Statistics of the Source Population Observed at Millimeter Wavelengths by the South Pole Telescope

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Berkeley Cosmology Seminar

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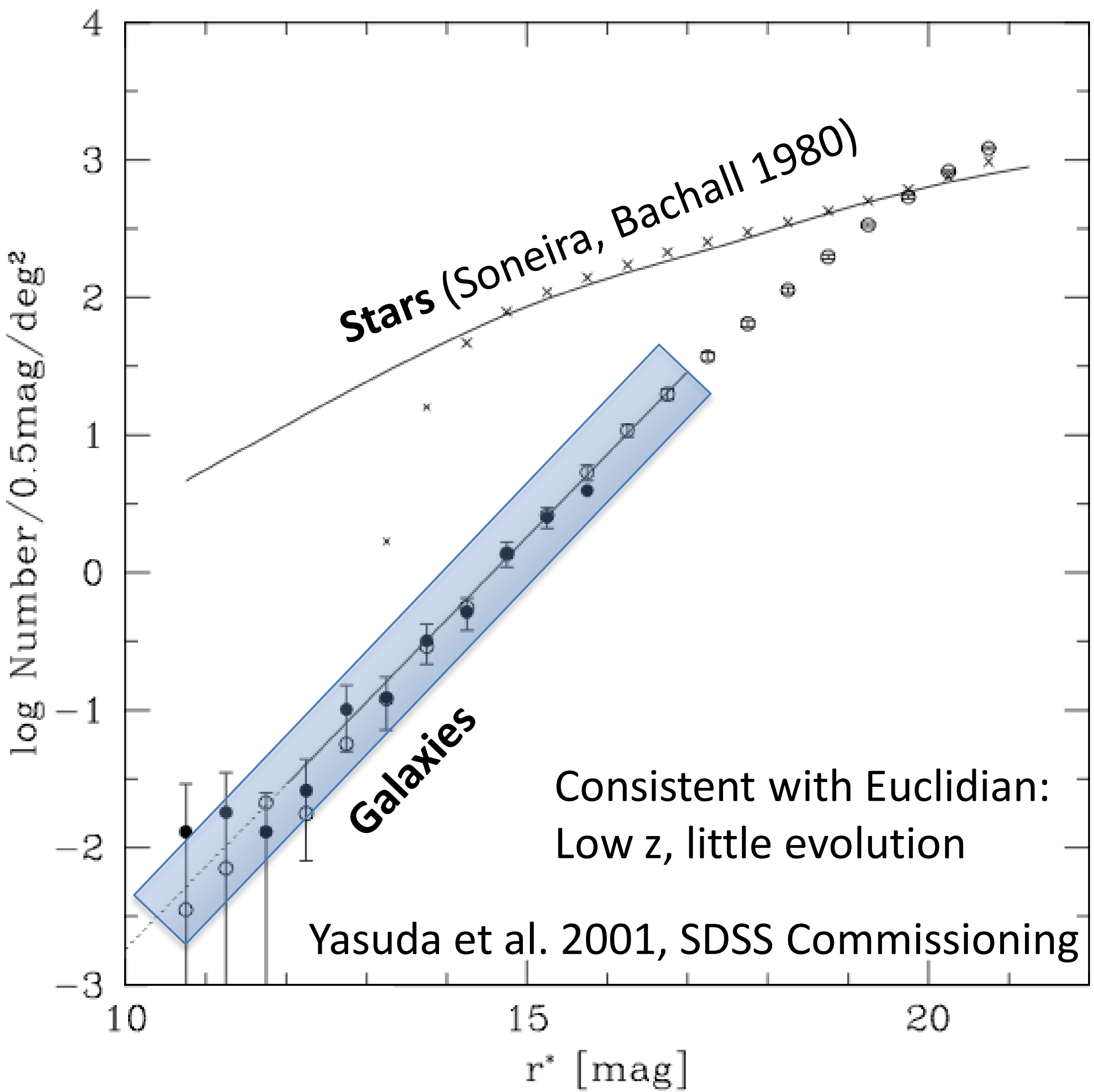
Photo: Nathan Gibbs

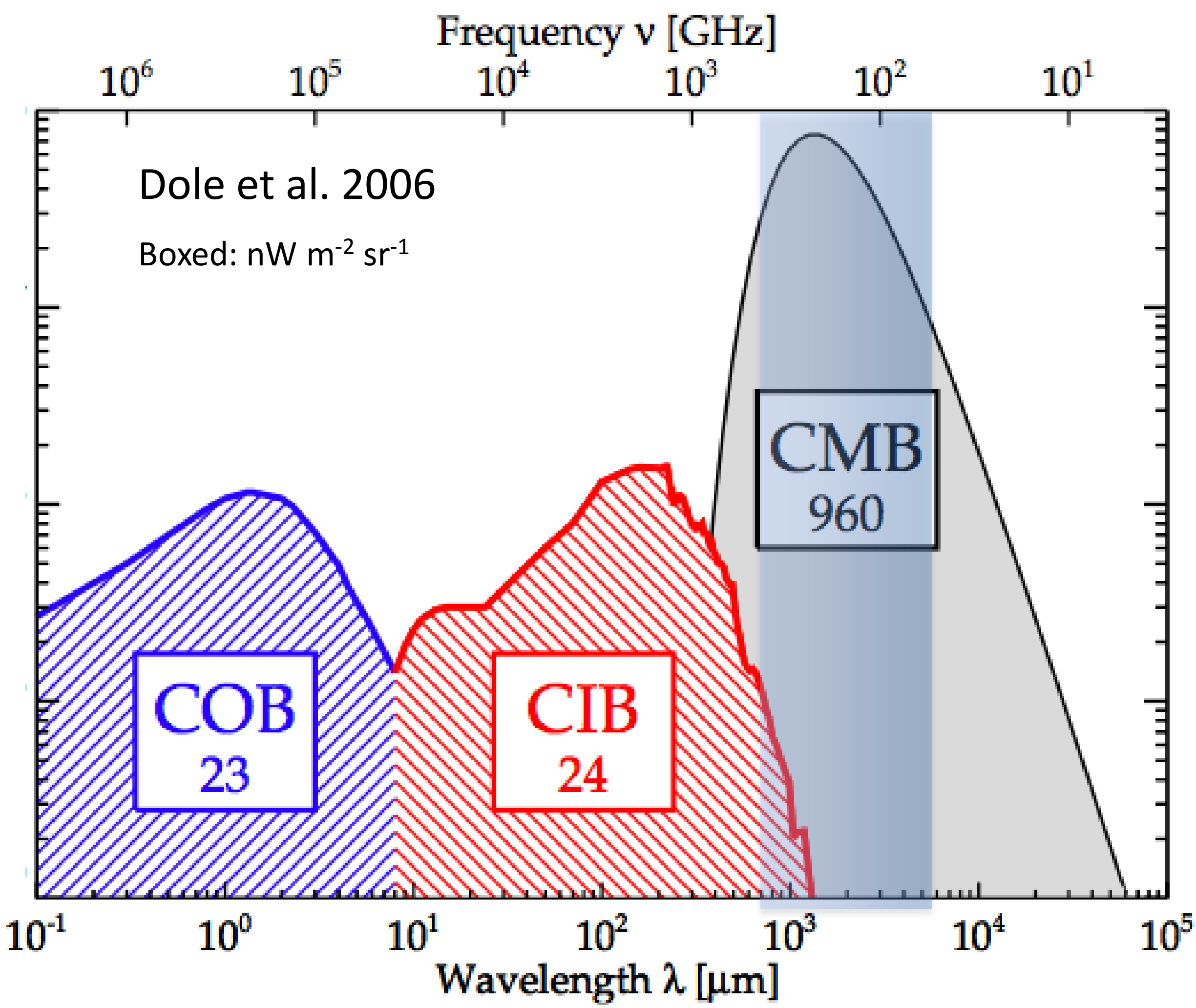
Ingredients

- Distribution of luminosity
- Evolution of luminosity with time
- Evolution of density with time
- Spectral energy distribution of the source
- Several different populations of objects
- Cosmology; luminosity and angular
- …wrapped into one function: dN/dS

Optical counts

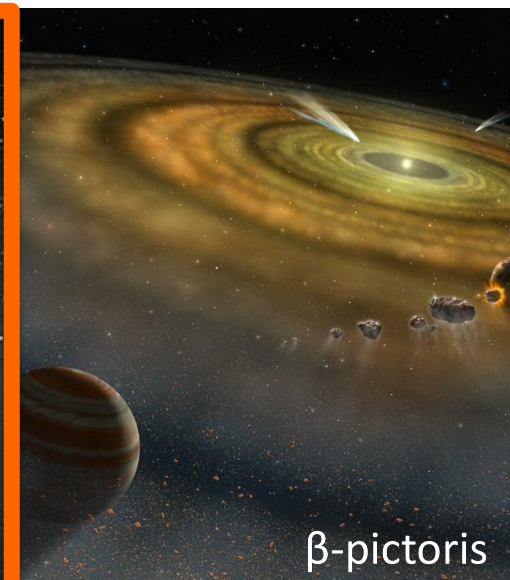


Cosmic backgrounds



Basic SPT parameters for the 2008 survey data described here:
1.4 mm = 220 GHz
2.0 mm = 150 GHz
~1′ resolution.

Mm-wave sources of emission



IR galaxies
Dust dominated (thermal)
Flux increases with frequency
High SFR and extinction

Radio sources
Synchrotron dominated
Flux decreases with frequency

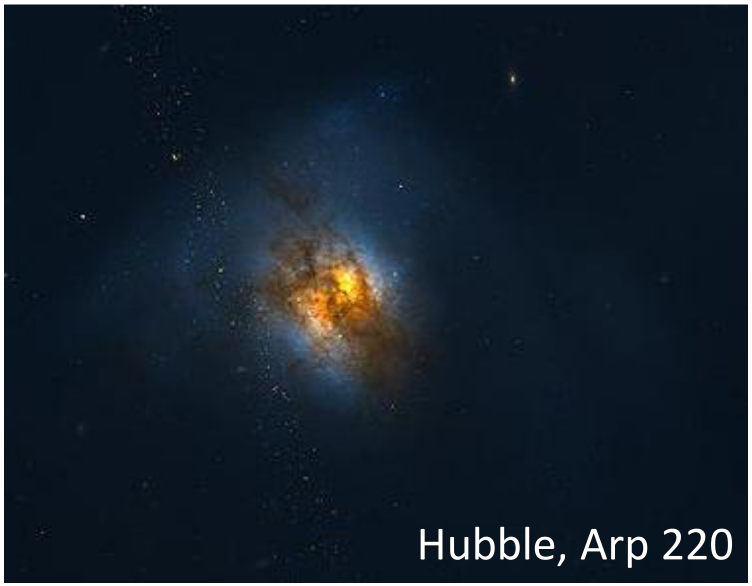
Debris disks
Thermal emission

Also: Planets, HII and cold clump regions of the galaxy.

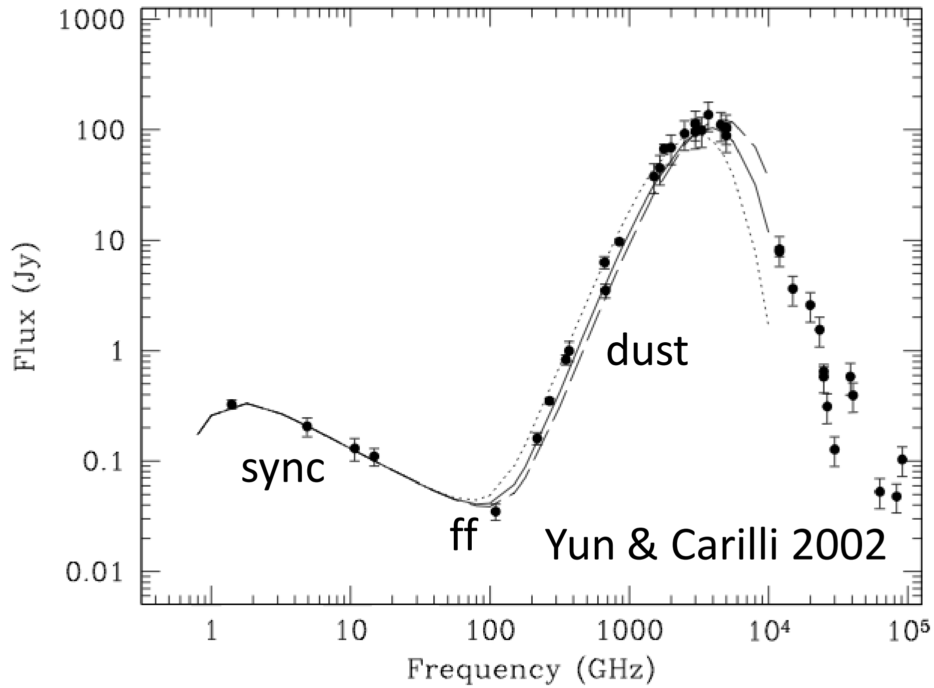
Implication: split into dust or synchrotron-dominated emission.

Images: NASA/Hubble/Chandra/LABOCA

SED: dust-dominated



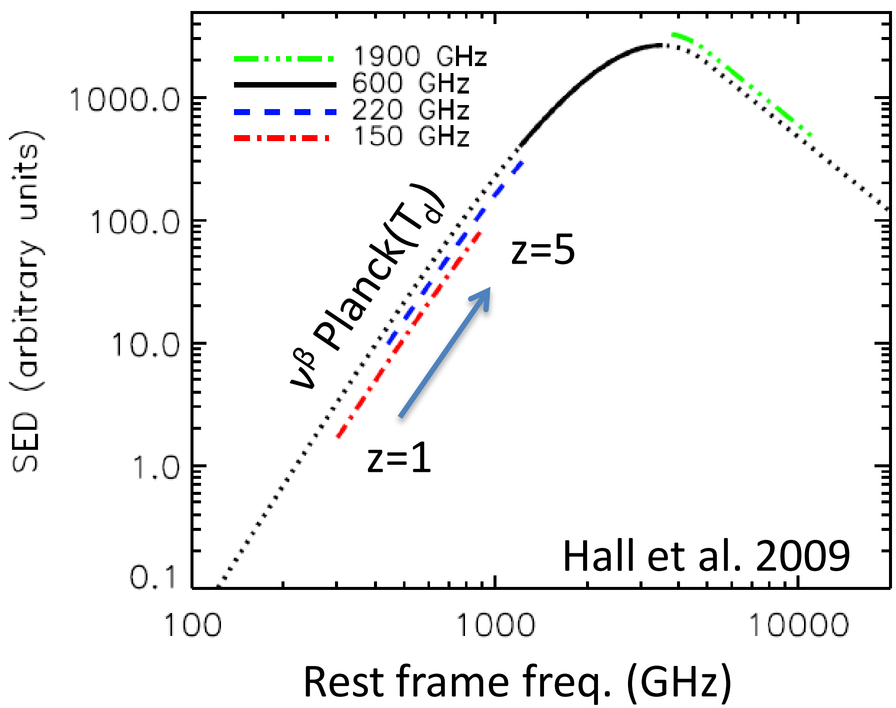
Hubble, Arp 220

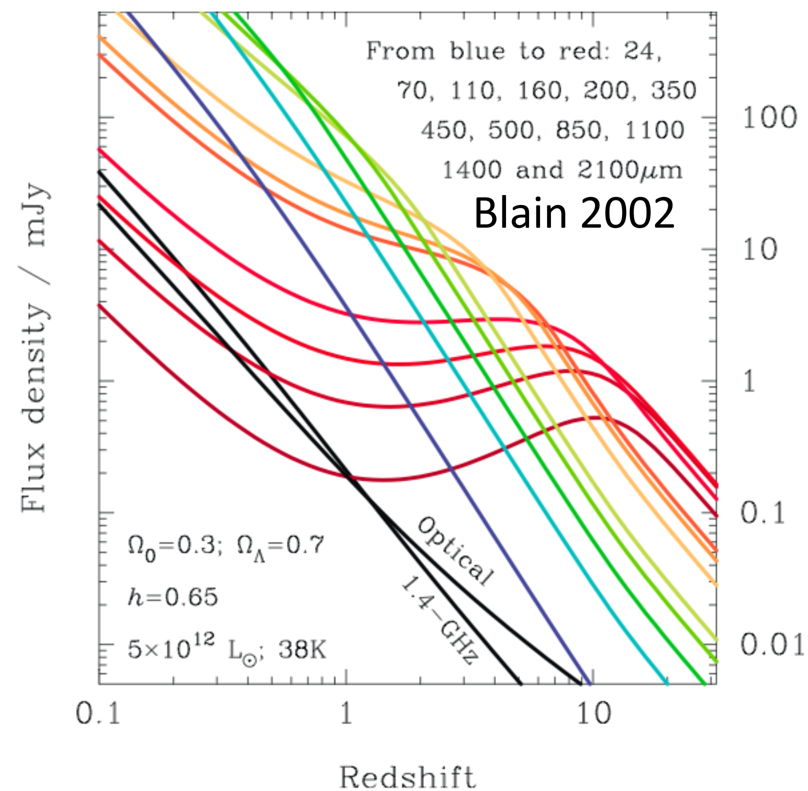


ULIRGs ~ 95% IR
A_V extinction ~ 5-50.

All emission mechanisms here ~ SFR

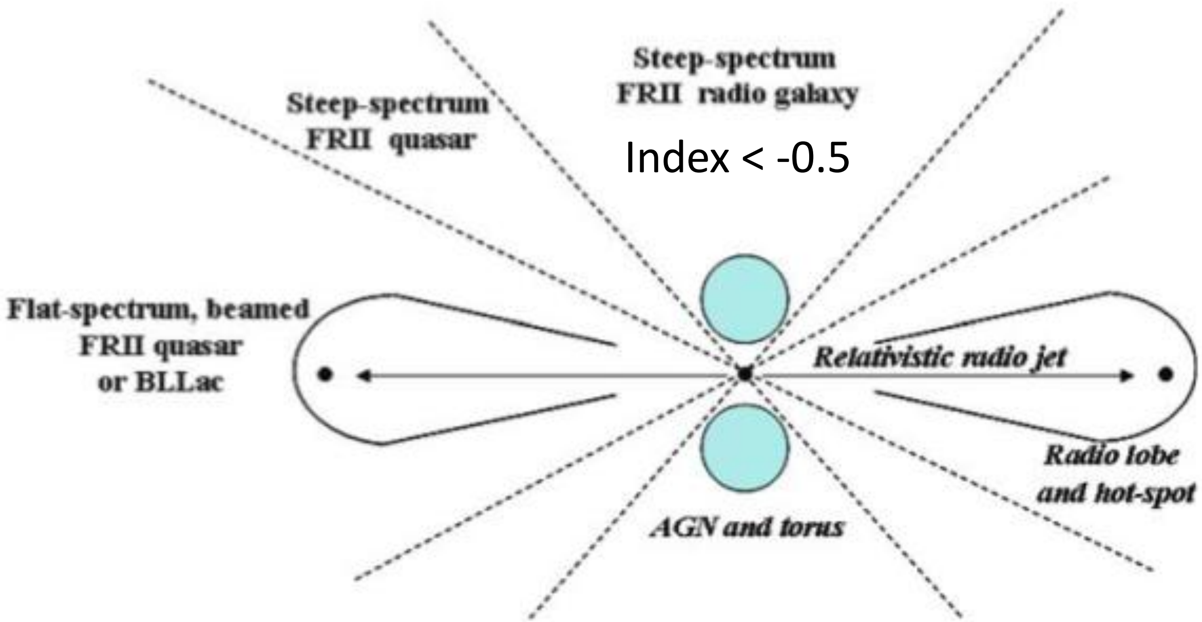
SED: dust-dominated





Sensitive mm-wave selected samples/maps measure the complete history of DSFGs
Large cosmological volumes and a strongly evolving population imply non-Euclidian counts.
Two main parameters: T_d =34 K (Dunne et al. 2000, Chapman et al. 2005) and emissivity = 2.

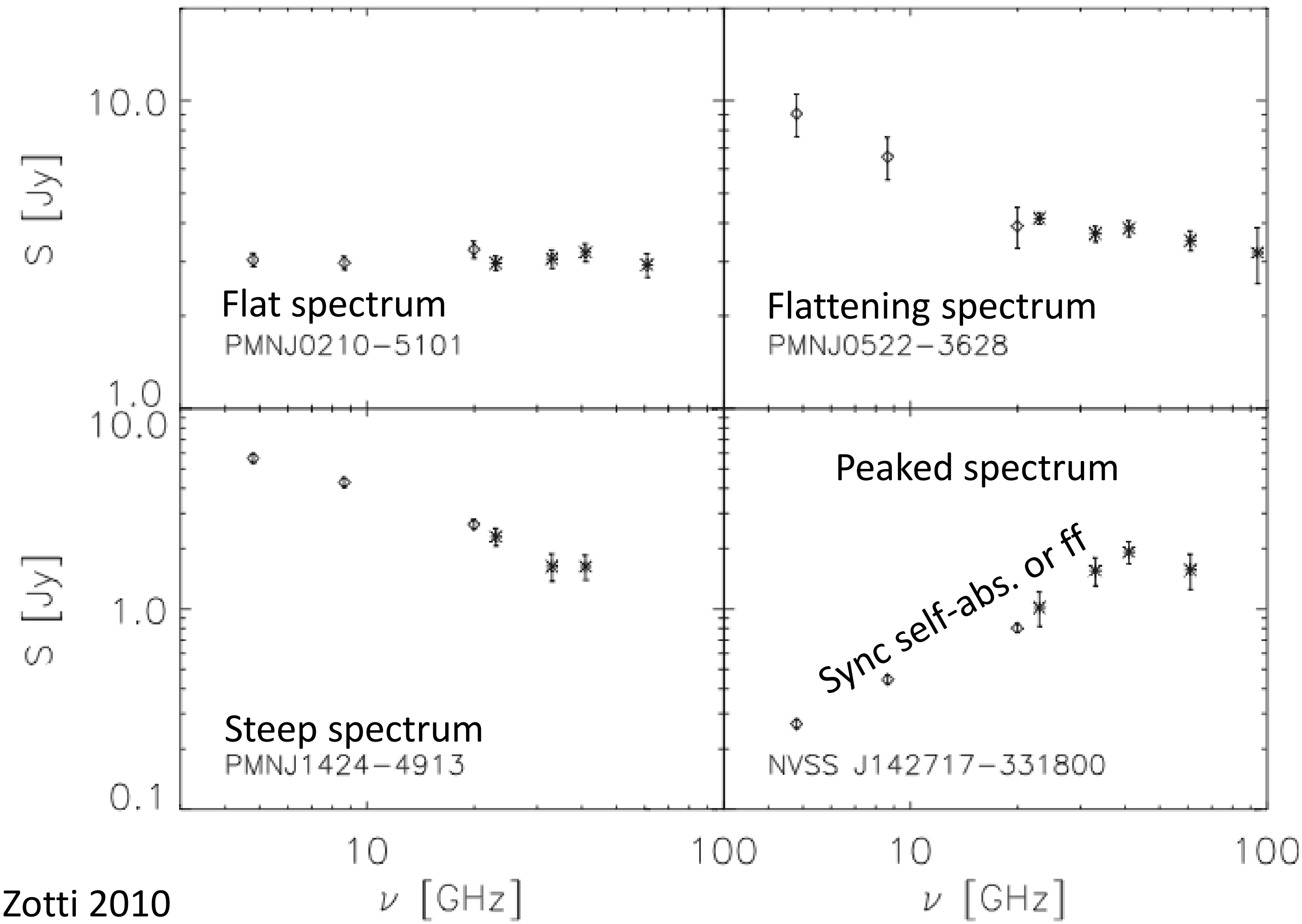
Synchrotron-dominated emission



De Zotti 2010

Generally: falling spectrum, but sources can have various sources of opacity (like self-absorption) which lead produce **complex spectra** over e.g. 10 MHz –THz (see examples in Kellermann & Owen 1988); **variability. Typical selection z~0.7.**

Example radio SEDs



De Zotti 2010

Expectations

Sources dominated by dust or synchrotron emission; split on spectral index (α), where flux

$$S \propto \lambda^{-\alpha}$$

AGN-powered, synchrotron-dominated, falling spectrum (in frequency). Dust emission-dominated, rising spectrum.

Non-Euclidian counts; large volumes and strong evolution.

The South Pole Telescope

References

- 0912.2338: Vieira et al. (*)
- 0912.2341: Crawford et al. (*)
- 0912.4315: Hall et al. (*)
- 0912.4317: Lueker et al.
- 1003.0003: Vanderlinde et al.
- Joaquin Vieira (Apr. 13): the nature of the dusty sources, follow-up, and Herschel.

SPT collaboration

NSF

KICP
Kavli Institute for Cosmological Physics at the University of Chicago

Berkeley
University of California

Case
Case Western Reserve University

The University of Chicago

UC Davis
University of California

Astronomy
University of Illinois at Urbana-Champaign

McGill

Harvard-Smithsonian Center for Astrophysics

Cardiff University
Prifysgol Caerdydd

Colorado
University of Colorado at Boulder

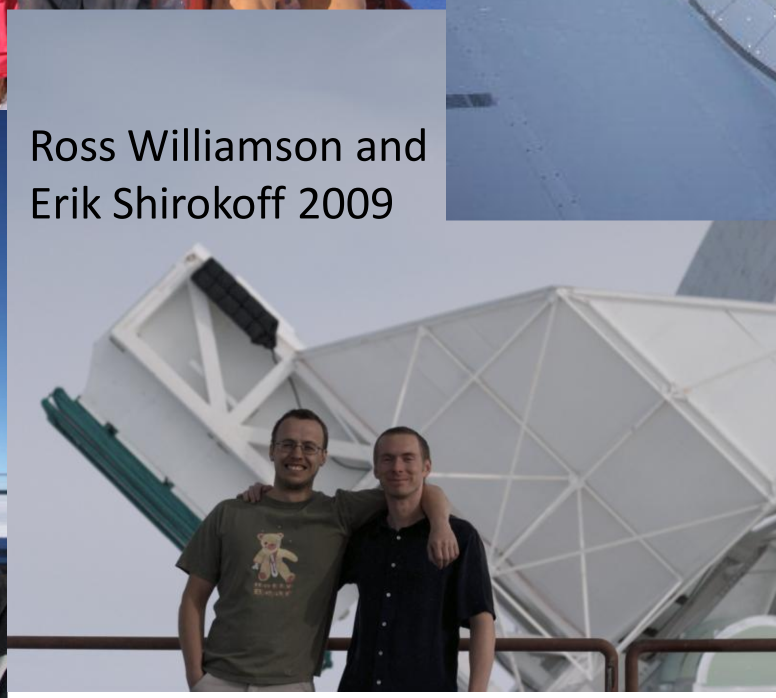
Berkeley Lab

SPT Winter-overs

Steve Padin 2007

Dana Hrubes 2008

Keith Vanderlinde 2008



Ross Williamson and Erik Shirokoff 2009

Zak Staniszewski 2007

Photo: Keith Vanderlinde

10 m telescope: 1’ at 150 GHz (2.0 mm)

Off-axis Gregorian design

20 µm RMS surface accuracy

Scan up to 4 deg/sec (~0.44 deg/sec in 2008)

1 deg^2 FOV, <3” pointing RMS (recovered, not blind)

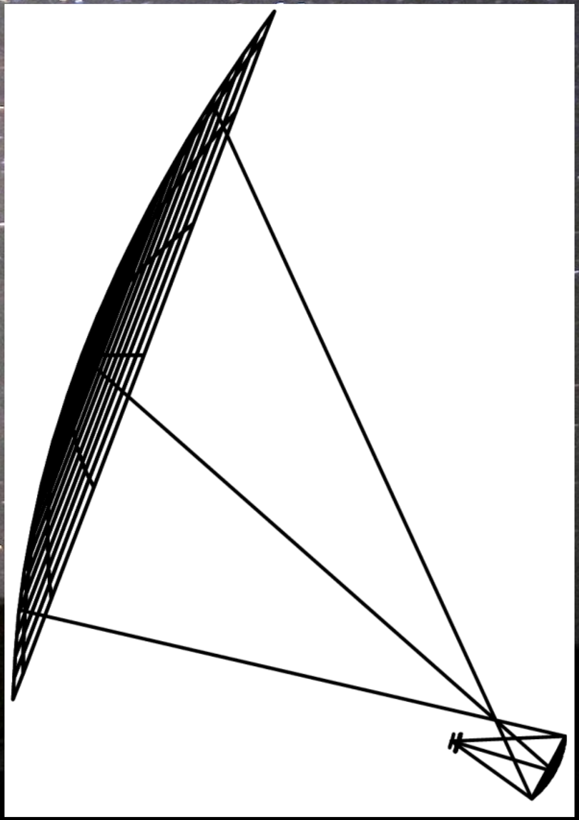
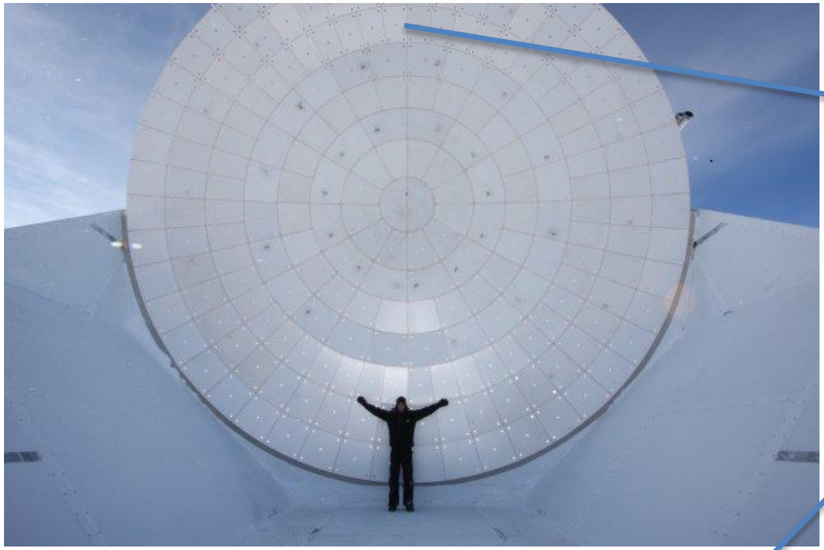
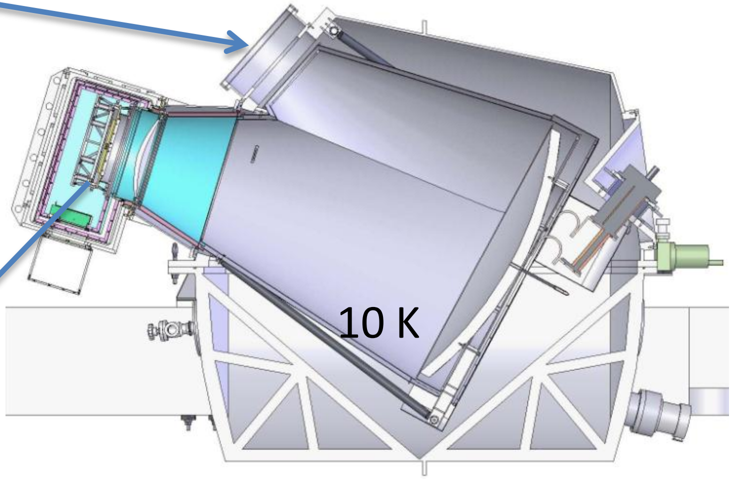
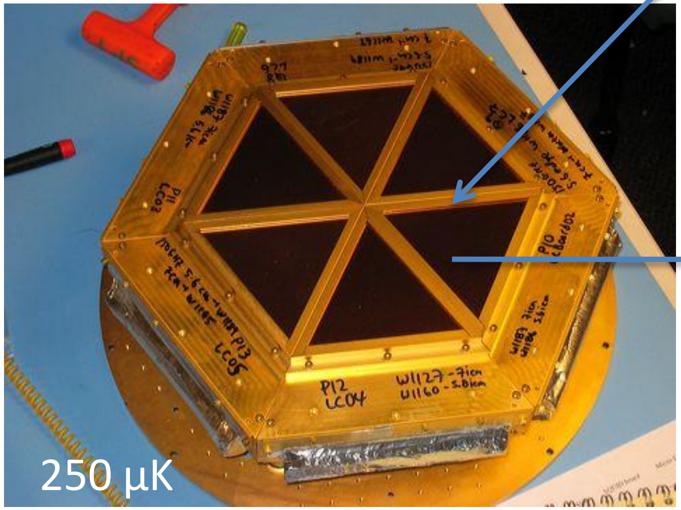


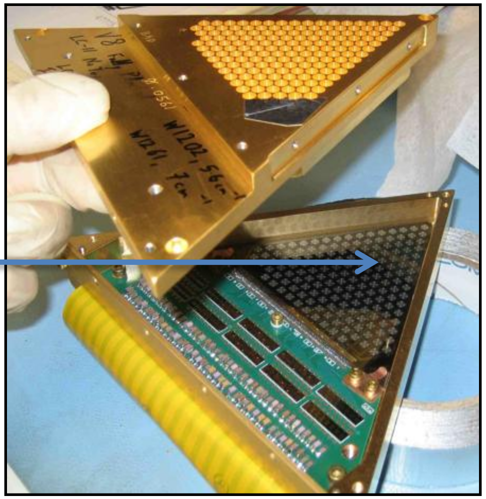
Photo: Keith Vanderlinde

Optics to the receiver



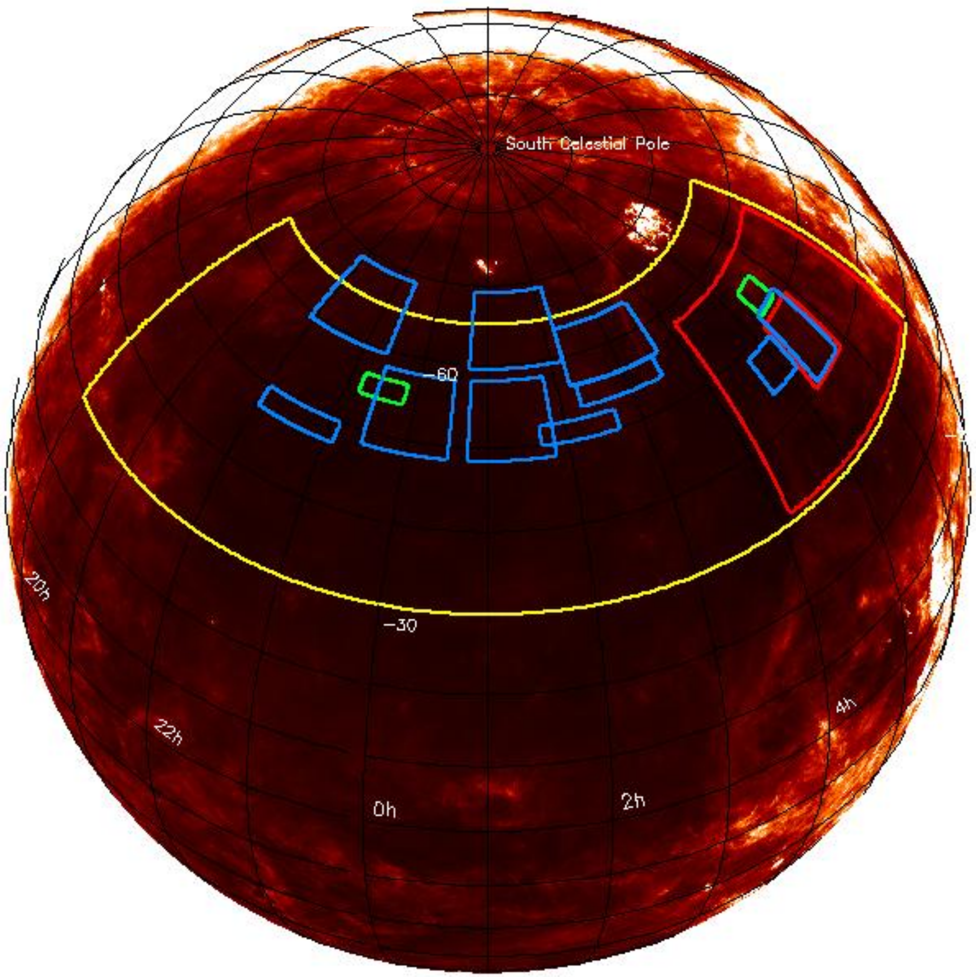






Detectors developed and built at Berkeley! (E. Shirokoff)

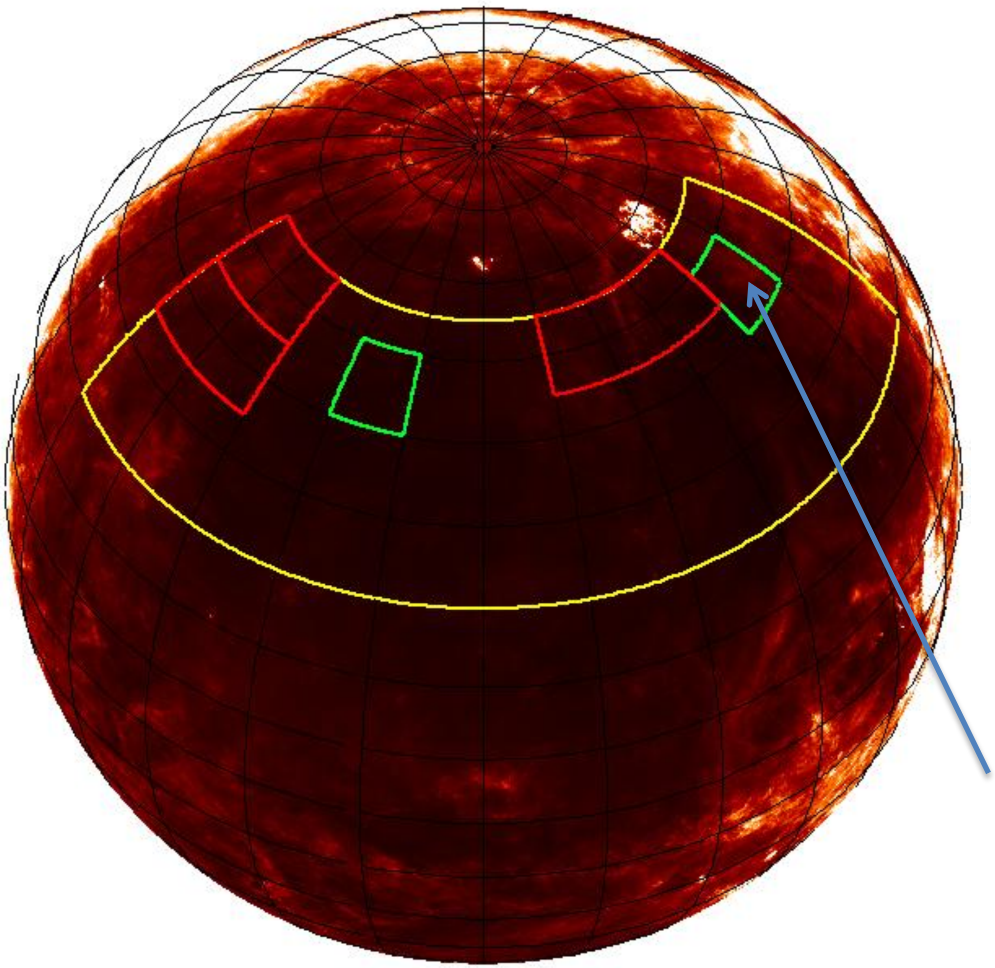
Target region



- Yellow: 4000 deg^2 SPT sane
- Green: 5h30 and 23h BCS
- Red: Boomerang
- Blue: ACBAR fields

- 20 h < RA < 7 h limit from dust
- >30deg. El. from atmosphere

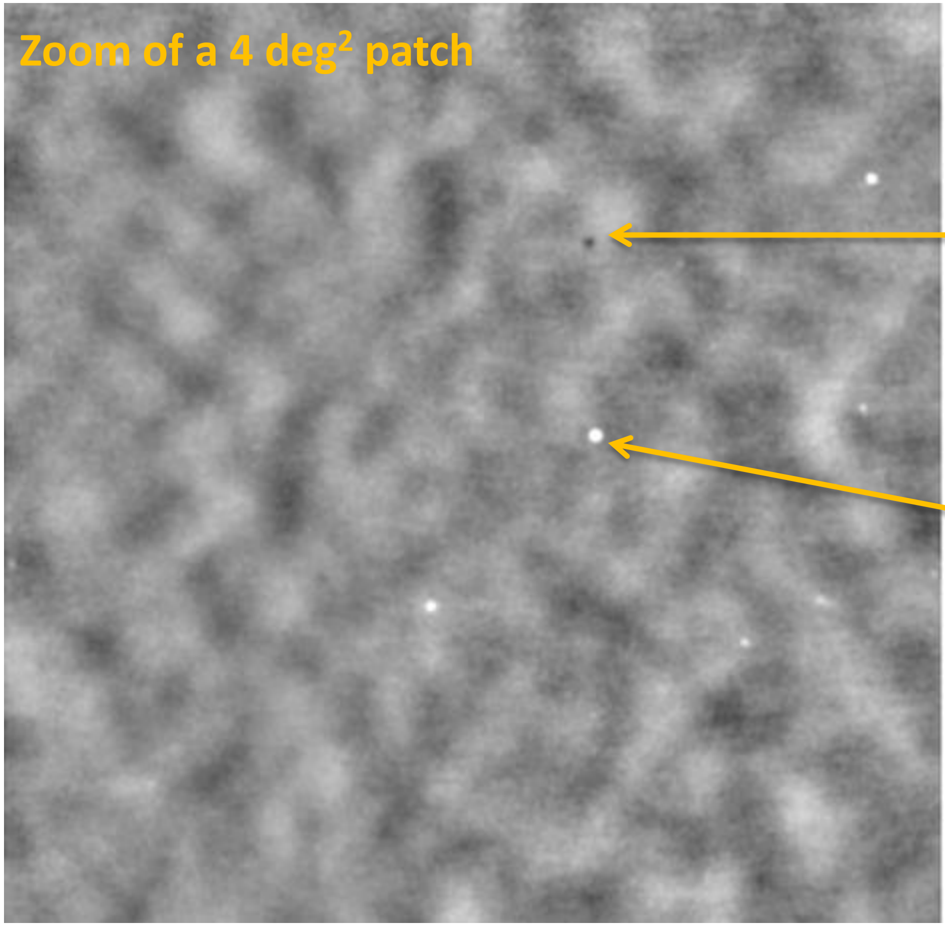
SPT survey regions



- Yellow: 4000 deg^2 SPT sane
- Target: 1500-2000 deg^2
- Green: 5h30 and 23h, 2008
- Red: 2009 fields
- As of Feb., 2010: 800 deg^2

The 2008 5h30 field described here (at -55 dec).
Area = **87 deg^2**
Pointing for follow-up of the brightest sources determined within ~15”.

The 150 GHz (2.0 mm) sky



CMB

(see Lueker et al. 2009: tSZ detection)

SZ

(see Staniszewski et al. 2009 for detections, Plagge et al. 2009 for targeted studies, Vanderlinde et al. 2010 for cosmology, High et al. 2010 for optical)

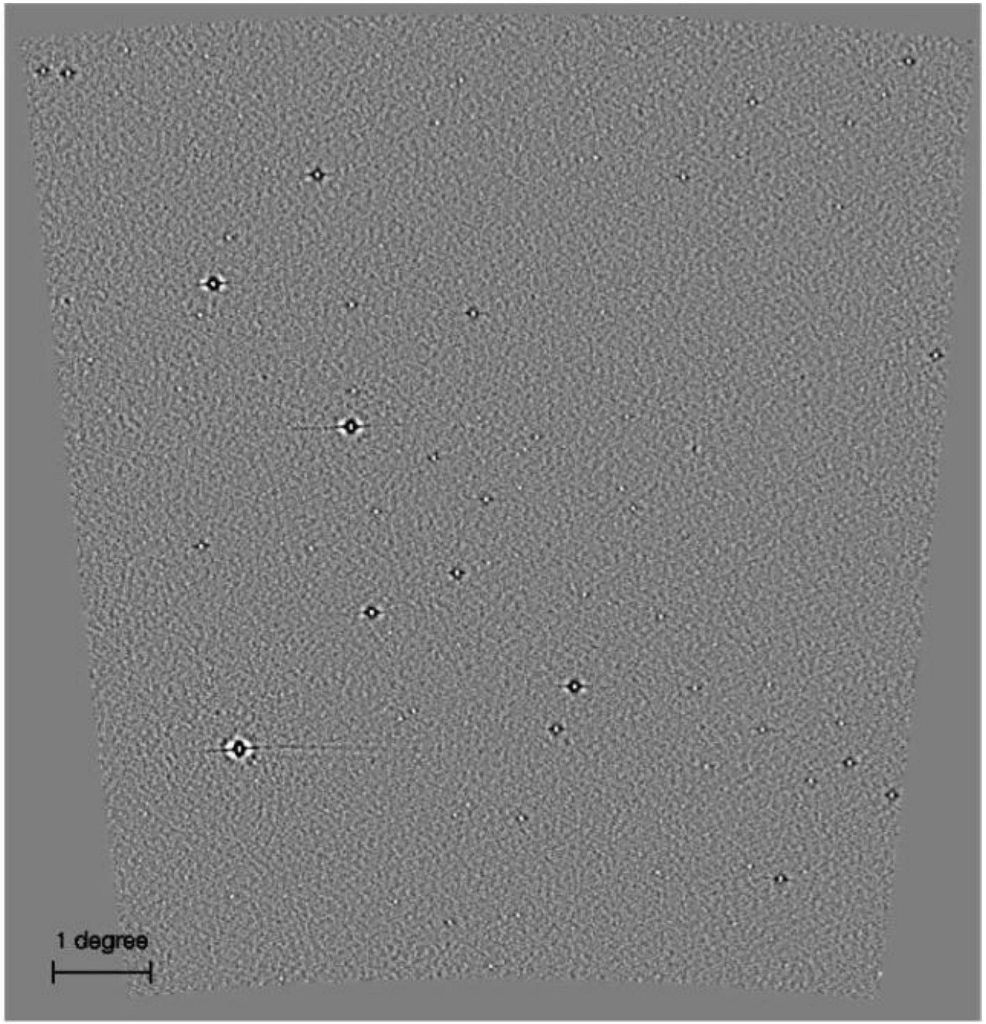
Point sources

(see Vieira et al. 2009, Hall et al. 2009 and Crawford et al. 2009)

~1' resolution: normal galaxy is pointlike for z>0.05 (200 Mpc), "point sources"

Beams measured using Jupiter (large separation), Venus (medium separation), brightest point source in the field (core beam, to include random pointing reconstruction). Calibration from specialized WMAP scans. Average of 286 bolometers (of 394) at 150 GHz and 161 (of 254) at 220 GHz. Noise sources: detector noise, atmospheric turbulence, background point sources (if you call that noise).

The mm-wave sky (filtered for point sources)



2.0 mm = 150 GHz
Black=-6.5 mJy; white=6.5 mJy (5σ)

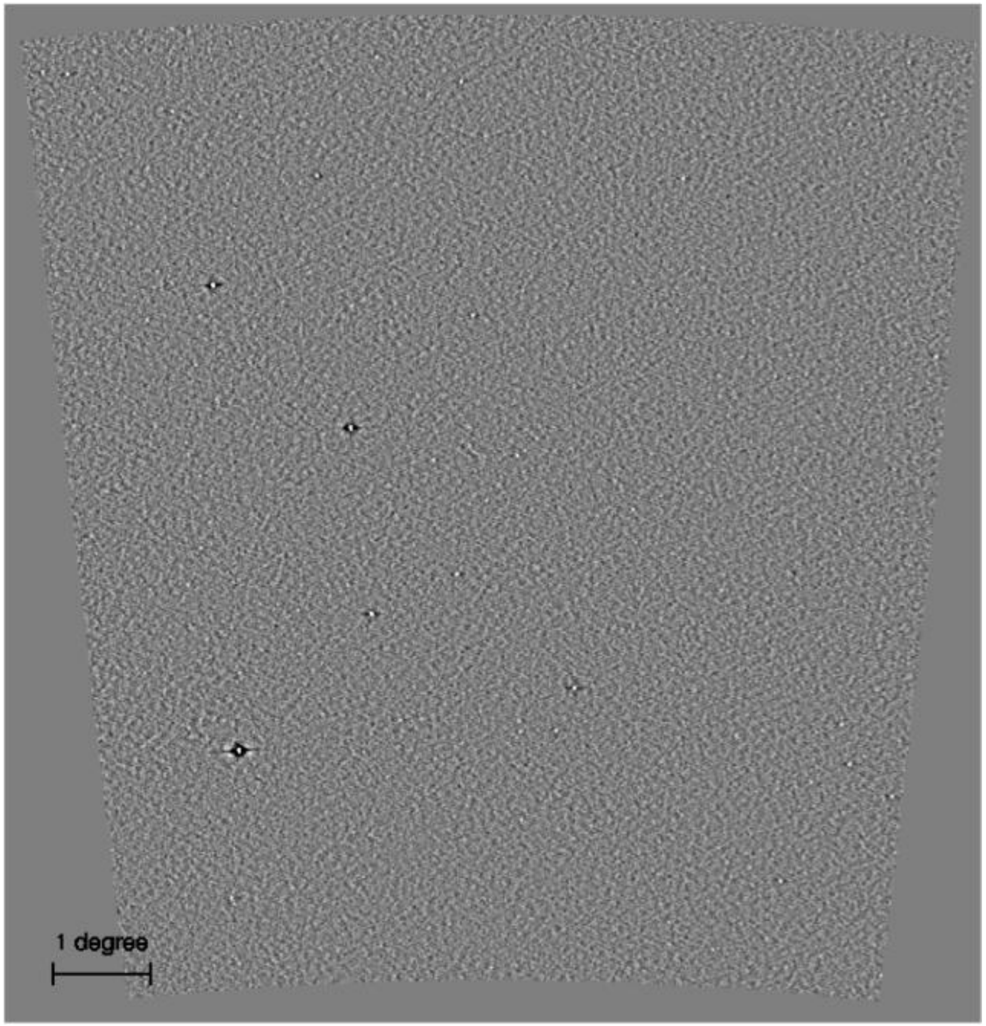
Map depth: 1.3 mJy at 2.0 mm.
Noise: ~18 μK(CMB) arcmin^2

87 deg^2

centered on 5h30m and -55 dec

It is easy to find point sources: apply a matched filter at the instrument resolution.

The mm-wave sky
(filtered for point sources)



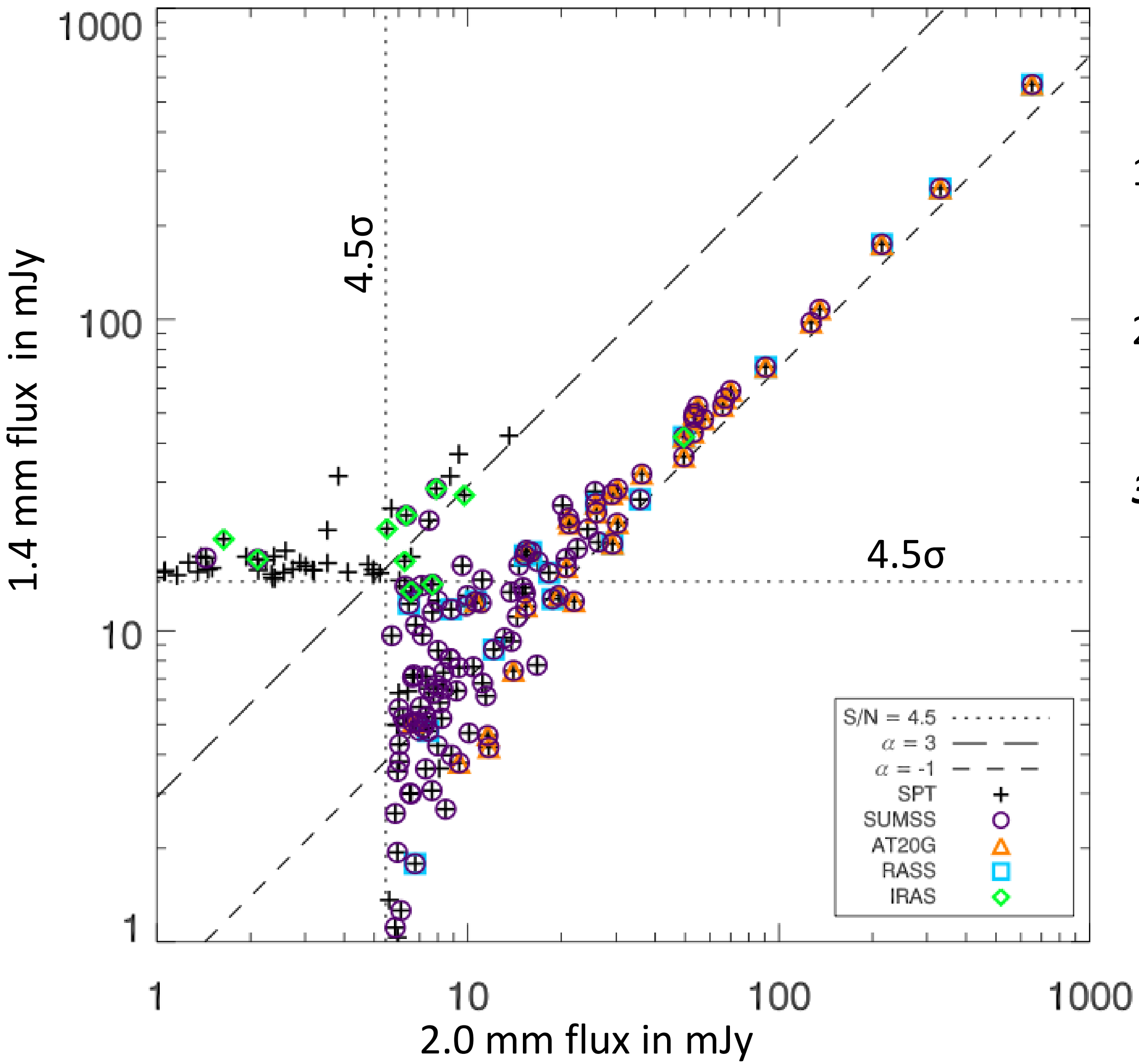
1.4 mm = 220 GHz (SZ null)
Black=-17 mJy; white=17 mJy (5σ)

Map depth: 3.4 mJy at 1.4 mm
Noise: ~40 μK(CMB) arcmin^2

87 deg^2

centered on 5h30m and -55 dec

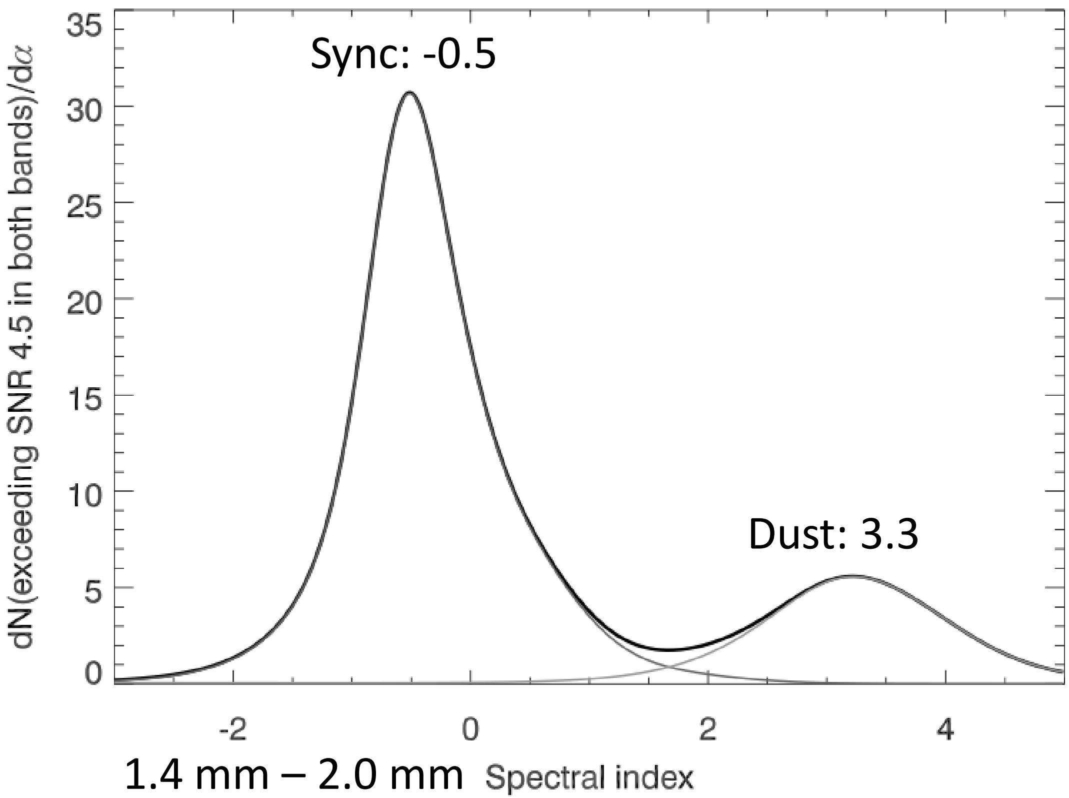
Raw fluxes



1. Synchrotron dominated: appear in existing radio catalogs.
2. Dust dominated sources in the IRAS FSC, at low redshift.
3. ***Previously undetected bright sources consistent with dust emission.***

Most relevant here:
SUMSS = 843 MHz
IRAS = 100 μm

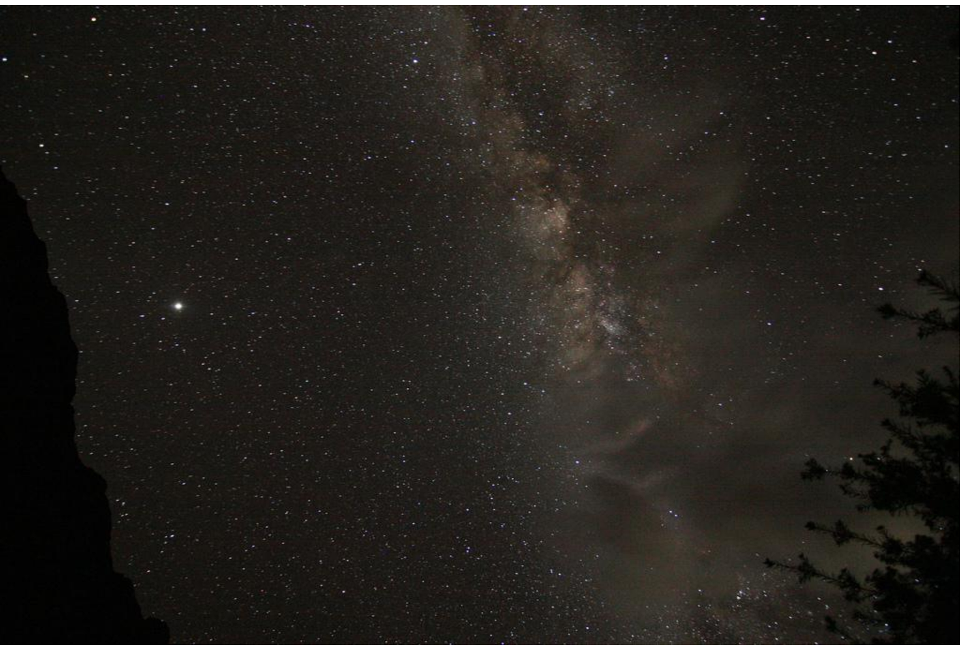
Source families

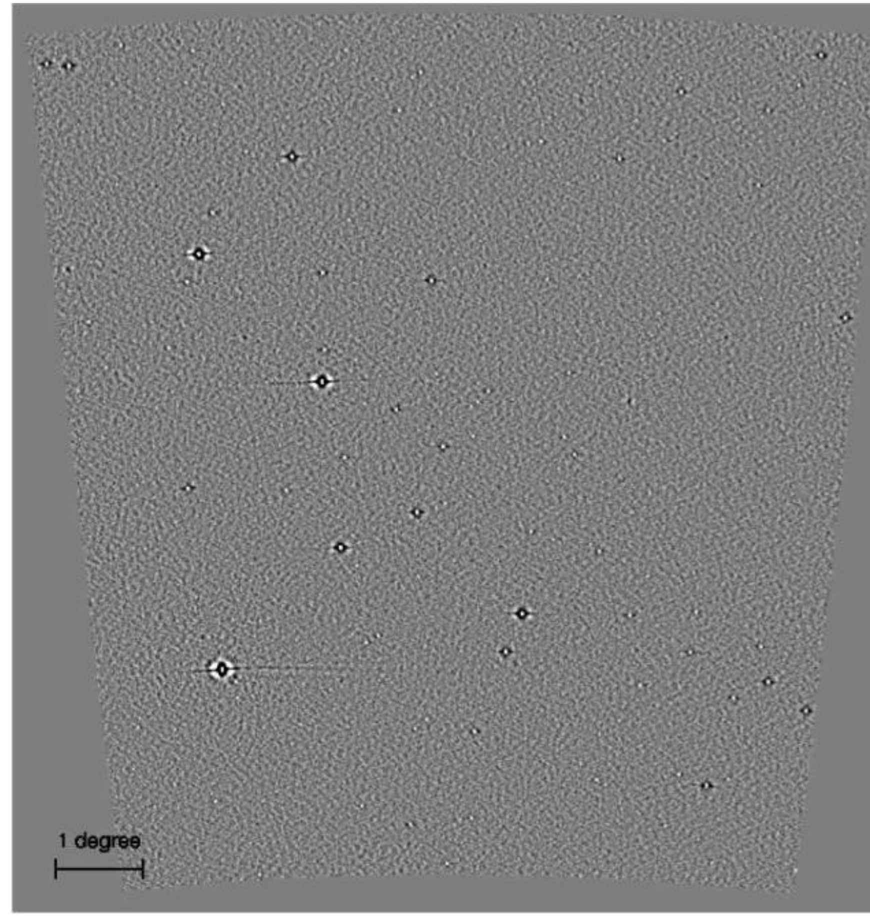


1.4 mm – 2.0 mm

Threshold index between populations: 1.66
For dusty source SED in mm-wave: ν^{β} Planck(T_d), spectral index = emissivity index + 1.38, or emissivity index ~ 1.9, consistent with dust (observationally between 1 and 2)

Measuring the counts





How to count…more rigorously

Completeness and purity

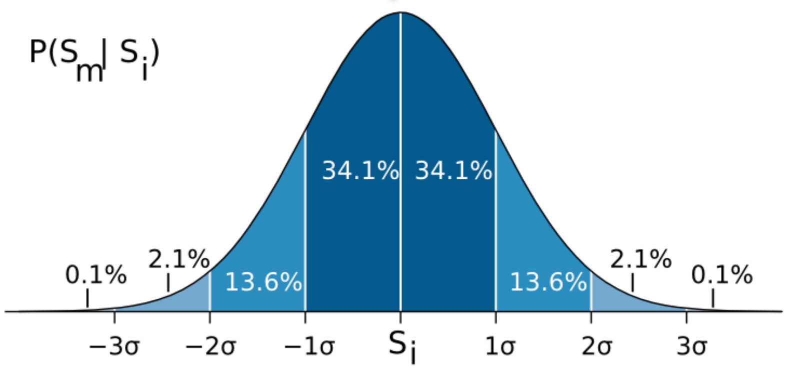
- Map depths are 1.3 mJy (2.0 mm) and 3.4 mJy (1.4 mm), but what real sources are actually detected, which detections are actually false?
- Completeness ~ P(detect source with intrinsic flux S). Place sources at some intrinsic flux into the map are they detected?
- **Complete > 6 mJy at 2.0mm and > 15 mJy at 1.4 mm.**
- Purity ~ P(detection at some SNR is noise). Invert real map, or simulate source-free map; what is the false rate?
- **Pure at SNR > 5 in both bands.**

Counts methods

- Counts covariance: instrument noise, calibration, Poisson, multiband information subject to spectral index uncertainty, fair sample?
- "P(D)" – what is the PDF of underlying counts model parameters which reproduce the PDF of pixel fluxes? (See e.g. Patanchon 2009)
- Bayesian – what is the posterior distribution of intrinsic fluxes *per source*; what counts are implied by this catalog of intrinsic flux PDFs?

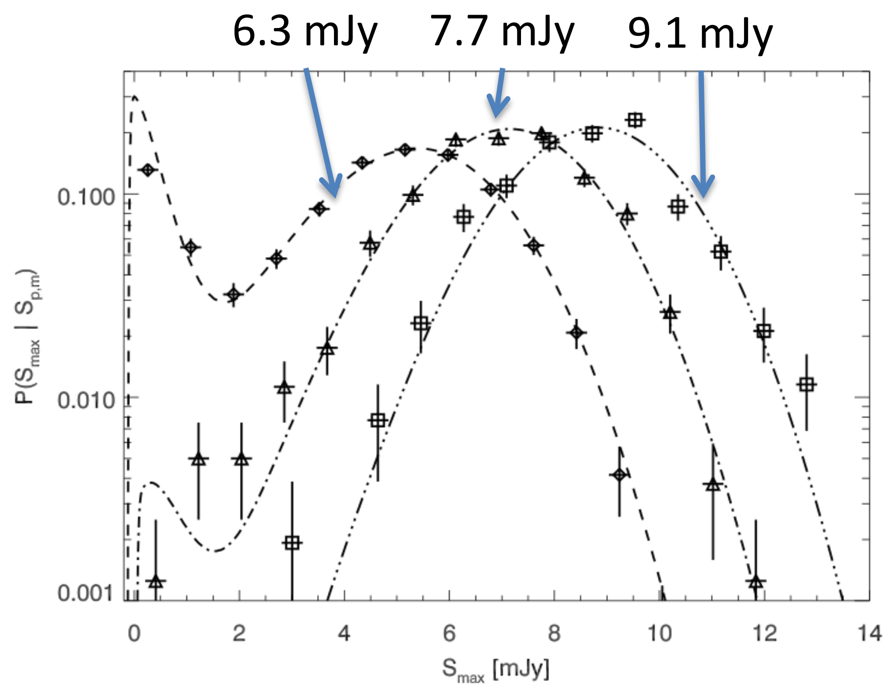
Bayesian flux determination

$$P(S_i|S_m) \propto P(S_m|S_i)P(S_i)$$



Prior: intrinsically dim sources are much more probable than bright sources. Flux of an individual source can be biased high; need to "deboost".

The posterior flux distribution and a Monte Carlo test:

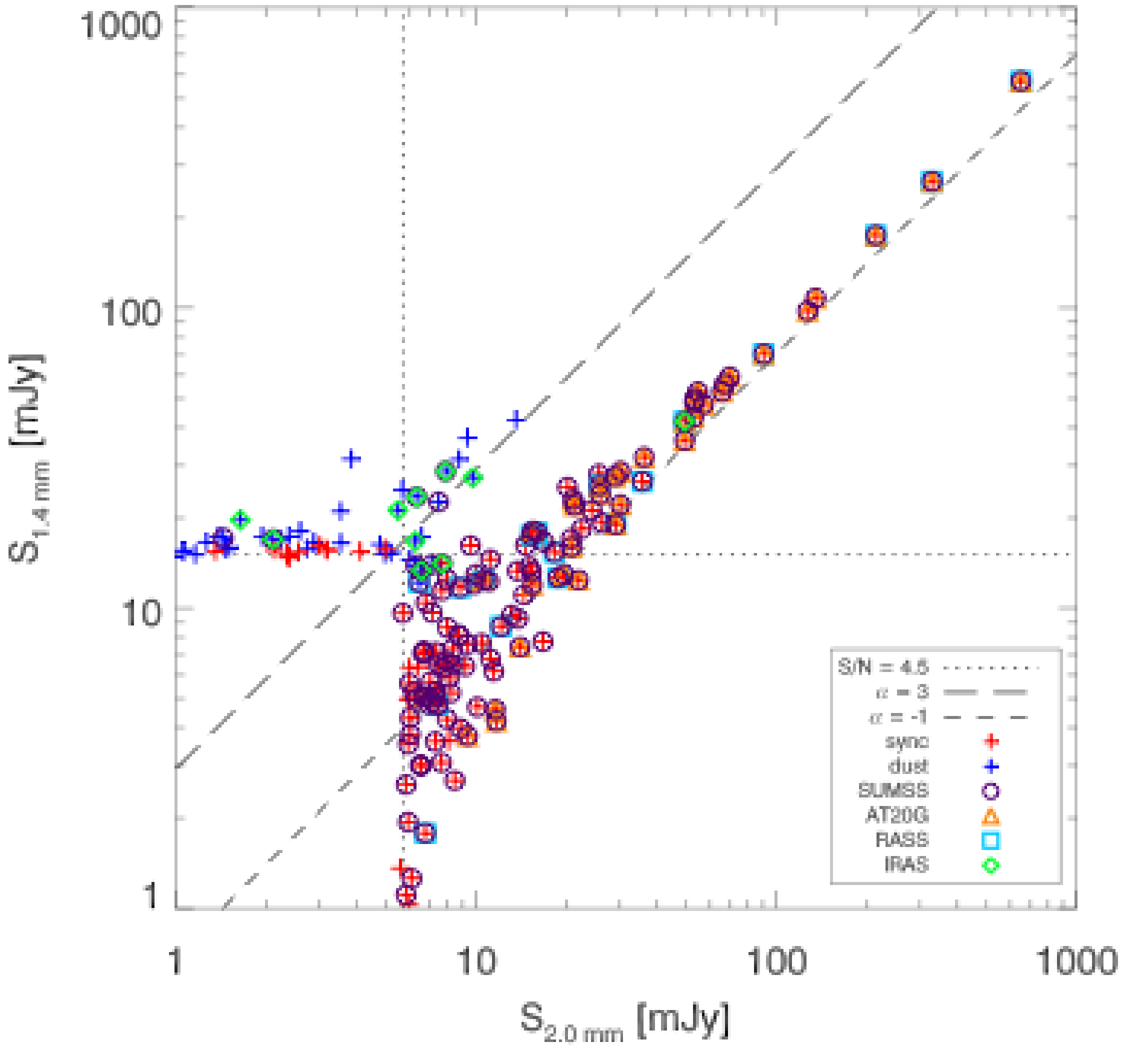


Advertisement

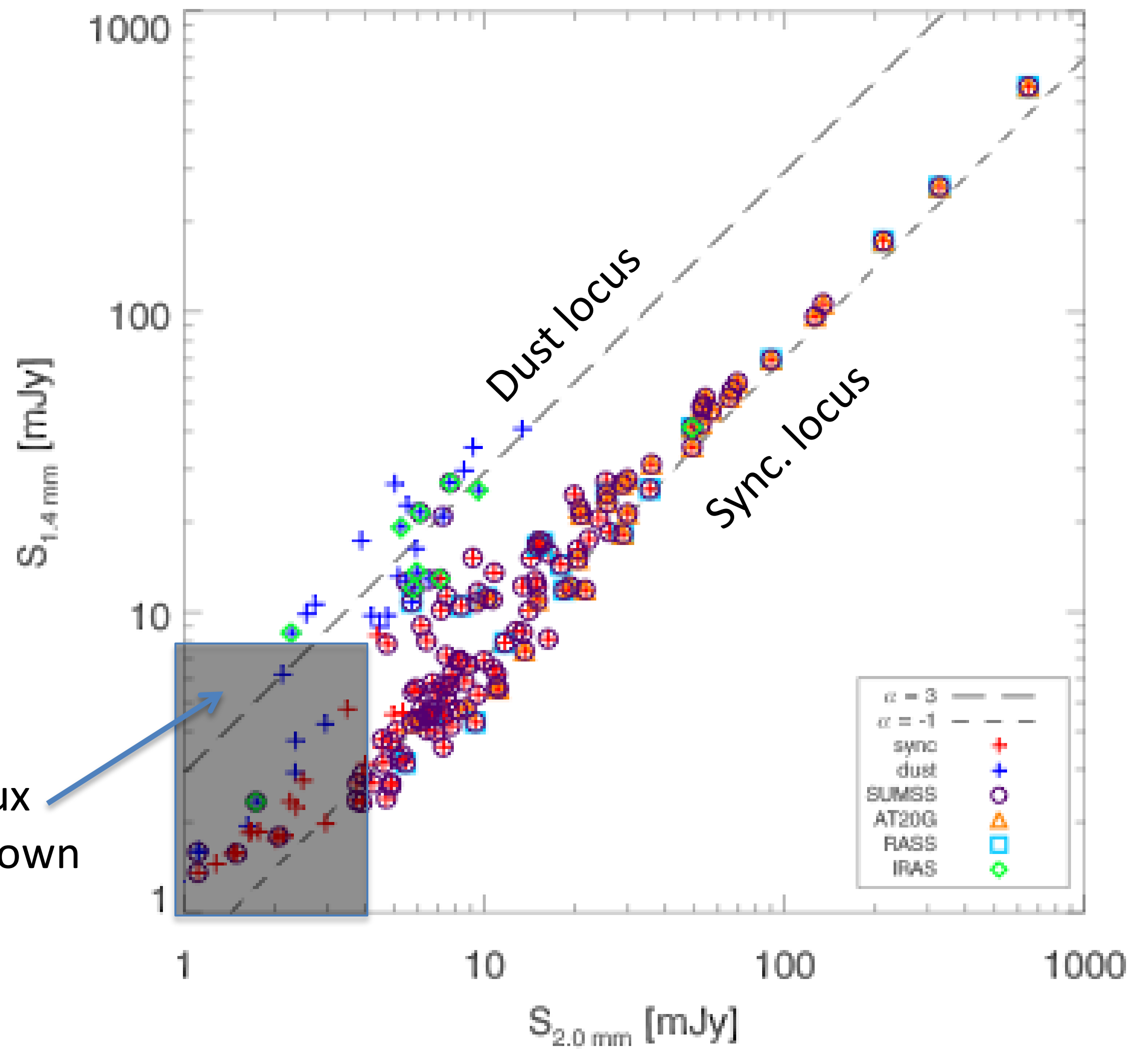
- **Definitional Issue**: is intrinsic flux the flux of all sources in the beam, and so resolution-dependent (traditional), or does it represent the intrinsic flux of any *single* source?
- **Solution**: we calculate the case where intrinsic flux refers to the flux of the brightest source in the resolution element.
- **Multiband issue**: how do strong detections in one band inform weak detections in other bands?
- **Solution**: we calculate the joint flux posterior over bands assuming a broad (physically-motivated) prior on the spectral index distribution.

See Crawford et al. 2009

Deboosting in the flux plane

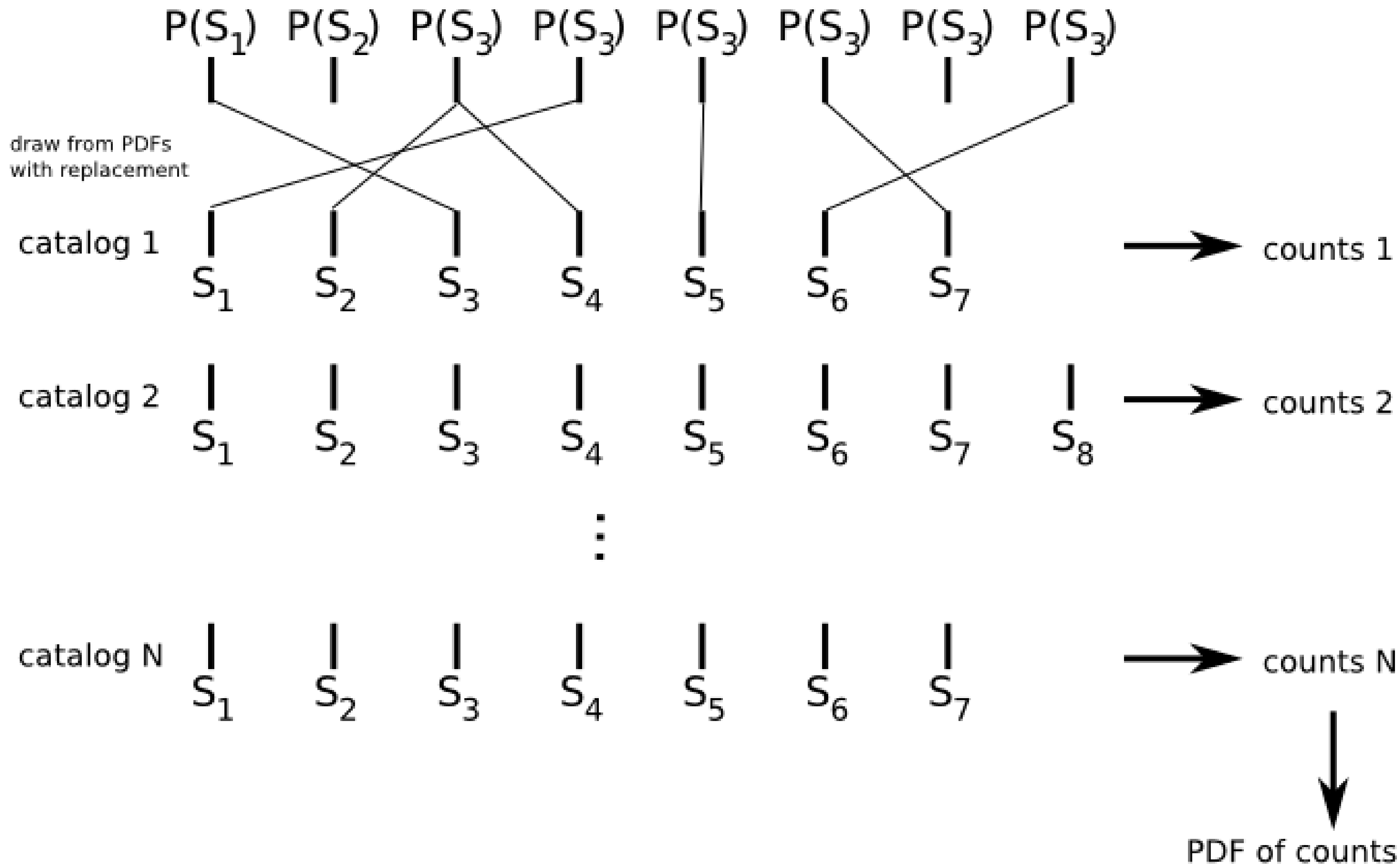


Deboosting in the flux plane

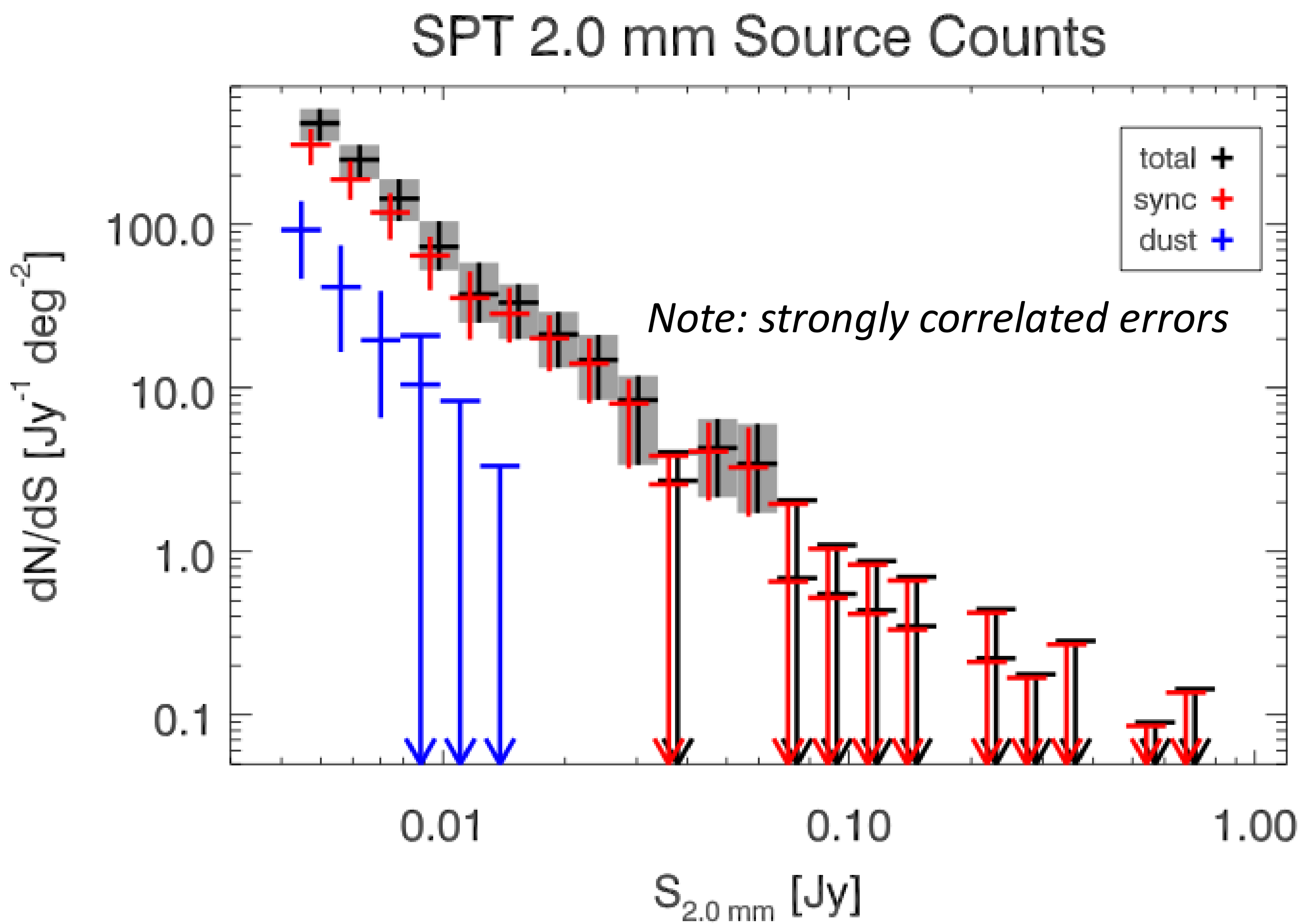


Region of large flux error bars (not shown for simplicity)

The source counts bootstrap

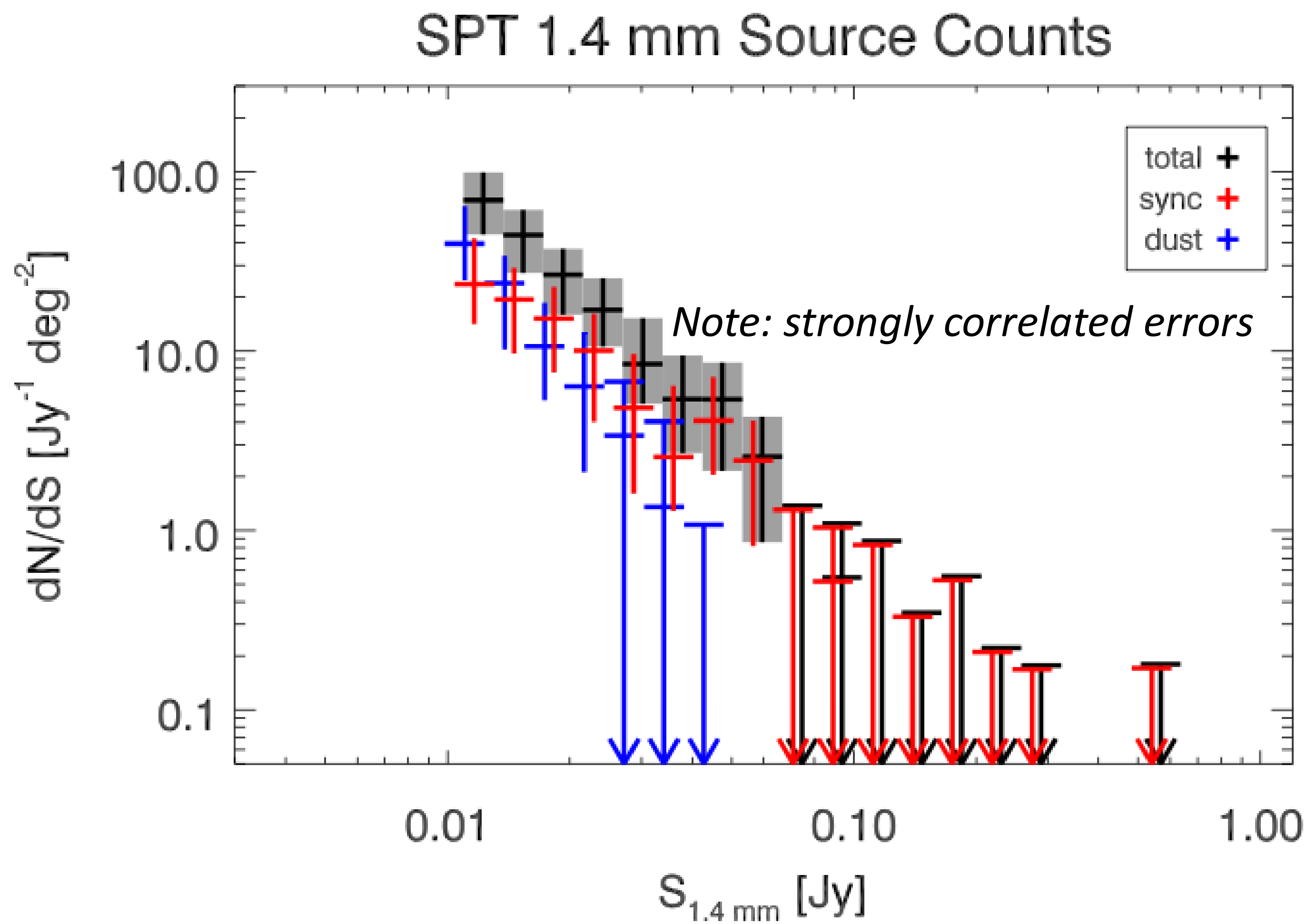


dN/dS by family



Mostly synchrotron-dominated sources.

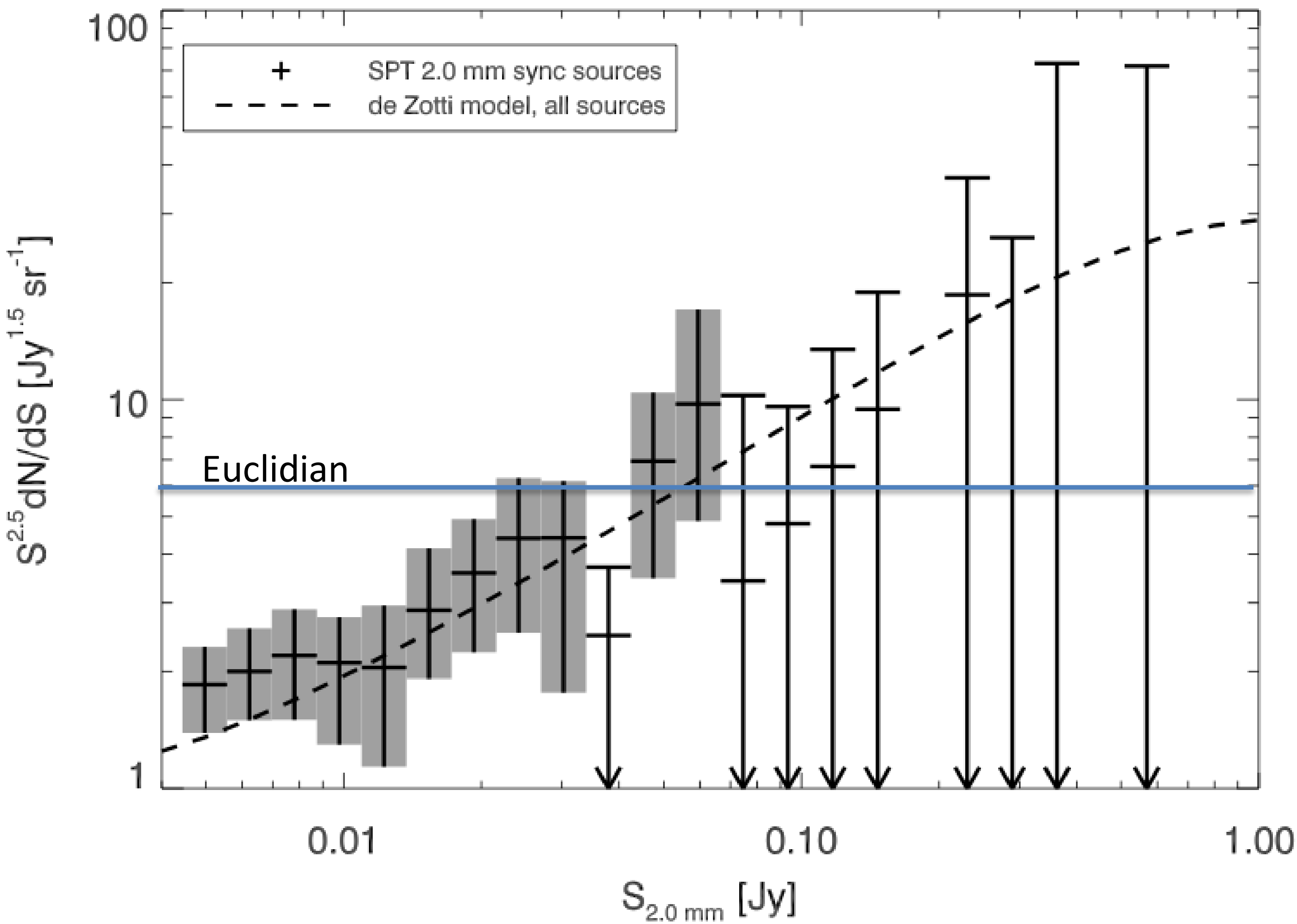
dN/dS by family



Mixture of synchrotron and dust-dominated sources.

Interpreting the counts

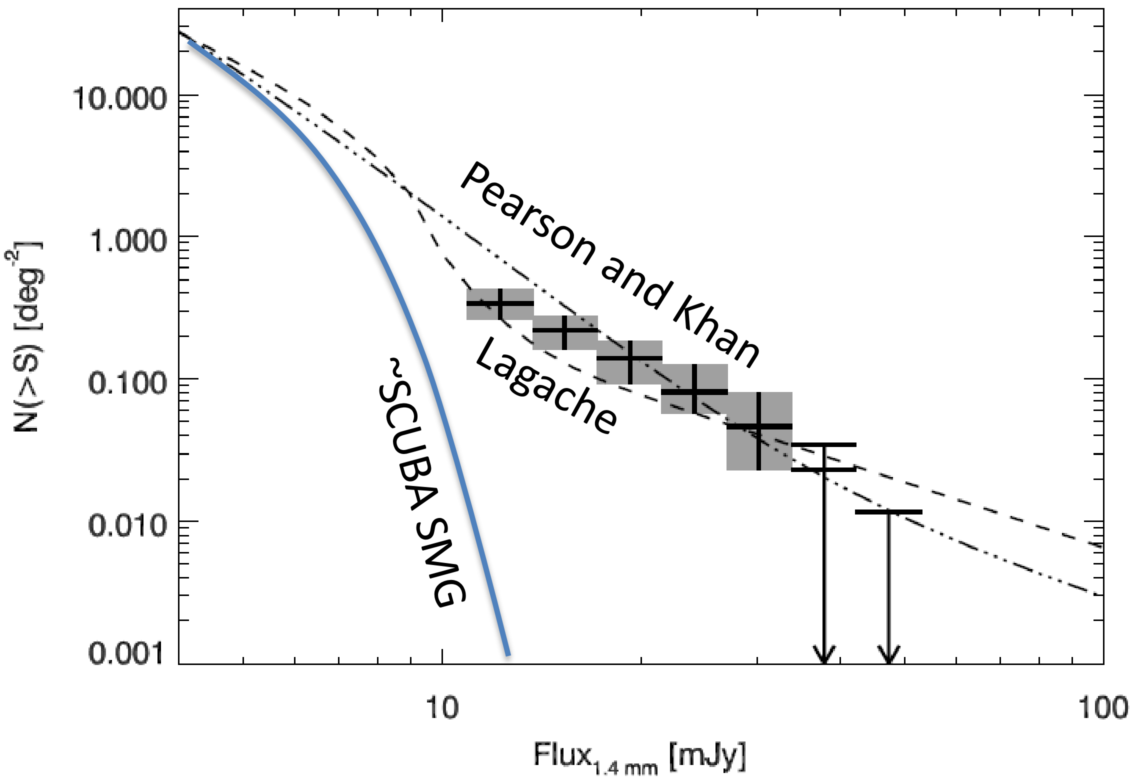
The synchrotron-dominated counts



The synchrotron-dominated population

- High flux, radio wavelengths: negligible contribution from normal and starburst galaxies. AGN dominated. (de Zotti 2010)
- Expectation: at $\lambda<1$ cm at high flux: dominated by flat-spectrum (index > -0.5) sources rather than steep spectrum AGN.
- Relevant for CMB and SZ and not well known: does the spectrum steepen at short wavelengths?
- SPT finding: sync sources have indices~-0.1 from radio bands to mm-wave; index ~-0.5 from 2.0 mm to 1.4 mm; reasonable evidence for steepening.

The dust-dominated counts

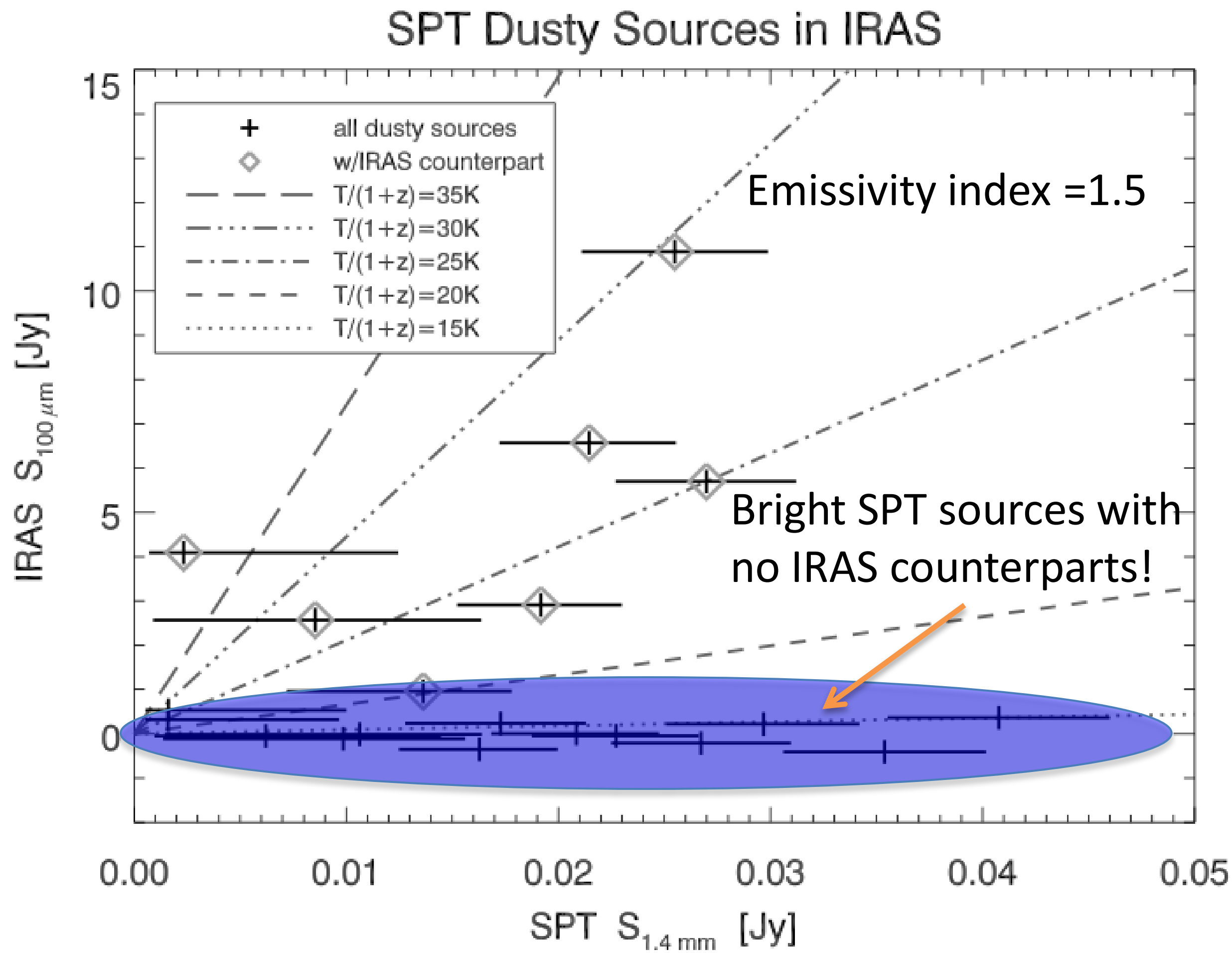


Extrapolating the Schechter functions determined by SCUBA (850 μm) and AzTEC (1.1 mm), one finds << 1 source above 10 mJy in the 87 deg^2 field. Finding: 20 dusty sources with flux > 10 mJy.

One order of magnitude brighter (effective 850 μm flux) and three orders of magntiude more rare than the SCUBA galaxies.

Most of the contribution at high flux in these models is from galaxies that could have been detected by IRAS (a low-z ULIRG population), but we know many of these SPT-detected, bright, dusty sources are not detected by IRAS!

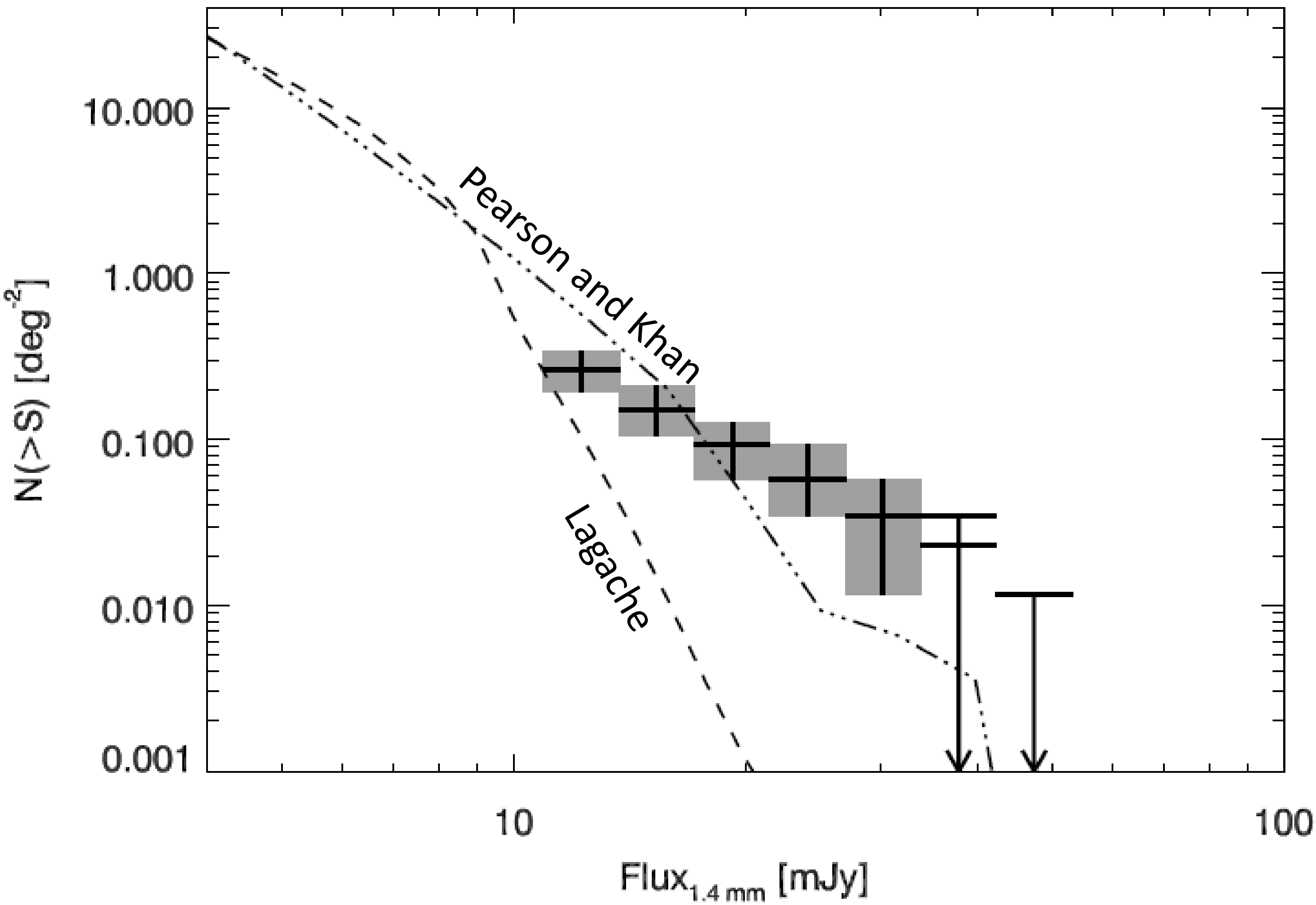
Why: undetected in IRAS?



Graybody spectra depend on T/(1+z), so those are degenerate.
Example: light from T_d =34K sources at z=2.4 is the same as T_d =20K sources at z=1.
IRAS 60 μm and 100 μm Faint Source Catalog are at z < 1.

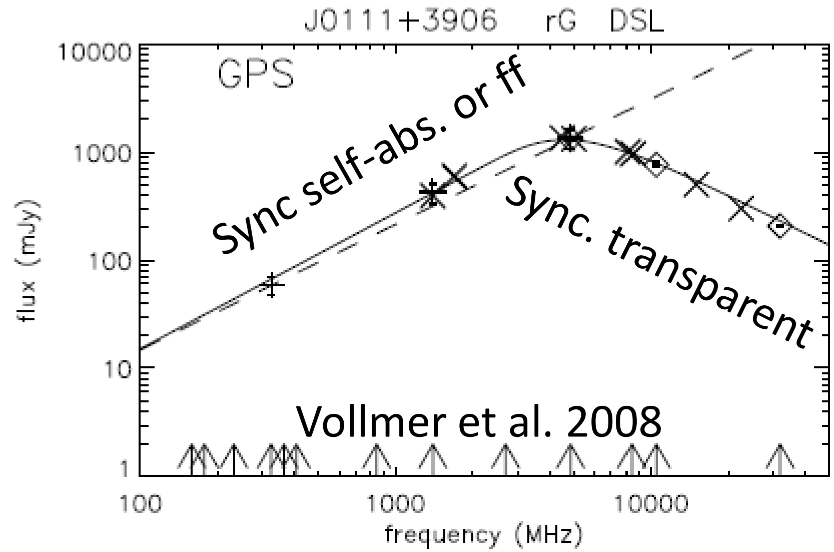
The observed counts suggest a new population of dusty sources

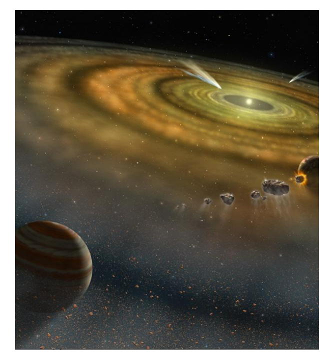
The dust-dominated counts with IRAS galaxies removed



GPS or galactic sources?

- GPS: GHz-peaked source
- Not GPS: tend to peak at lower frequency and have shallower spectral indices (~0.8), which alpha~3.2 rules out confidently.
- Not GPS: no observed radio or x-ray counterparts.
- Not GPS: sources peaking at ~mm wavelengths should be 2.5 orders of magnitude brighter than cm-wave peakers. (Kellermann & Pauliny-Toth 1981)
- Not Galactic: barely resolved by the SMA (few “).
- Galactic: if cold and visible to SPT, then they should have high extinction – from BCS, no detectable extinction.



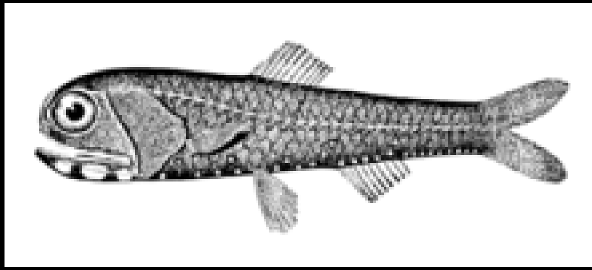


One galactic source we did see: β-Pic. Spectral index 2.7 (±0.6) with 1.4 mm flux 25 pm 4.4 mJy.

Some possibilities

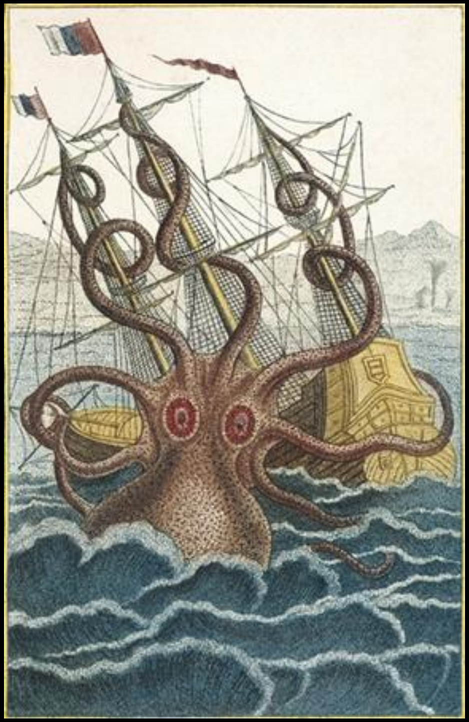
1. Unlensed galaxies with Lsun ~ 10^{13} -10^{14}? (see Devriendt et al. 2009)
2. Low redshift cold dust ~10-15 K?
3. Strongly-lensed high redshift SMG? (See e.g. Negrello et al. 2007, Blain 1996, and Blain et al. 1999)
4. Others?

Creatures of the deep



The lensed high-redshift lanternfish

The anomalously cold jellyfish



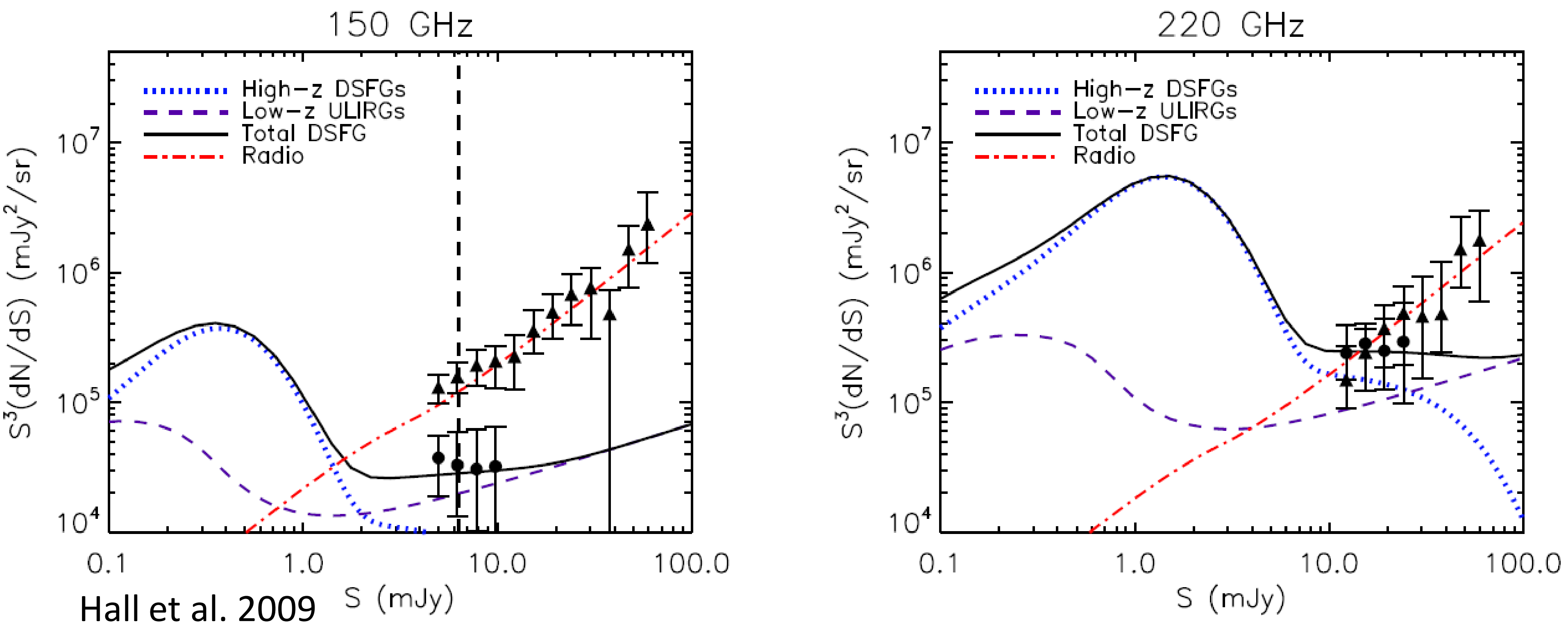
The ultraluminous giant Pacific octopus

Attend Joaquin Vieira's talk on Apr. 13th: the bright dusty source population is likely strongly lensed SMGs.

Relation to CMB studies

Poisson-distributed source anisotropy

$$C_\ell = \int_0^{S_{\rm cut}} S^3 \frac{dN}{dS} d(lnS)$$



Hall et al. 2009

1. While sync sources dominate detections, sub-threshold DSFGs dominate anisotropy.

2. Emission of sub-threshold galaxies is confused: a mean with some rms.

3. Specifically sub-thresold contamination: dN/dS derived above is as not relevant here!

Clustered point source contribution

Angular anisotropy power ~ integral over mean emissive density-squared times a bias factor (squared) times the matter power spectrum.

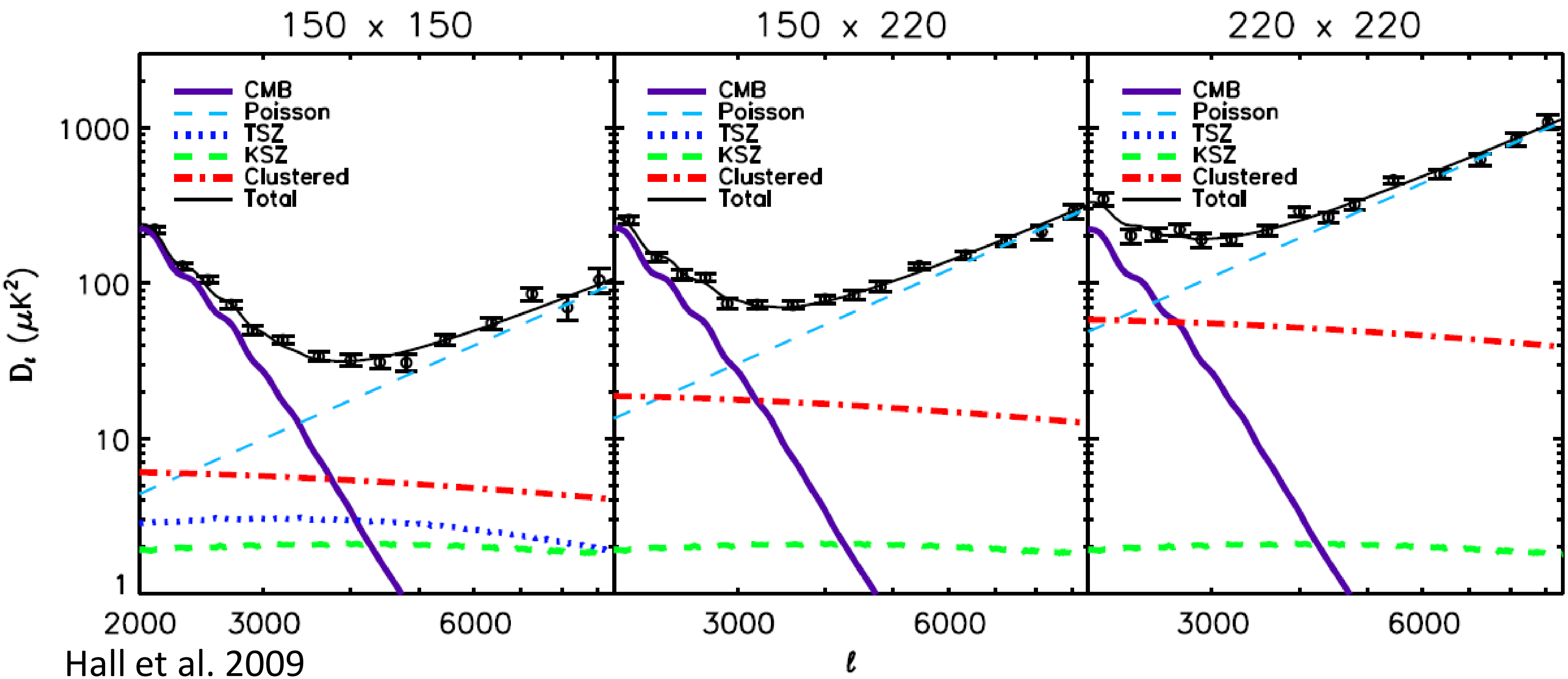
Few arcmin → few cMpc → order unity variance → average over few hundred such regions along a l.o.s. → DSFG signal is ~1% of the mean background power is clustered.

The mean emissive density is:

$$\bar{j}(\nu, z) = (1+z) \int_0^{S_{\rm cut}} dS S \frac{d^2N}{dSdz}$$

Hall et al. 2009

Components of the total anisotropy



Hall et al. 2009

Sources detected to 5σ (6.4 mJy in 2.0 mm) are removed; 150x220, 220x220 ML fit.
Sync-dominated sources contribute ~11% of the Poisson power (rest DSFG).
Half of ptsrc anisotropy at l=3000 at 2.0 mm is clustering.

Findings

- The residual contamination in the 150GHz-220GHz DSFG subtracted maps is dominated by radio (Poisson); residual DSFG clustering and Poisson are negligible. (Lueker et al. 2009, Hall et al. 2009)
- First detection of diffuse SZ; indication that either models overpredict tSZ, or that σ_8 is lower. (Lueker et al. 2009)
- First detection of clustering of dusty star-forming galaxies in the mm-wave. Hall et al. 2009, Previous in other wavebands: Spitzer 150 μm (Lagache et al. 2007) and BLAST (Viero et al. 2009).
- Model consistent with data has 50% of background light at 150 GHz coming from **z>3.2** (assuming T_d = 34 K sources). (Hall et al. 2009)
- tSZ, kSZ, DSFG clustering are degenerate in 150x150, and bound on their sum at l=3000 is 14 μK^2. (Hall et al. 2009)

2008: 1.4 mm and 2.0 mm to 18 μK/arcmin^2 over ~180 deg^2

2009: 1.4 mm, 2.0mm, and 3 mm over 565 deg^2

2010: 1.4 mm, 2.0mm, and 3 mm over 600 deg^2

Three bands: better separate kSZ, DSFGs and tSZ

Positions (arcsec) → redshifts, morphology, photometry, CO studies

Photo: Keith Vanderlinde

An intriguing population of dusty sources (Vieira et al. 2009)
Detection of clustering of dusty sources at high redshift (Hall et al. 2009)
A multi-band Bayesian method (Crawford et al. 2009)
SPT primary science is well underway: diffuse SZ (Lueker et al. 2009), SZ clusters and cosmology (Vanderlinde et al. 2010)

Photo: Keith Vanderlinde