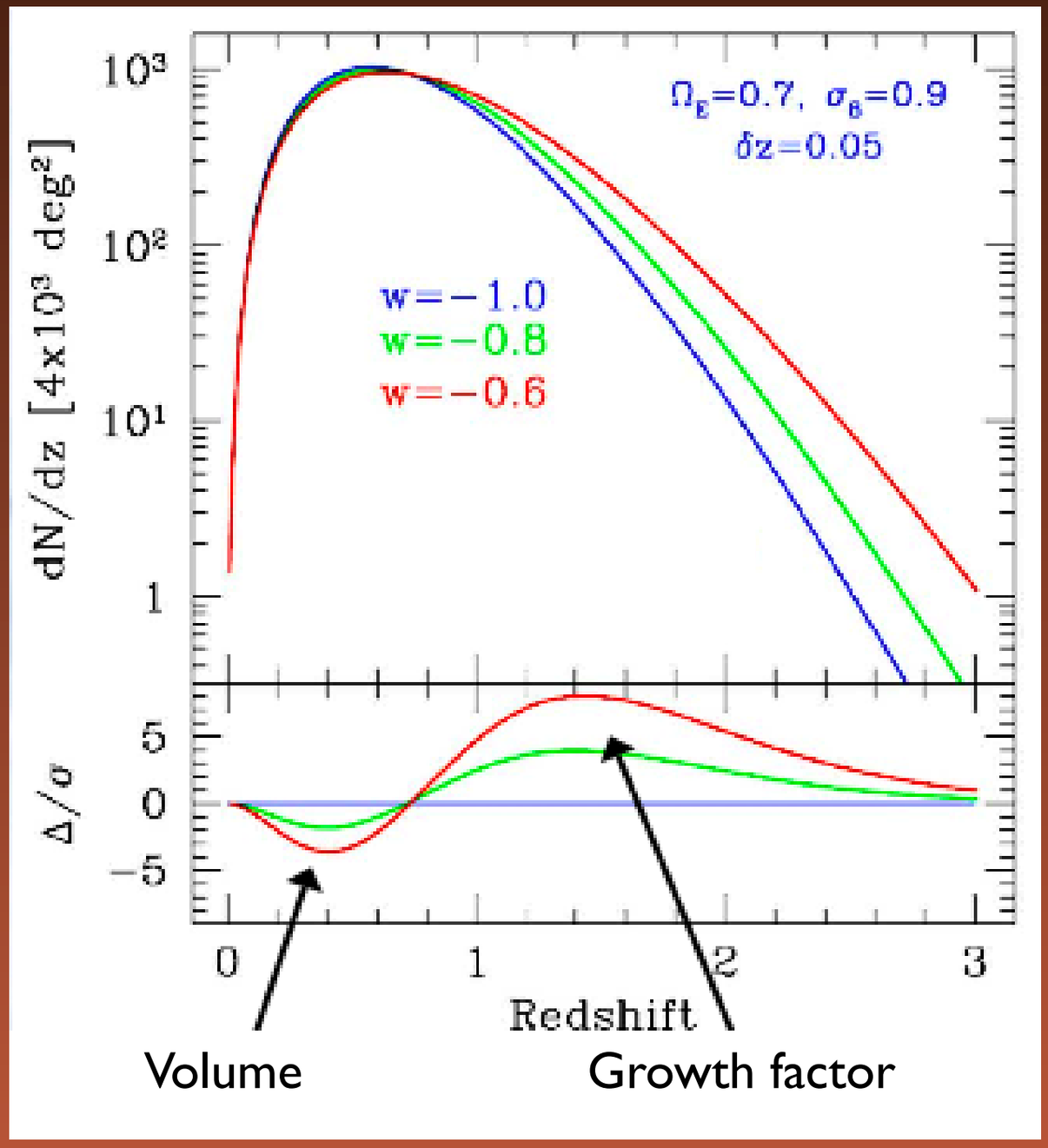
SZ cluster number counts

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

Growth Volume

$$\rho(z) = \rho_\circ (1+z)^{3(1+w)}$$

where $w = \frac{p}{\rho}$ is eq. of state



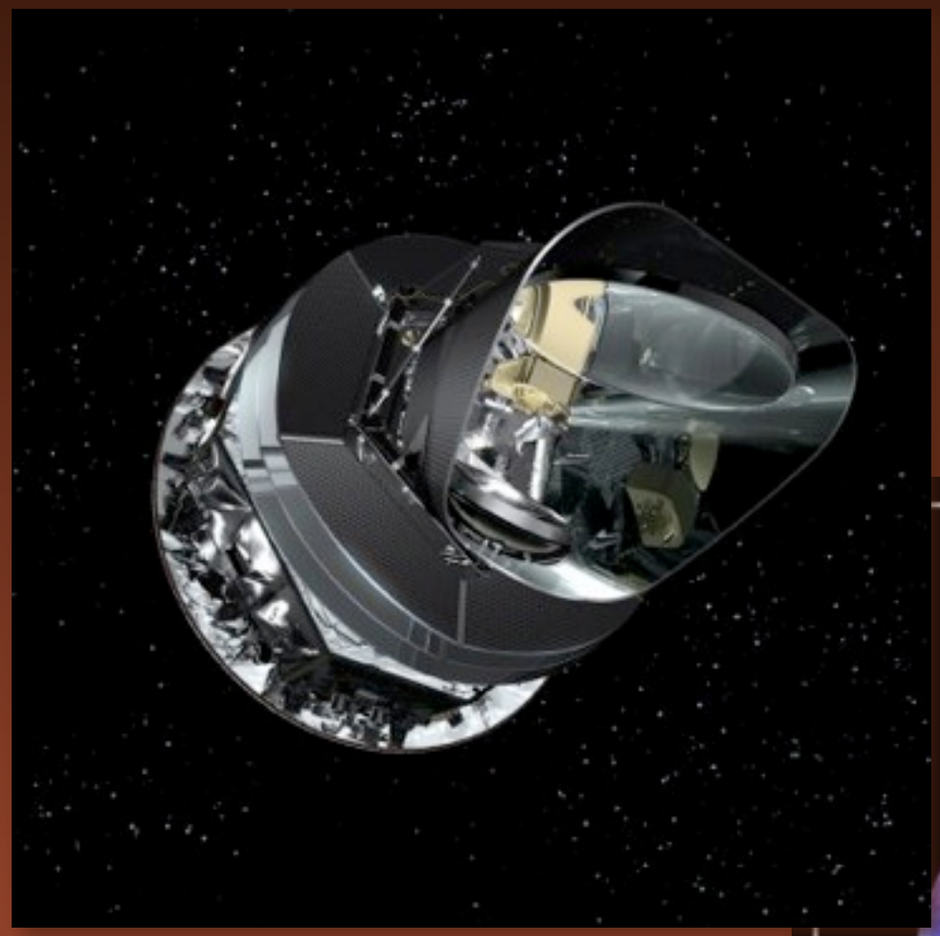
Joe Mohr

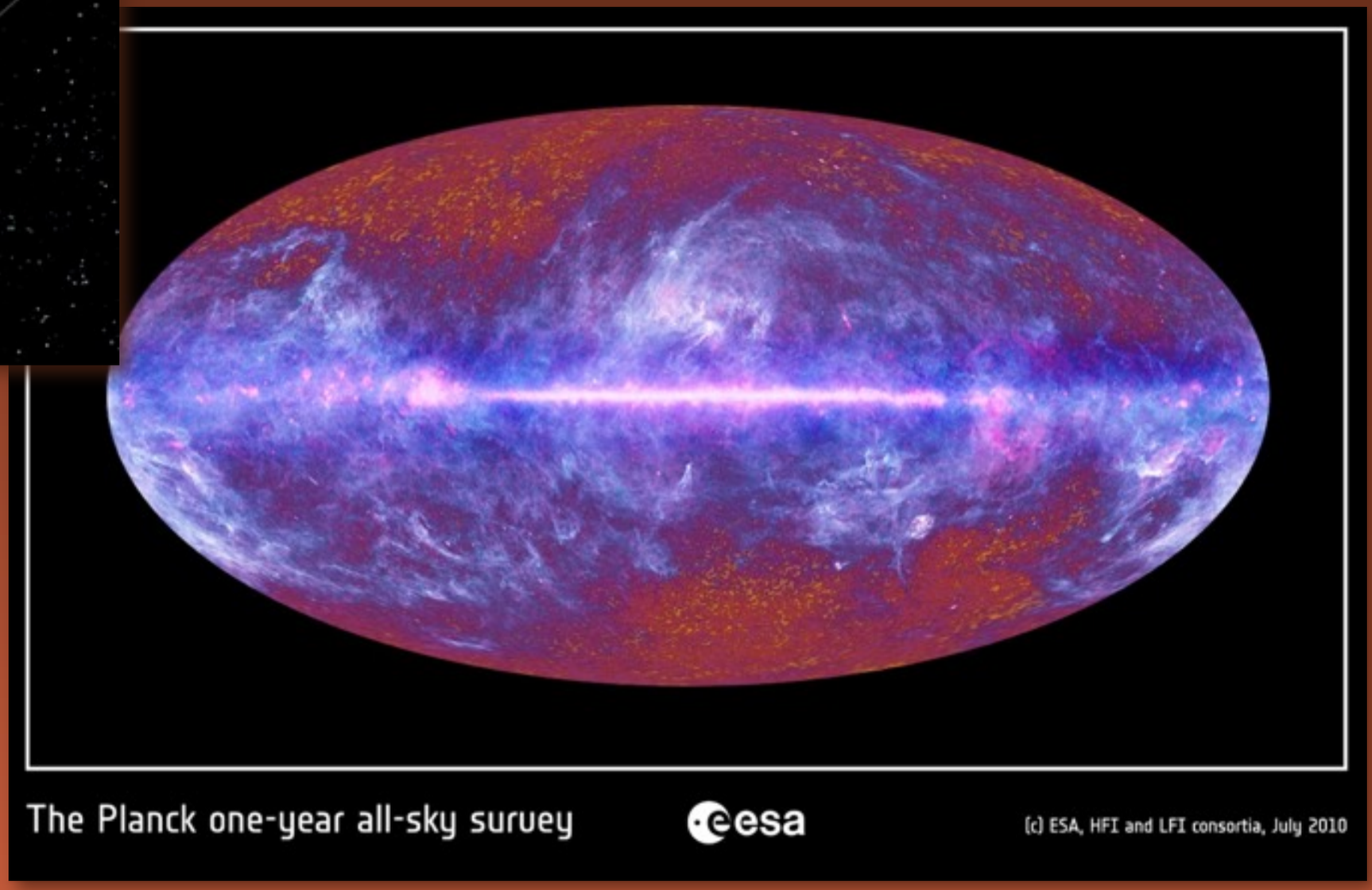
ACT and SPT

Fine scale CMB temperature and polarization telescopes

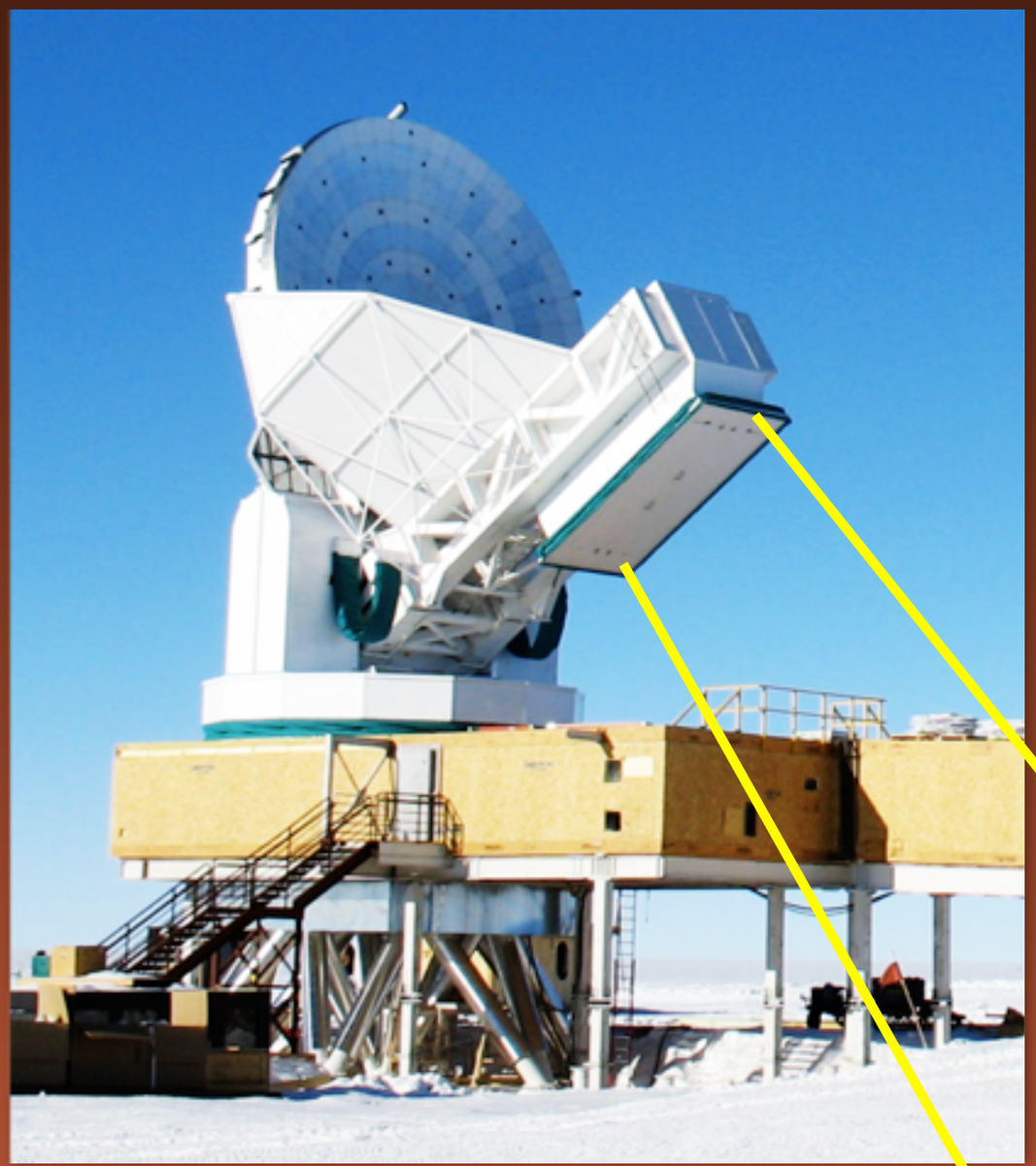
- Exceptional high and dry sites for dedicated CMB observations.
- Exploiting ongoing revolution in low-noise bolometer cameras

Planck all-sky low-resolution SZ-survey



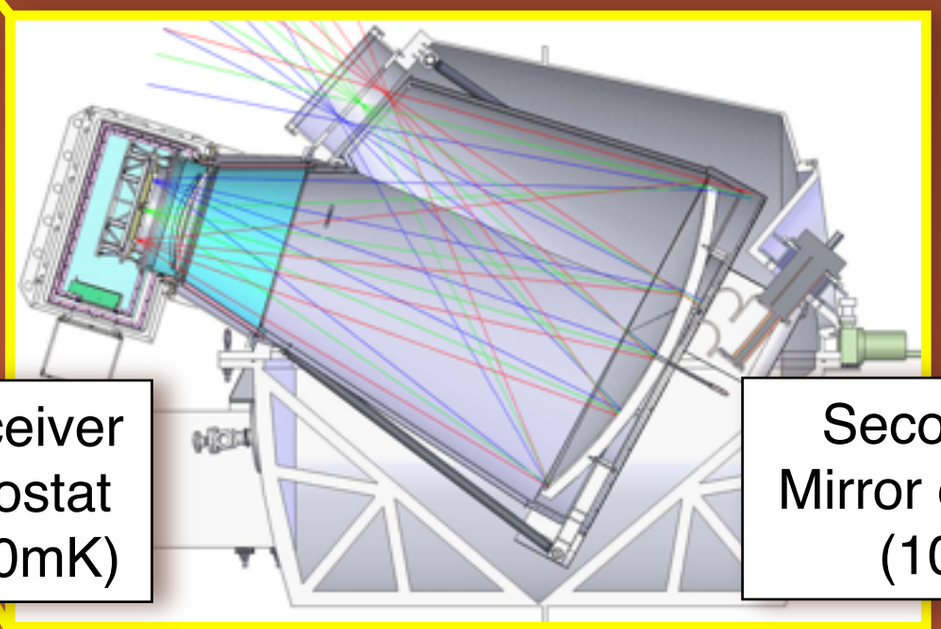


The 10 meter South Pole Telescope (SPT)



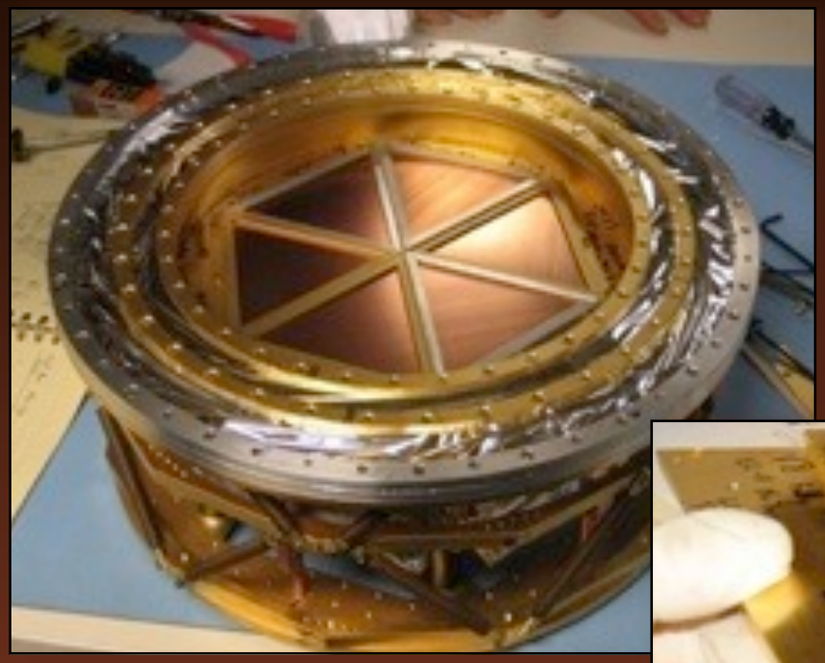
Some Key Features:

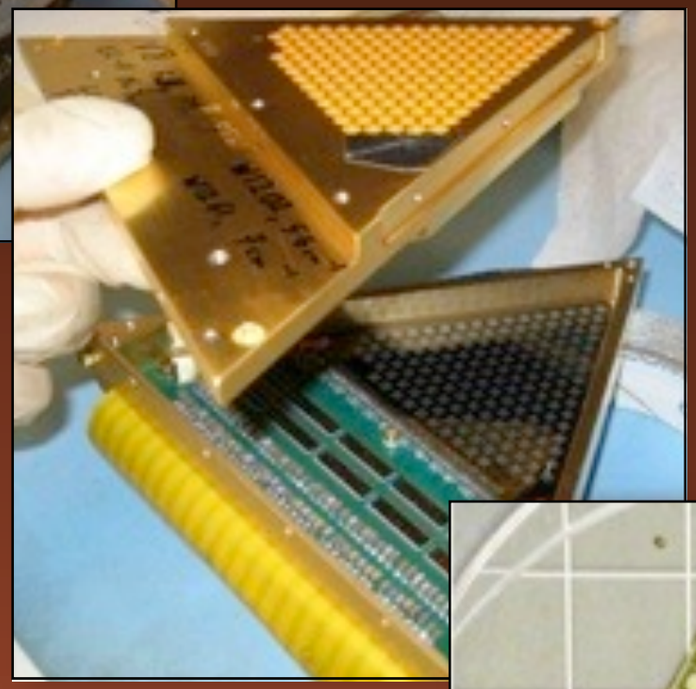
- 1 arcmin resolution at 150 GHz
- 1 deg FOV
- 960 feedhorn coupled detectors matched to Airy disk
- Observe in 3+ bands 90, 150 & 220 GHz simultaneously with a modular focal plane



South Pole Telescope Camera

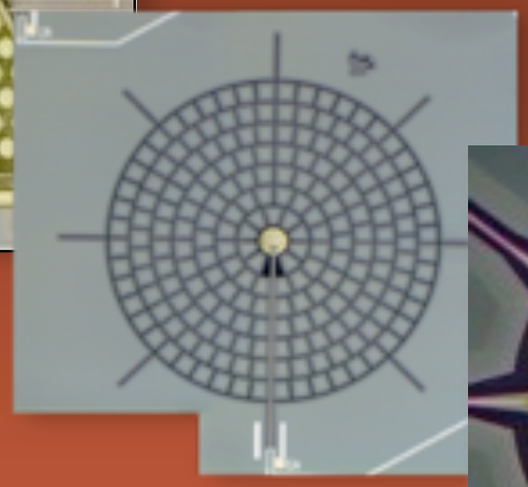
developed and built at U.C. Berkeley





Erik Shirokoff

Brad Benson



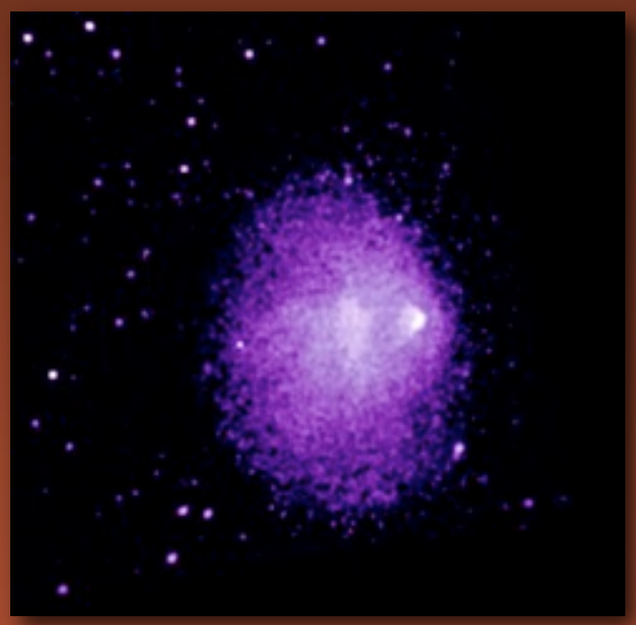
Ongoing revolution of mm & submm arrays. Soon it will be possible to field tens to hundreds of thousands of detector focal plane arrays.

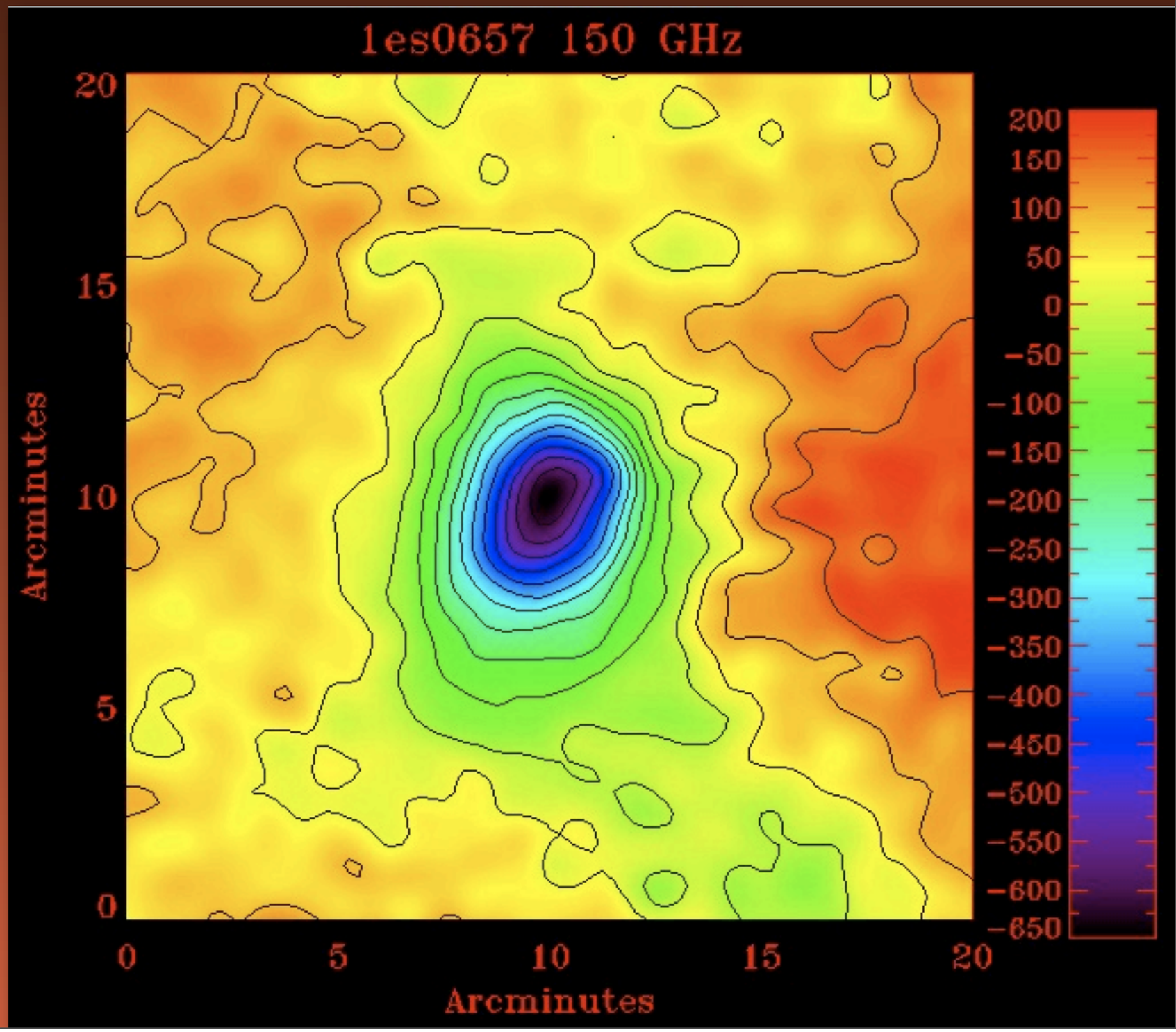
Pointed Cluster SZ Maps

SZ Image of Bullet Cluster

- **z = .297**
- **7 hours of observation**
- **~ 20 μK RMS per arcmin**

Chandra X-ray Image

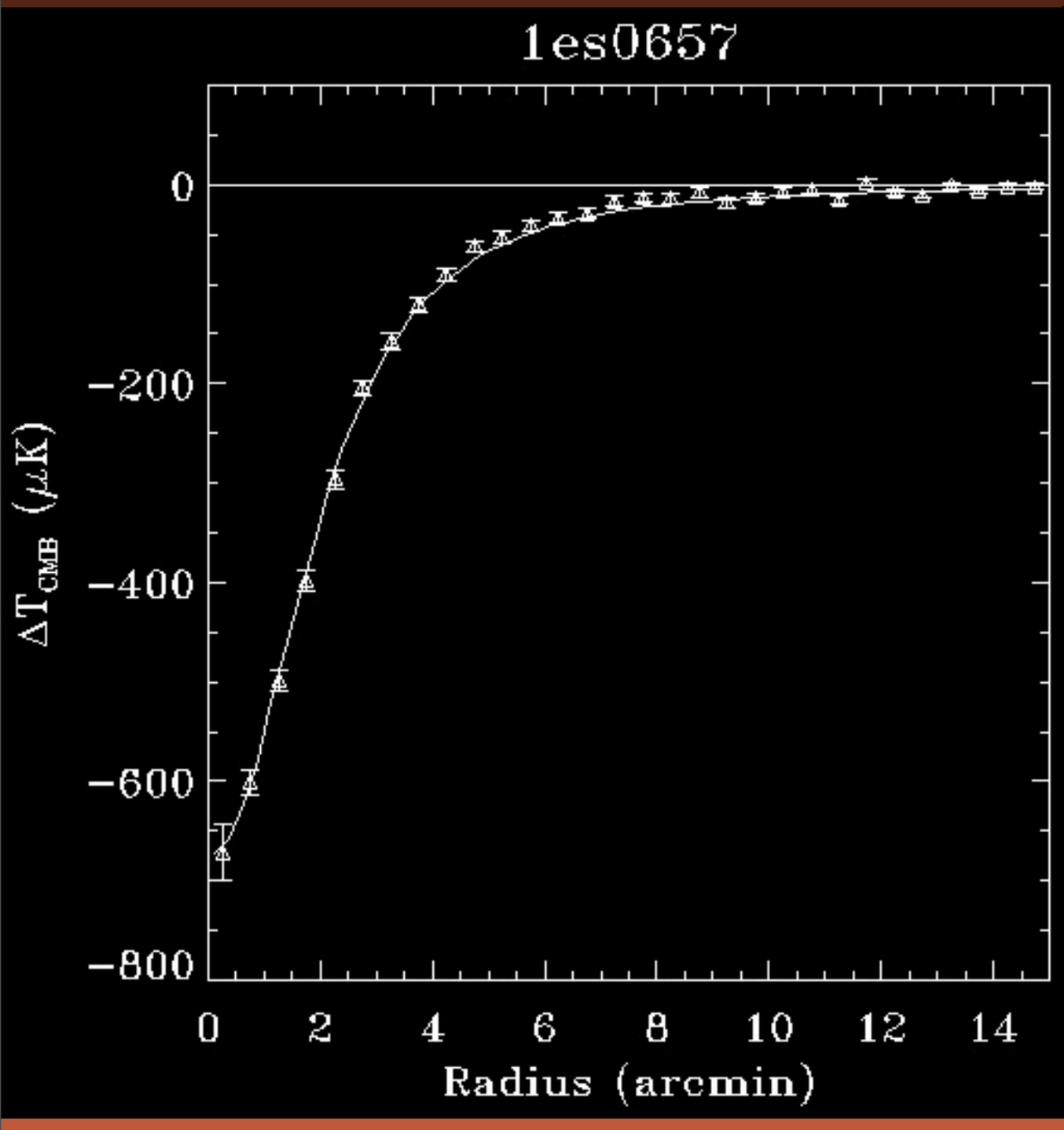


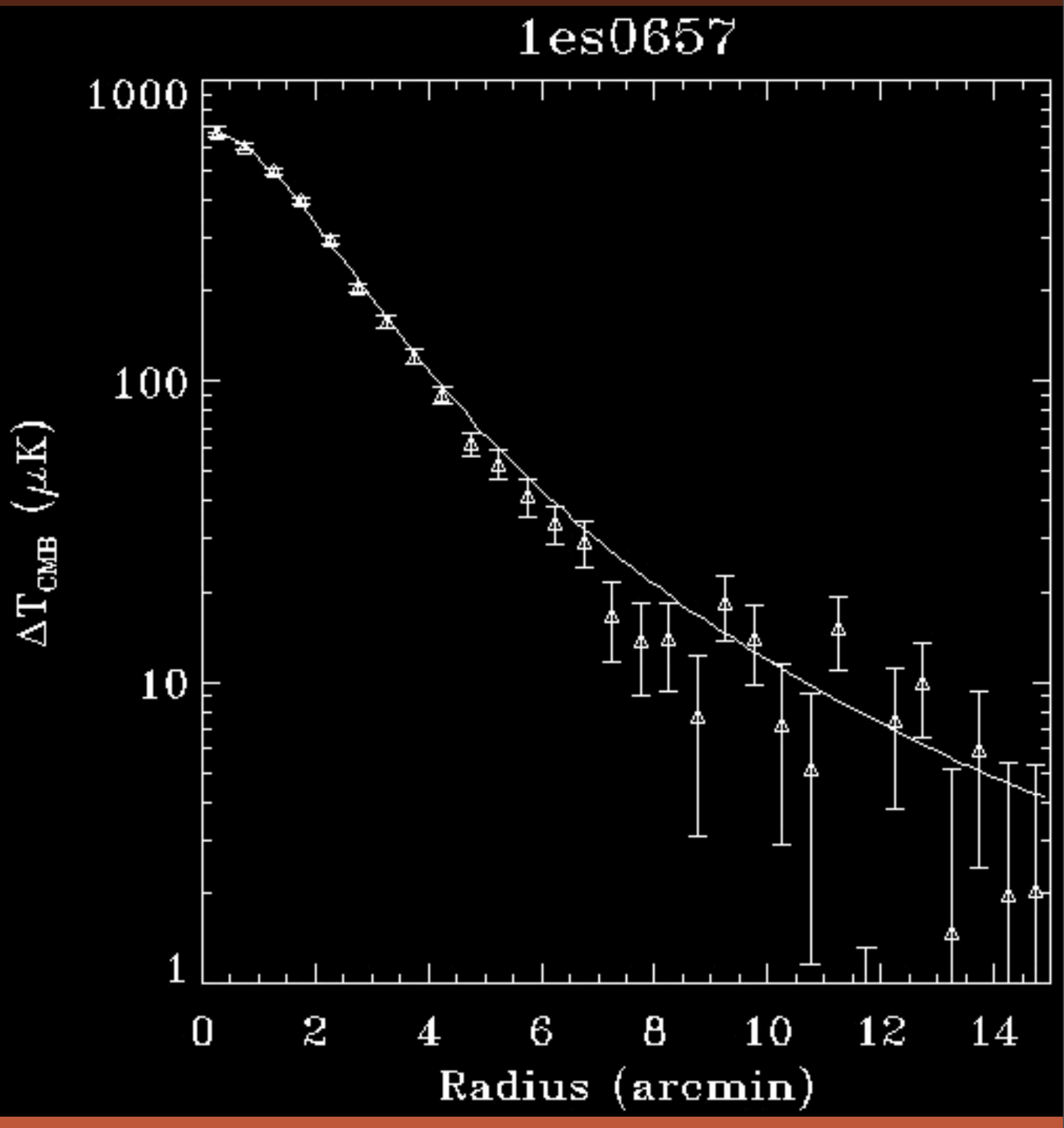


SZ emission radial profile

r_{500} = 1.6 Mpc; θ_{500} = 5.4'; θ_{200} = 8.6'

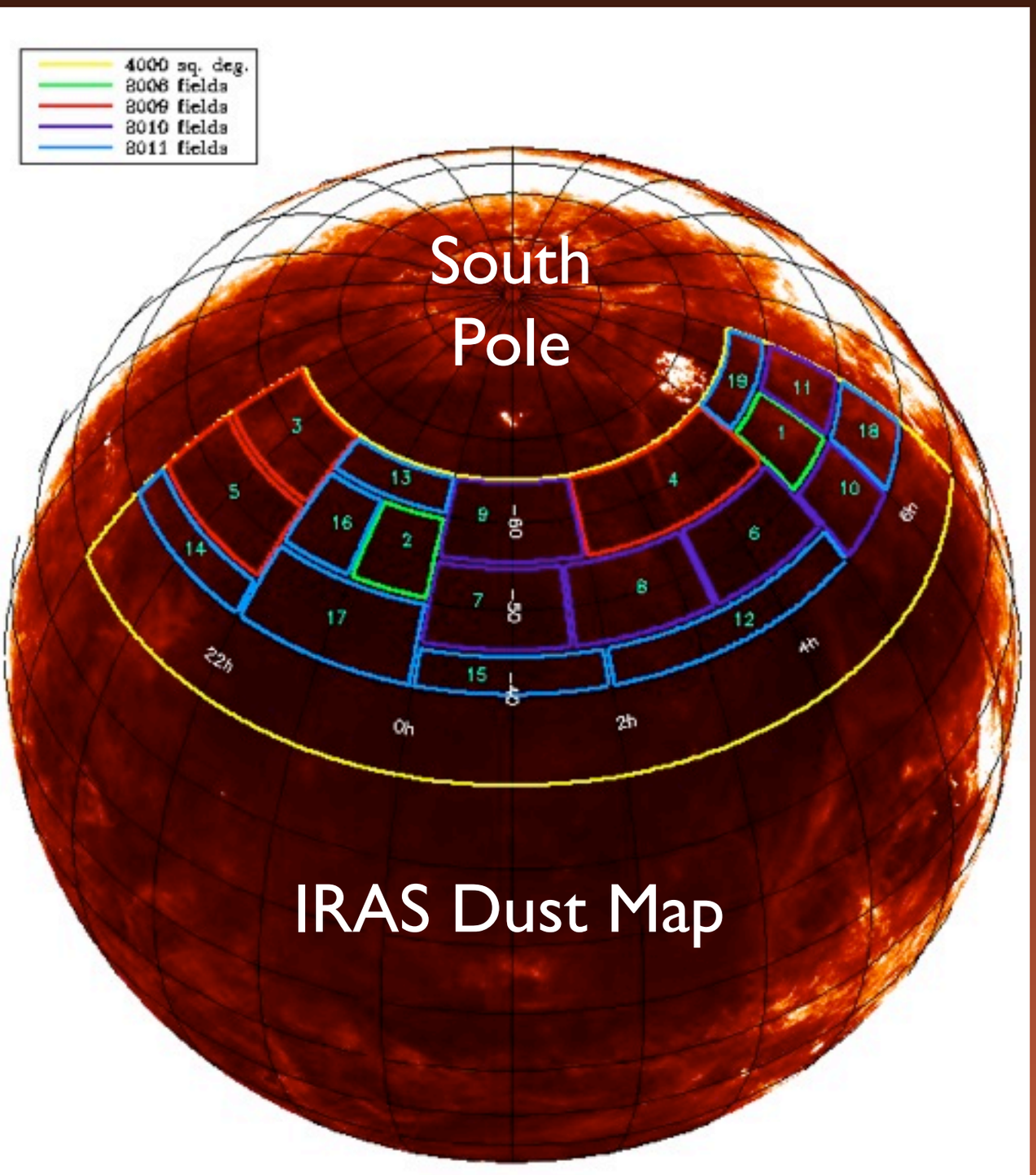
Significant signal seen at θ > 12' radius





Over 35 clusters targeted clusters mapped with rms 10-15 μK CMB/arcmin^2

SPT 2500 deg^2 SZ Survey



Status:

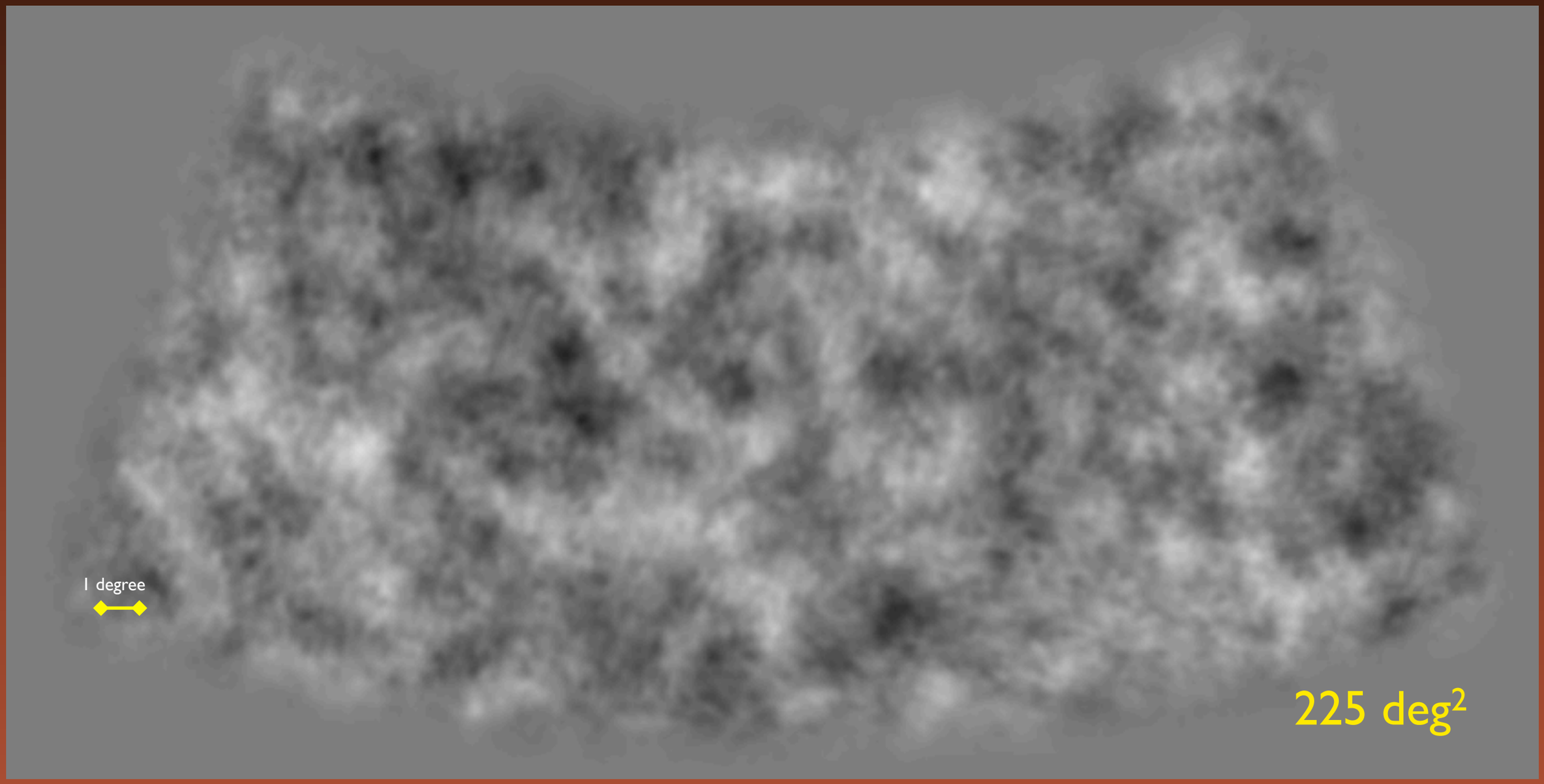
- 1500 deg^2 to full depth
- additional 1000 deg^2 to shallow depth (3x noise)
- Survey complete by Nov 2011

Final survey depths of:

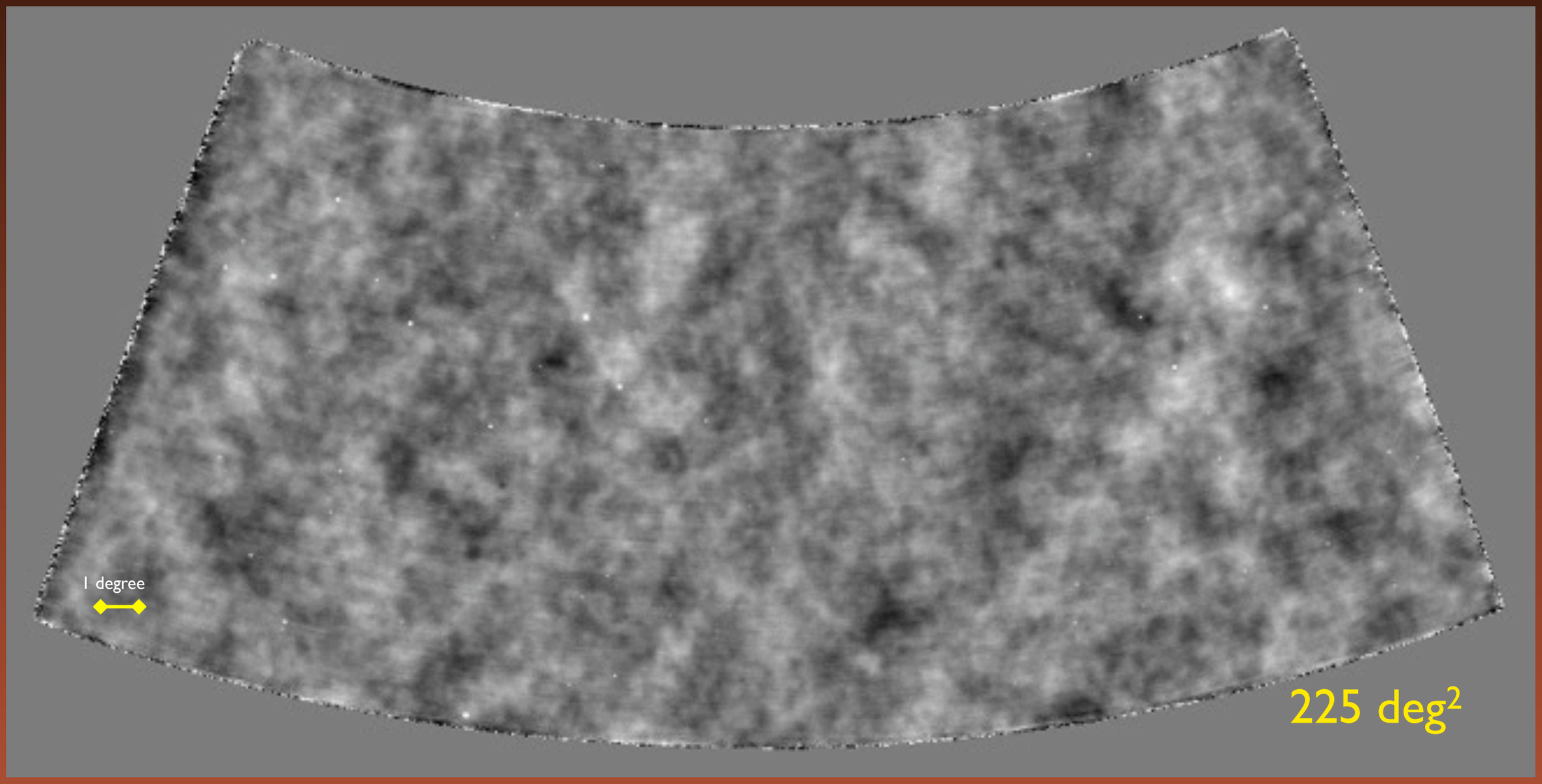
- 90 GHz: 42 uK$_{CMB}$-arcmin
- 150 GHz: 18 uK$_{CMB}$-arcmin
- 220 GHz: 85 uK$_{CMB}$-arcmin

(In these units, SZ is 1.7 times brighter at 90 GHz than at 150 GHz)

WMAP CMB map covering one of our SPT fields

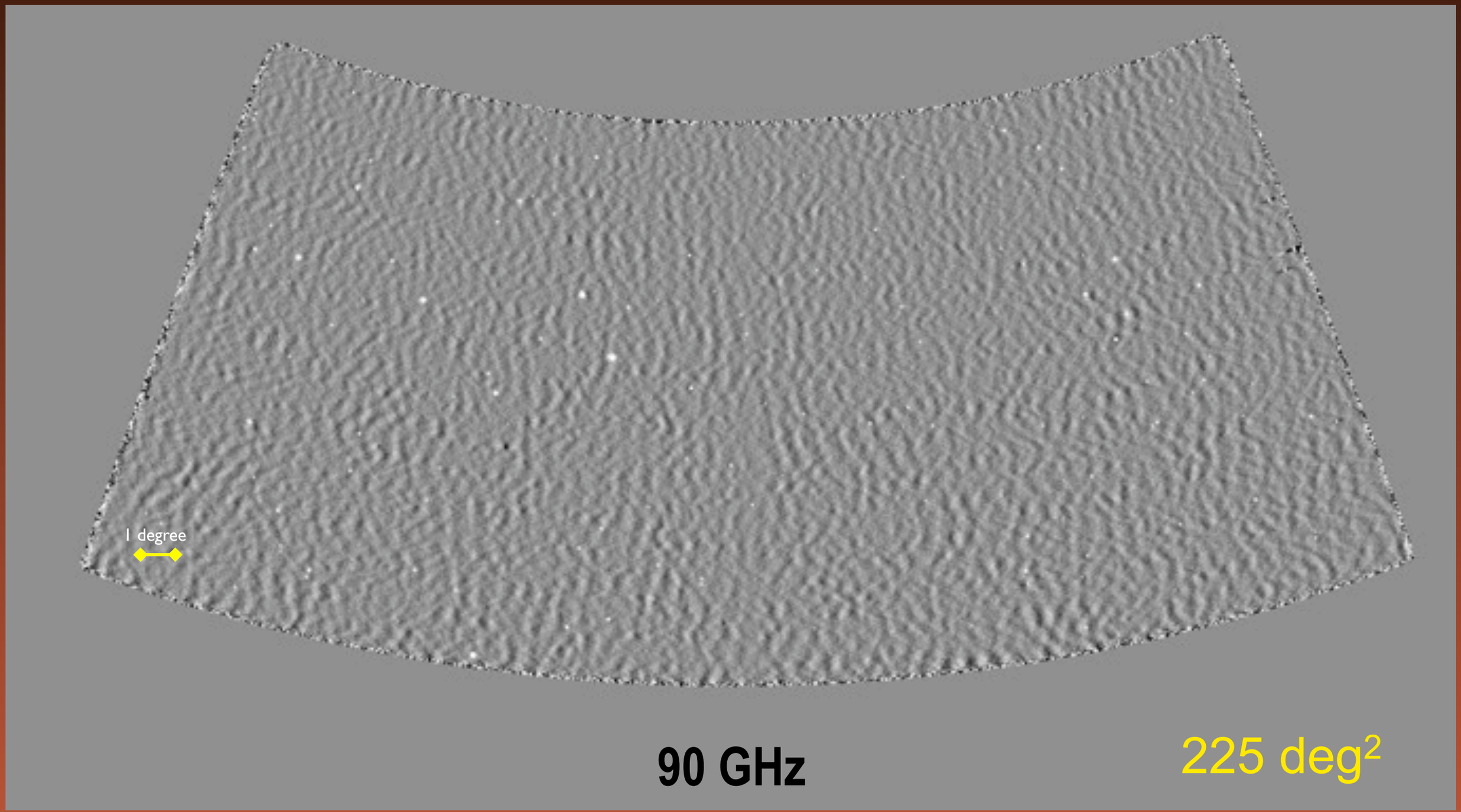


Lightly filtered SPT map at 90 GHz



Shows structure from degrees to arc minutes:
from large-scale CMB to SZ & unresolved sources.

A typical SPT survey field



Filtered to remove large-scale CMB

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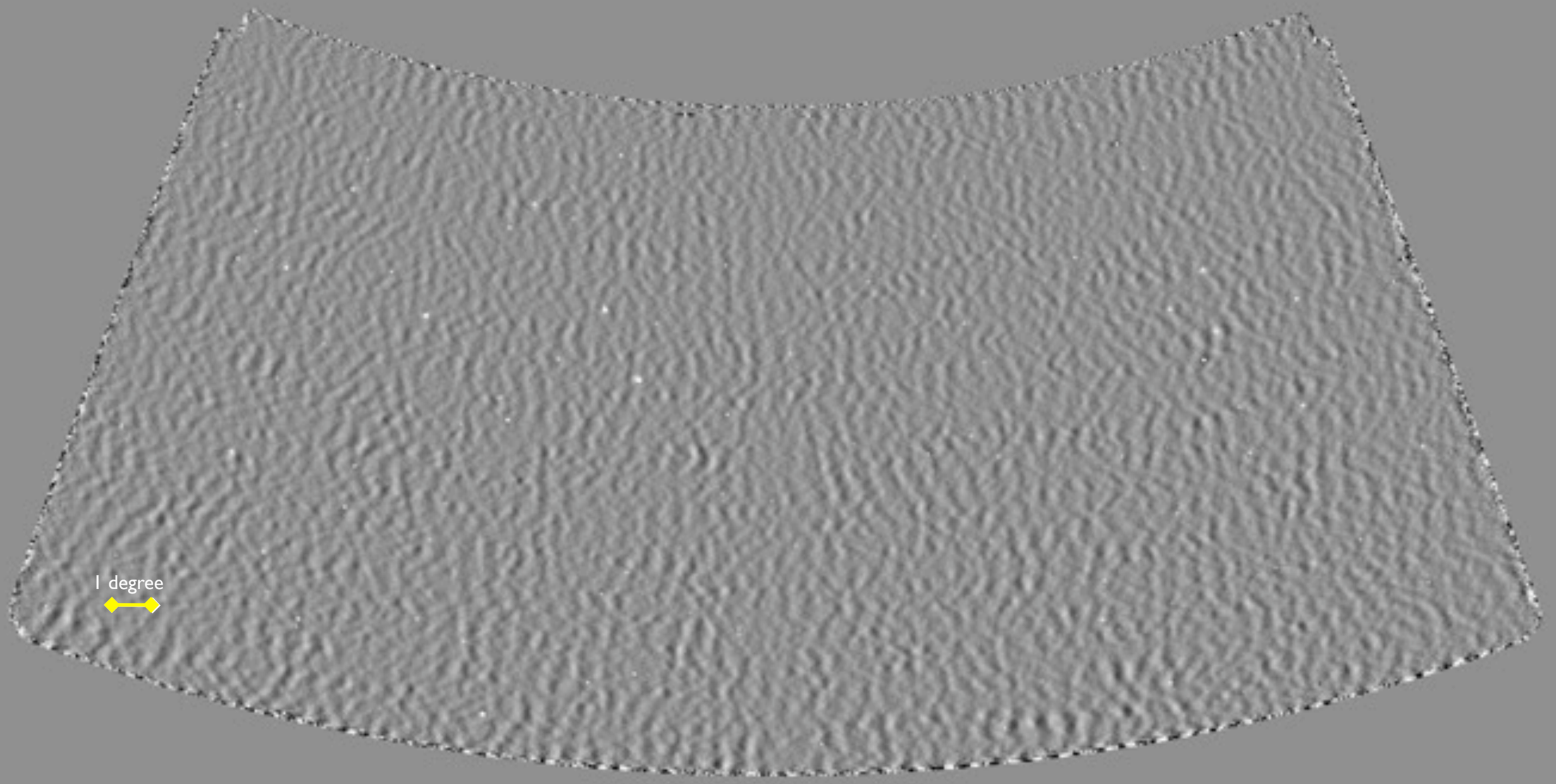
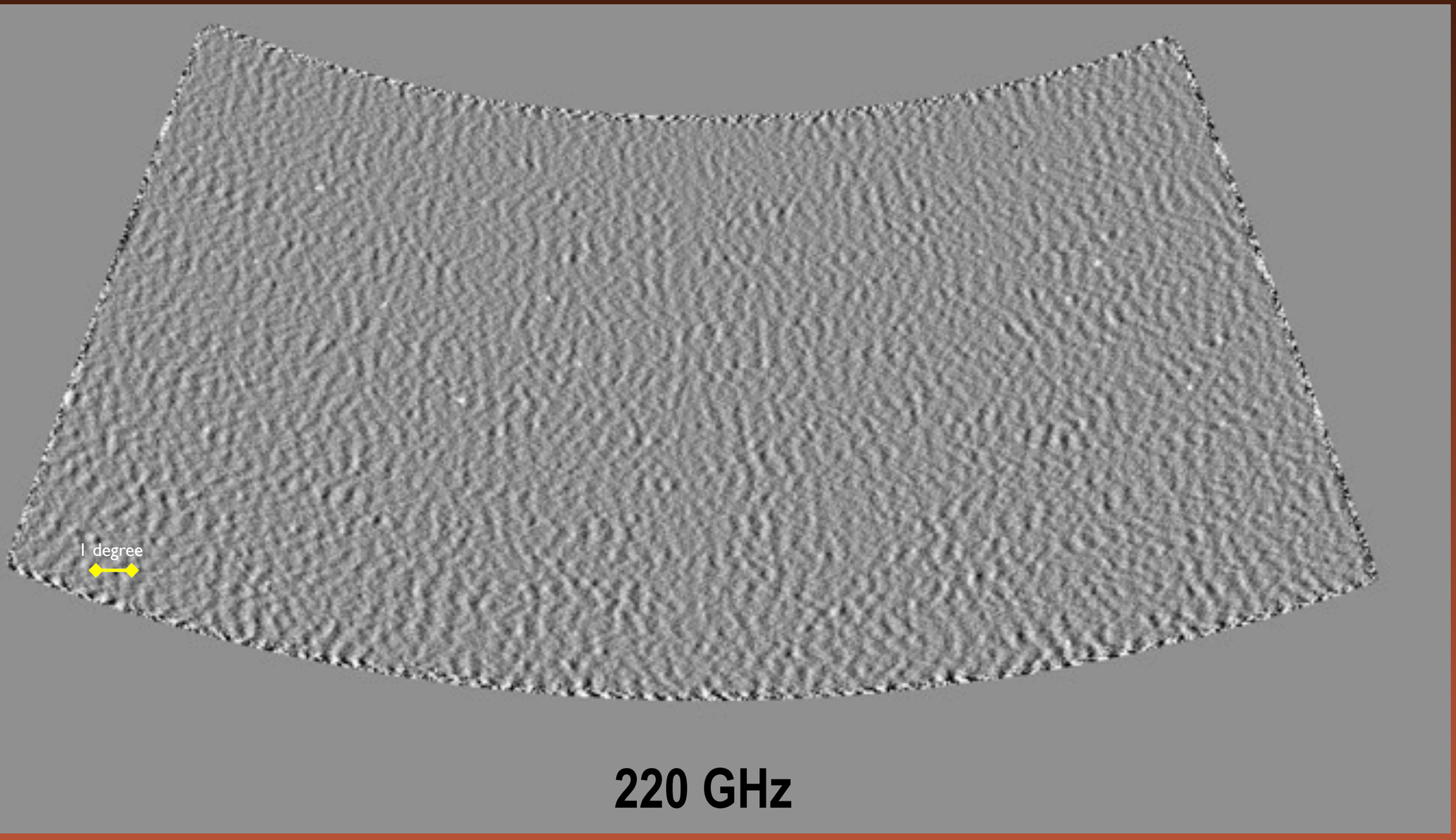


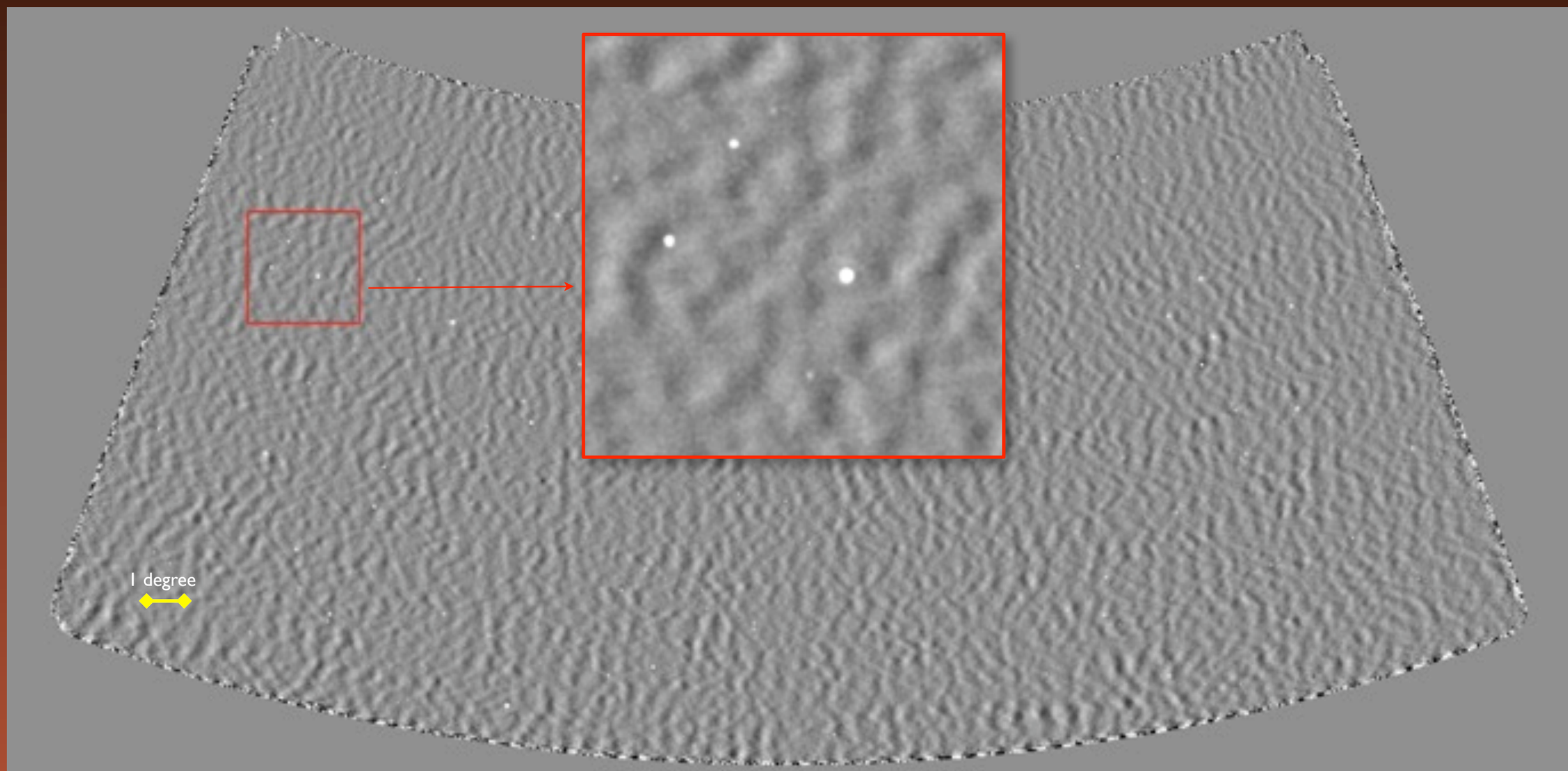
150 GHz

A typical SPT survey field



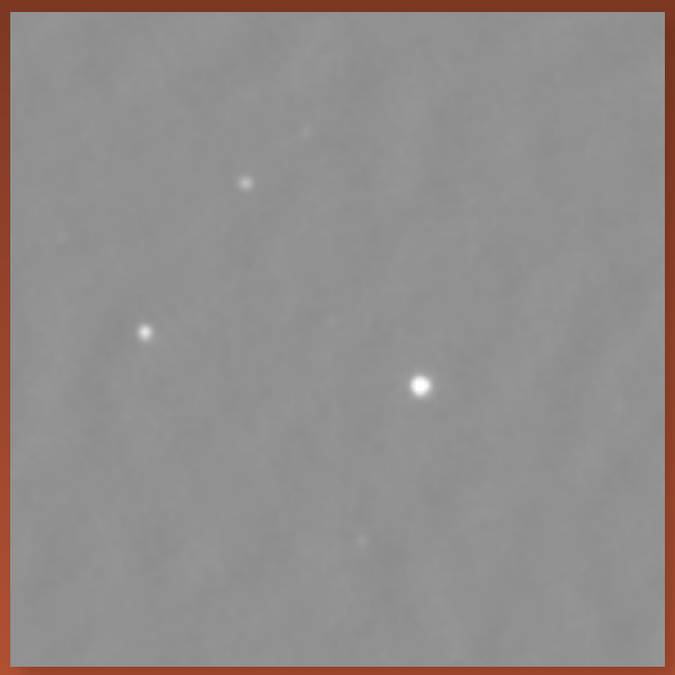
220 GHz

‘Point’ Sources - i.e., Galaxies

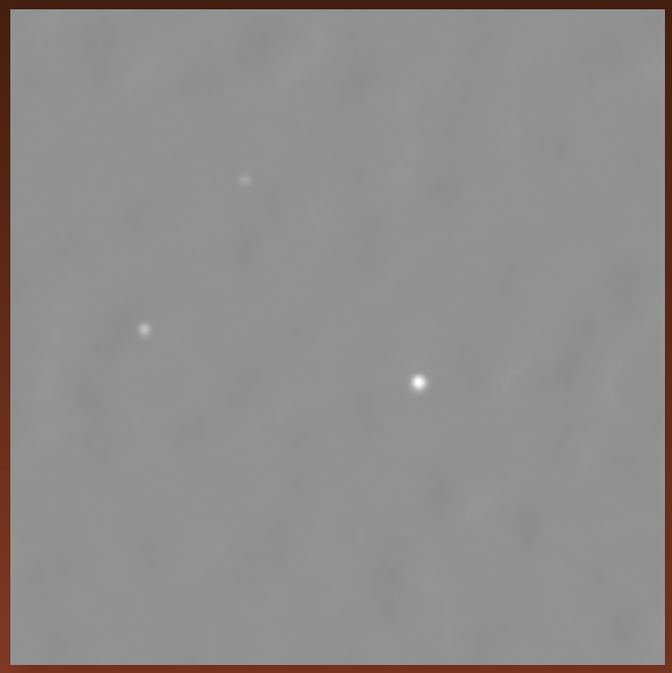


150 GHz

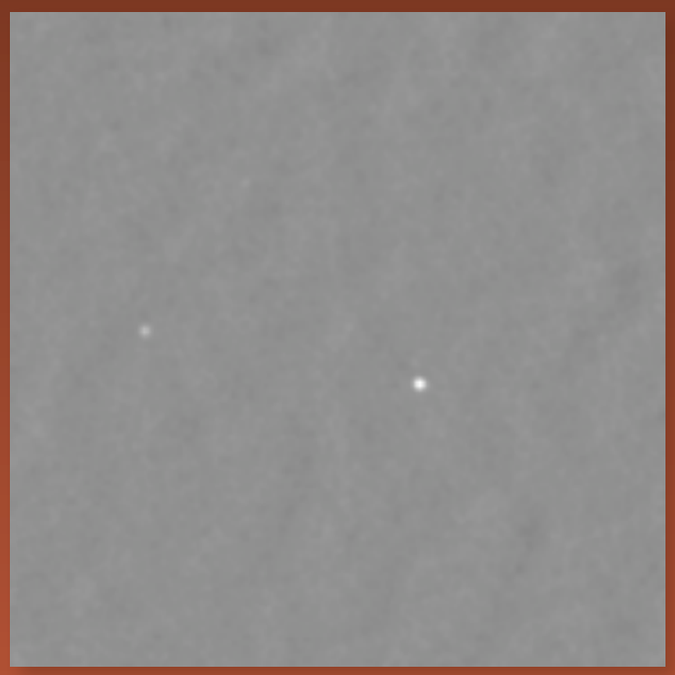
‘Point’ Sources - Galaxies



90 GHz



150 GHz

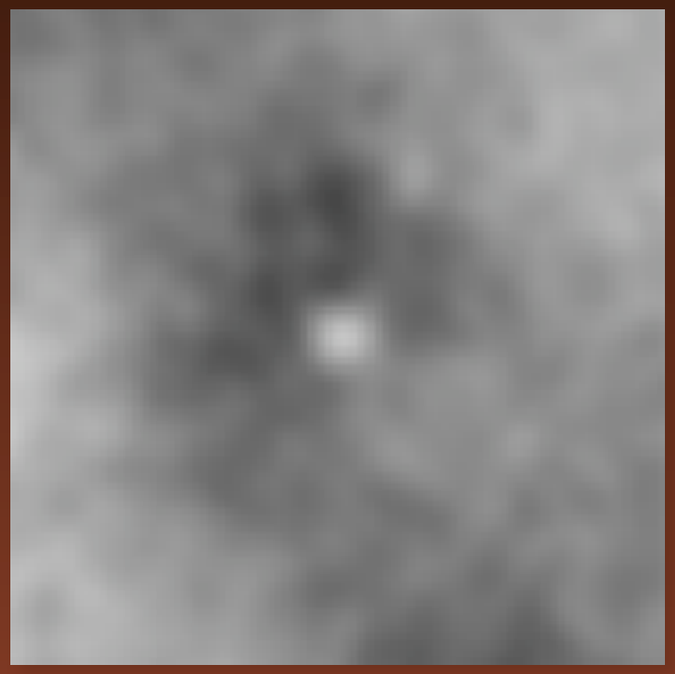


220 GHz

2 degrees

(grayscale +/- 100 mJy)

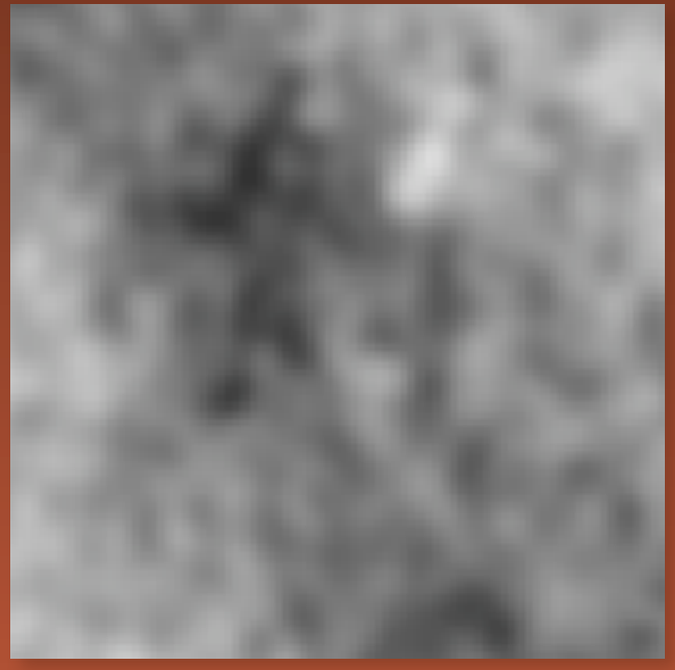
New population of rare luminous dusty star forming galaxies



20 arcminutes

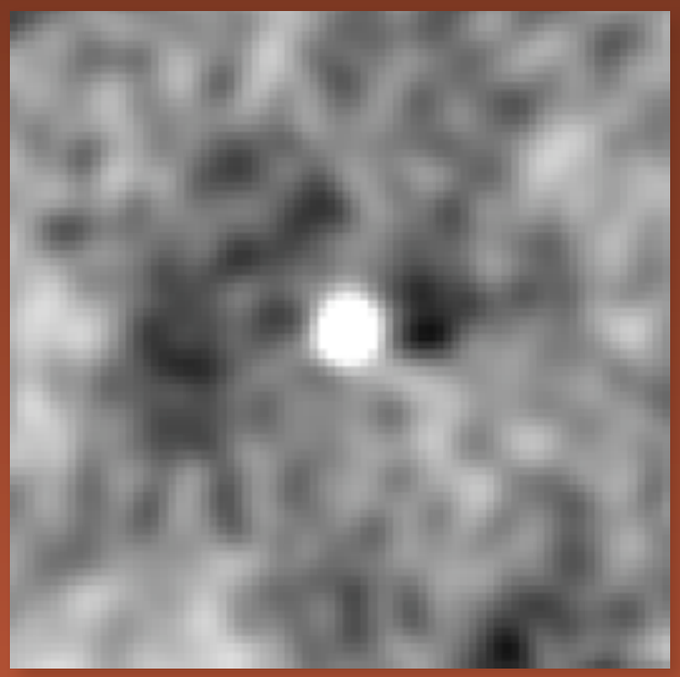
150 GHz

Follow-up indicates lensed high redshift star forming galaxies.



90 GHz

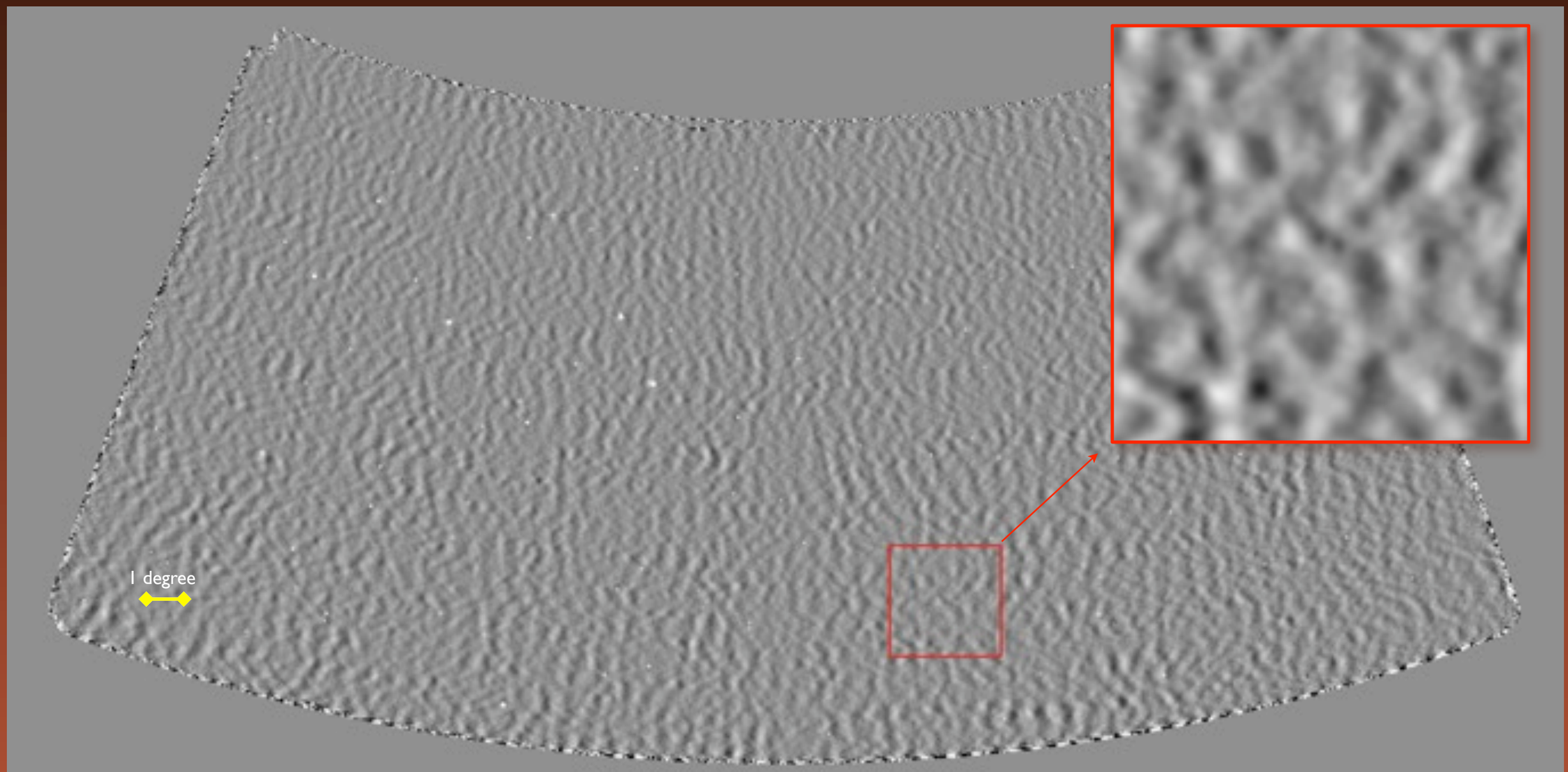
(grayscale +/- 100 mJy)



220 GHz

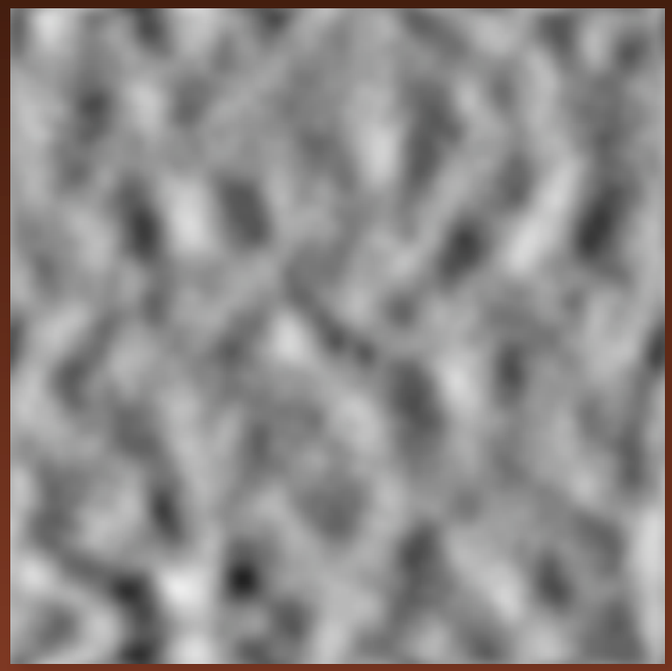
Vieira et al., arXiv:0912.2338

Primary CMB anisotropy



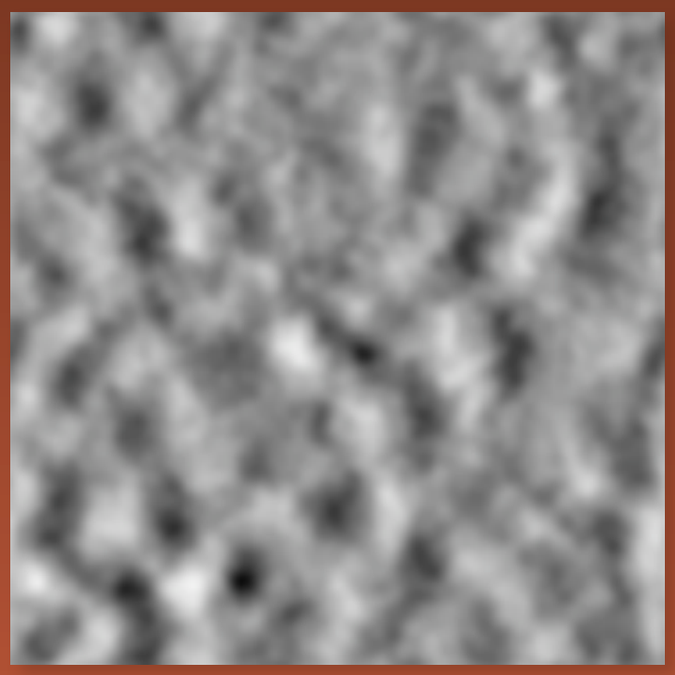
150 GHz

Primary CMB anisotropy



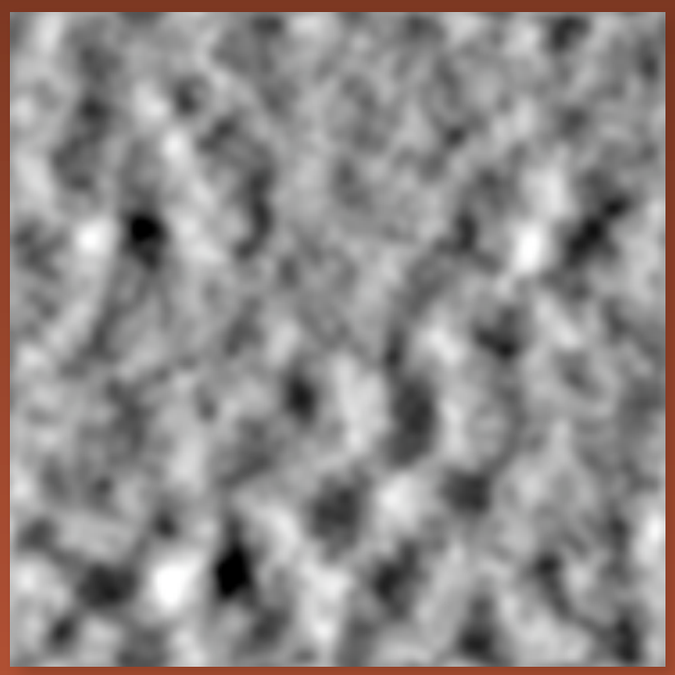
2 degrees

150 GHz



90 GHz

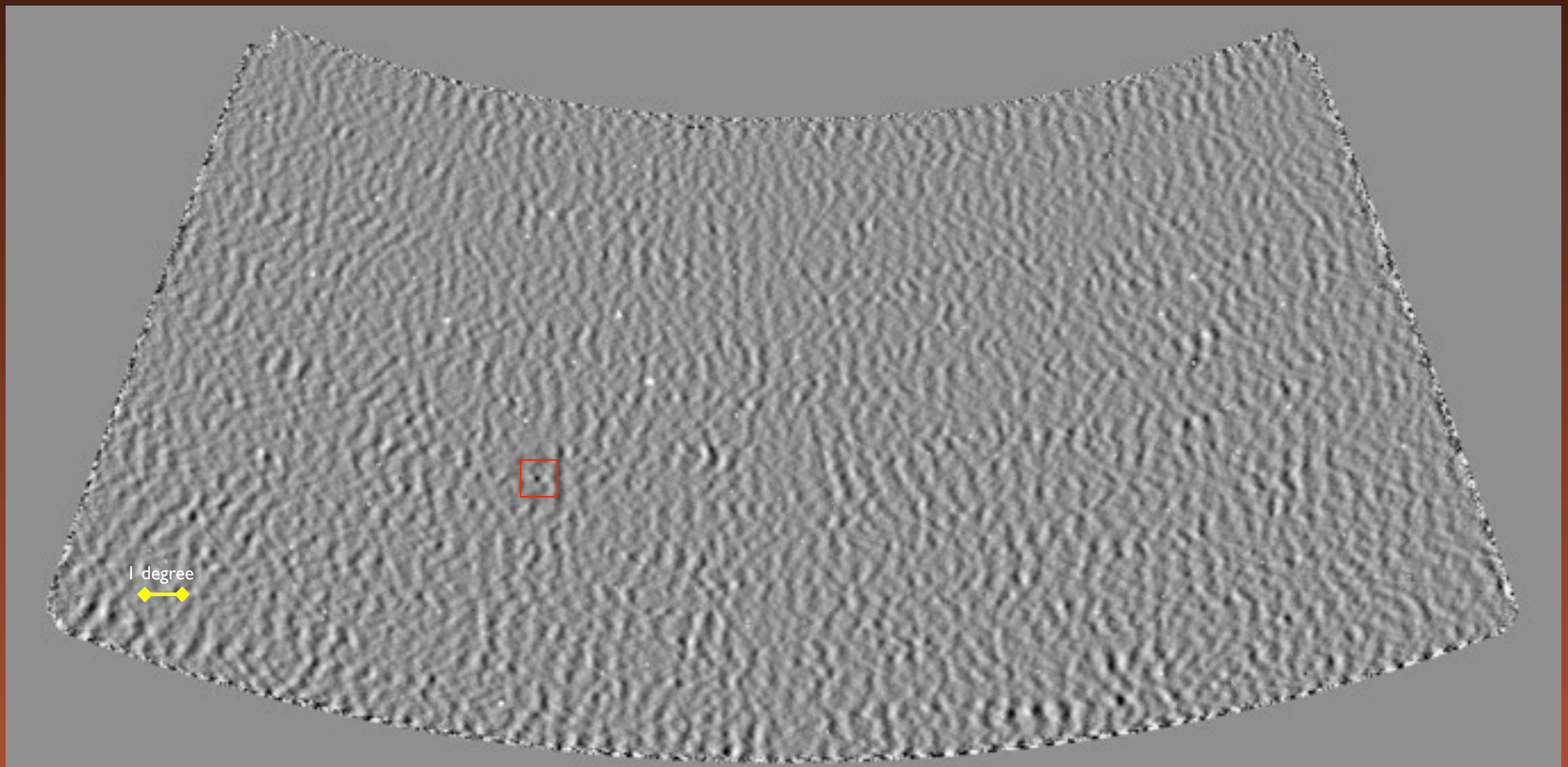
(grayscale +/- 100uK_CMB)



220 GHz

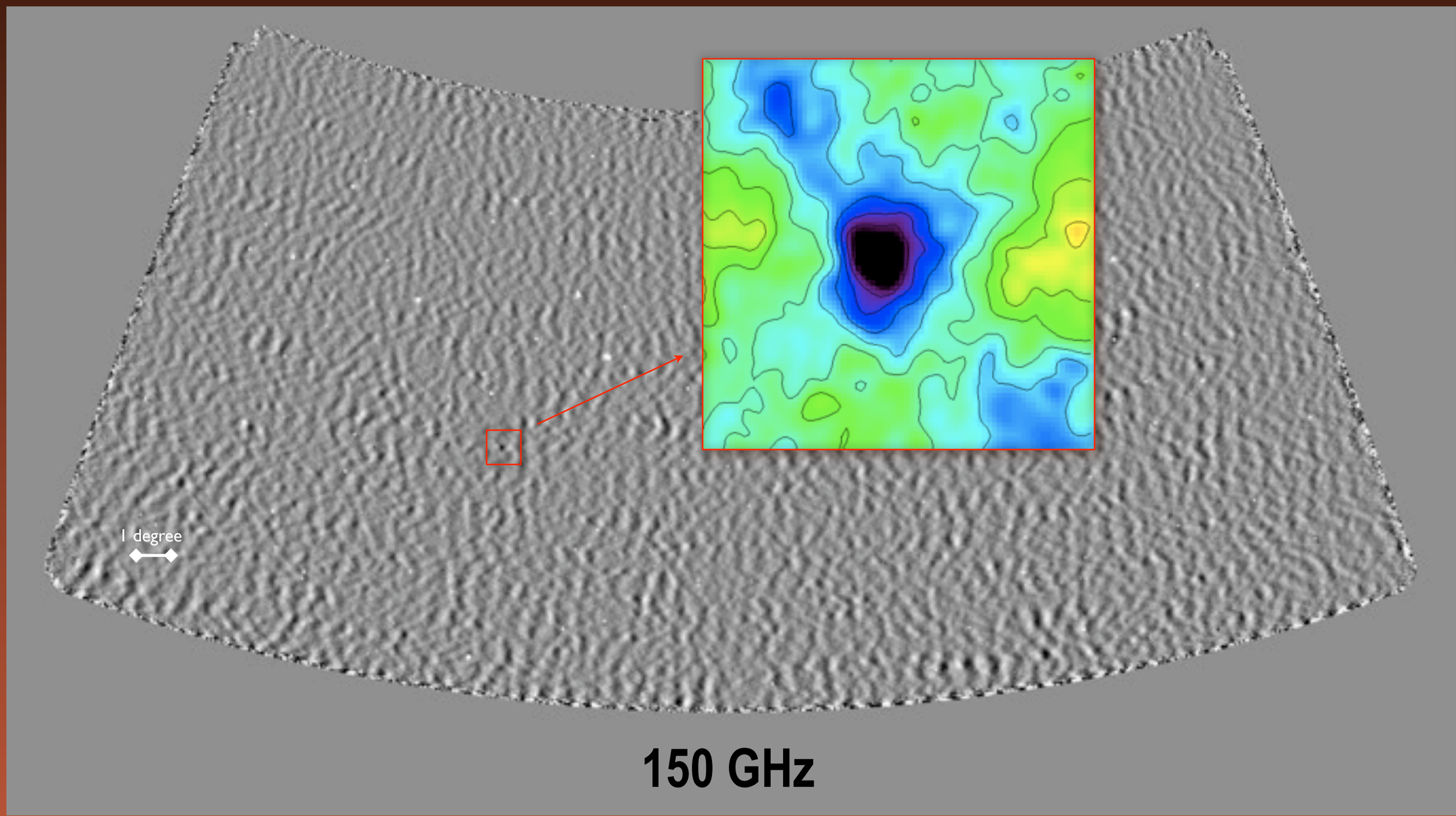
SPT high-l CMB anisotropy: Lueker et al., arXiv:0912.4317, Shirokoff et al, arXiv:1012.4788

Galaxy Clusters!



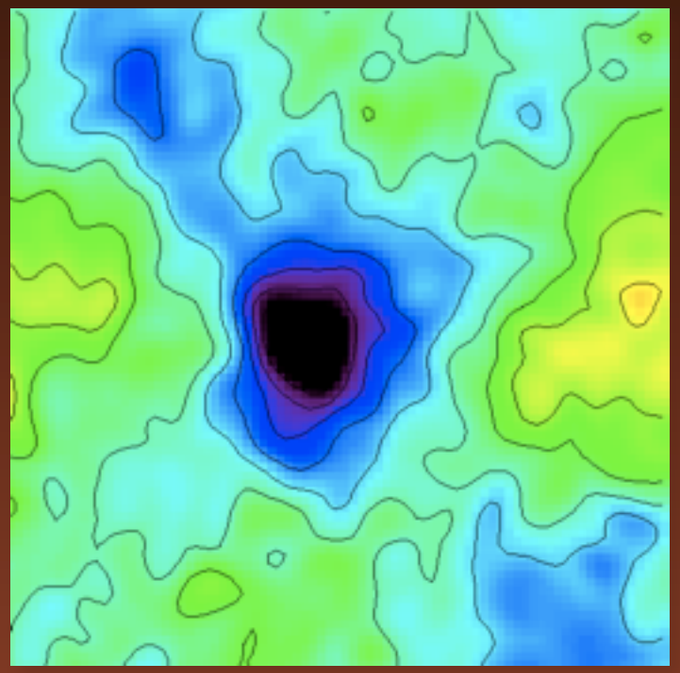
150 GHz

A lot of Galaxy Clusters!



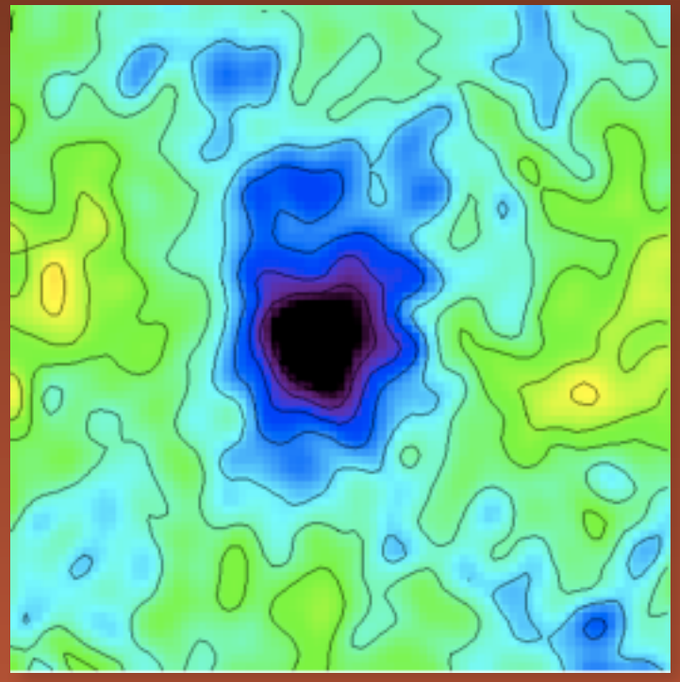
150 GHz

Galaxy Clusters via SZ effect



20 arcminutes

150 GHz

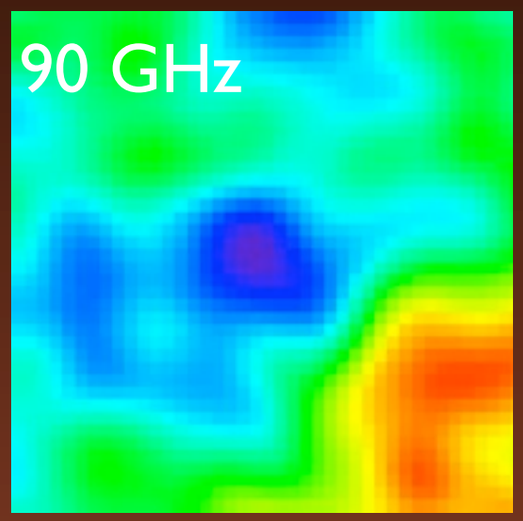


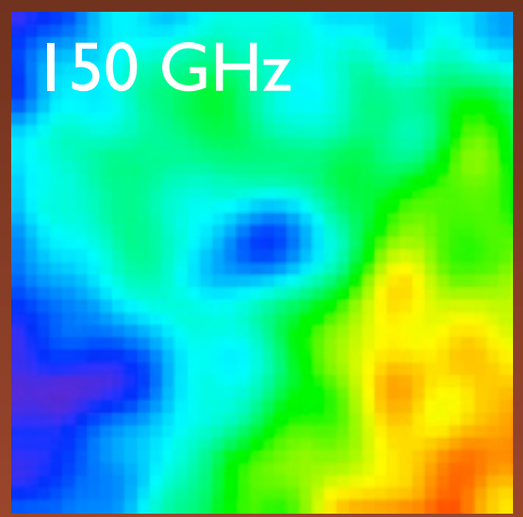
90 GHz

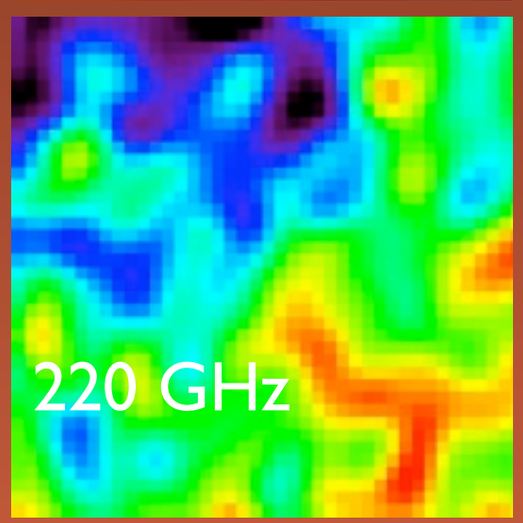
220 GHz

First SZ discovered clusters Staniszewski & SPT team, ApJ 701, 2009.
We have now found 100's of clusters.

Finding Clusters in a SZ Survey

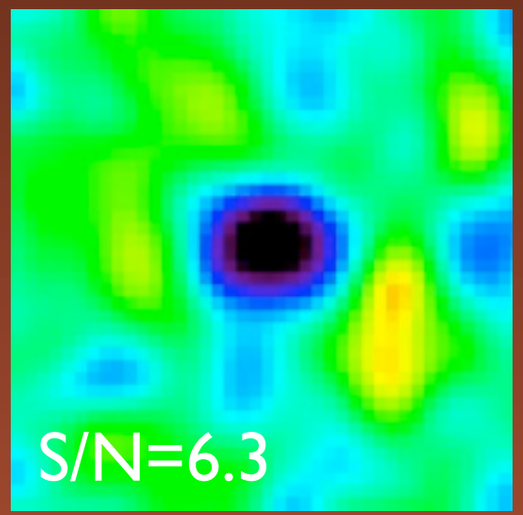






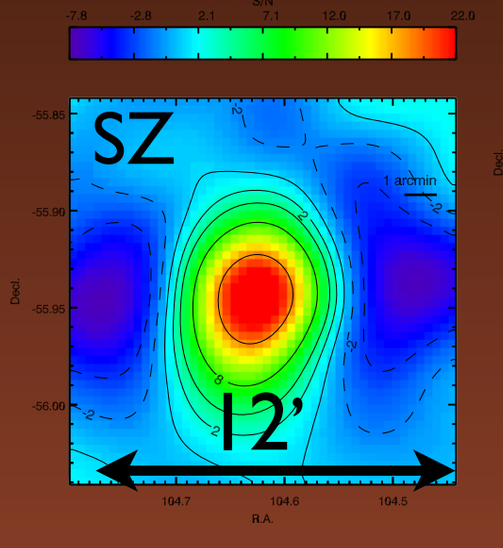
- Combine maps at different frequencies into a synthesized thermal SZ map, and find significant objects in that map
- [OR: these steps can be combined into a single spatial-spectral filter (e.g. , Tegmark 2000, Herranz et al. 2002, Melin et al. 2006).]

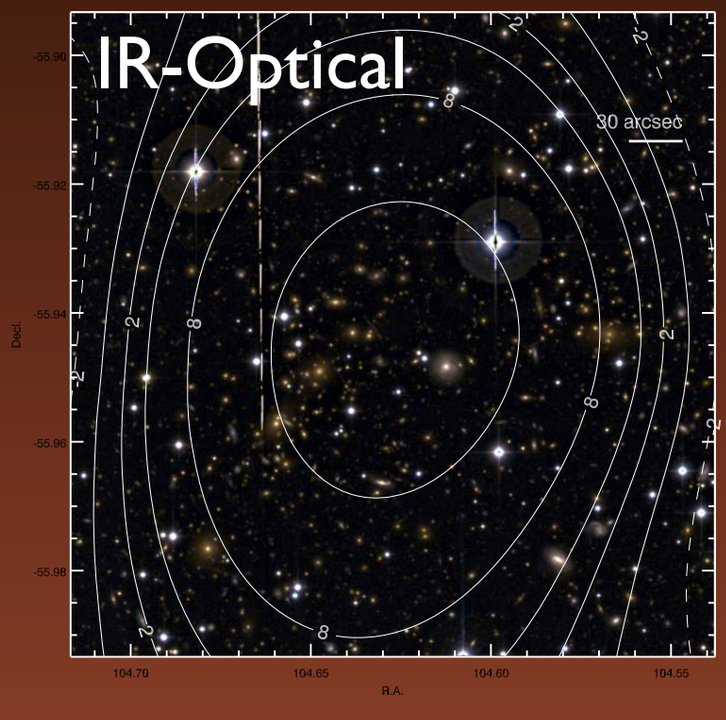
Matched Filter



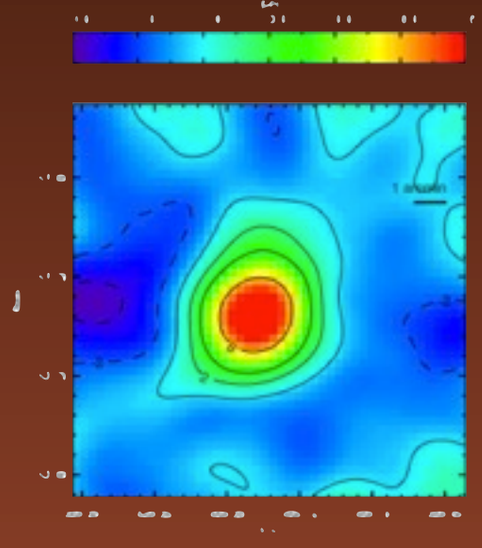
Example SPT Cluster Images

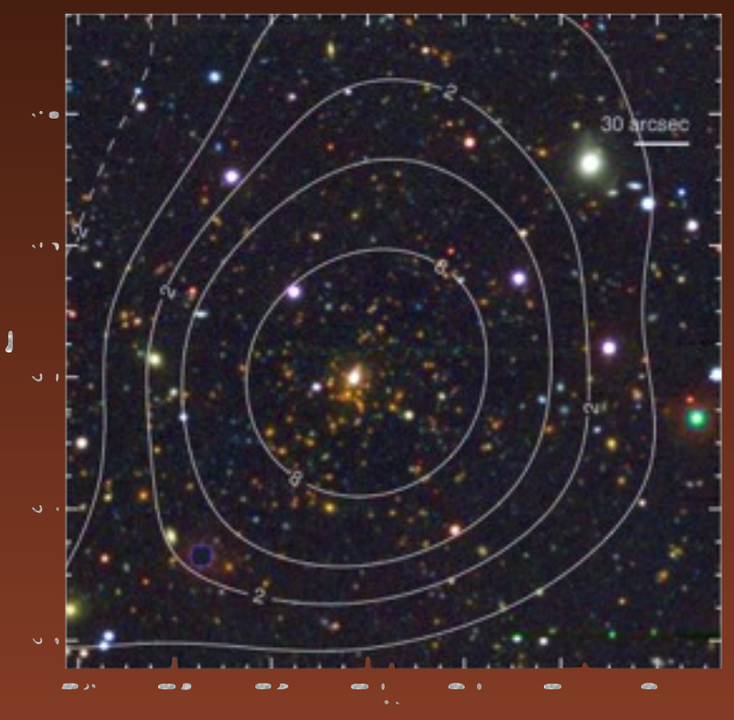
0658-5358
(z=0.30)
Bullet Cluster



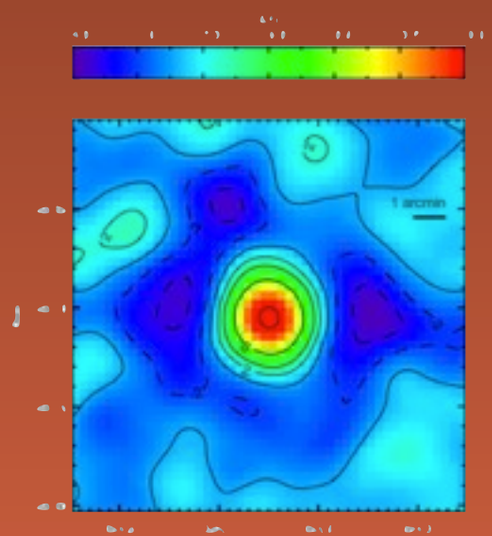


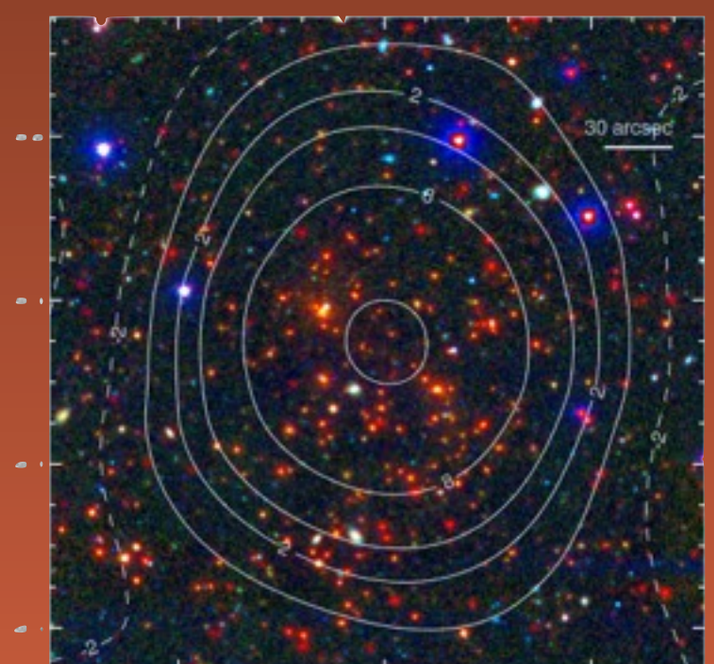
2344-4243
(z=0.62)



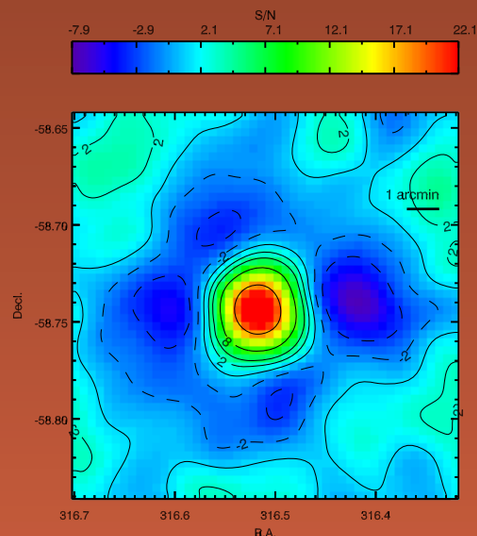


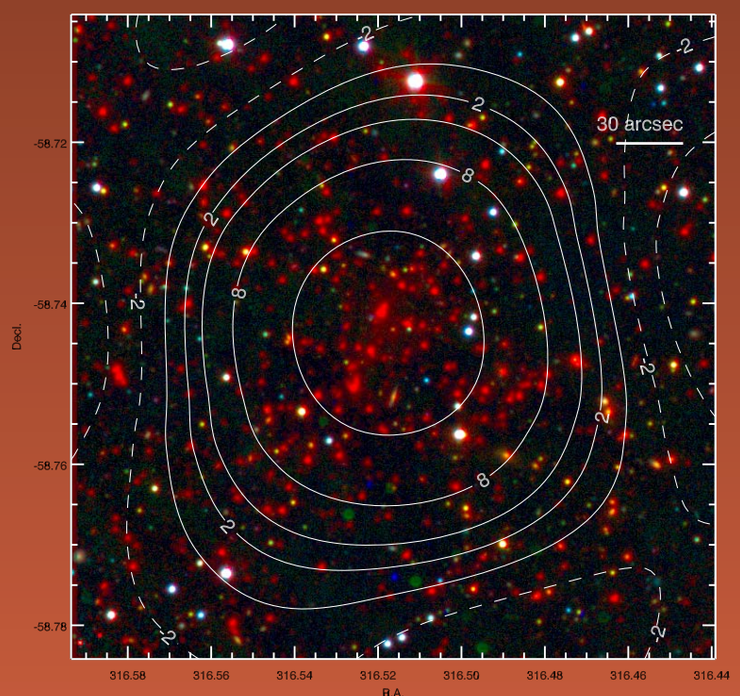
2337-5942
(z=0.78)





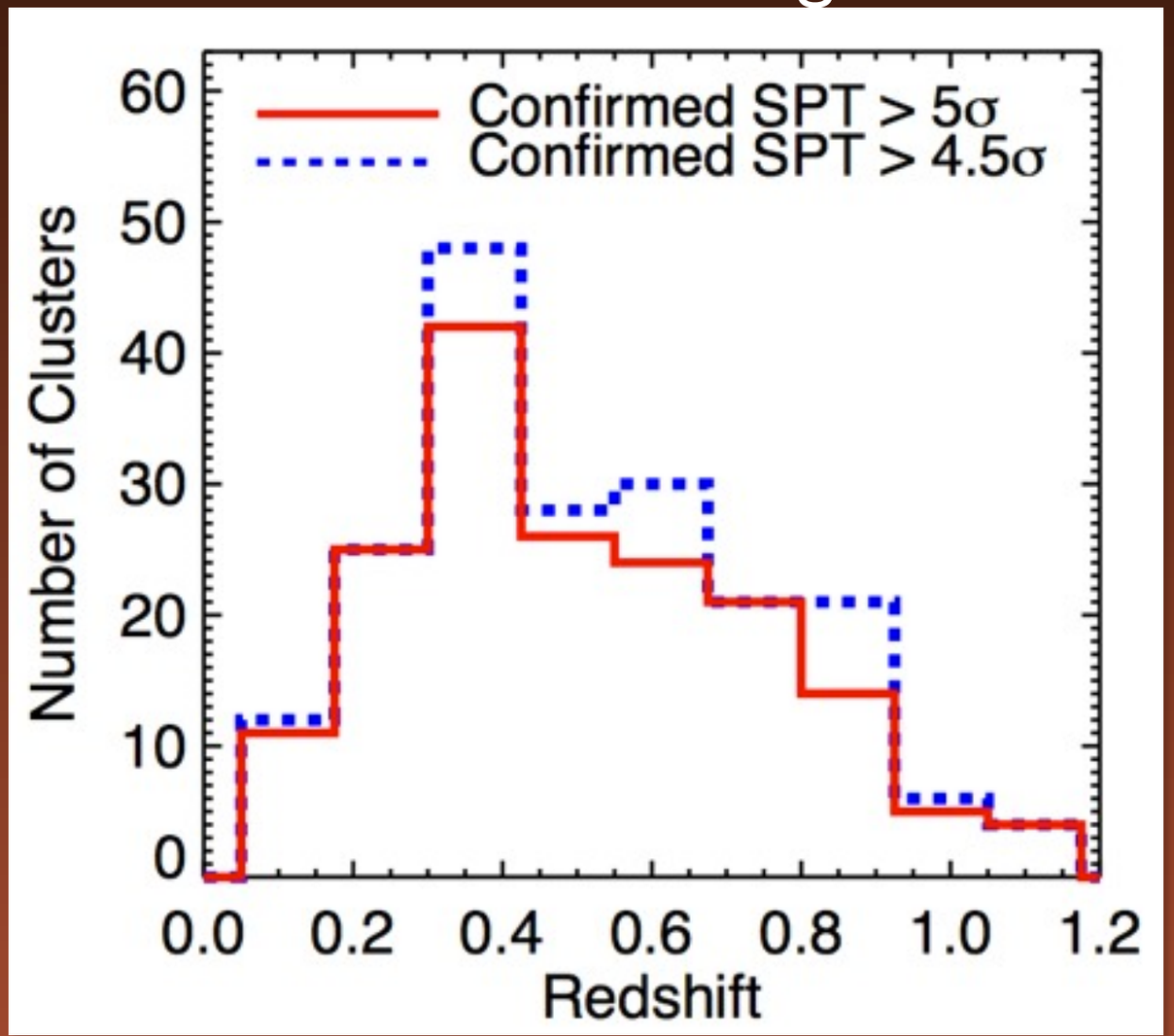
2106-5844
(z=1.13)



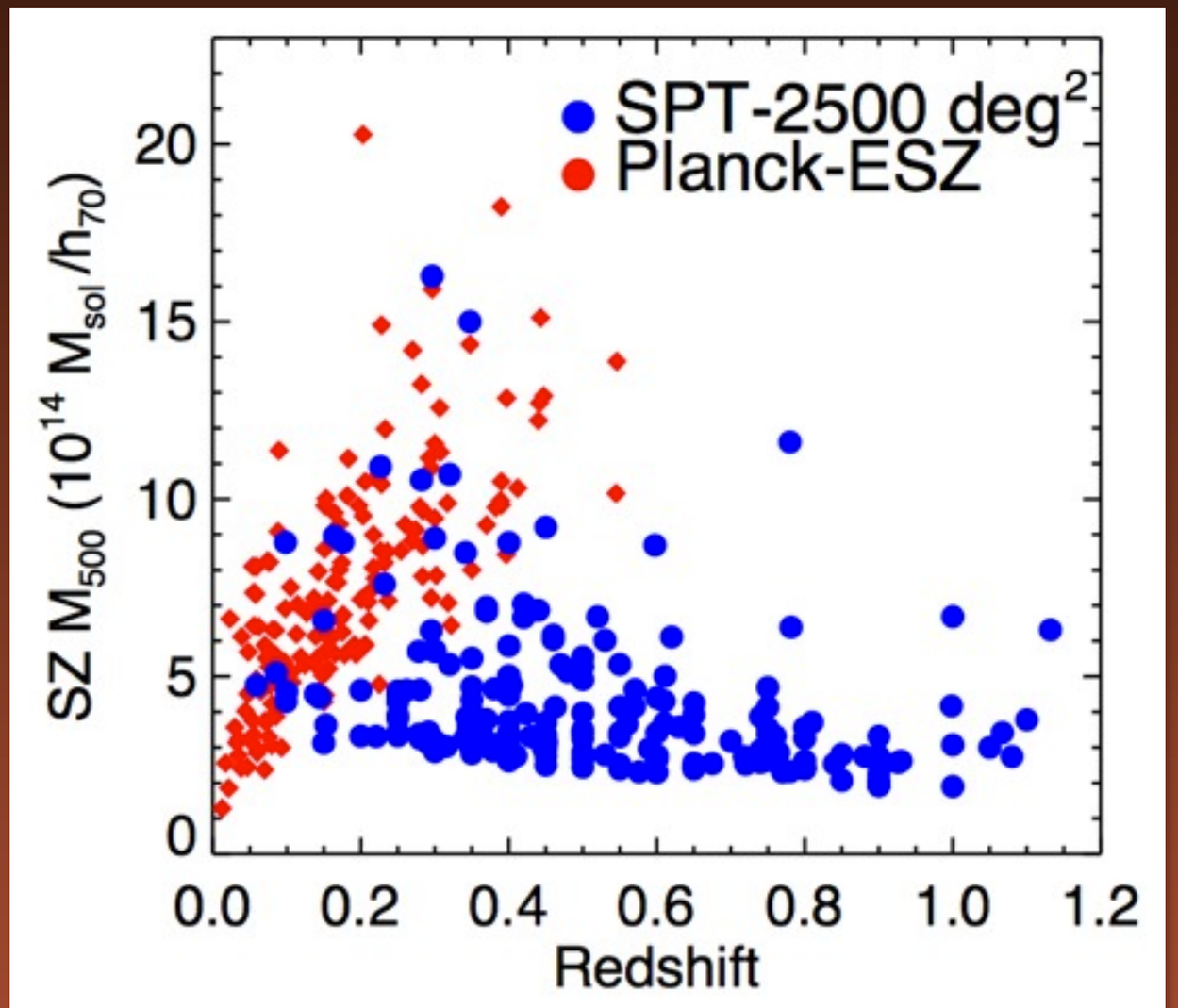


SPT Cluster Sample Properties

Redshift Histogram



SZ Mass vs Redshift



Over 300 clusters optically confirmed, ~80% newly discovered

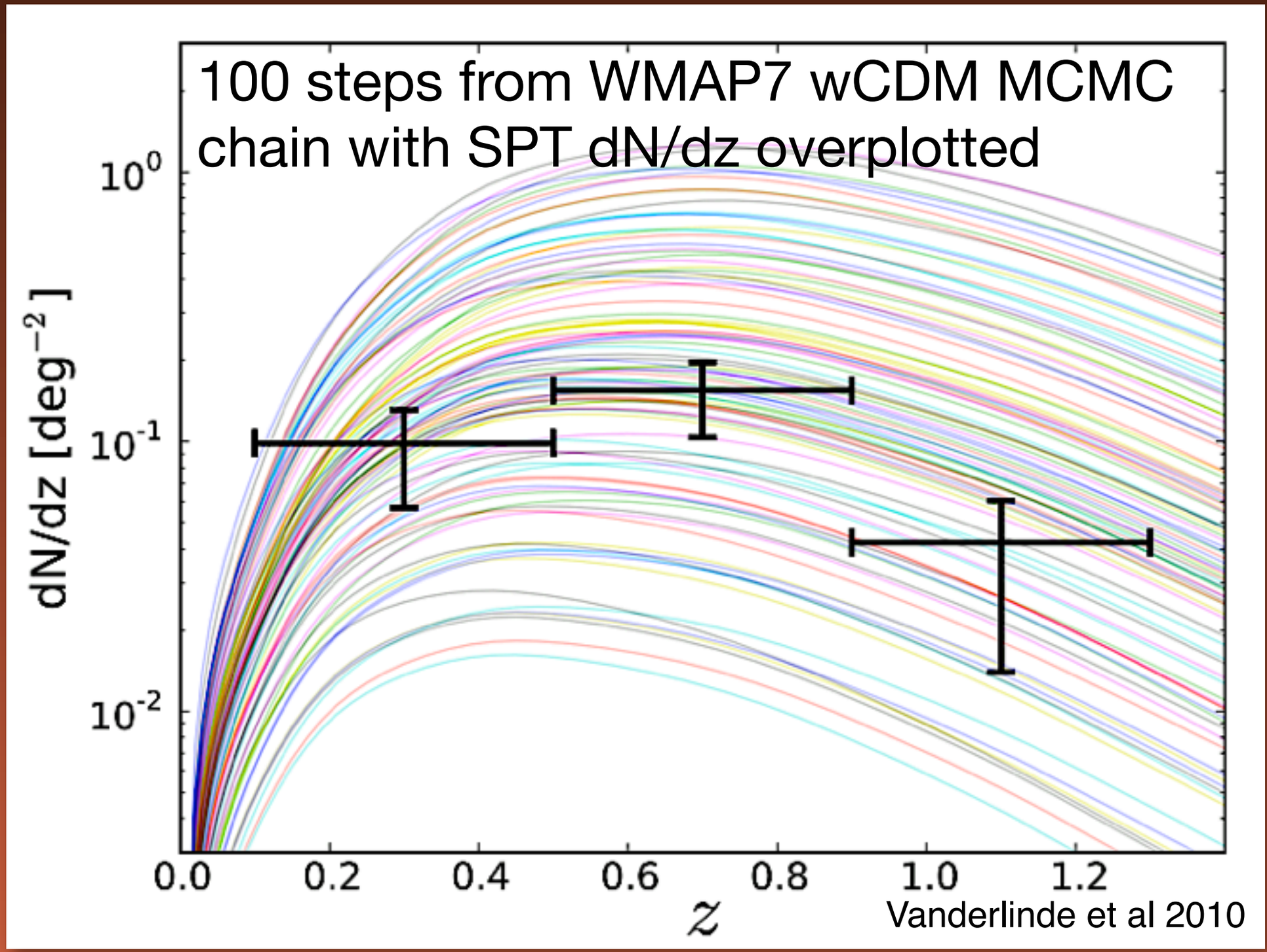
High redshift: $\langle z \rangle$ = 0.5 - 0.6

Optical measurements also confirm ~95% purity at snr ≥ 5

Mass threshold flat/falling with redshift: $M_{500}(z=0.6) > 3 \times 10^{14}\ M_o/h_{70}$

First step to Dark Energy

Used only first 200 deg^2 of survey (21 clusters with snr ≥5) to constrain cosmology.



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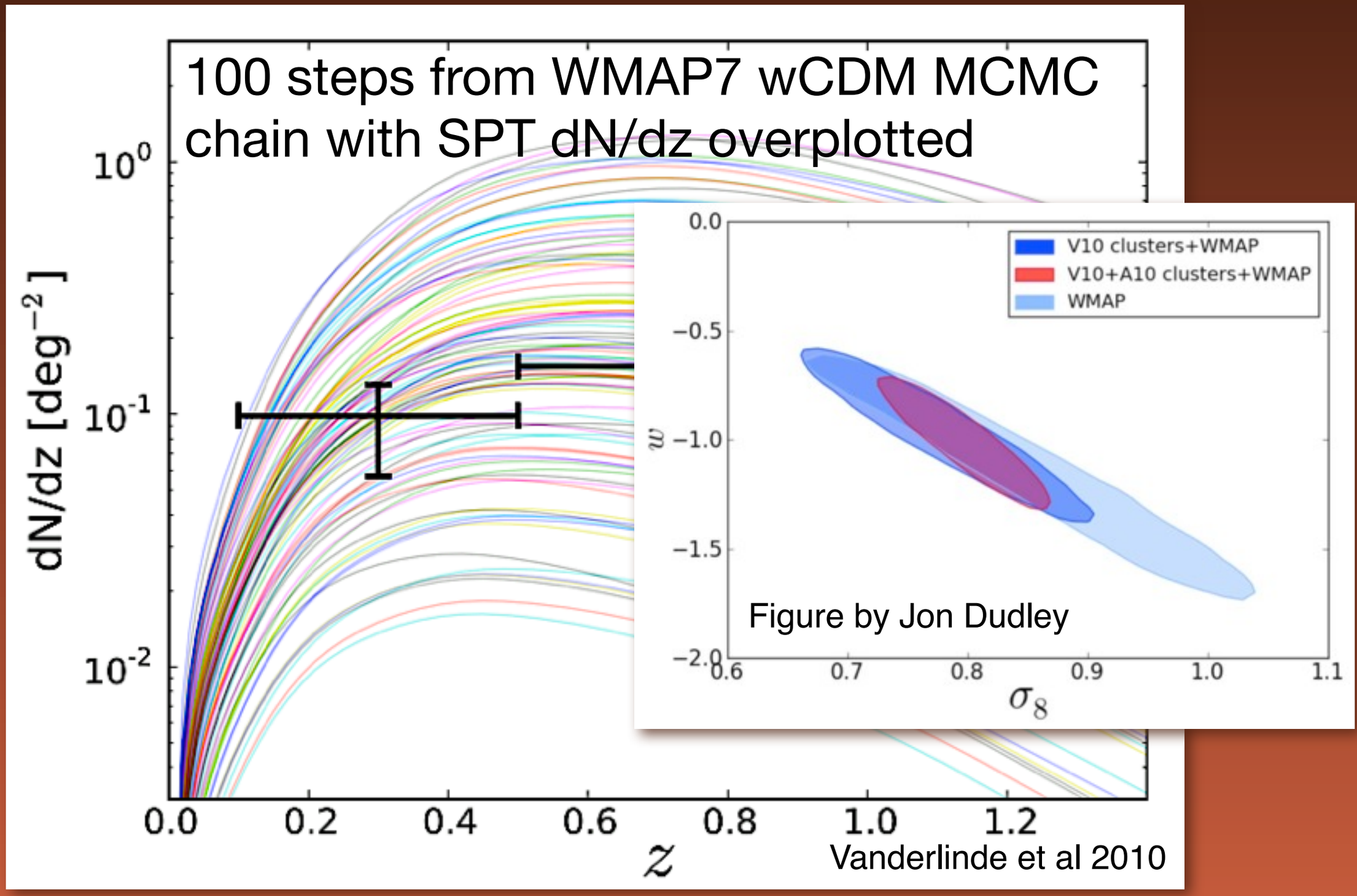
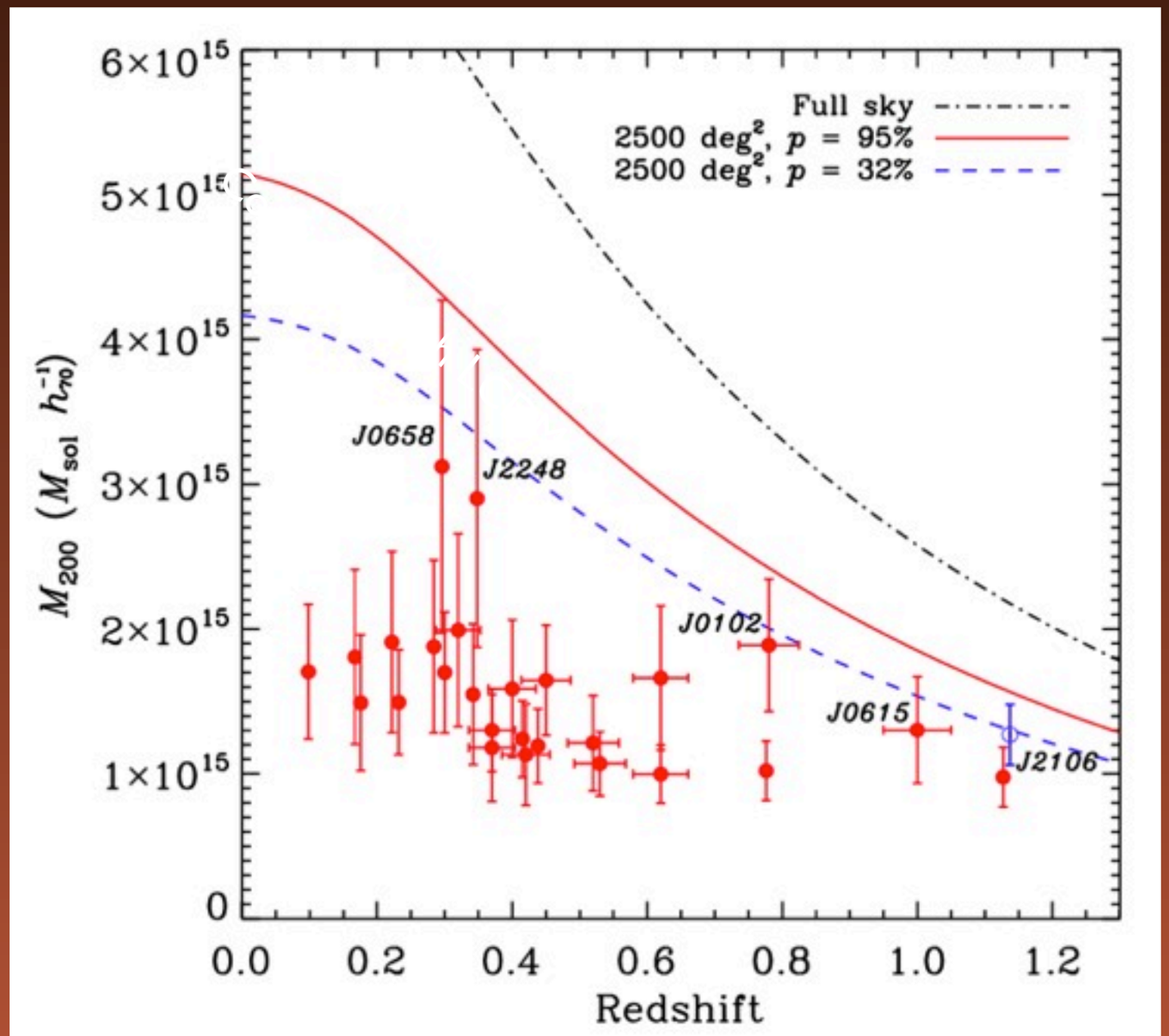


Tests of ΛCDM and Non-Gaussianity



Williamson et al 2011, arXiv:1101.1290

The 26 most significant clusters over full 2500 deg^2 SPT survey.

- Tests extreme tail of matter power spectrum (high-mass, high-redshift clusters)
- Even a single massive cluster could indicate tension with λCDM (Mortonson, Hu, Huterer 2010).

We find:

- consistent with λCDM
- consistent with initial Gaussian density fluctuations

Future SZ observations

- Current: SZ Surveys & low-resolution imaging
  - Many ongoing experiments, SZA, AMIBA, AMI, SPT, ACT, Planck, APEX-SZ...
  - Lots of progress on global properties and comparison with other tracers
- Future: high resolution, high fidelity SZ (i.e., pressure) imaging to probe Cluster Astrophysics
- Complement x-ray of emission measure, n_e^2, SZ ideal probe of cluster outskirts.
- Probe cluster structure: cold fronts, shocks. Merging, collision history
- And the future is very near!
  - Starting: 23 element CARMA, GBT
  - Future: CCAT, LMT, ALMA

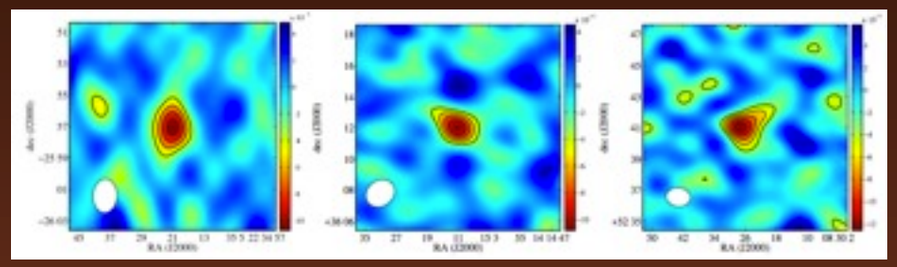
CARMA heterogeneous array
6x10m + 9x6.1m + 8x3.5m

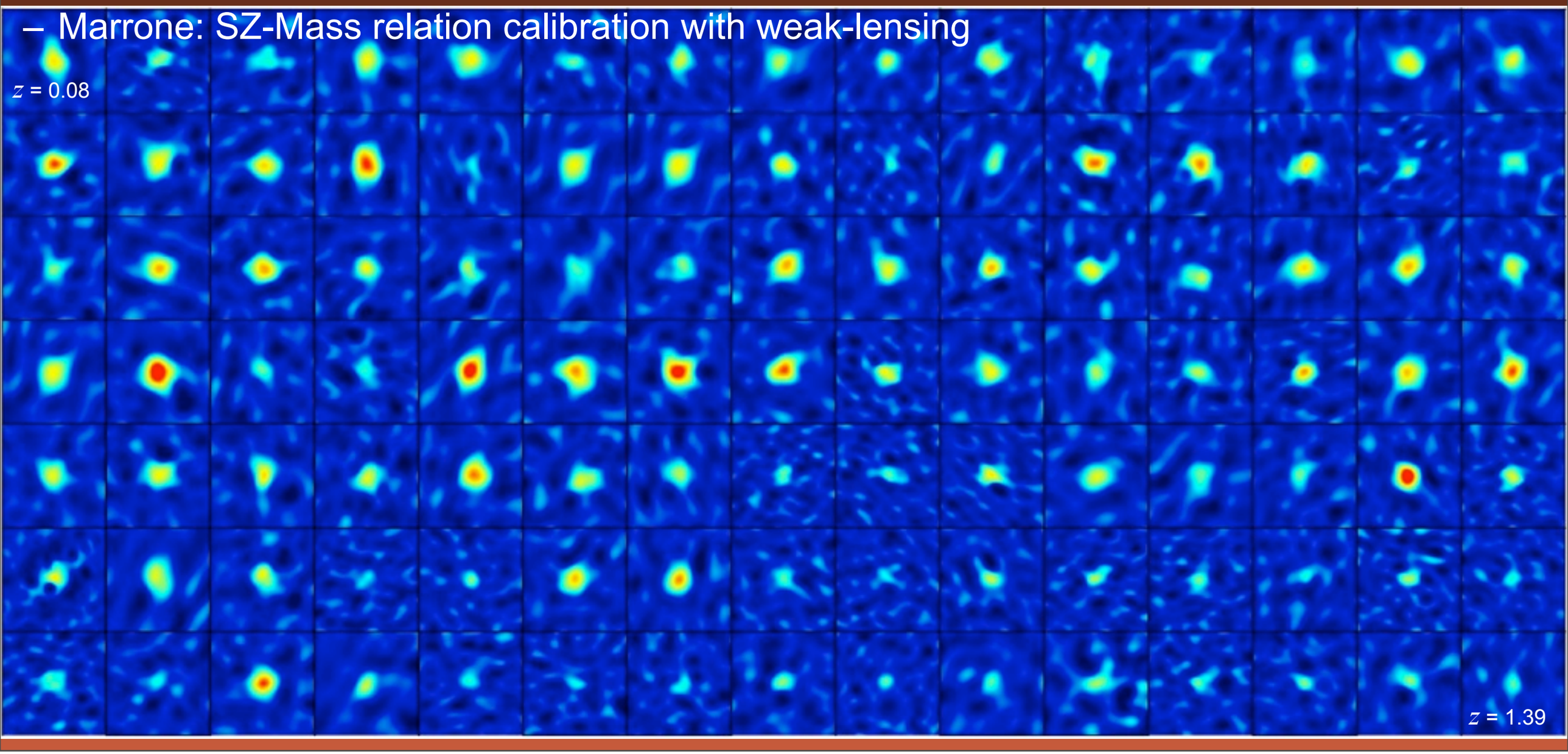
Image from D. P. Marrone

Ongoing CARMA SZ science

Observations of known clusters as calibration samples:

- Culverhouse, et al. (2010): Galaxy clusters at $z>1$
- Gralla: Effects in clusters selected to be strong lenses
- Greer: Comparisons of clusters across selection techniques
- Hasler: Measurements cluster gas content
- Marrone: SZ-Mass relation calibration with weak-lensing

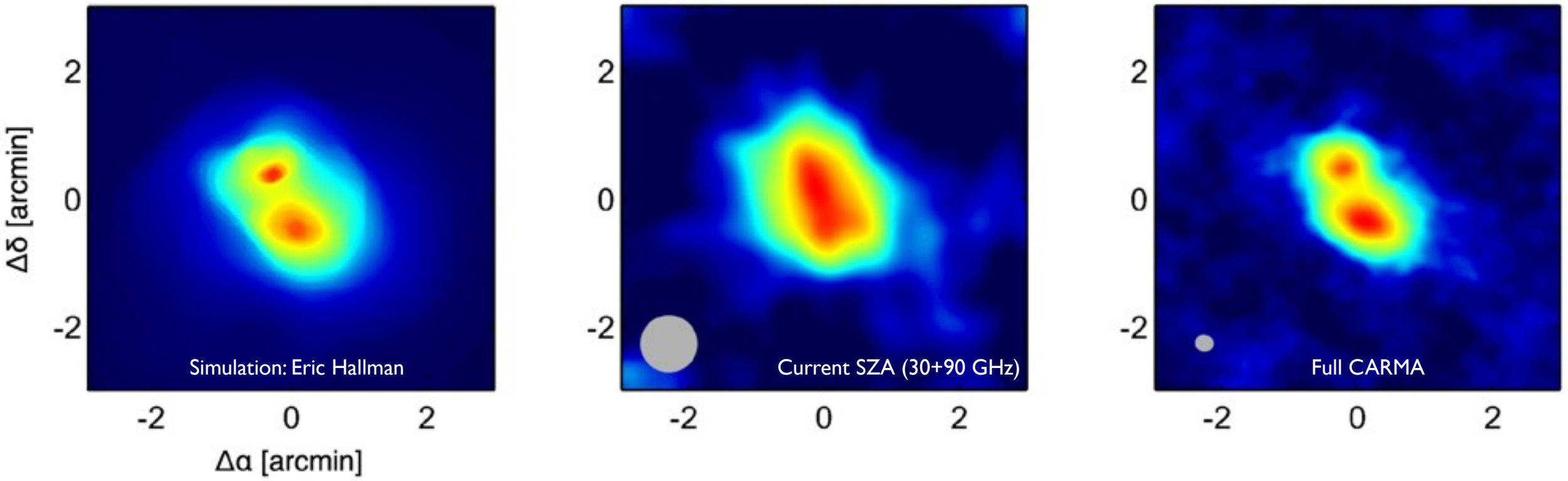




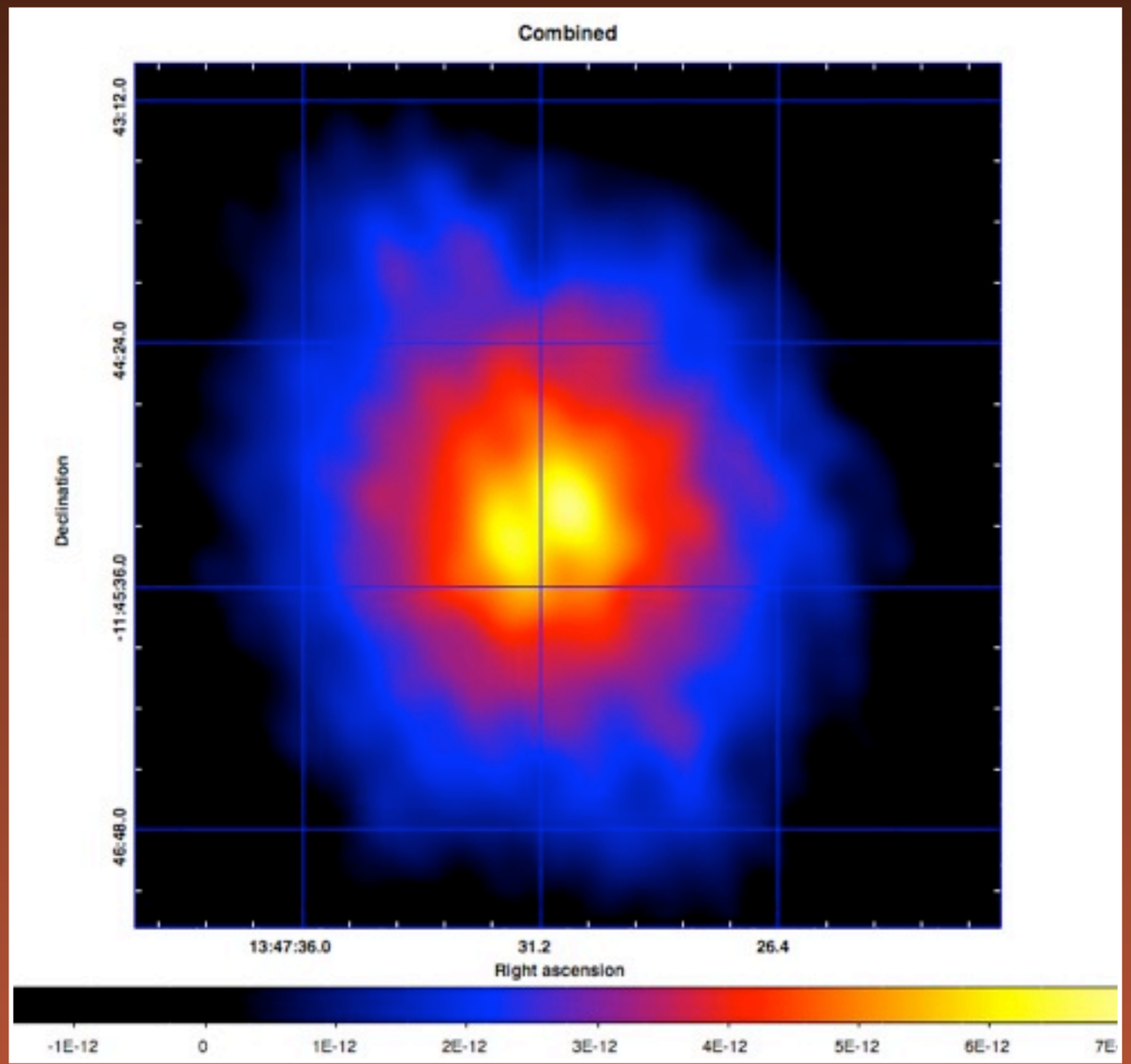
CARMA 23-element heterogeneous SZ imaging

- Frequency synthesis of two bands provides 3x greater range of angular scales
- Short baselines critical for extended emission
- Long baselines critical for measuring radio sources

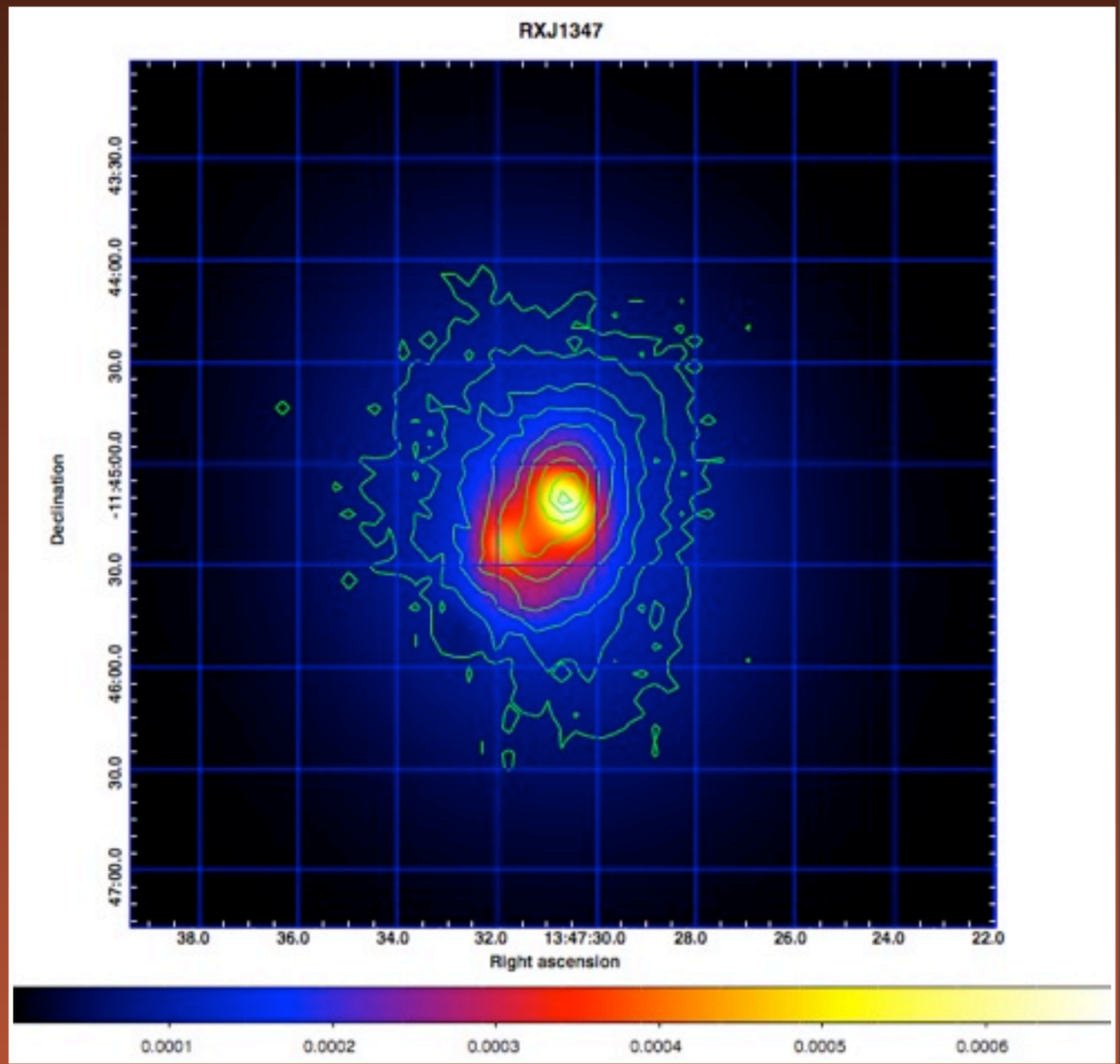
Detailed (10”) cluster SZ imaging with high angular dynamic range.



Example: CARMA RXJ1347.5-145 observations
15 element (3mm) + 3.5 element (3mm, 1cm)



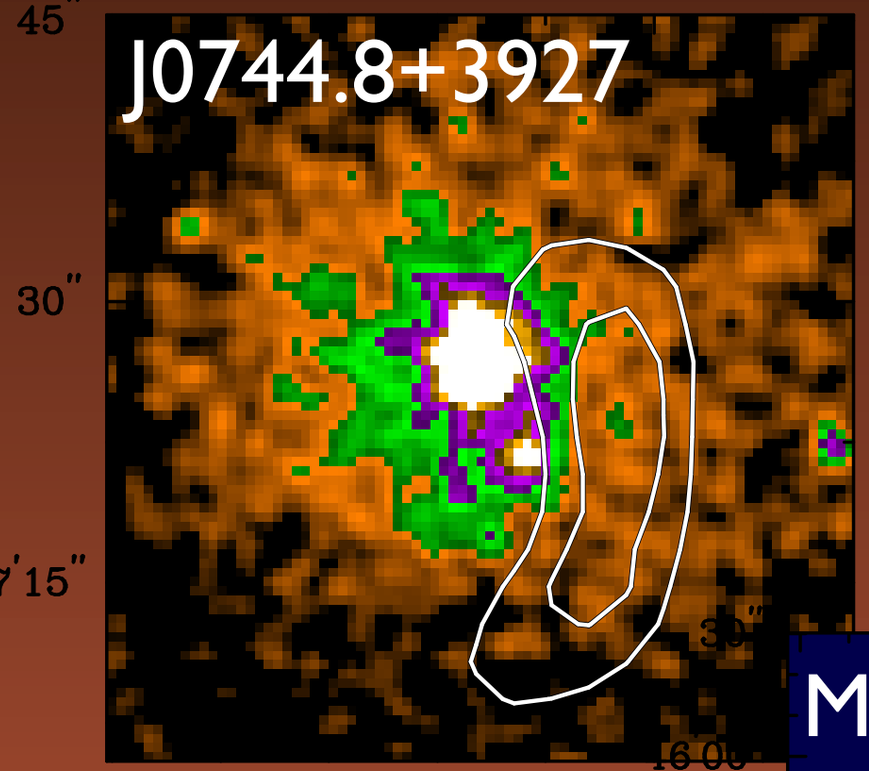
Dirty image

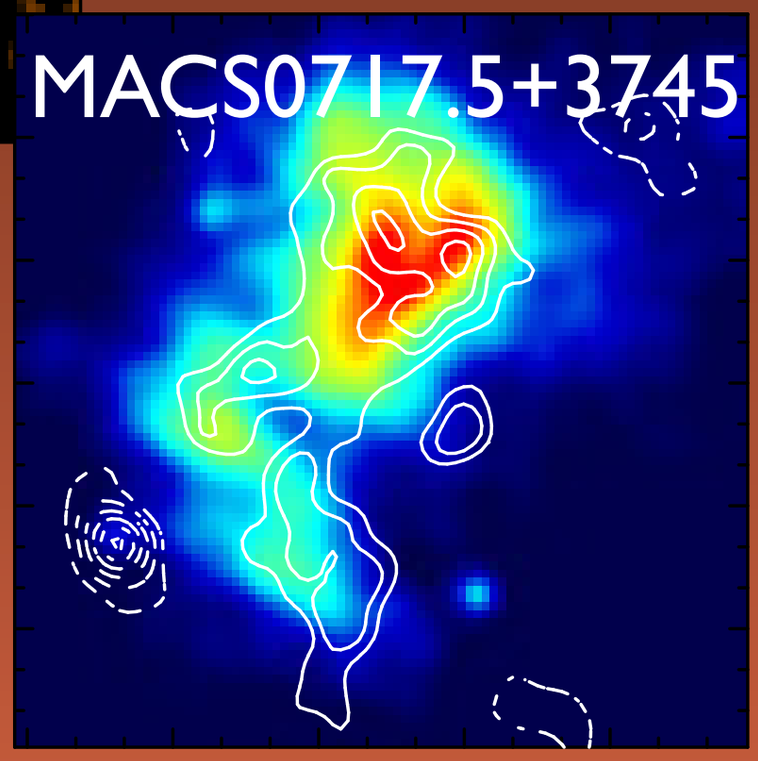


‘Clean’ SZ image

with *Chandra* X-ray surface brightness (contours)

MUSTANG, 8x8 array of 90 GHz TES bolometers on the GBT



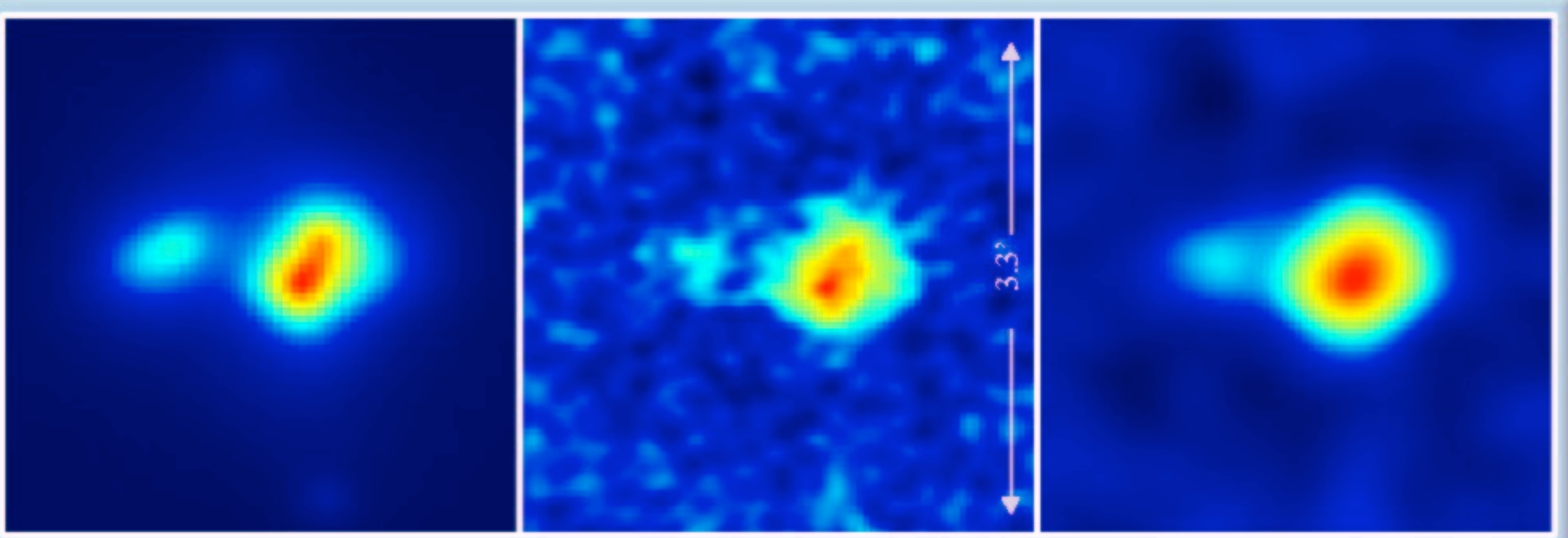


- UPenn built GBT facility instrument
- Res ~9” and can image a massive cluster to a peak S/N ~ 6 in about 5 hours.
- 42" field of view on the sky.

See Brian Mason’s talk!

ALMA SZ Band 1

to study high-z clusters & cluster details



Left: Simulation of a 2.5×10^{14} Mo galaxy cluster at z=1.

Center: ALMA 4 hr mock observation at 34 GHz (band 1) in its ultracompact array. The cluster is easily imaged with high confidence, 1.5 uJy per 9.7" beam which corresponds to 14 uK.

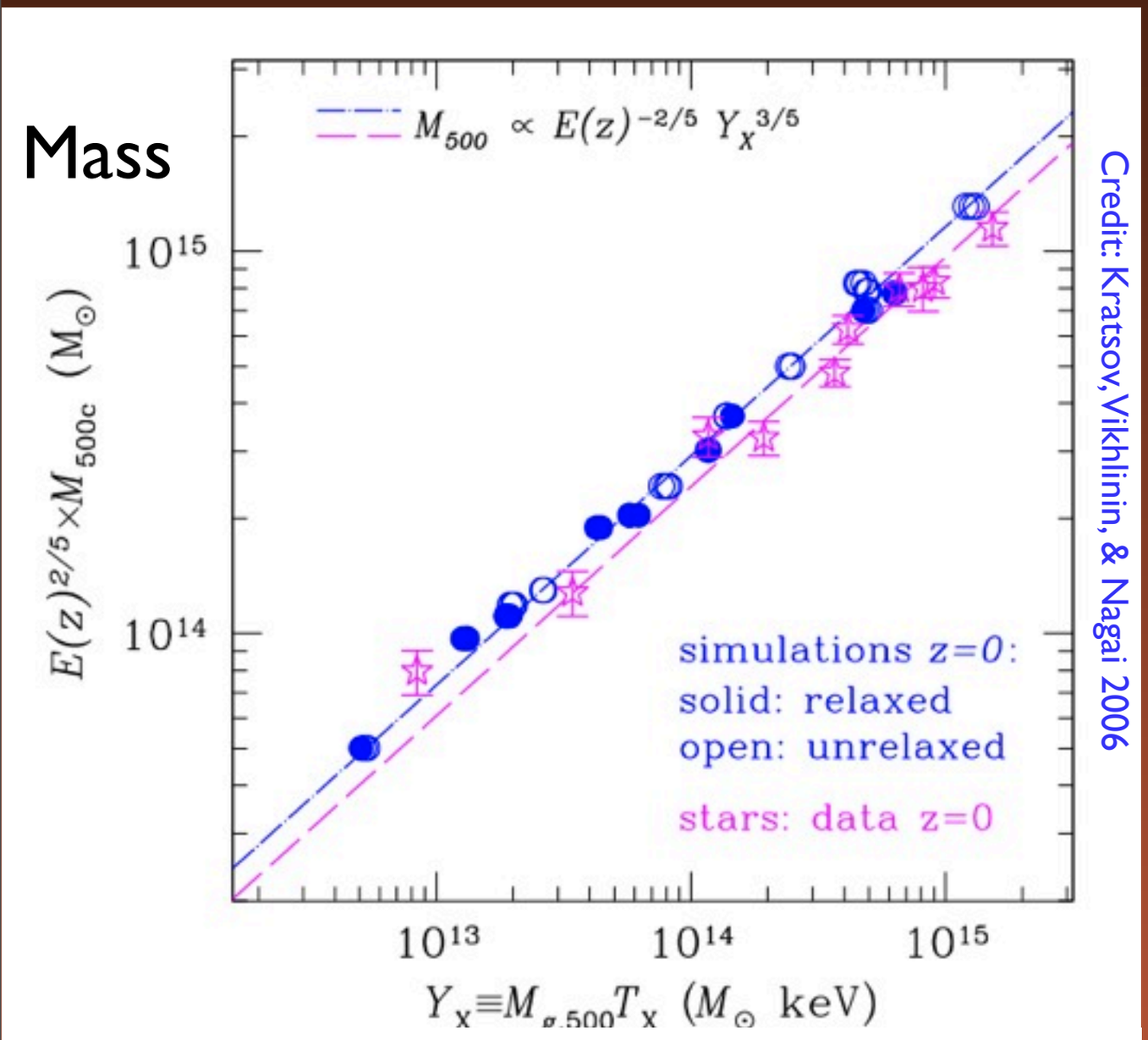
Right: Same obs after applying a 4 kλ uvtaper resulting in a 22" FWHM beam, 2.8 uJy per 22" beam which corresponds to 2.7 uK.

last words

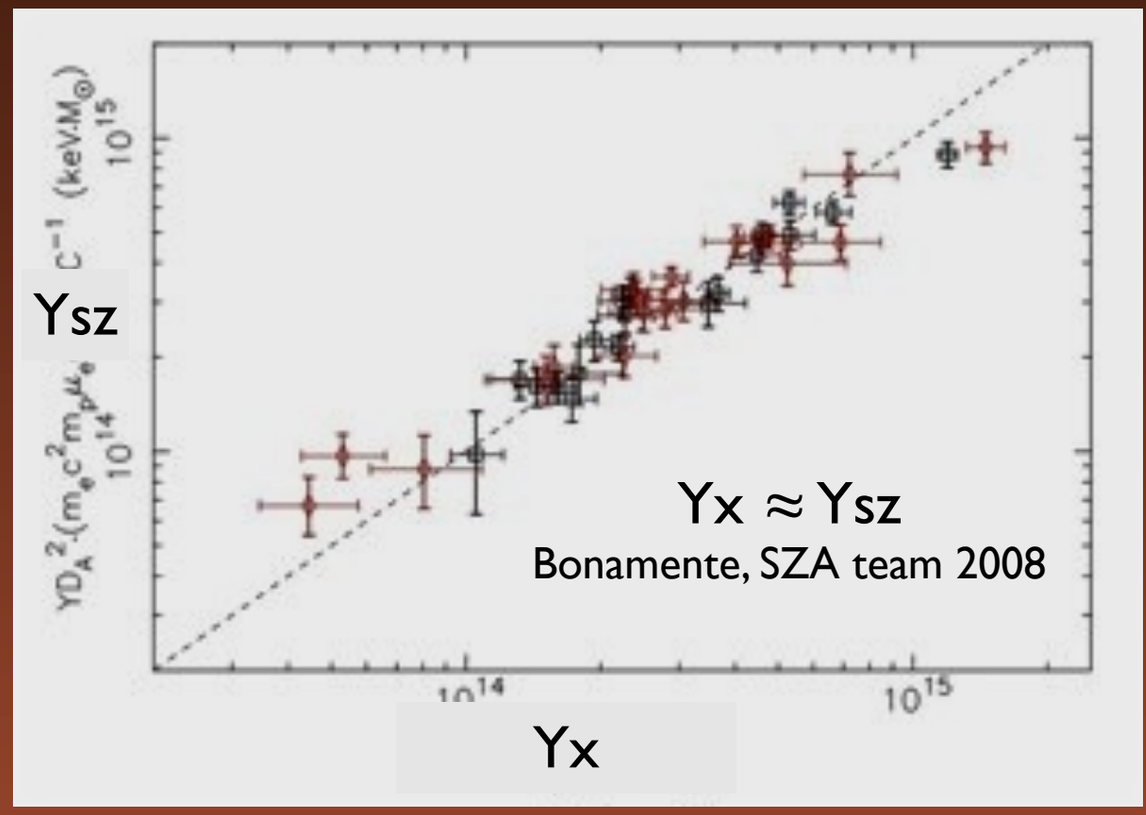
We expect the next ten years to be as exciting as the last ten.

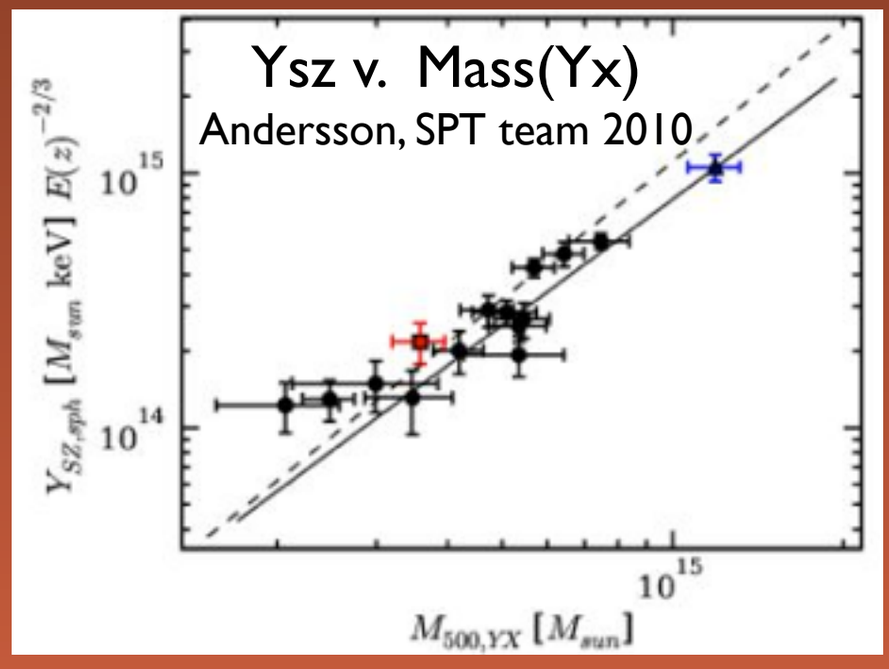
- Understand galaxy cluster astrophysics and evolution.
- Tests of dark energy. Is it just Λ, or...
- Put ΛCDM to the test & constrain extensions. More surprises?
- Probe reionization with kSZ
- Test inflation - n_s and CMB polarization
- Neutrino masses from CMB polarization

Cluster Gas Pressure is a "Clean" Mass Estimator



Credit: Kratsov, Vikhlinin, & Nagai 2006

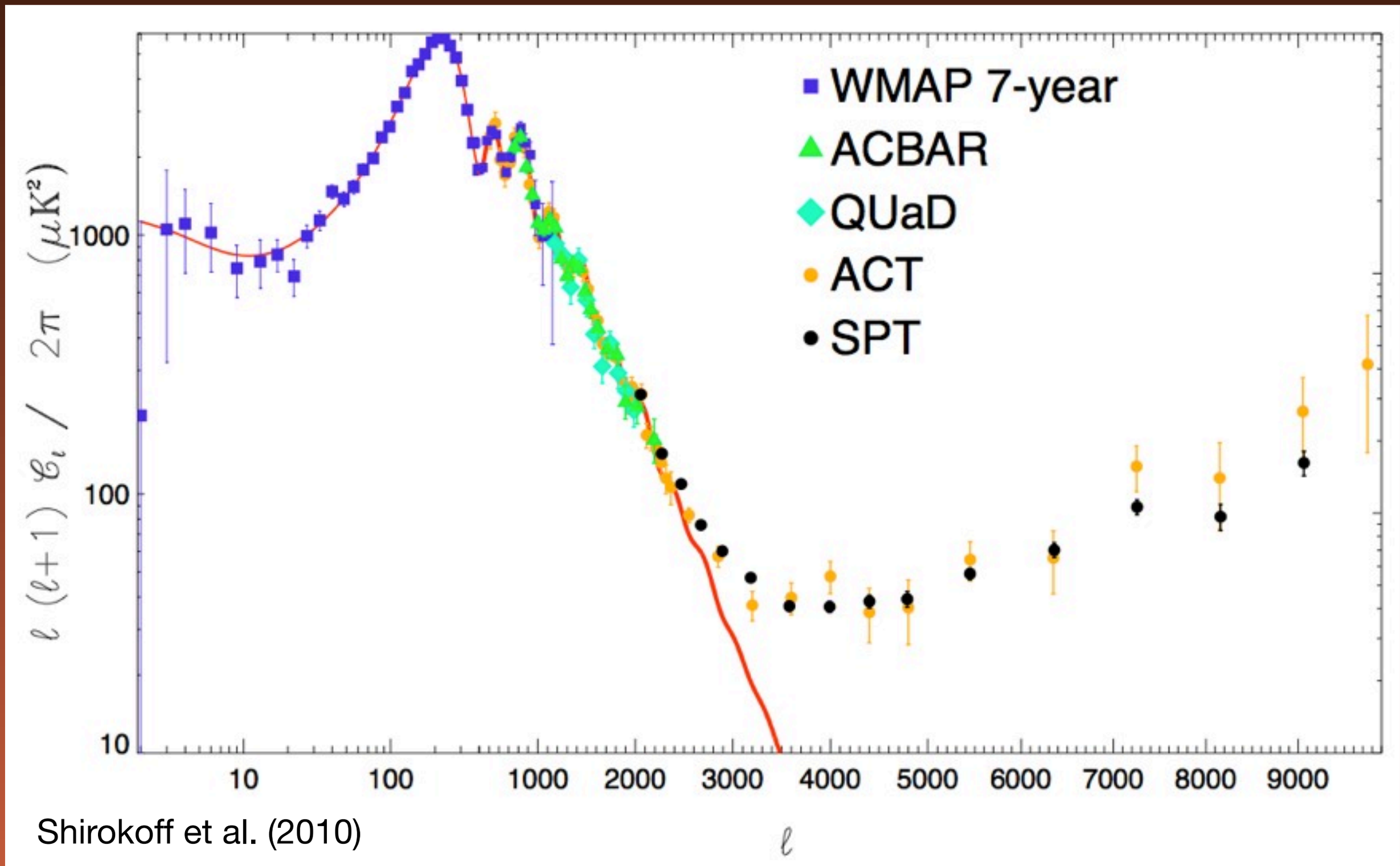




Integrated Pressure from X-ray (Y_X)

Simulations predict ~7 pct scatter in cluster total mass vs integrated pressure (Y_X or Y_{SZ})

CMB Temperature Power Spectrum



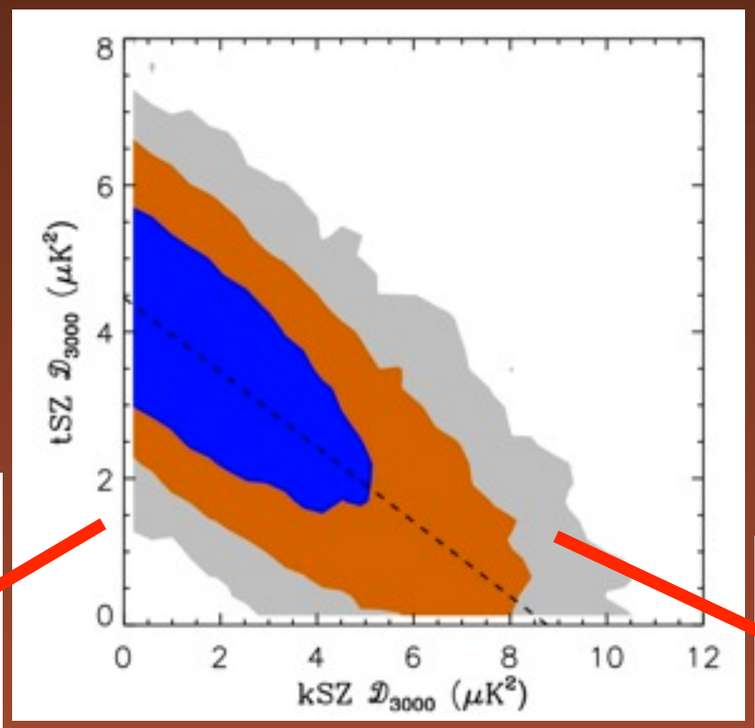
Shirokoff et al. (2010)

SPT Temperature Power Spectrum

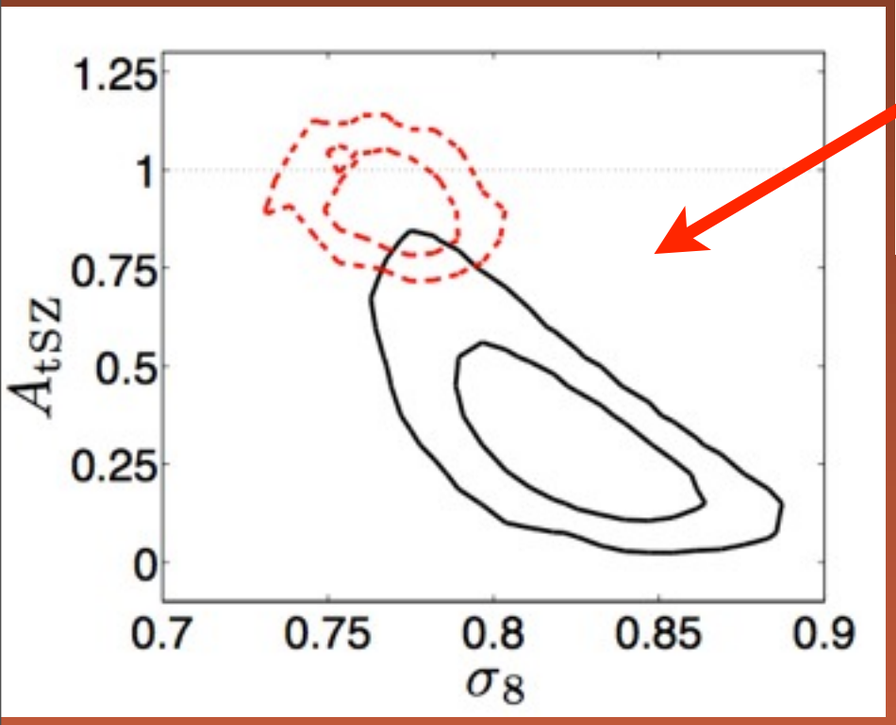
Two SZ Components that are partially degenerate:

1) Thermal SZ (tSZ) - from unresolved clusters (sensitive to σ_8)

2) Kinetic SZ (kSZ) - from (partially) bulk motions during reionization (z ~10) (sensitive to duration of reionization, Δz_{rei})

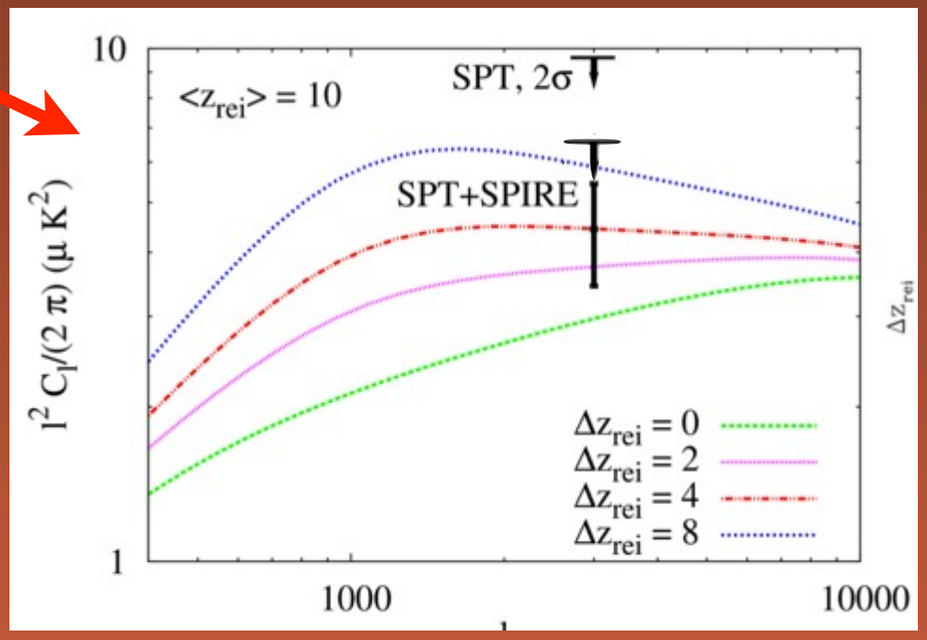


tSZ σ_8 constraints



kSZ Δz_{rei} constraints

& projected for SPT/Herschel/Spire



Lueker et al. (2010), Shirokoff et al. (2010)