South Pole Telescope Science

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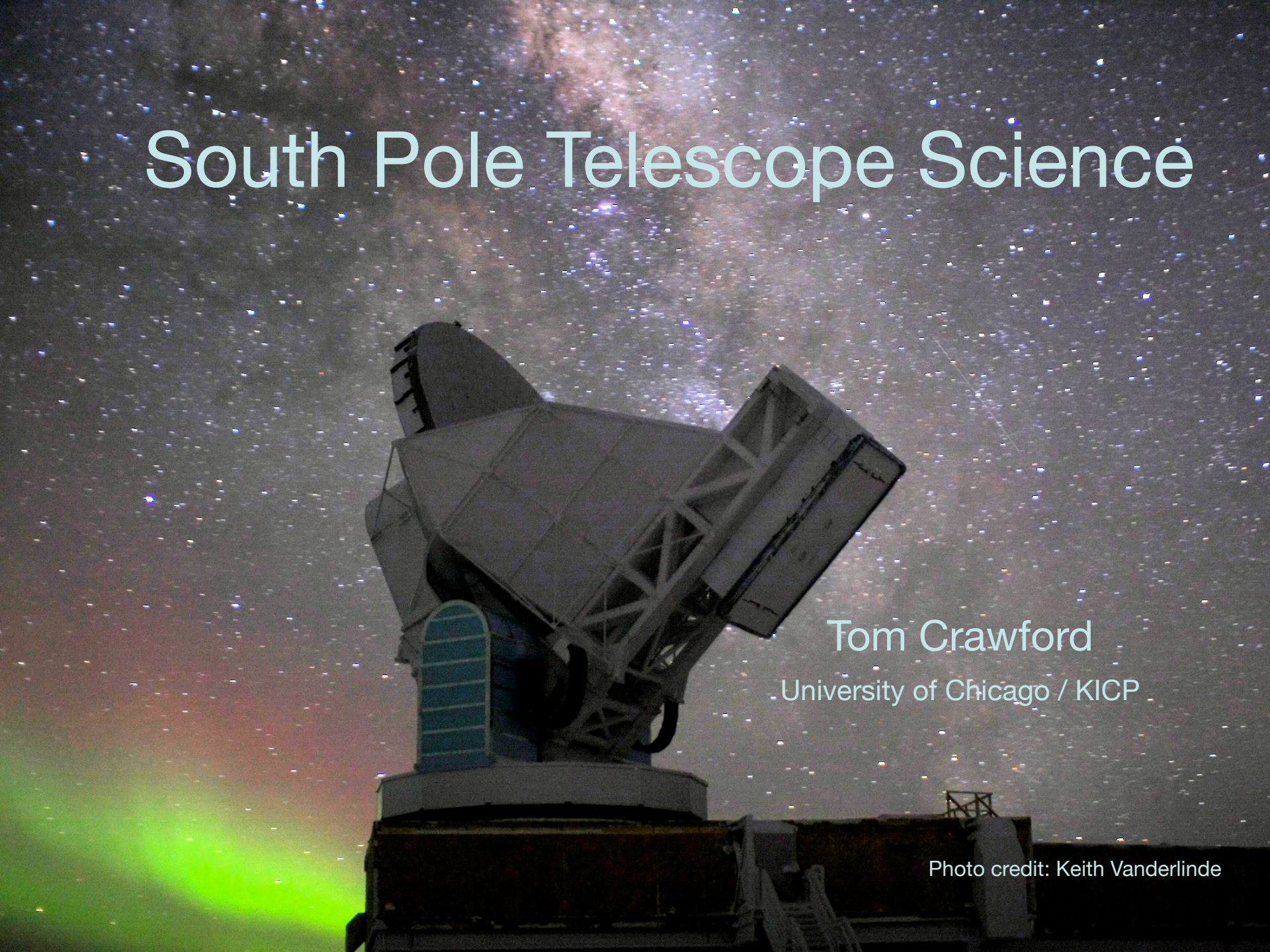


Photo credit: Keith Vanderlinde

Outline

- **Scientific motivation for an ~8m mm-wave telescope with a square-degree FOV**
  - **short intro to SZ effect**
- **mm-wave bolometer data**
  - **what does it look like?**
  - **what's in it?**
- **Recent results**
  - **CMB power spectrum**
  - **mm-wave extragalactic sources of emission**
  - **observations of targeted clusters**
- **Coming soon**
  - **cosmology with an SZ-selected cluster catalog**
- **Coming later: n_s, 3- and 4-point functions, polarization**

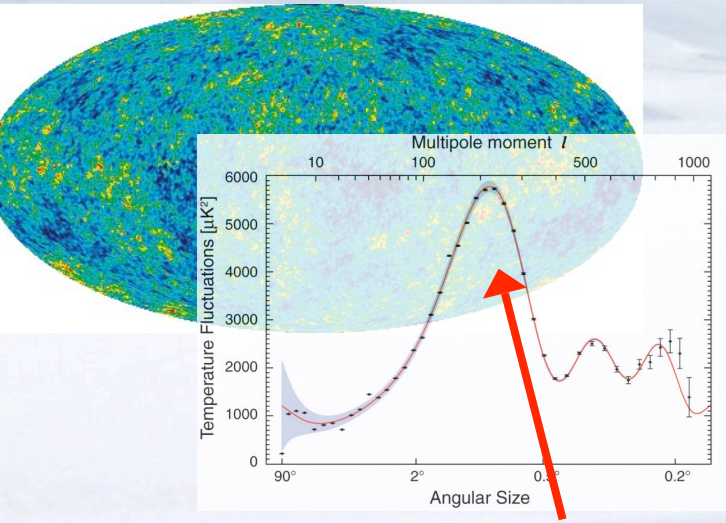
Outline

- **Scientific motivation for an ~8m mm-wave telescope with a square-degree FOV**

Outline

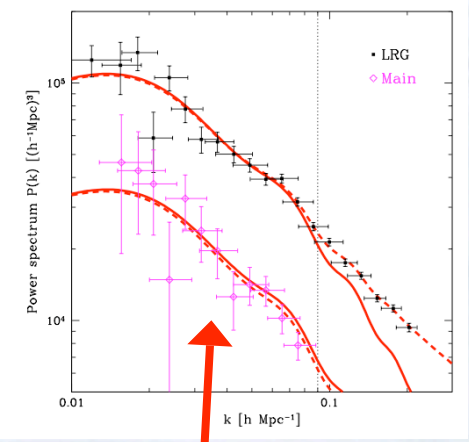
- **Scientific motivation for an ~8m mm-wave telescope with a square-degree FOV**
  - **e.g., Bolocam on the CSO, APEX-SZ, ACT, SPT**

We Live in a Universe Dominated by Dark Energy

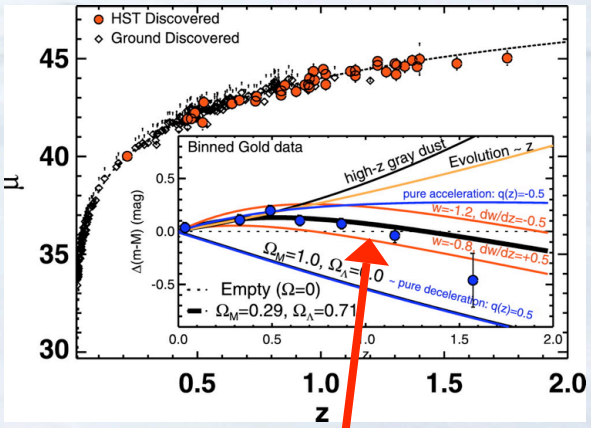


Komatsu et al 2008

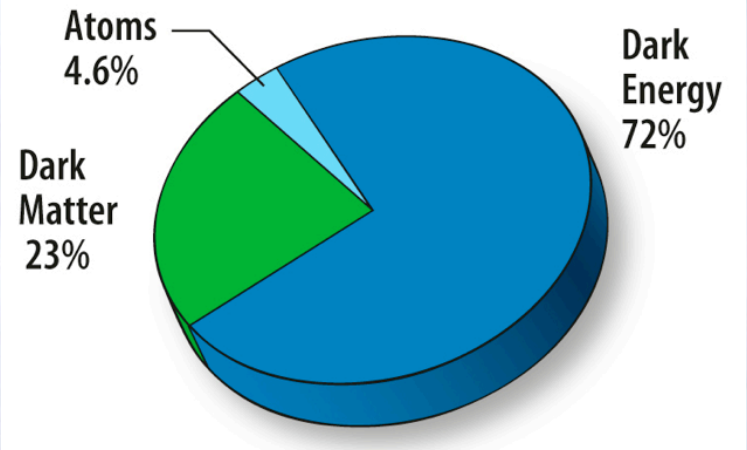
Tegmark et al 2006



Riess et al 2007



CMB + Large Scale Structure + SNe Ia



We live in a flat universe whose density is dominated dominated by dark energy

$$\Omega_\Lambda = 0.721 \pm 0.015$$

... but what is dark energy?

Dark Energy Constraints with Clusters of Galaxies

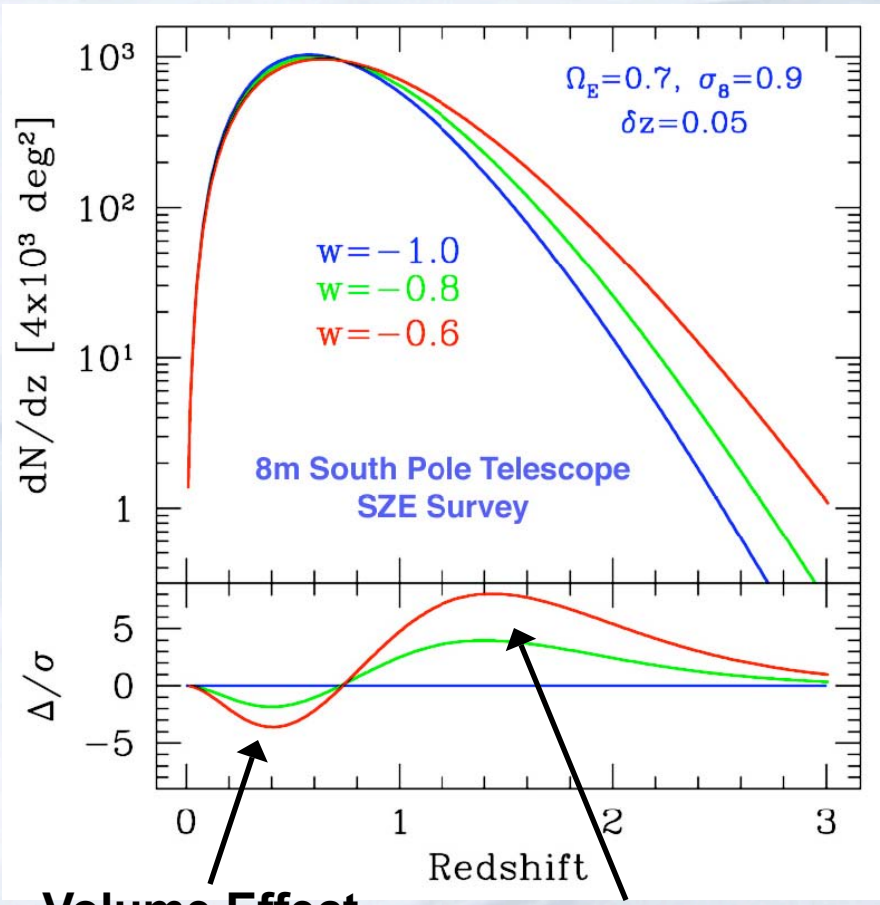
Cluster Abundance, dN/dz

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

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

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

Credit: Joe Mohr



Volume Effect

Growth Effect

For fixed Ω_{DE} and less negative *w*:

1. Fewer clusters at low redshift, due to decreased volume surveyed
2. More clusters at high redshift, due to decreased growth rate

Outline

- **short intro to SZ effect**

Sources of Secondary Anisotropy in the CMB

- **ISW**
- **Rees-Sciama effect**
- **gravitational lensing**
- **thermal SZ effect**
- **kinetic SZ effect**
- **Ostriker-Vishniac effect**
- **patchy reionization**

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} gravitational effects

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} inverse Compton scattering off hot intervening gas

Sources of Secondary Anisotropy in the CMB

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inverse Compton scattering off hot intervening gas

1st-order in electron velocity, no spectral distortion

Sources of Secondary Anisotropy in the CMB

2nd-order in electron velocity, significant spectral distortion

- **thermal SZ effect**
- **kinetic SZ effect**
- **Ostriker-Vishniac effect**
- **patchy reionization**

} inverse Compton scattering off hot intervening gas

Sources of Secondary Anisotropy in the CMB

from structure in the non-linear regime, predominantly clusters of galaxies

- **thermal SZ effect**
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inverse Compton scattering off hot intervening gas

Sources of Secondary Anisotropy in the CMB

from structure in the non-linear regime, predominantly clusters of galaxies

detect effect in individual clusters => cluster survey

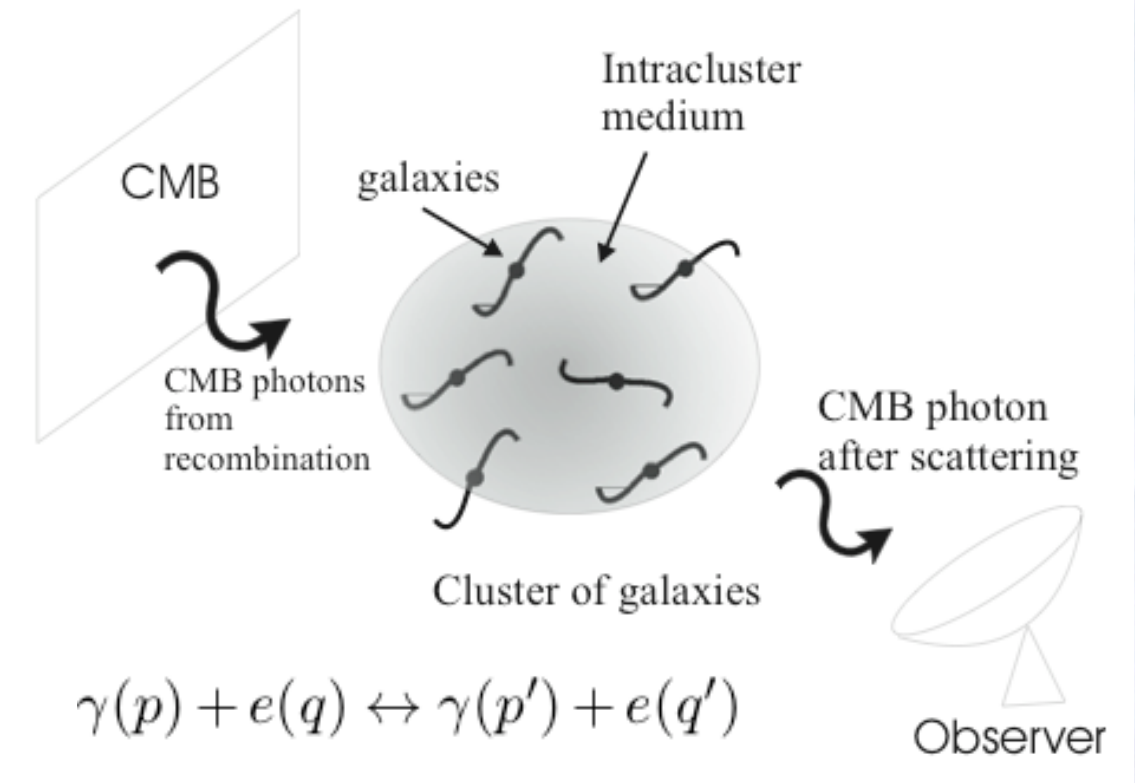
detect effect statistically e.g. 2-point function => SZ power spectrum

- **thermal SZ effect**
- **kinetic SZ effect**
- **Ostriker-Vishniac effect**
- **patchy reionization**

inverse Compton scattering off hot intervening gas

The Sunyaev-Zel'dovich Effects

Inverse Compton scattering of CMB photons
off hot gas in galaxy clusters



from A. Lasenby (2006)

Decompose hot electrons into two components: one with a bulk velocity w.r.t. the CMB and one isotropic w.r.t. the CMB.

The Sunyaev-Zel'dovich Effects: Kinetic

Decompose hot electrons into two components: one with a bulk velocity w.r.t. the CMB and one isotropic w.r.t. the CMB:

Bulk velocity gives simple Doppler shift:

$$\frac{\Delta T}{T} = \frac{v_b}{c}\tau + \mathcal{O}\left(\frac{v_b^2}{c^2}\right)$$

Typical cluster bulk velocities are < 1000 km/s, so:

1. quadratic term completely negligible
2. typical kSZ signal is: $\Delta T \sim 10^{-3} \times \tau \times T_{\rm CMB} \lesssim 30\mu{\rm K}$

The Sunyaev-Zel'dovich Effects: Thermal

Decompose hot electrons into two components: one with a bulk velocity w.r.t. the CMB and one isotropic w.r.t. the CMB:

For isotropic contribution, equal scatterings in all directions (duh):

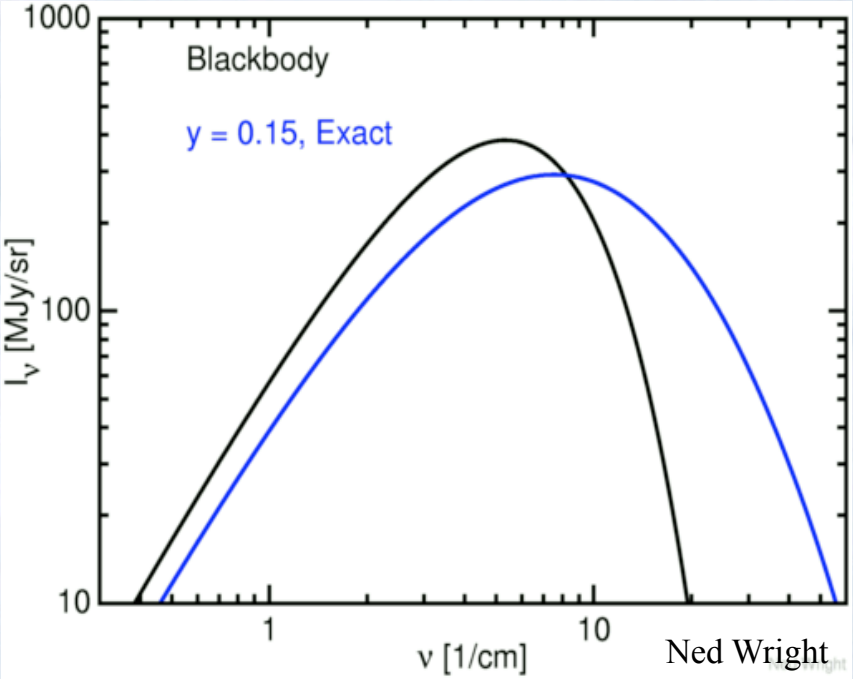
1. First-order contribution vanishes.

2. Can't change photon #.

3. But will impart mean energy (assuming thermal electron distribution):

$$\frac{\Delta E}{E} \sim \frac{v_{\rm therm}^2}{c^2}\,\tau = \frac{kT_e}{m_e c^2}\,\tau$$

- must distort spectrum, moving photons from RJ to Wien region
- only detectable because cluster gas is HOT
- implies a typical signal of a few hundred uK for a ~5 keV cluster (where the signal is largest).



The Thermal Sunyaev-Zel'dovich Effect

Why is it so awesome for a cluster survey?

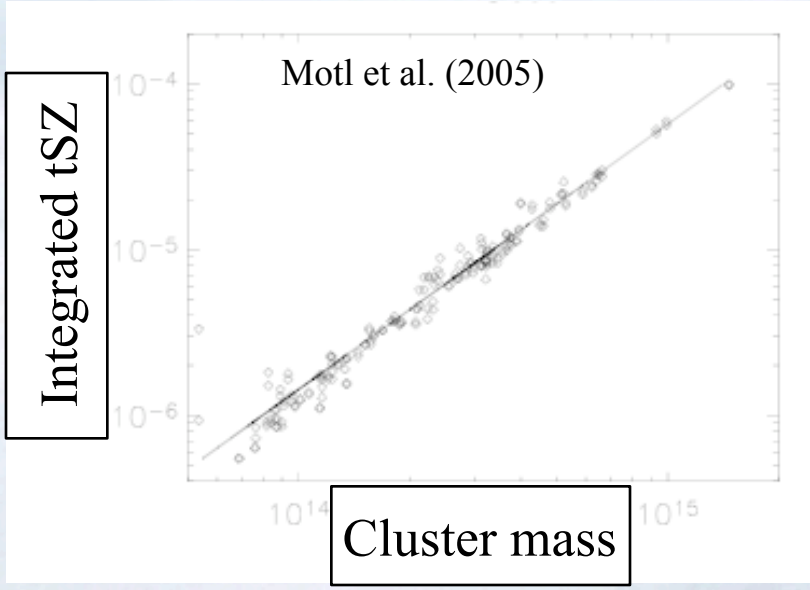
- surface brightess of effect is redshift-independent
  - Kompaneets eqn. (ignoring electron recoil) gives

$$\Delta I_\nu = y\ \nu\ \frac{d}{d\nu}\left[\nu^4 \frac{d}{d\nu}\left(\nu^{-3} I_\nu\right)\right]$$

$$\Delta I_{obs}(\nu_{obs}) = \Delta I_{rest}\left(\frac{\nu_{obs}}{1+z_{scatt}}\right)$$

- integrated signal proportional to total thermal energy, should faithfully track total cluster mass

$$\int y\ d\Omega \propto \frac{kT_e}{m_e c^2}\ \sigma_T\ \frac{N_e}{D_A^2}$$



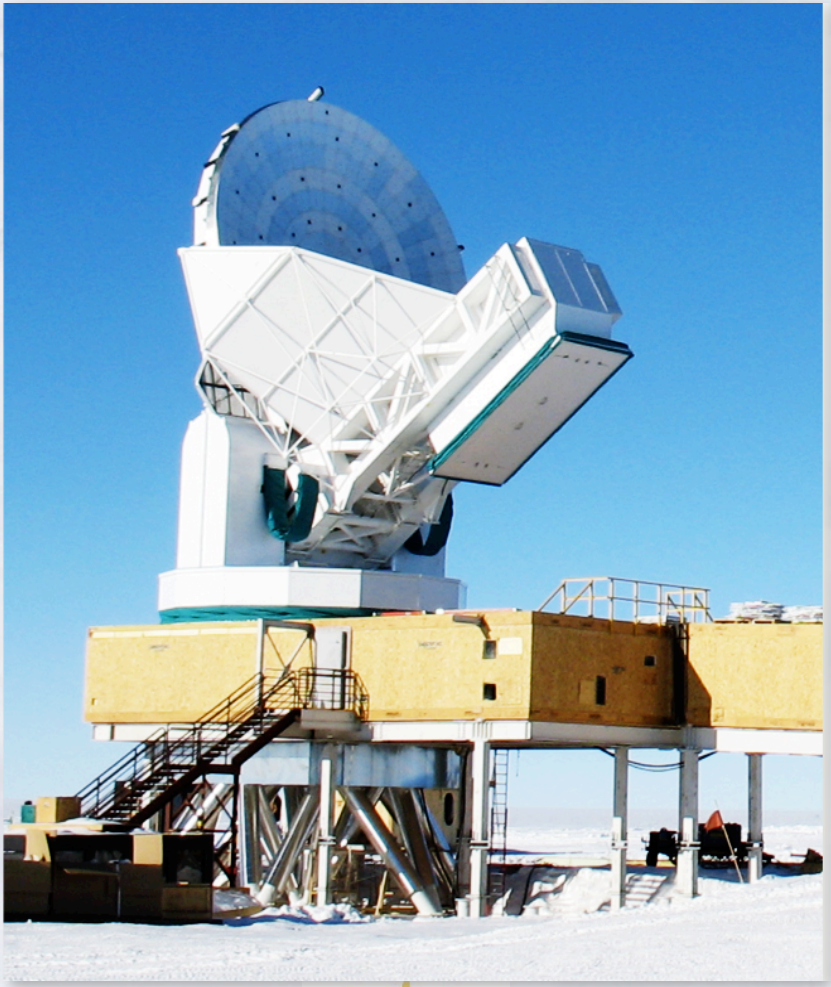
Requirements for an SZ cluster-finding machine

- **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 detectors!!!**

The South Pole Telescope (SPT)



Millimeter Wavelength Telescope (also good enough to use at sub-mm):

- 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 95-220 GHz simultaneously with a modular focal plane

Funded by NSF

Outline

- **mm-wave bolometer data**
  - **what does it look like?**
  - **what's in it?**

Outline

- **mm-wave bolometer data**
  - **what does it look like?**

A typical SPT survey field. (OK, maybe one of the bigger ones)

1 degree

90 GHz

A typical SPT survey field. (OK, maybe one of the bigger ones)

1 degree

150 GHz

A typical SPT survey field. (OK, maybe one of the bigger ones)

1 degree

220 GHz

Outline

- **mm-wave bolometer data**
  - **what's in it?**

Point Sources

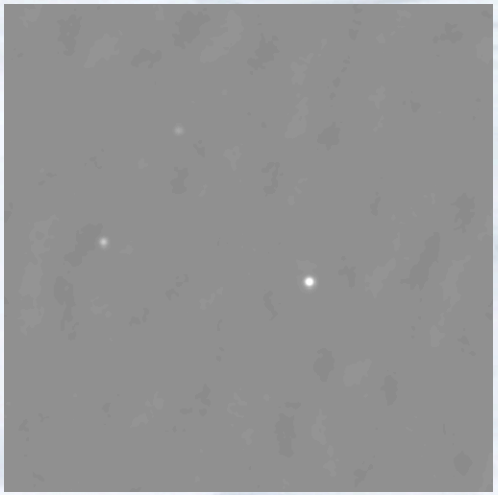
1 degree

150 GHz

Point Sources

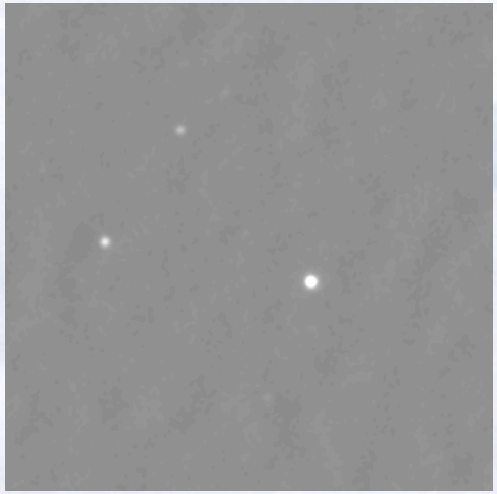
150 GHz

Point Sources



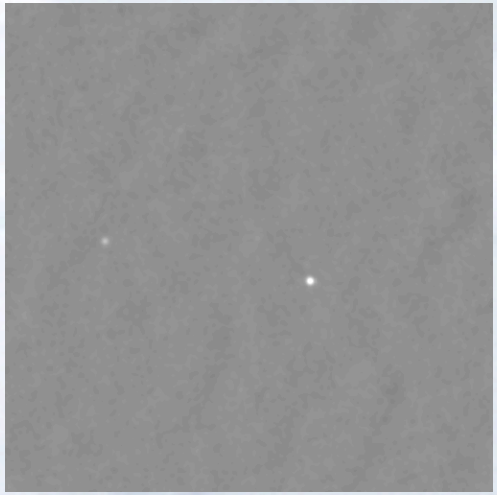
2 degrees

150 GHz



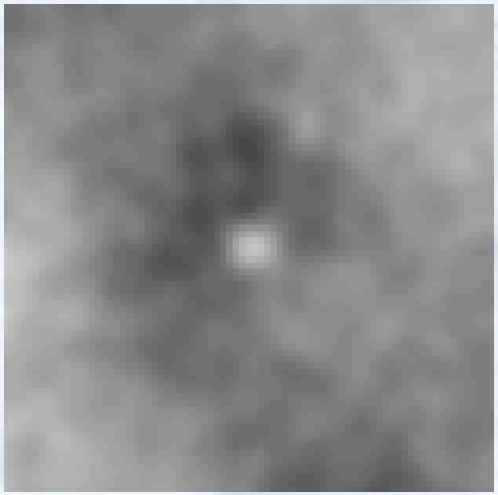
90 GHz

(grayscale +/- 100 mJy)



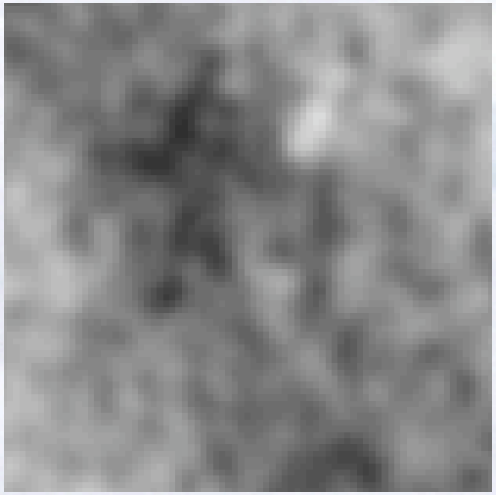
220 GHz

Point Sources



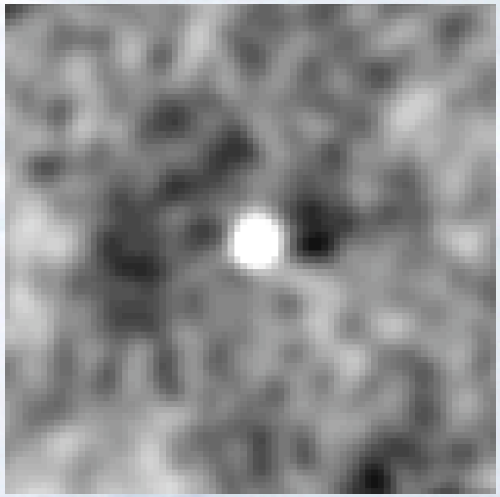
20 arcminutes

150 GHz



90 GHz

(grayscale +/- 10 mJy)



220 GHz

Outline

- **mm-wave bolometer data**
  - **what's in it?**

Primary CMB anisotropy

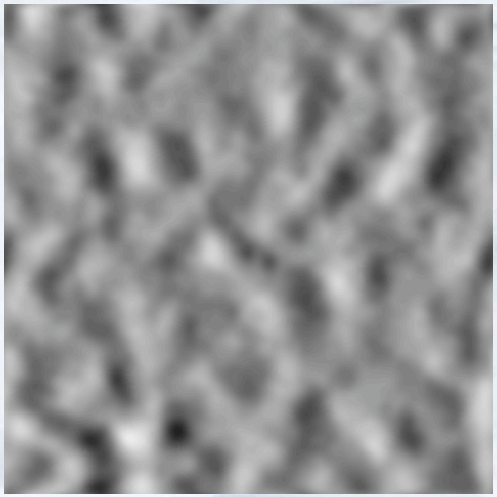
1 degree

150 GHz

Primary CMB anisotropy

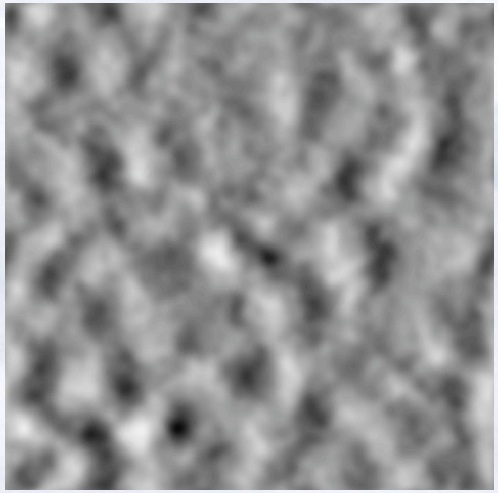
150 GHz

Primary CMB anisotropy



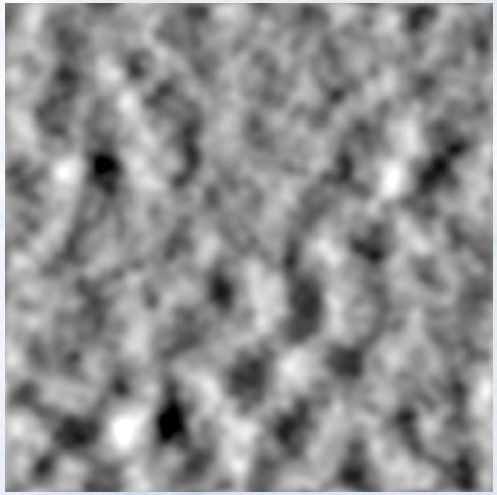
2 degrees

150 GHz



90 GHz

(grayscale +/- 100uK_CMB)

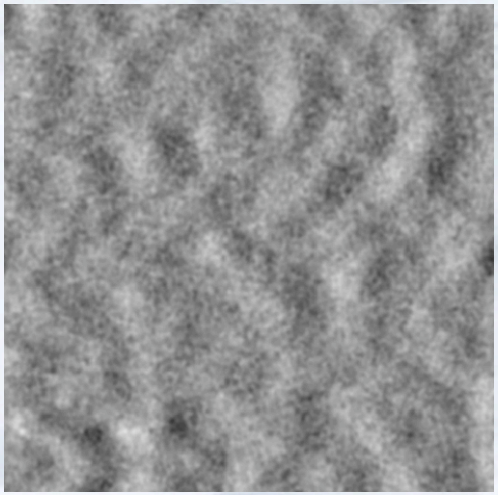


220 GHz

Outline

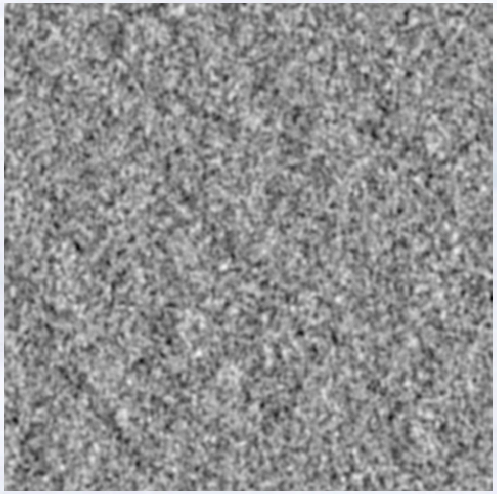
- **mm-wave bolometer data**
  - **what's in it?**

Noise (boo!)



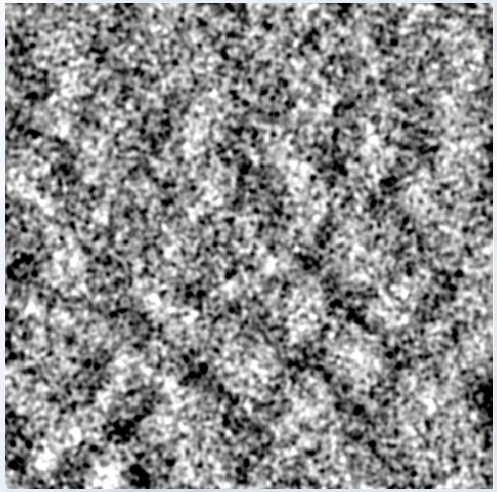
2 degrees

150 GHz



90 GHz

(grayscale +/- 100uK_CMB)



220 GHz

Outline

- **mm-wave bolometer data**
  - **what's in it?**

Galaxy Clusters!

1 degree

90 GHz

Galaxy Clusters!

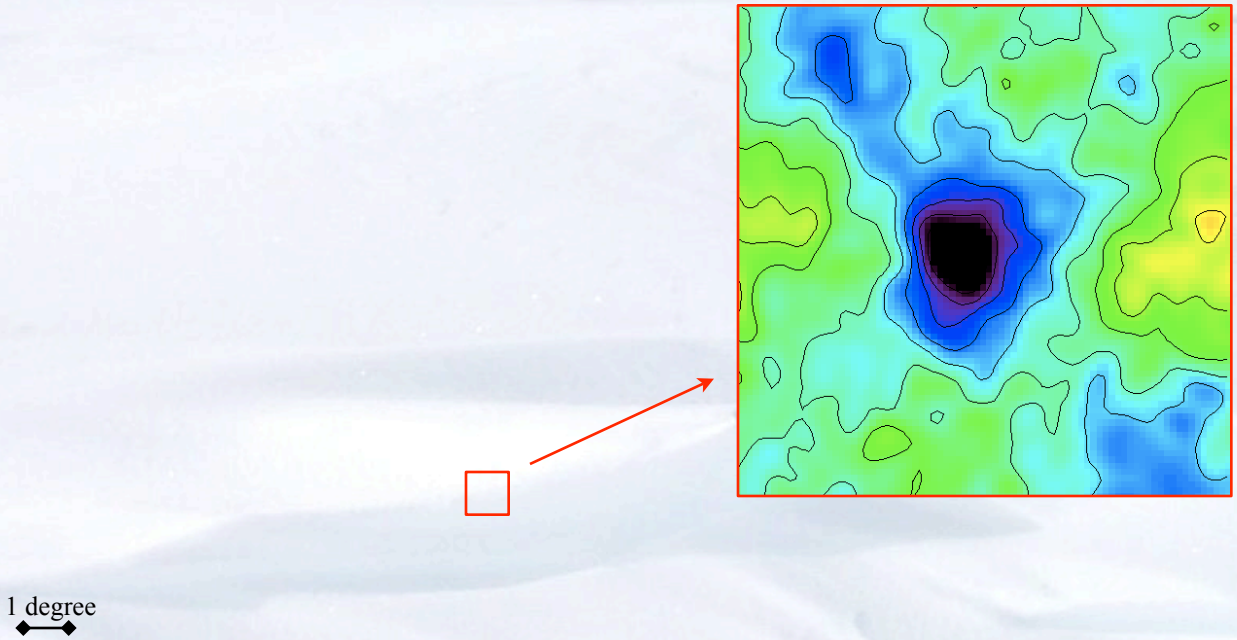
1 degree

150 GHz

Galaxy Clusters!

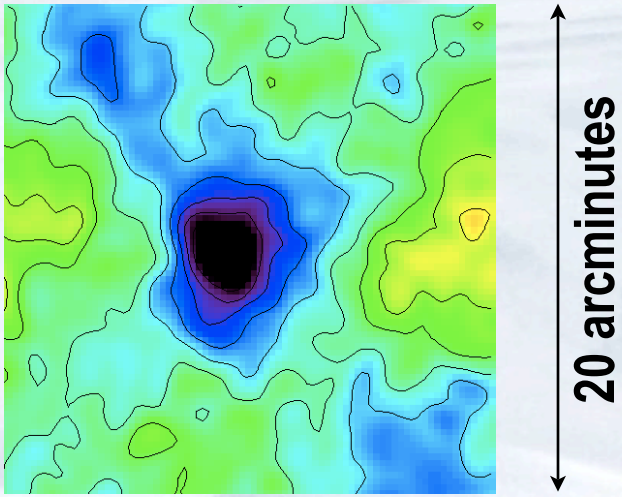
150 GHz

Galaxy Clusters!



150 GHz

Galaxy Clusters!

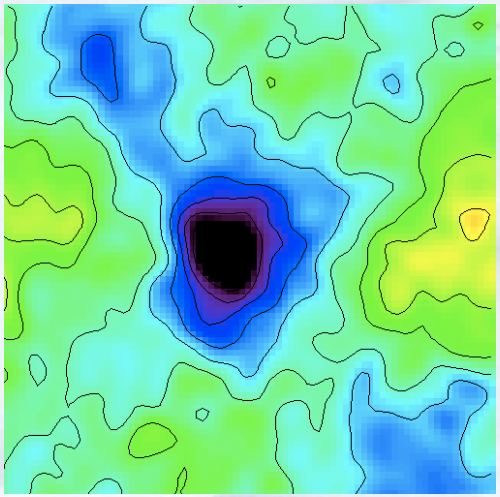


150 GHz

90 GHz

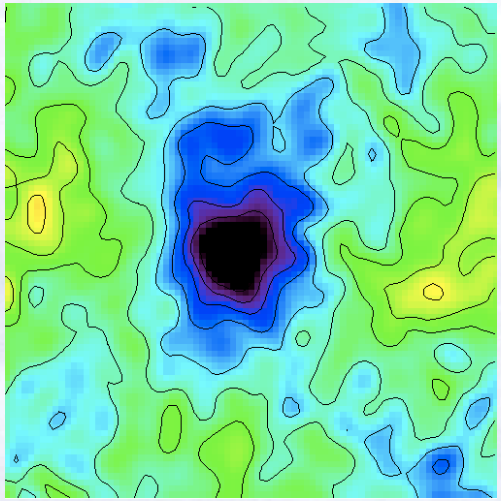
220 GHz

Galaxy Clusters!



20 arcminutes

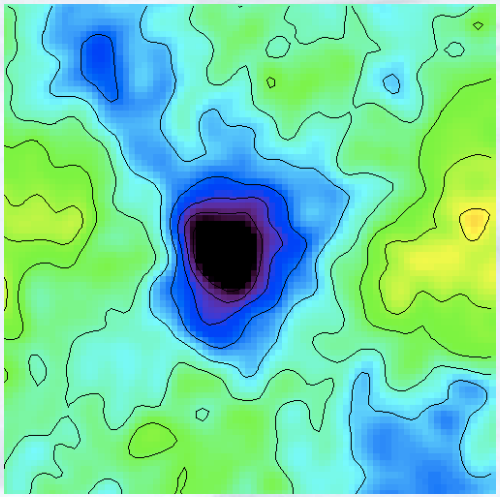
150 GHz



90 GHz

220 GHz

Galaxy Clusters!



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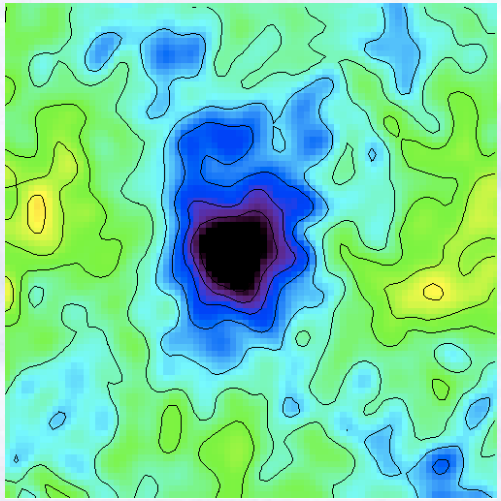
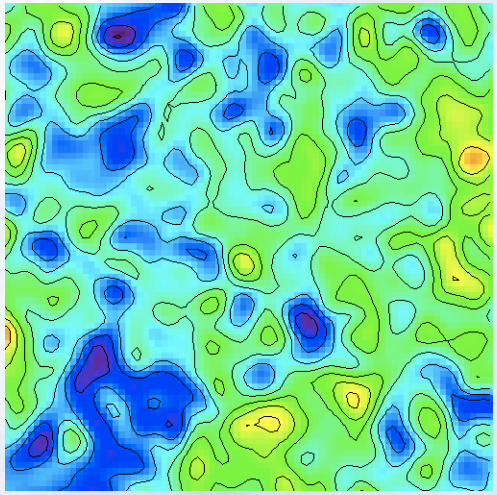


90 GHz



220 GHz

Outline

- **Recent results**
  - **CMB power spectrum**
  - **mm-wave extragalactic sources of emission**
  - **observations of targeted clusters**

Outline

- **Recent results**
  - **CMB power spectrum**

Small-scale CMB: Why?

- Well, what do you mean by "small-scale"
  - $500 < l < 2000$: nail damping tail and constrain n_s.
  - $l > 2000$: secondaries
    - thermal SZ power spectrum:
      - measure of sigma8 independent of cluster counts
      - resolve long-standing argument in the field
    - other interesting contributions:
      - kSZ, Ostriker-Vishniac, patchy reionization, ...

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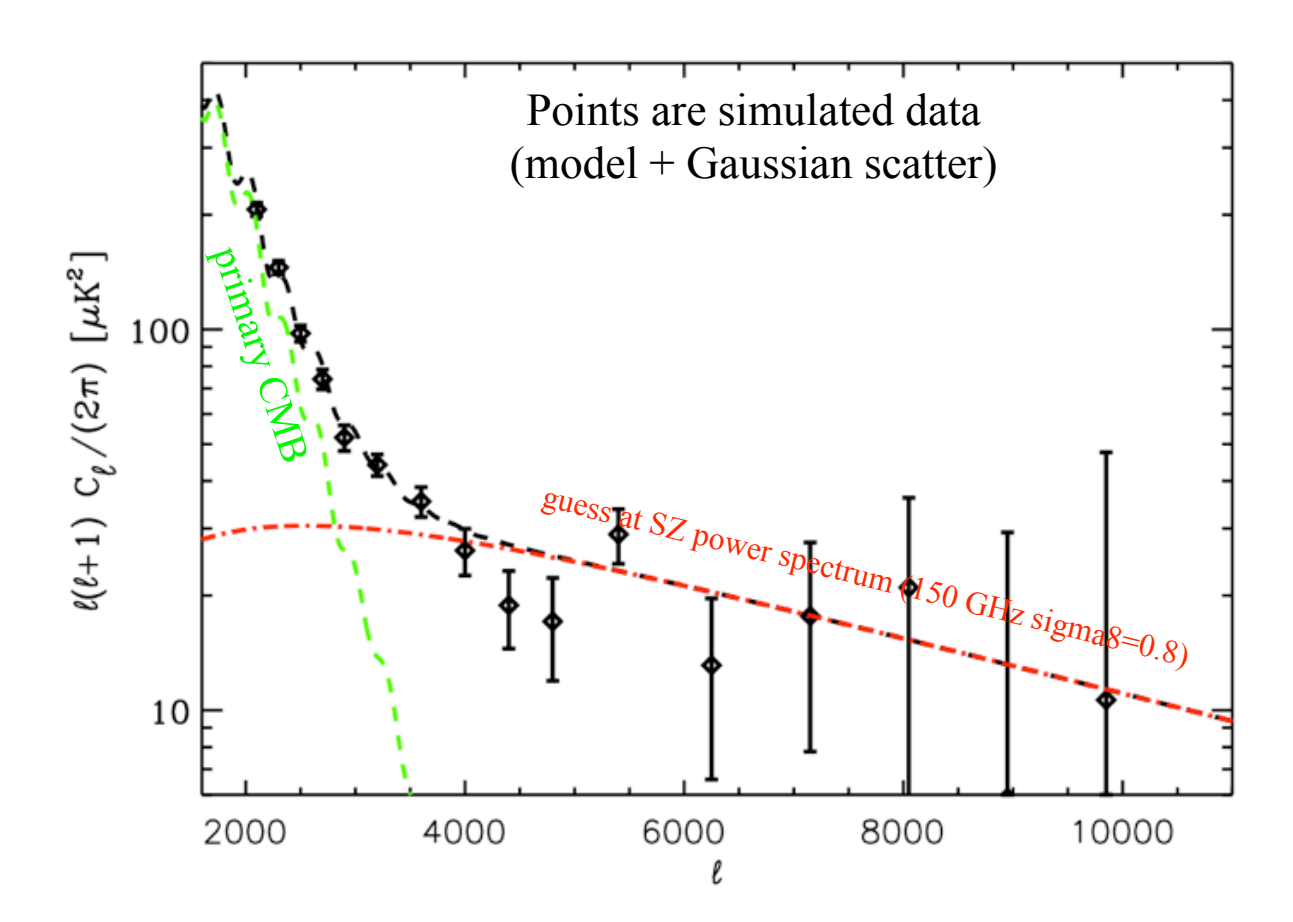
Prospects for Statistical Detection of SZ

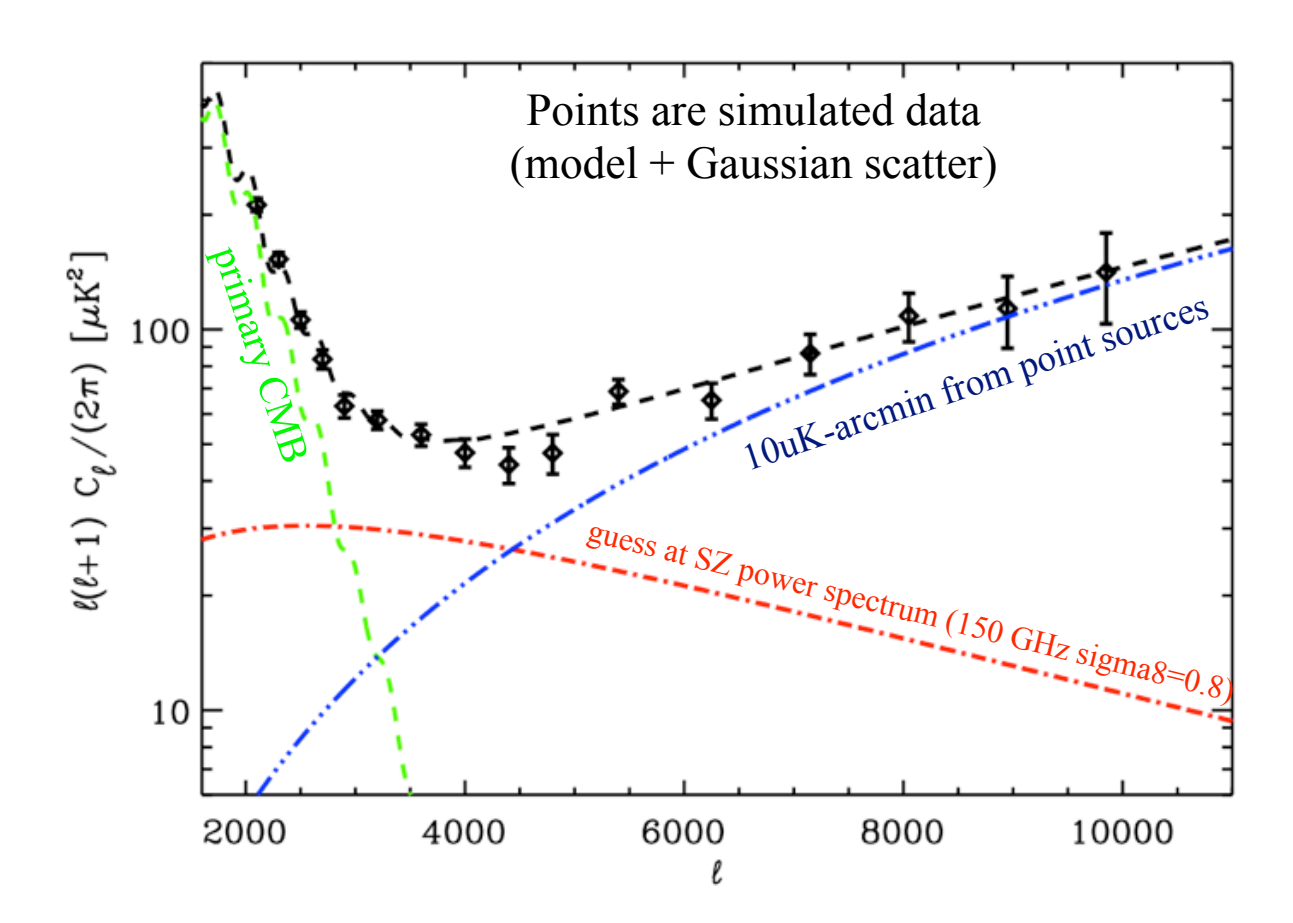
- 150 GHz only
- 100 square degrees
- 18 uK-arcmin
- cross-spectrum analysis



Prospects for Statistical Detection of SZ

Point-source mitigation techniques:

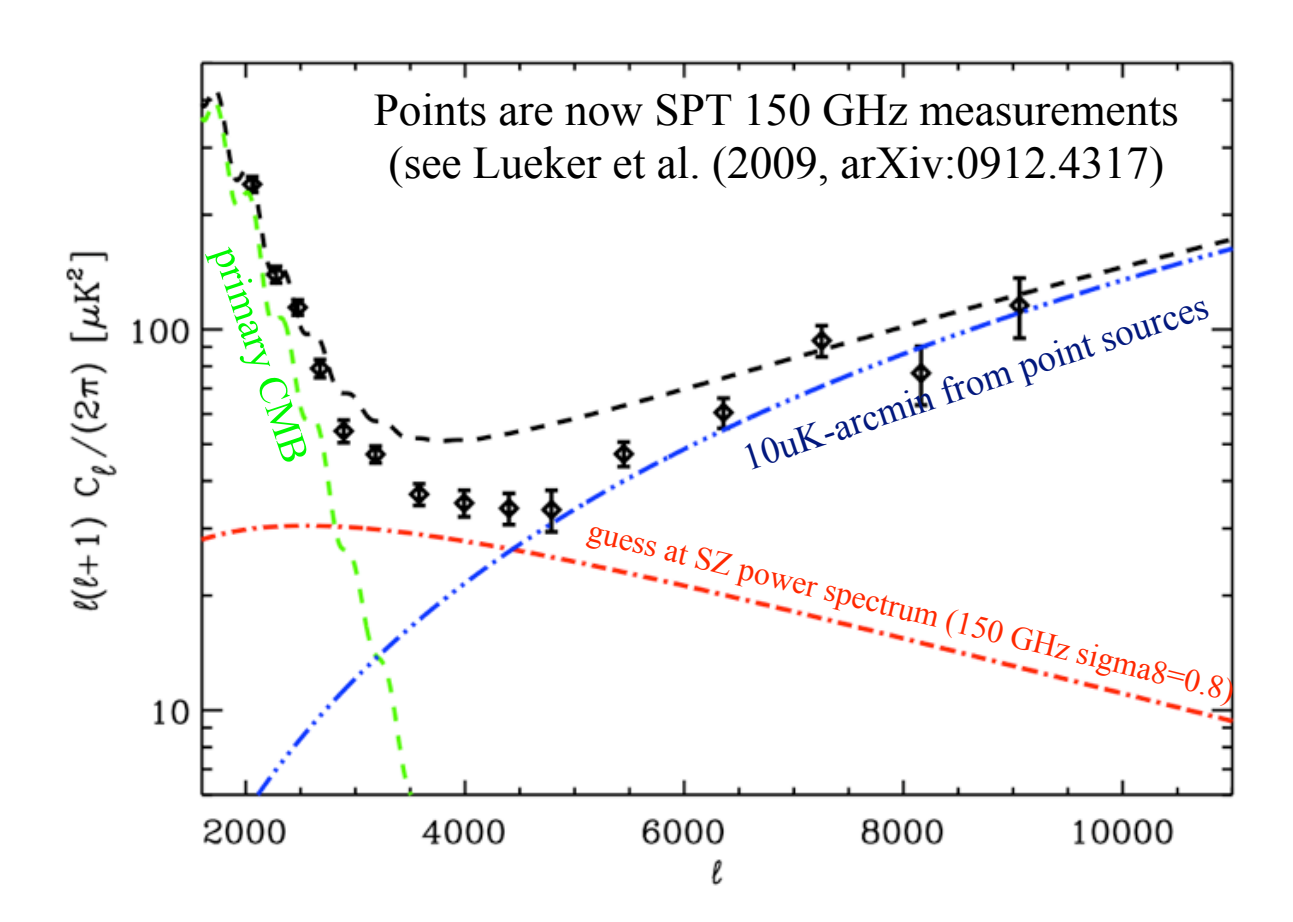
- combine 150 GHz & 220 GHz data (adds noise but reduces bias)
- fit simultaneously for primary, SZ, point-source contributions to C_l spectrum (requires excellent knowledge of beam, what about point-source clustering?)



First Significant Detection of Secondary Anisotropy

- primary and Poisson-distributed point-source contributions are just what we expected.

- what happened to all the thermal SZ (or kinetic SZ or clustered point-source power)?



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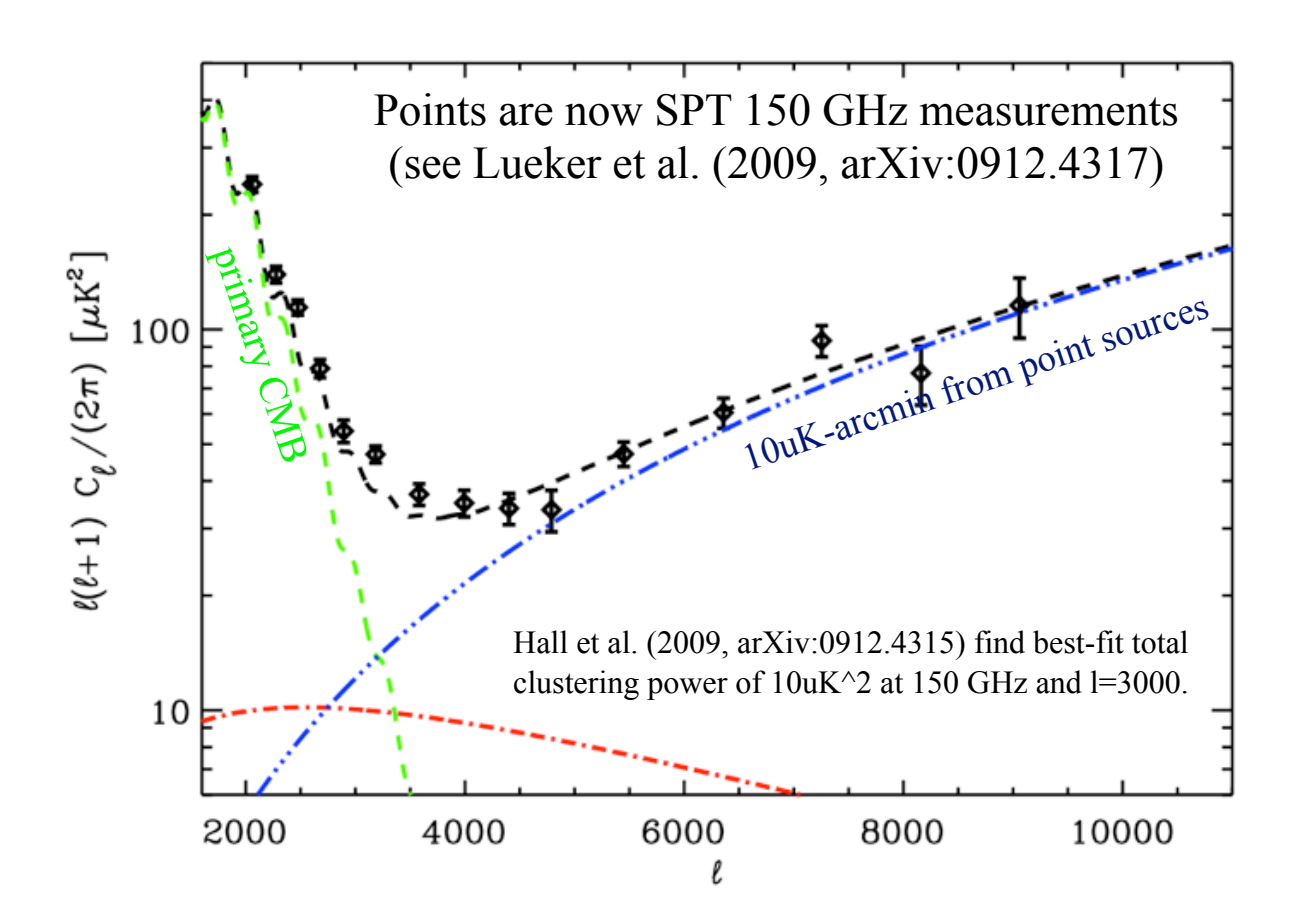
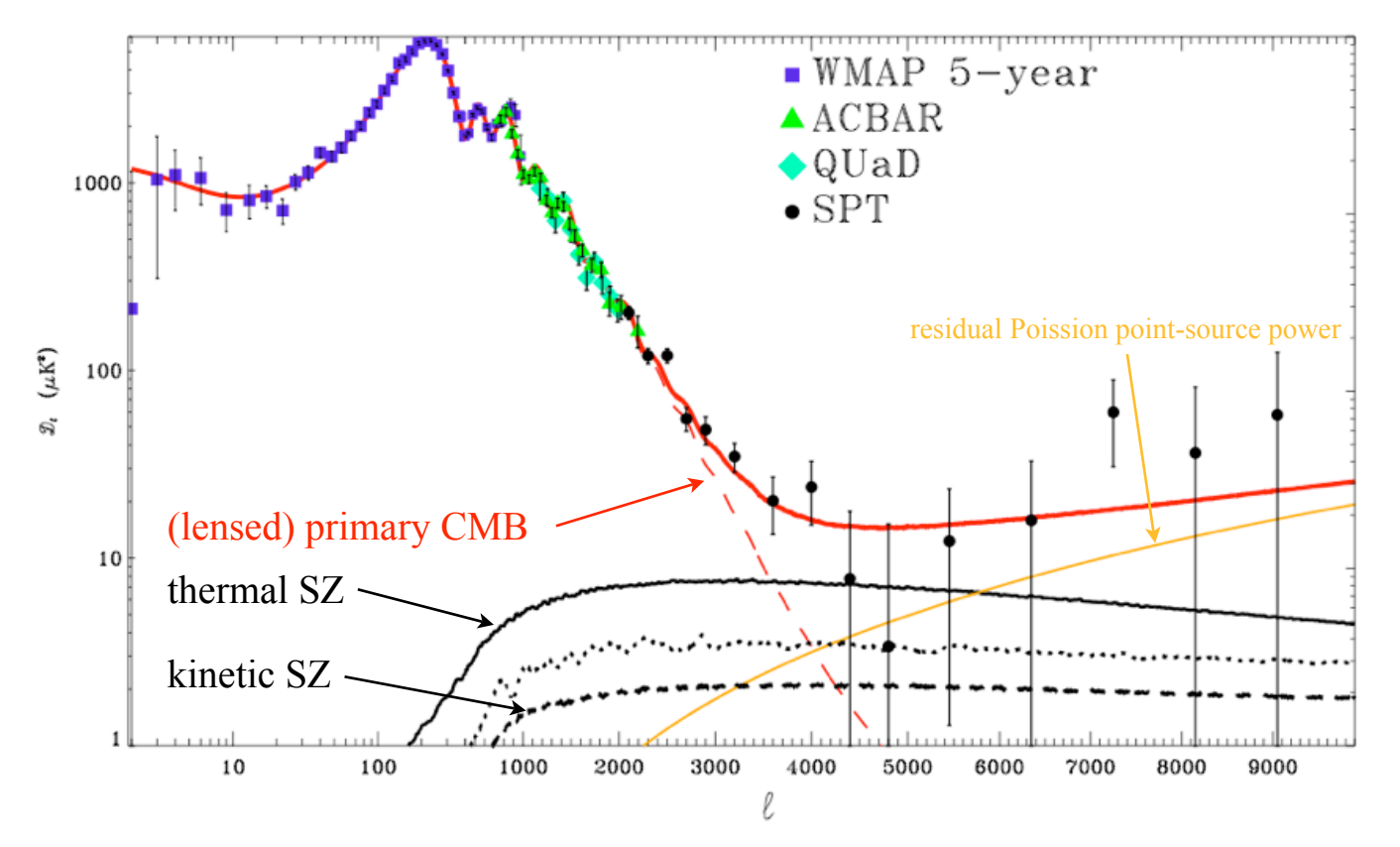


First Significant Detection of Secondary Anisotropy

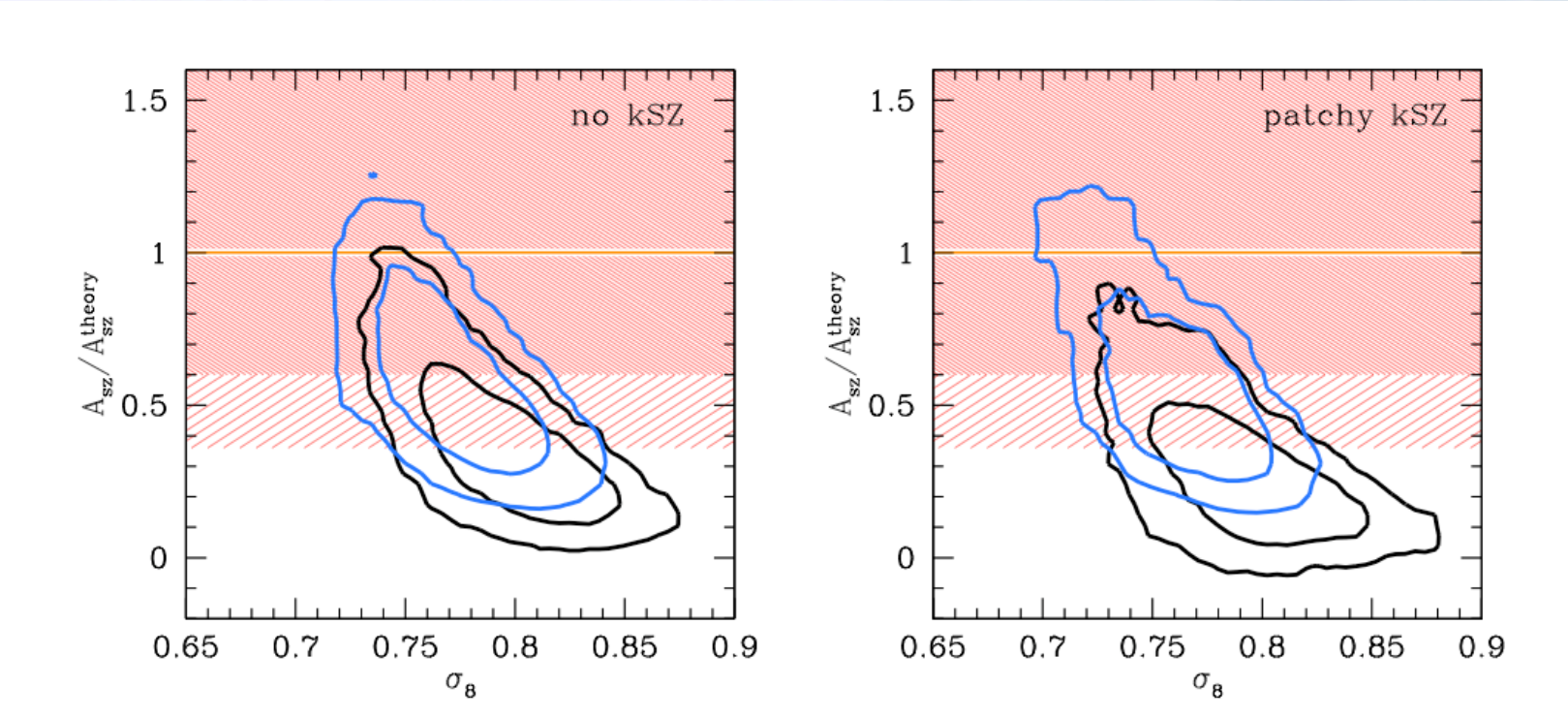
"Subtract off" some fraction of 220 GHz data from 150 GHz data. ("subtraction" actually performed using linear combos of cross-spectra.)

- Poisson point-source power knocked down by ~x10.

- residual clustered point-source power negligible, so remaining SZ-like signal is really SZ. But thermal or kinetic?



Interpretation of SZ power Measurement



- If we assume no modeling uncertainty and a fiducial kSZ template, $\sigma_8 = 0.746 \pm 0.017$.
  - cf. $\sigma_8 = 0.794 \pm 0.028$ for WMAP5 + ACBAR + QUaD
- Adding 50% tSZ modeling uncertainty gives $\sigma_8 = 0.773 \pm 0.025$.

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Extragalactic sources of mm-wave emission

R=90 GHz, G=150 GHz, B=220 GHz

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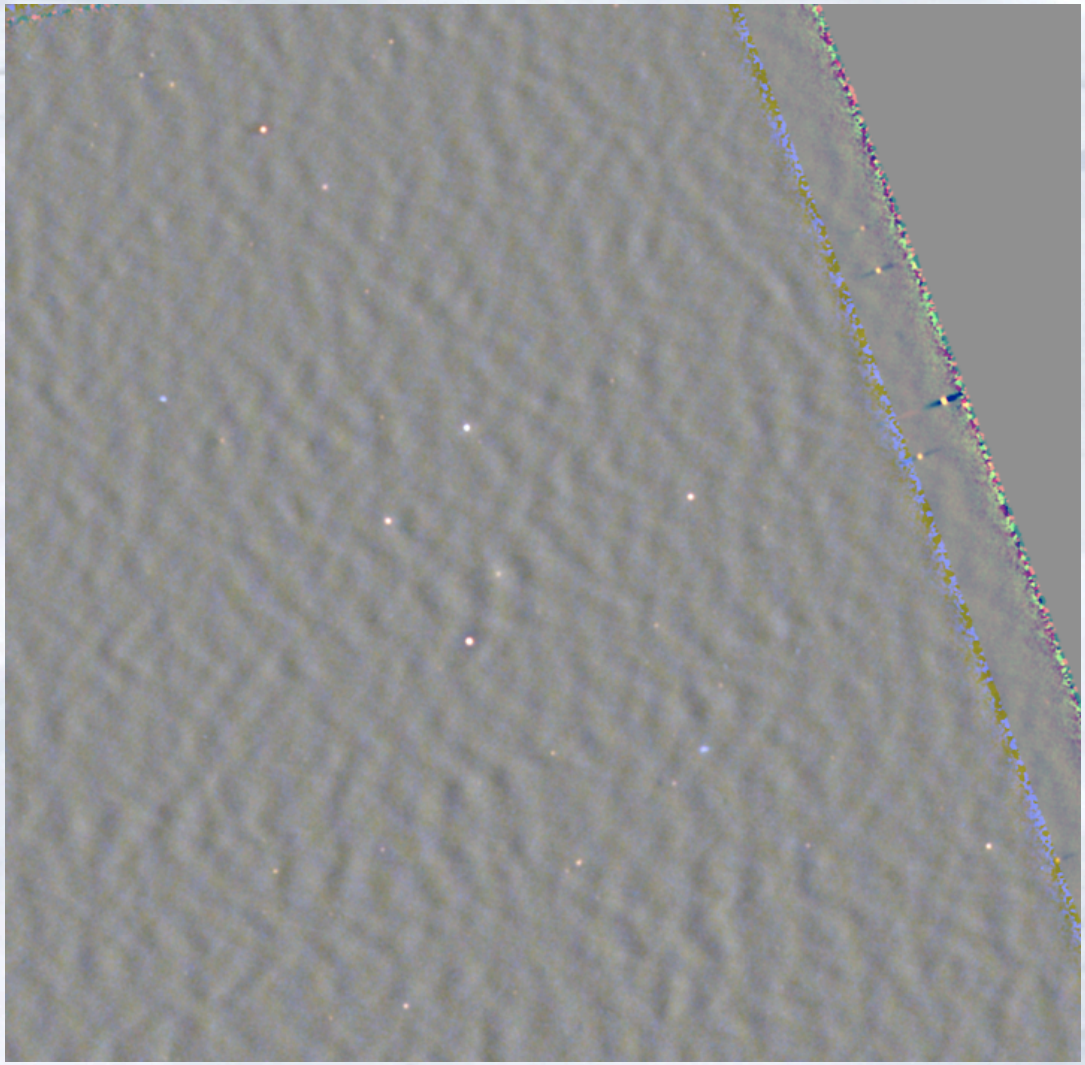
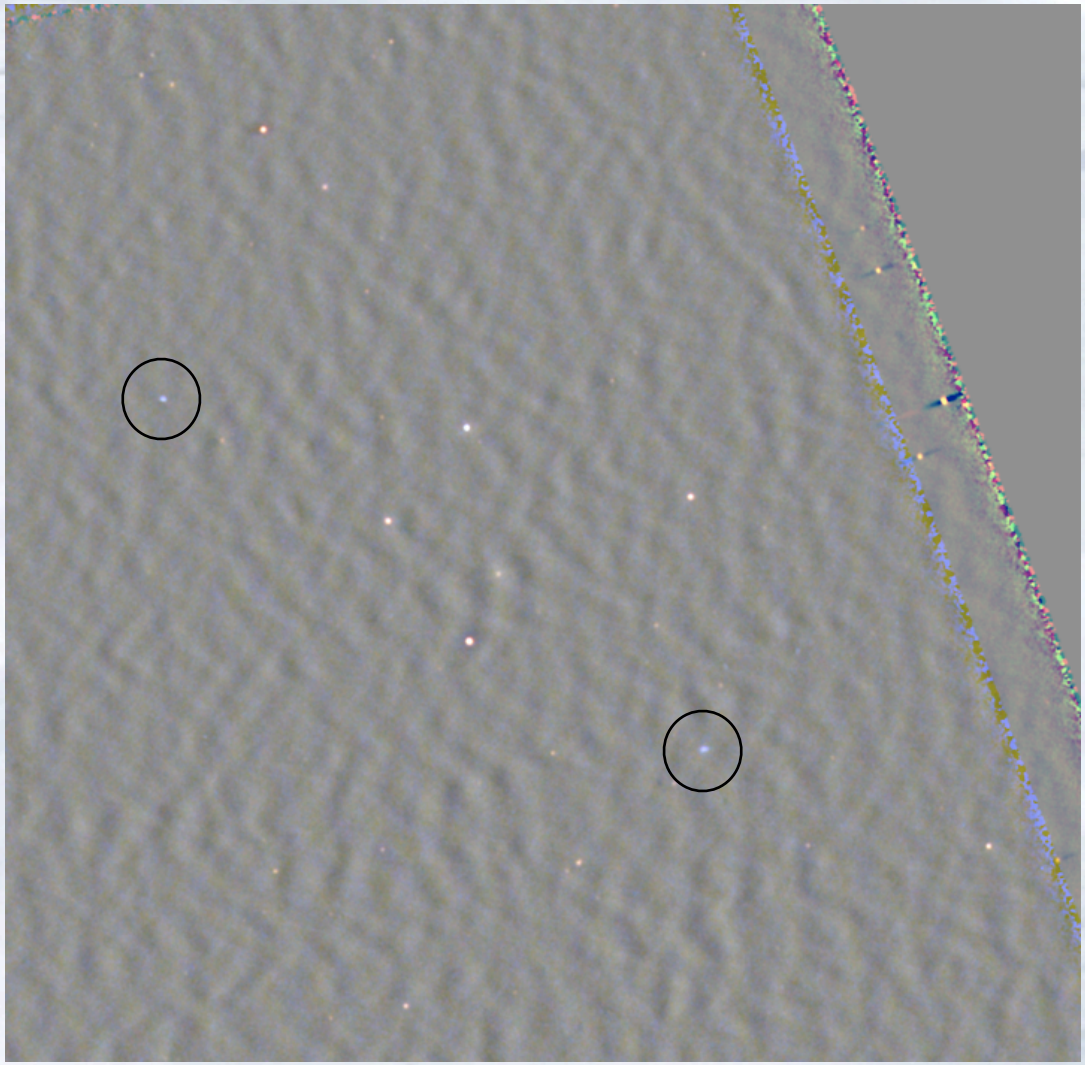
Extragalactic sources of mm-wave emission



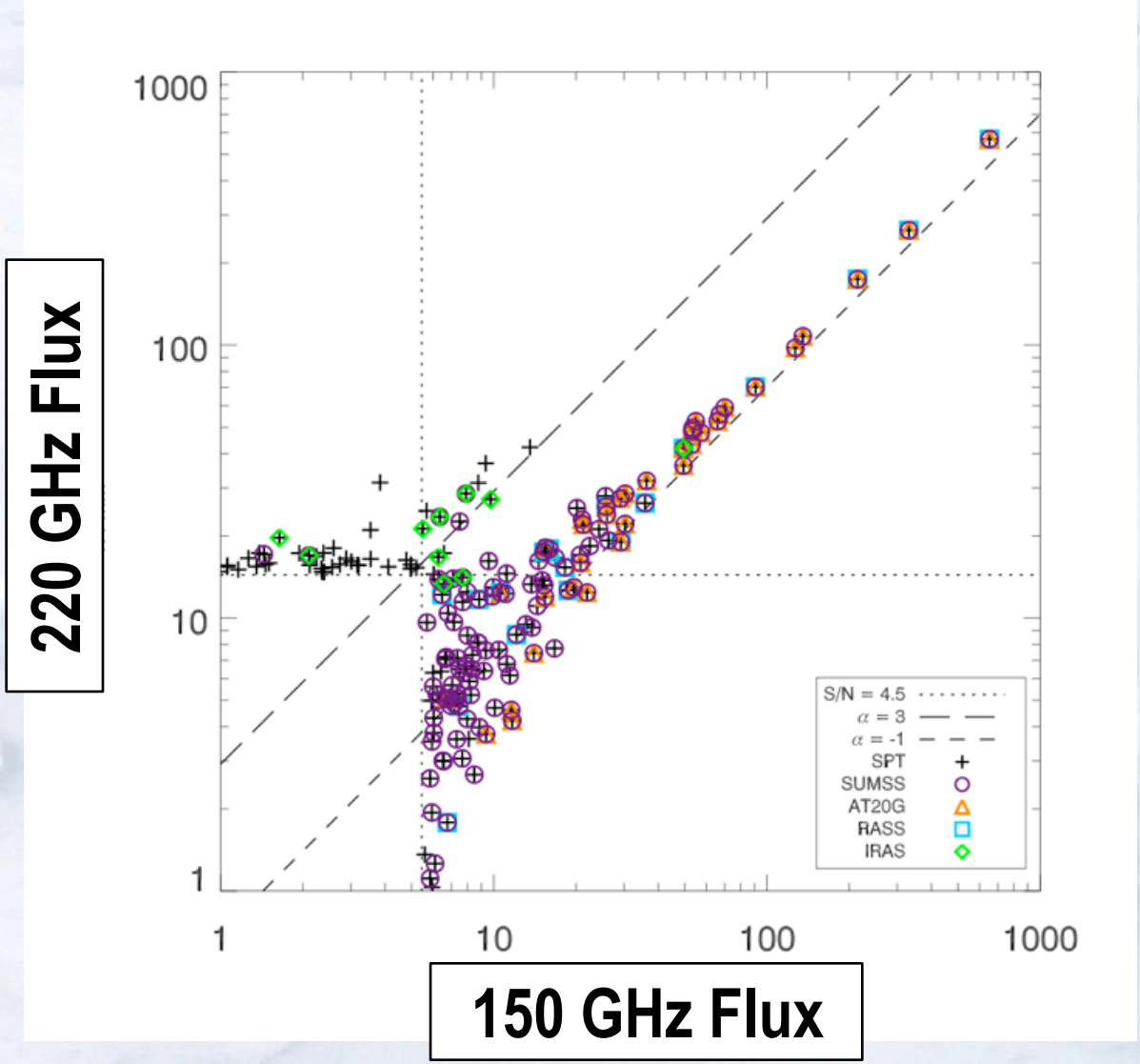
R=90 GHz, G=150 GHz, B=220 GHz

Extragalactic sources of mm-wave emission

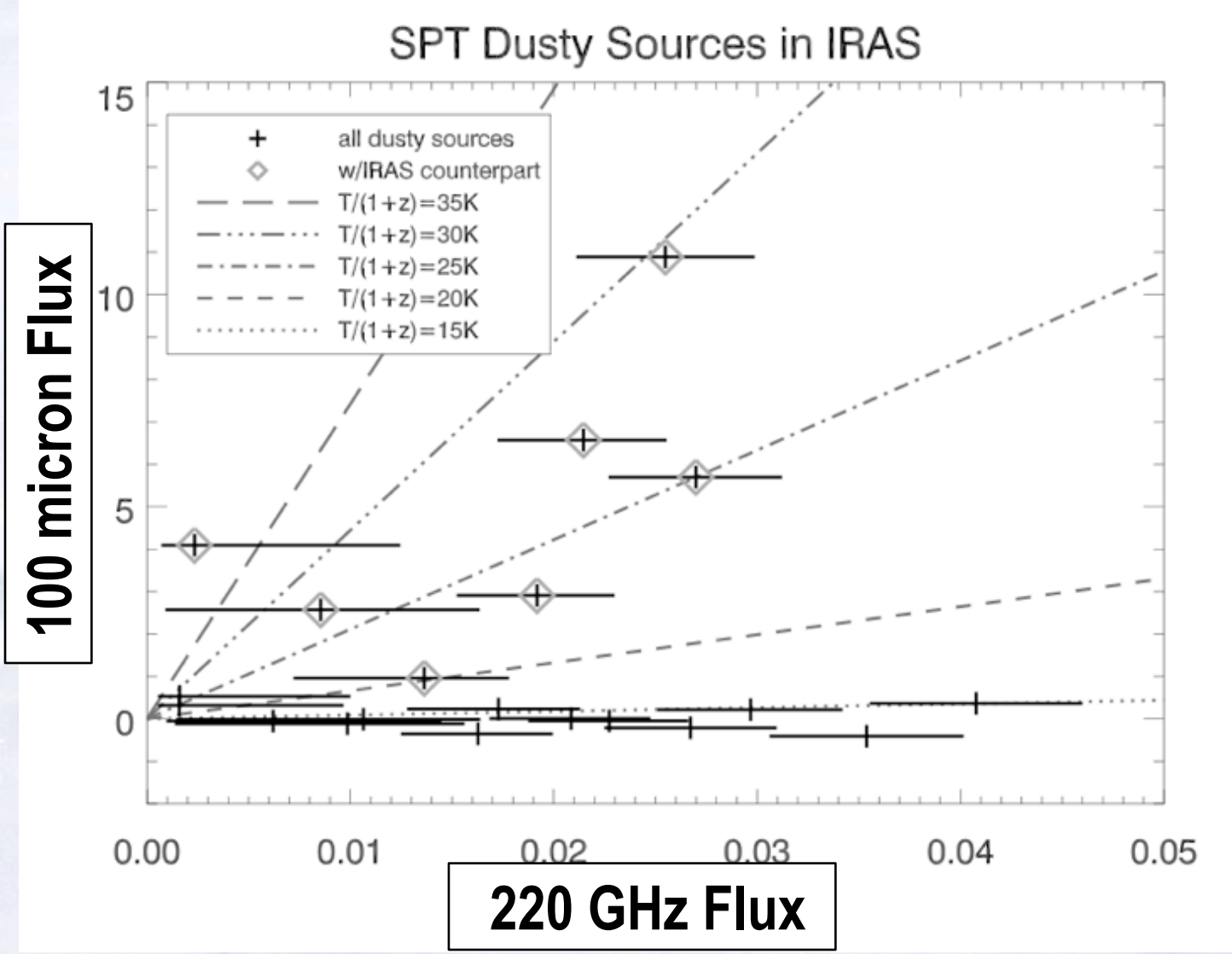


R=90 GHz, G=150 GHz, B=220 GHz

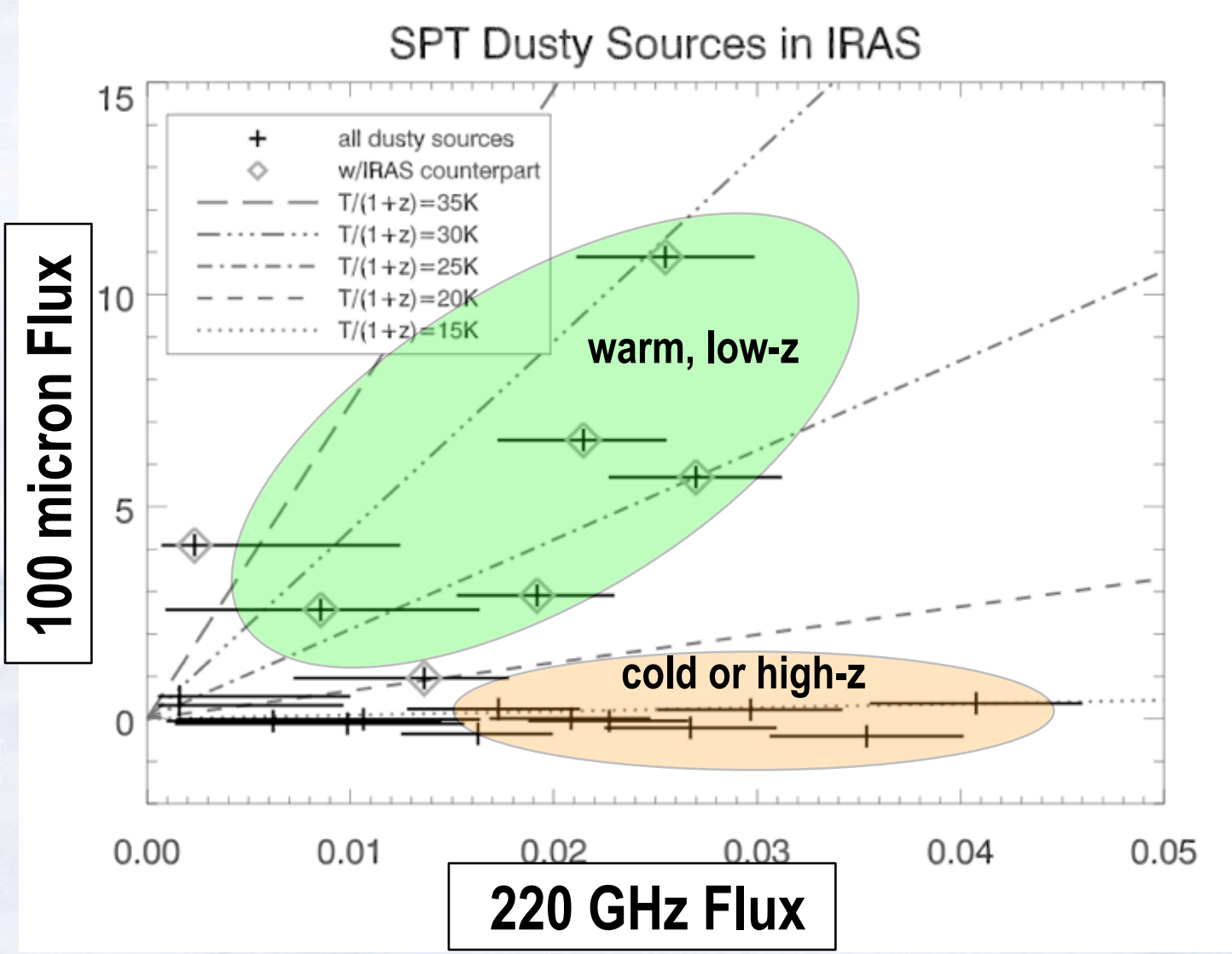
Extragalactic sources of mm-wave emission



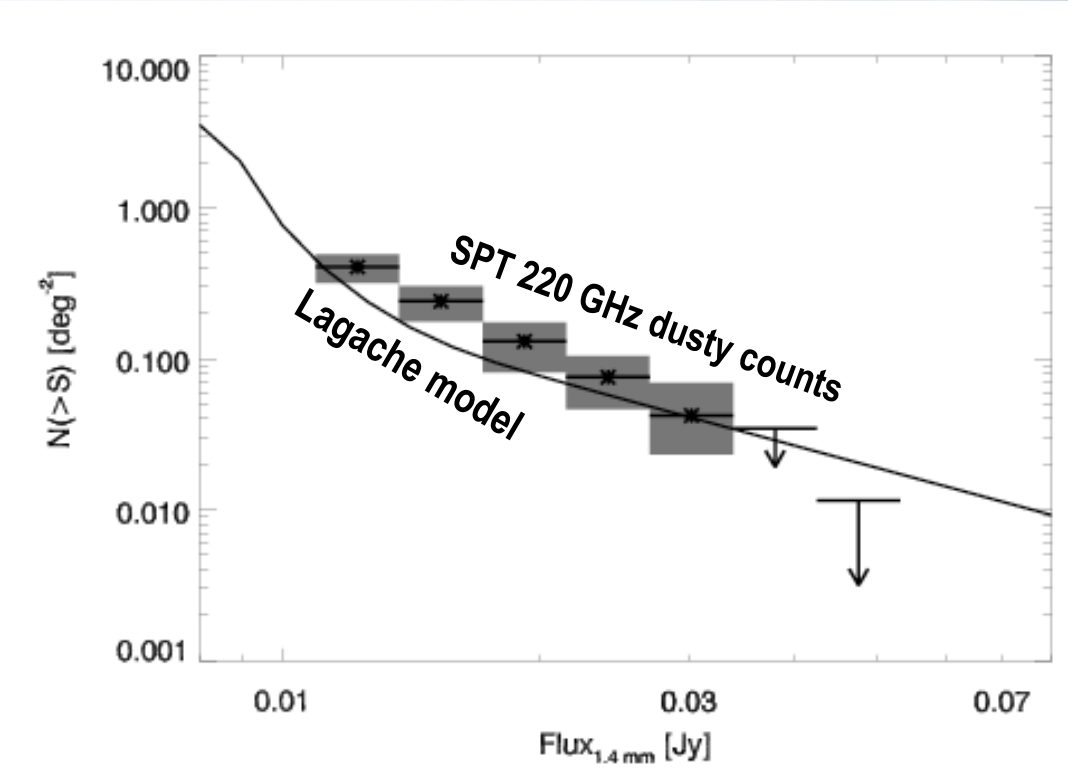
Extragalactic sources of mm-wave emission



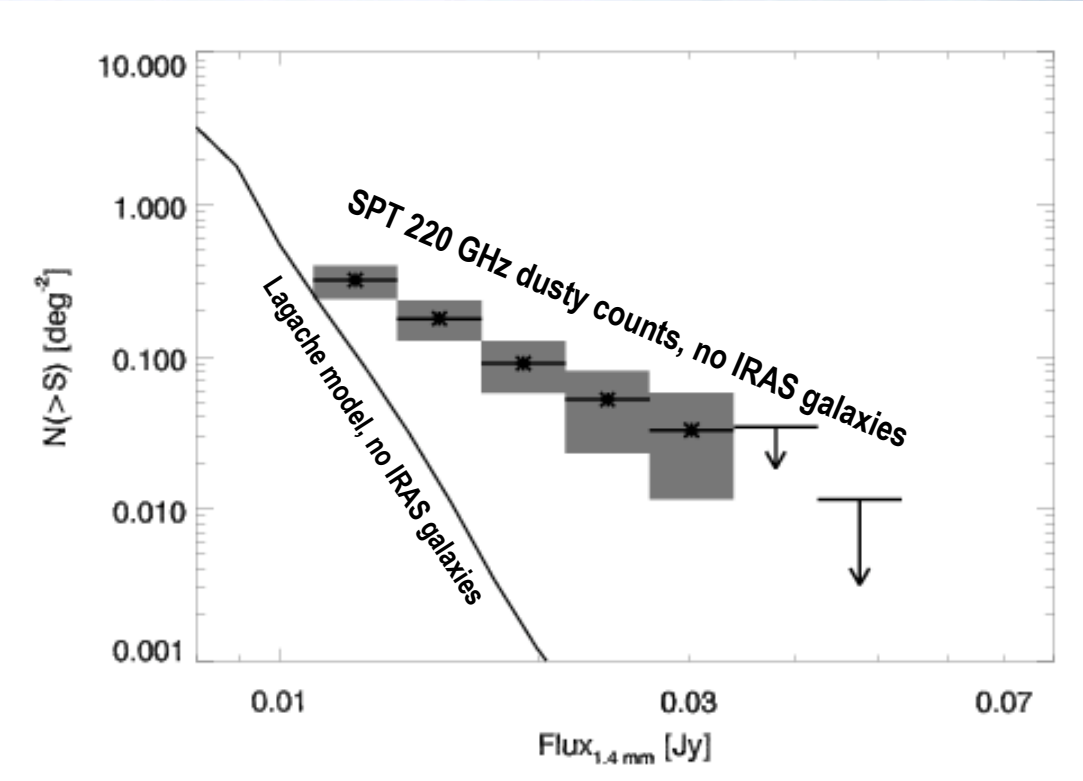
Extragalactic sources of mm-wave emission



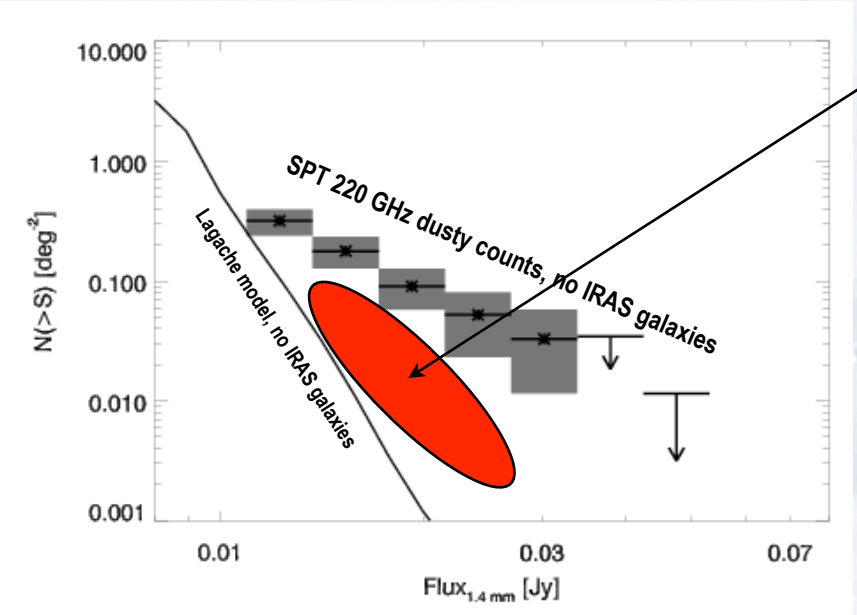
Extragalactic sources of mm-wave emission



Extragalactic sources of mm-wave emission



Extragalactic sources of mm-wave emission



What's going on here?

- **strong lensing of background sources?**
- **intrinsically bright, high-z population not predicted by models?**
- **cold, undiscovered local population?**

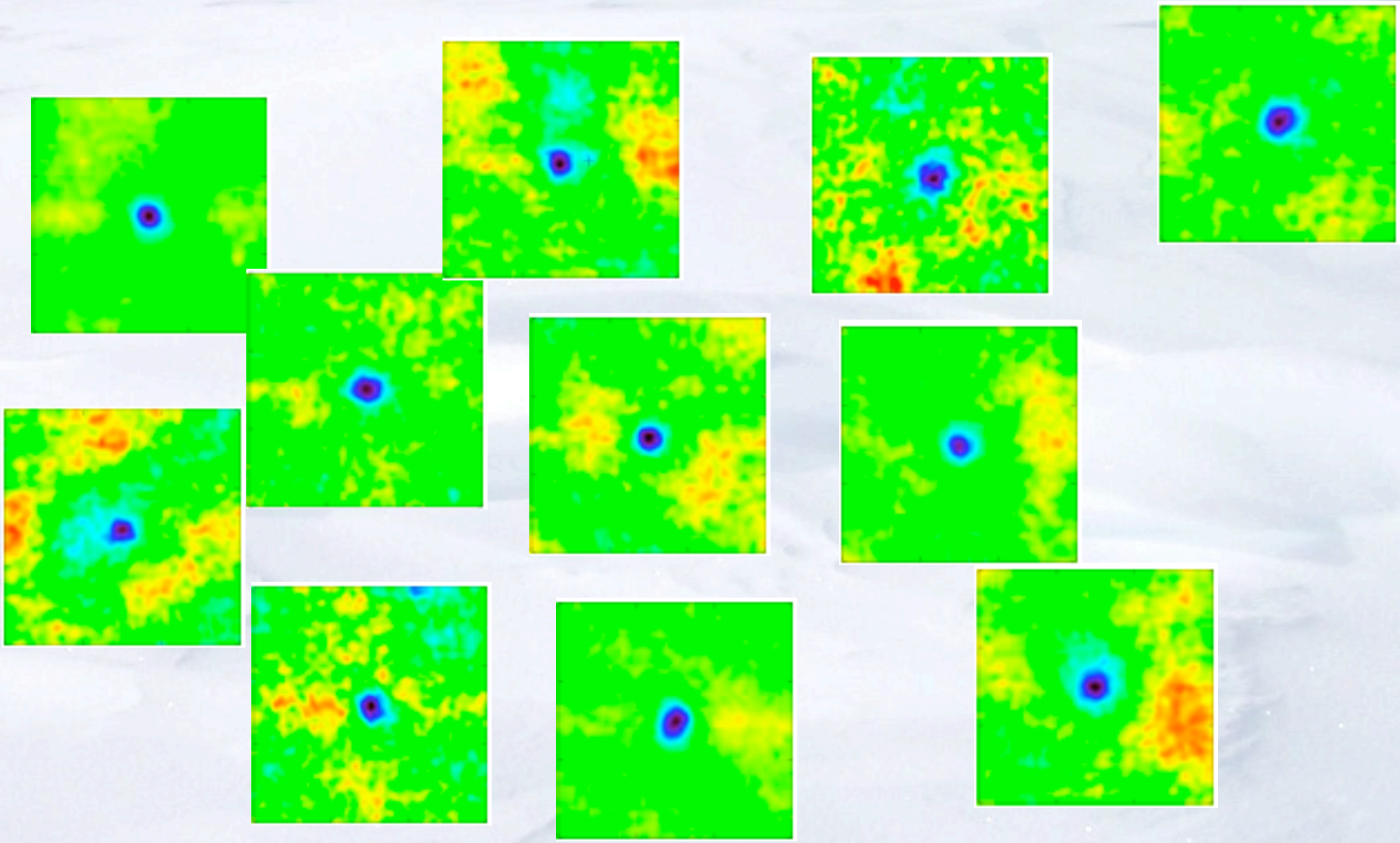
Outline

- **Recent results**
  - **CMB power spectrum**
  - **mm-wave extragalactic sources of emission**
  - **observations of targeted clusters**

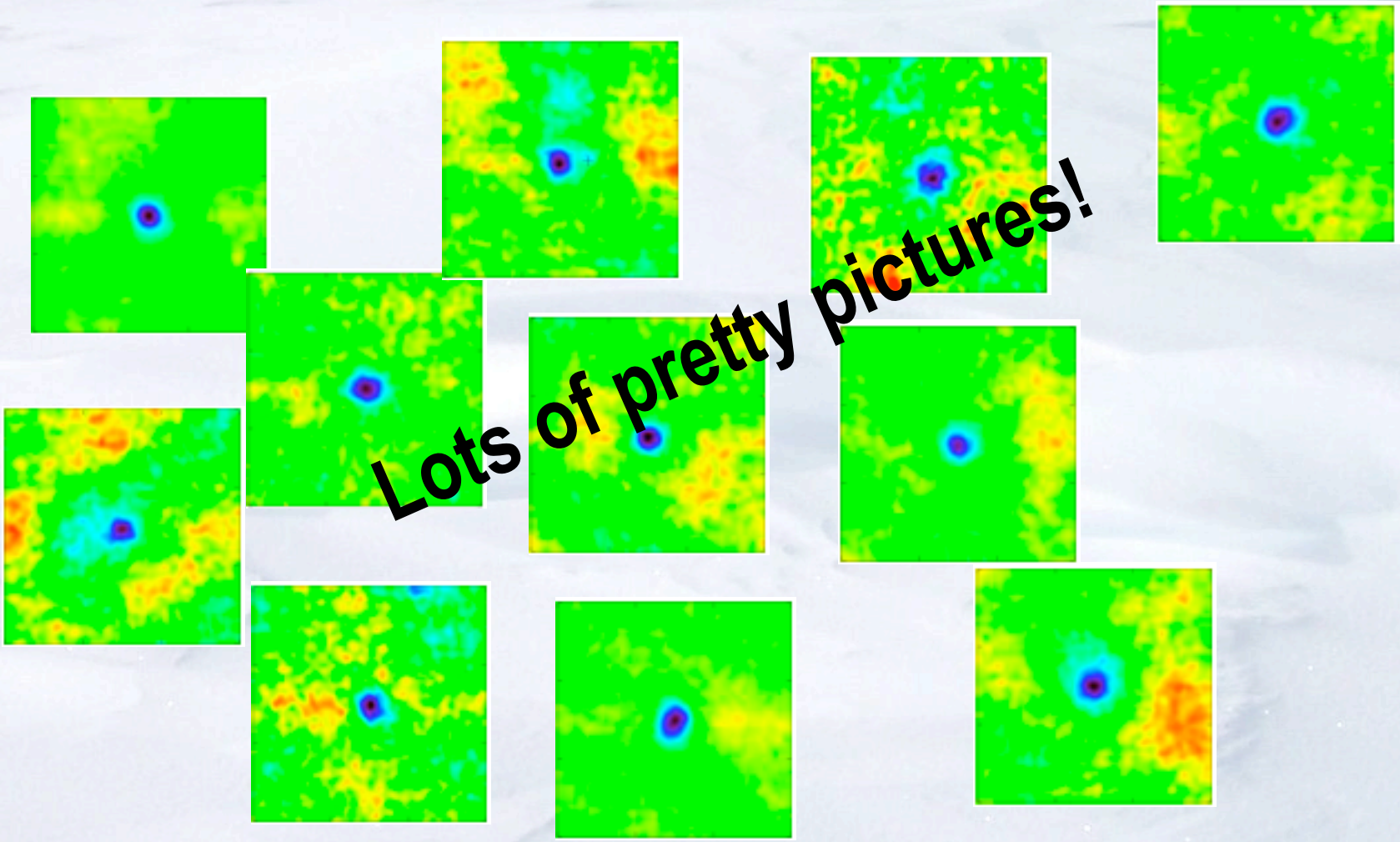
Outline

- **Recent results**
  - **observations of targeted clusters**

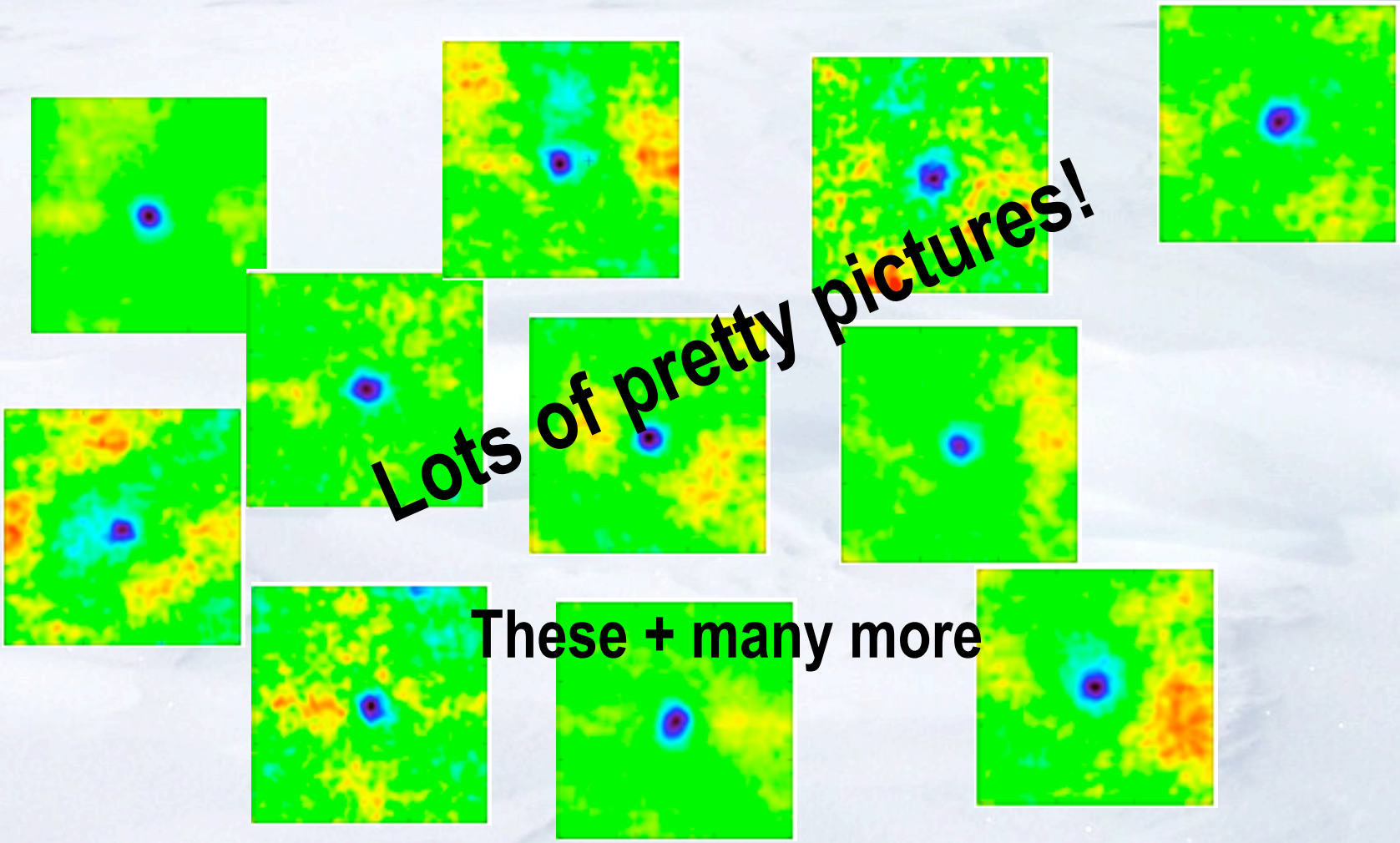
Observations of targeted clusters: Why?



Observations of targeted clusters: Why?

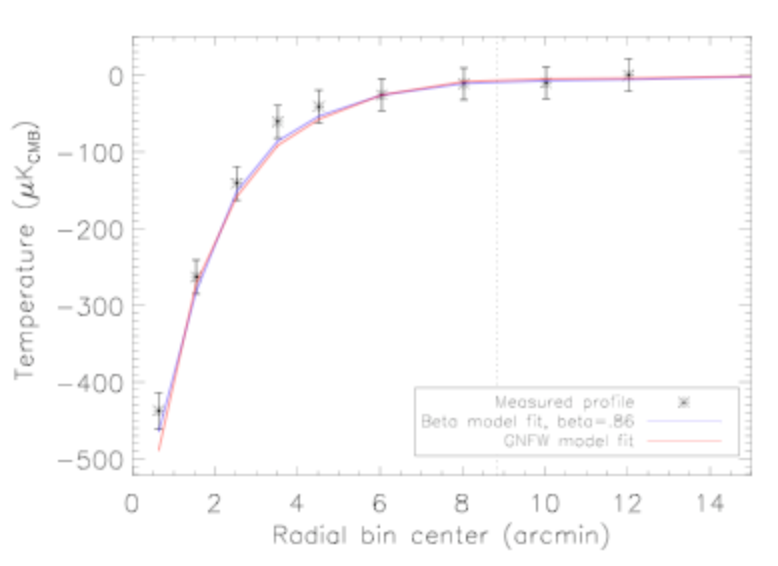


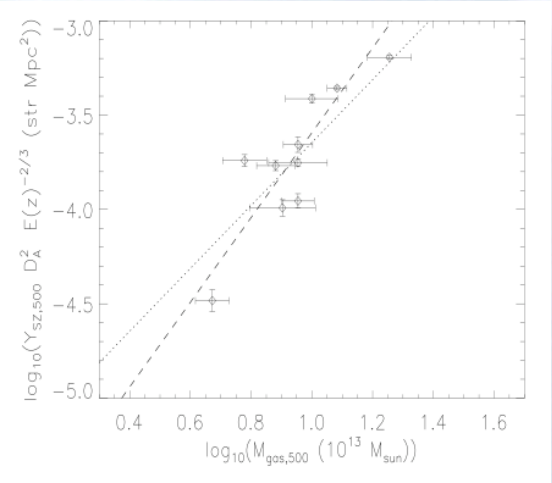
Observations of targeted clusters: Why?



Observations of targeted clusters: Why?

- Understand cluster structure
  - SZ probes pressure, X-ray probes density & temperature
  - SPT can probe out to virial radius
- Investigate scaling relations
  - between SZ & cluster mass or SZ & other observables
- Other:
  - Kinetic SZ?
    - need multiple bands, preferably spanning the 217GHz null
  - Constrain potential issues with SZ selection function
    - e.g., contamination by point sources





Outline

- **Coming soon**
  - **cosmology with an SZ-selected cluster catalog**

An SZ-selected galaxy cluster catalog

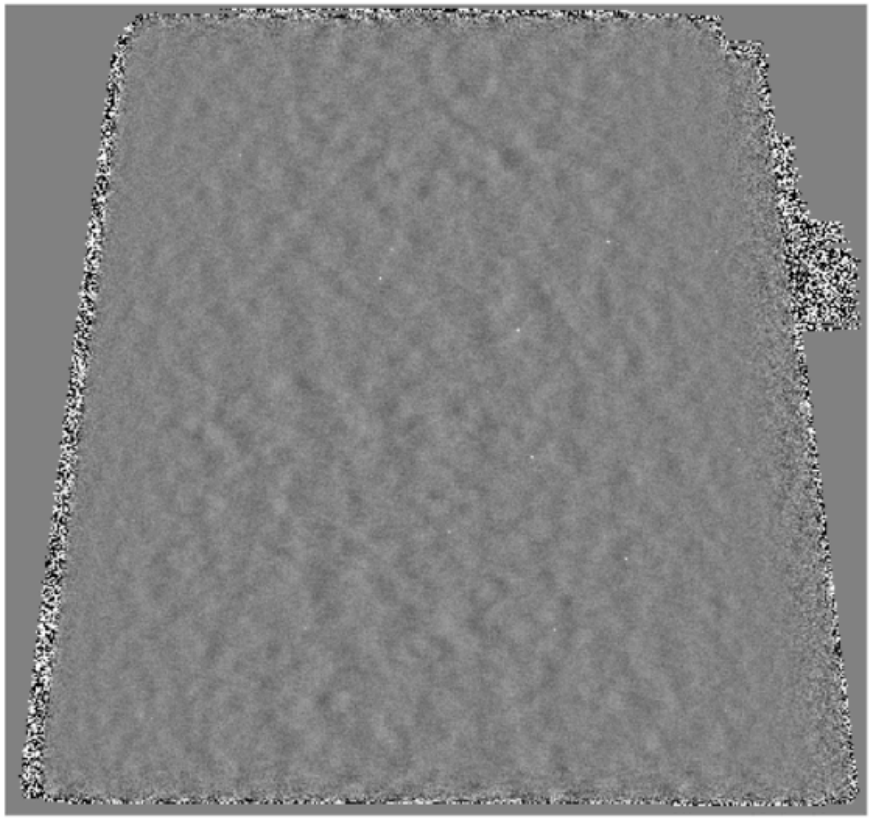
The situation:

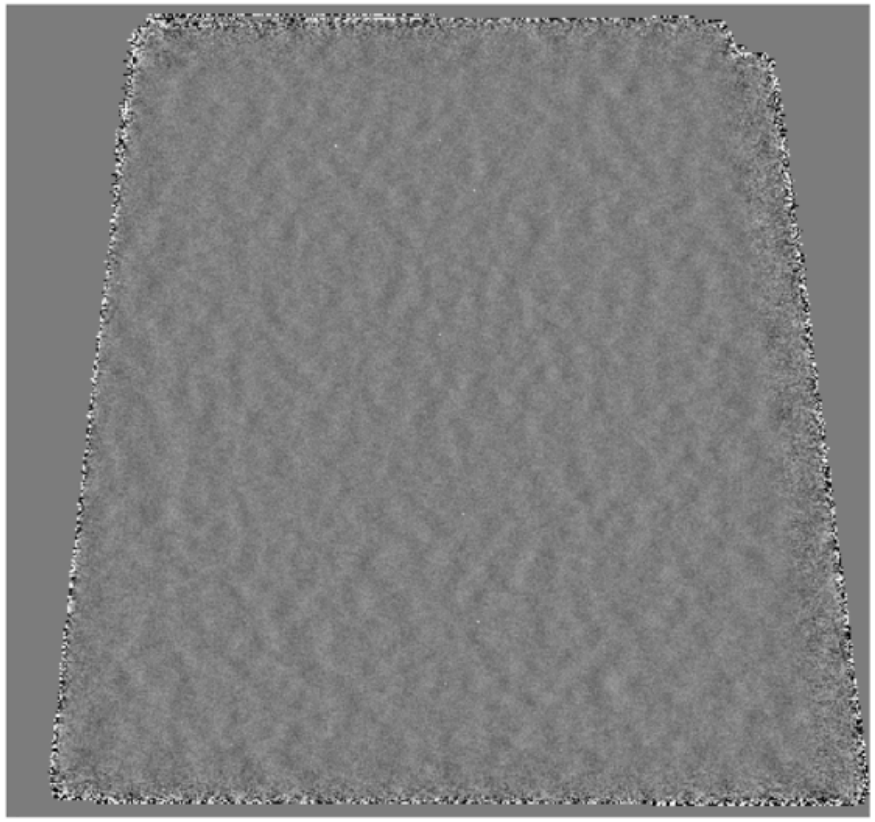
- We have an SZ-selected cluster catalog, followed up optically (with the Blanco Cosmology Survey and targeted Magellan observations).
  - about 2 dozen objects (above a given detection threshold and with optical coverage) in two ~100 sq. deg. fields.
- How do we assess the catalog selection function?
  - necessary for us or anyone else to do meaningful science.
- What do we use for a mass proxy?

An SZ-selected galaxy cluster catalog

How do we assess the catalog selection function?

– answer: simulated observations.

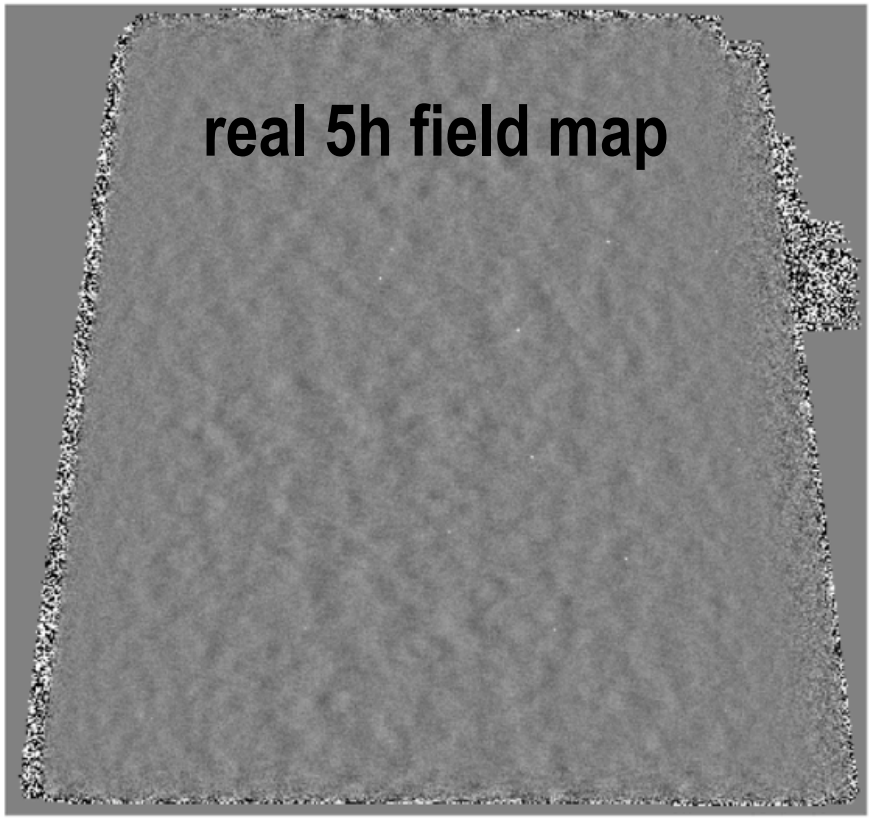


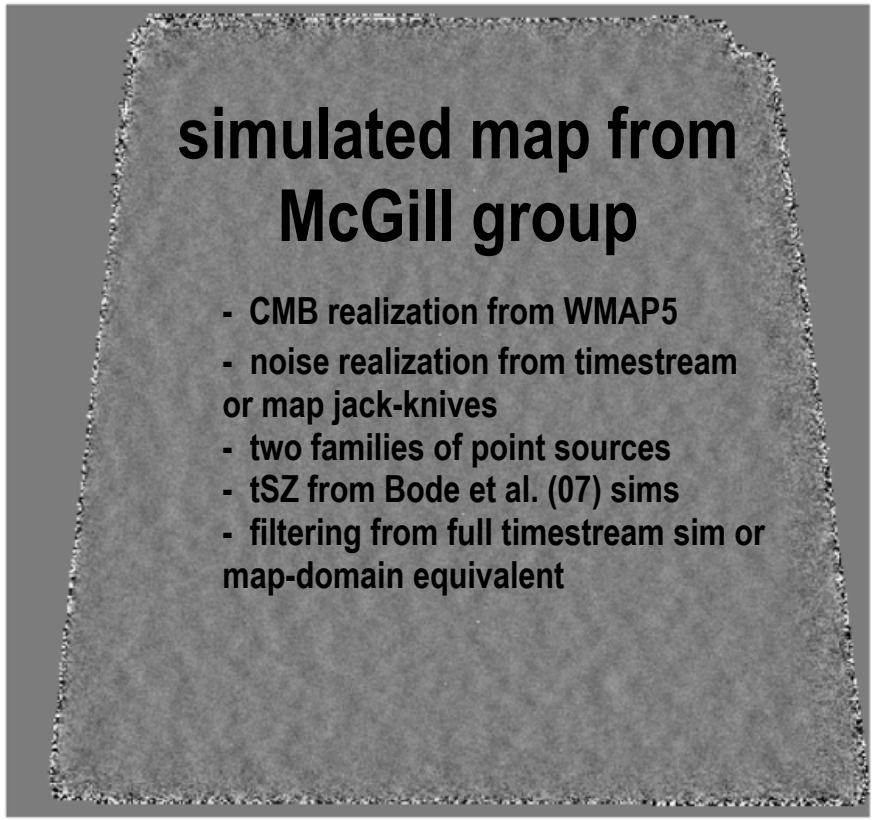


An SZ-selected galaxy cluster catalog

How do we assess the catalog selection function?

– answer: simulated observations.

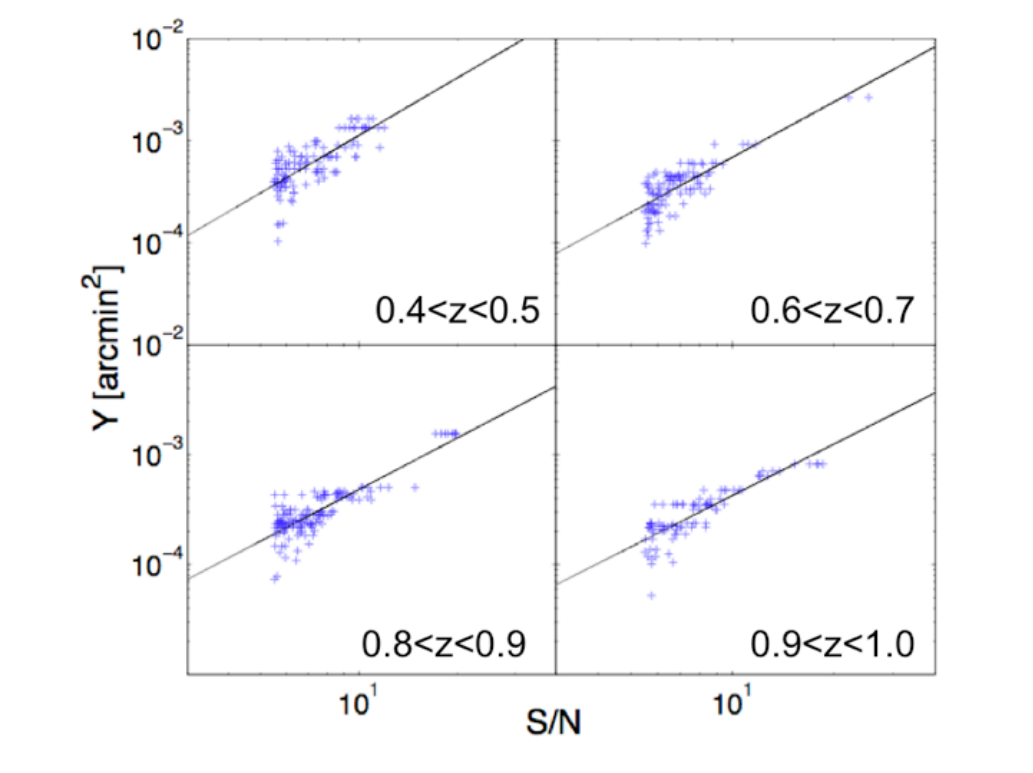




An SZ-selected galaxy cluster catalog

What do we use as a mass proxy?

- answer: plain old signal-to-noise.
  - makes part of the likelihood calculation trivial.
  - makes it clear where all the dangerous assumptions come in
  - it's actually not such a bad proxy
    - even better when tied to x-ray & WL observations



Work by Laurie Shaw & the McGill SPT group

Outline

- **Coming later: n_s, 3- and 4-point functions, polarization**

Summary

An ~8m mm-wave telescope with a square-degree focal plane full of detectors = lots of science.

Thanks!

Photo credit: Keith Vanderlinde