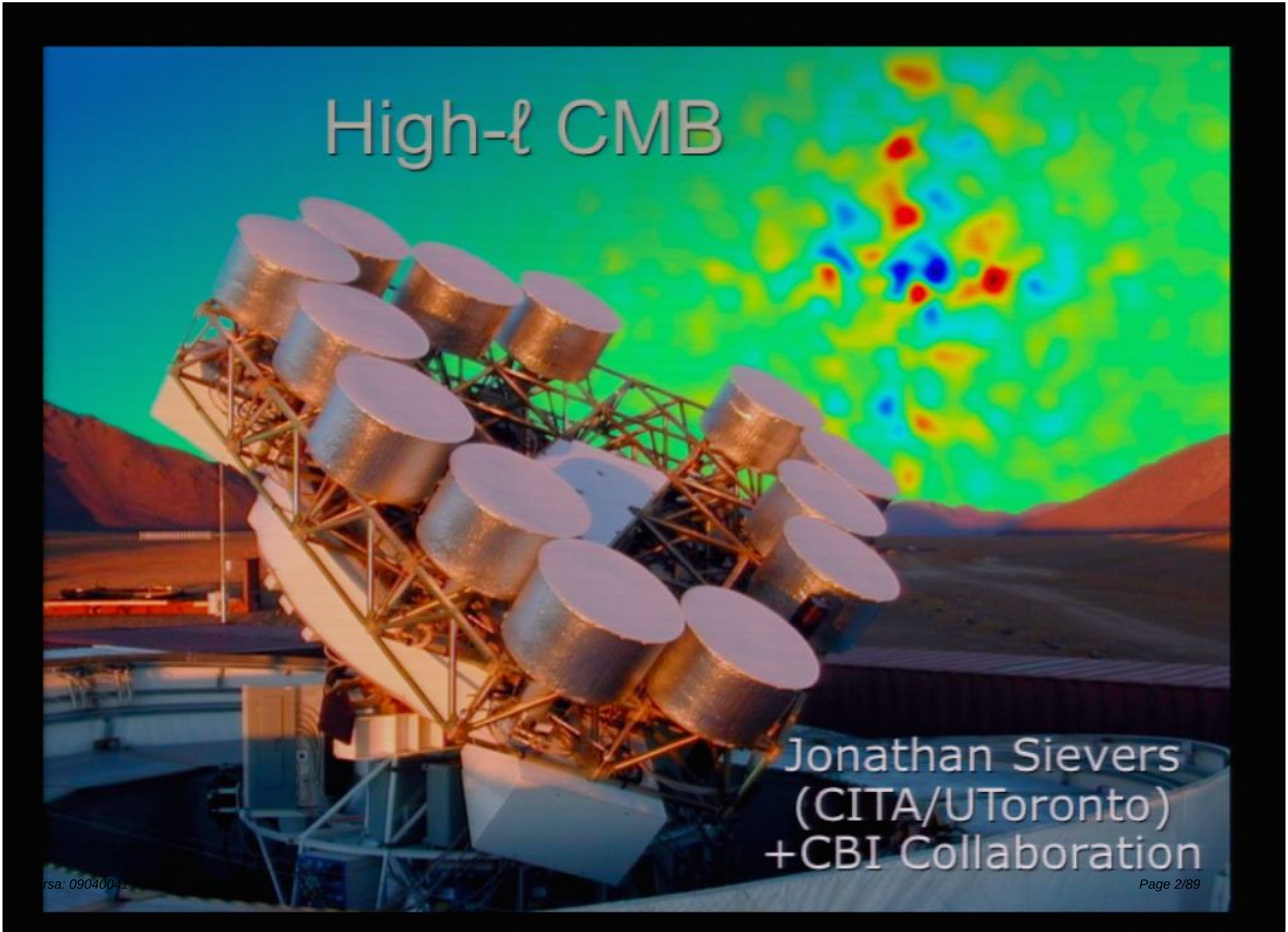
Title: Cosmic Background Imager

Date: Apr 28, 2009 11:00 AM

URL: http://pirsa.org/09040041

Abstract:


High-ℓ CMB
Jonathan Sievers
(CITA/UToronto)
+CBI Collaboration

submitted to ApJ

Cosmological Results from Five Years of 30 GHz CMB Intensity Measurements with the Cosmic Background Imager

J.L. Sievers[1], B.S. Mason[2], L. Weintraub[3], C. Achermann[4], P. Altamirano[4], J.R. Bond[1], L. Bronfman[4], R. Bustos[13], C. Contaldi[7], C. Dickinson[3,8], M.E. Jones[9], J. May[4], S.T. Myers[11], N. Oyarce[4], S. Padin[6], T.J. Pearson[3], M. Pospieszalski[12], A.C.S. Readhead[3], R. Reeves[13], M. C. Shepherd[3], A. C. Taylor[9], S. Torres[13]

ABSTRACT

We present final results on the angular power spectrum of total intensity anisotropies in the Microwave Background from the Cosmic Background Imager (CBI). Our analysis includes all primordial anisotropy data collected between January 2000 and April 2005, and benefits significantly from an improved maximum likelihood analysis pipeline. It also includes results from a 30 GHz foreground survey conducted with the Green Bank Telescope (GBT) which places significant constraints on the possible contamination due to foreground point

In room: JLS, JRB, BSM, ACT, JRA, MJ, STM
(unless they slept in...)

CMB @ High-ℓ

- Past ℓ~2000 (depending on frequency), power spectrum dominated by secondaries.
- Secondaries very non-Gaussian. tSZ from clusters of galaxies, kSZ, radio point sources, IR galaxies...
- Getting to CMB truth requires understanding these secondaries.
- Important for primordial NG, since more information at high-ℓ if you can get there.

3

CMB @ High-ℓ contd.

- Have been hints that power is higher than expected (CBI, ACBAR, BIMA). Two fundamental questions - what does the data say? What *should* we expect?
- There has been much development recently. Last two months- CBI, SZA, QUaD. Last night APEX.
- Theory developing rapidly - see this conference!

Outline

- Go over current high-ℓ data. Focus on CBI (what speaker knows best) combine two datasets. Also point sources and spectrum.
- Other high-ℓ data currently existing. ACBAR, BIMA, QUaD, SZA.
- Sunyaev-Zeldovich models - theory and sims.
- Future. Planck, ACT, SPT...

Even so, still a popular place...

Most shocking thing I've ever seen at the site.

The CBI Adventure…

CBI located at 5080 meters in Atacama desert, Chile at future ALMA site

Area is used by NASA as a proxy for Mars for testing/developing equipment.

Land mines along border w/ Bolivia (Hiking? Um, no.)

Atmosphere 55% of sea level.

Steve Padin wearing the cannular oxygen system

The Cosmic Background Imager

- 13 90-cm Cassegrain antennas
  - 78 baselines
- 6-meter platform
  - Baselines 1m – 5.51m
- 10 1 GHz channels 26-36 GHz
  - HEMT amplifiers (NRAO)
  - Cryogenic 6K, Tsys ~25 K
- Single polarization (R or L)
  - Polarizers from U. Chicago
- Analog correlators
  - 780 complex correlators
- Field-of-view 44 arcmin
  - Image noise 4 mJy/bm 900s
- Resolution 4.5 – 10 arcmin

The CBI Adventure…

CBI located at 5080 meters in Atacama desert, Chile at future ALMA site

Area is used by NASA as a proxy for Mars for testing/developing equipment.

Land mines along border w/ Bolivia
(Hiking? Um, no.)

Atmosphere 55% of sea level.

Steve Padin wearing the cannular oxygen system

The CBI Adventure…

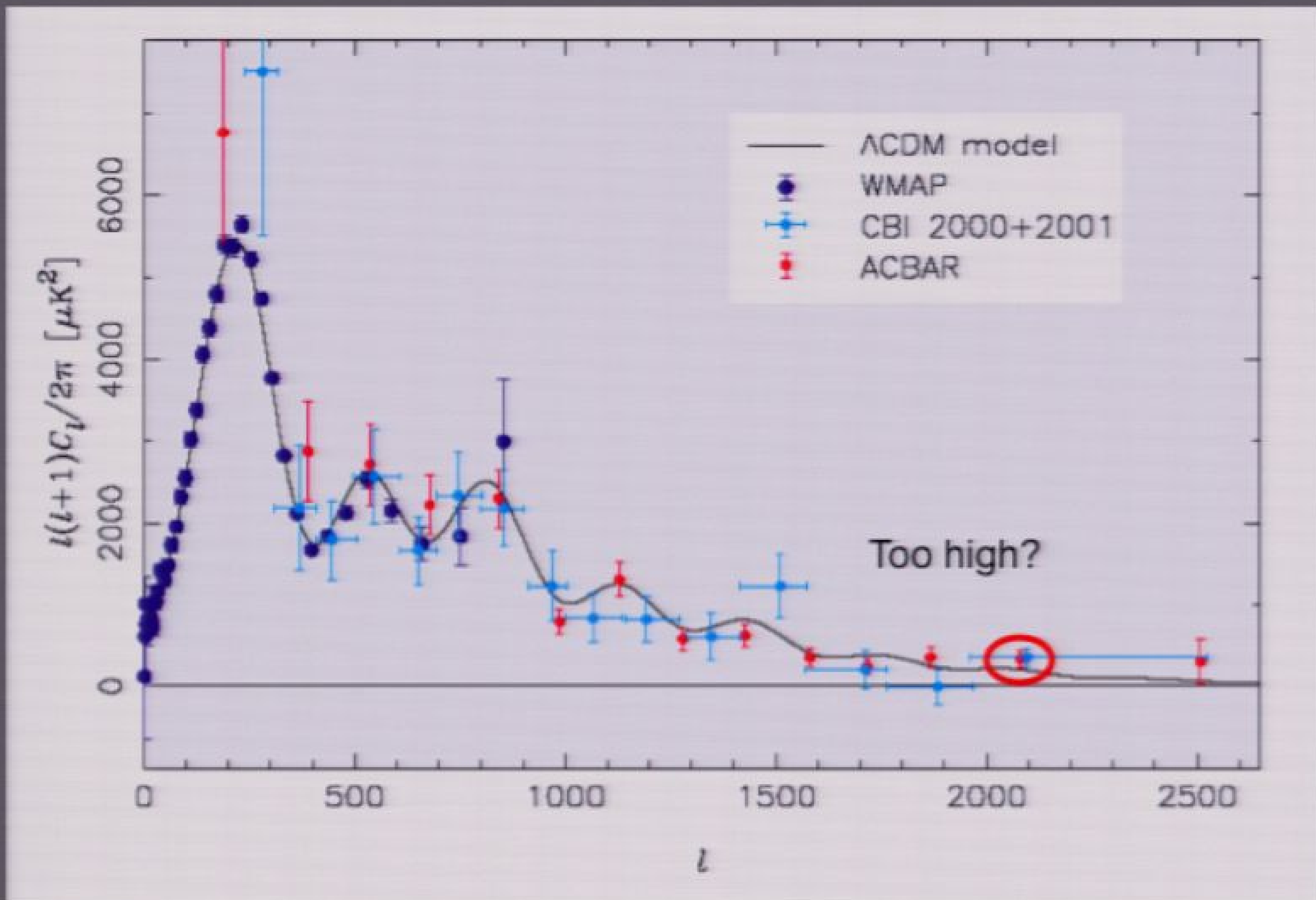
- Volcan Lascar (~30 km away) erupts in 2001

The CBI Adventure…

- Volcan Lascar (~30 km away) erupts in 2001

And even the odd flamingo…

CMB in 2004, Readhead, et al.

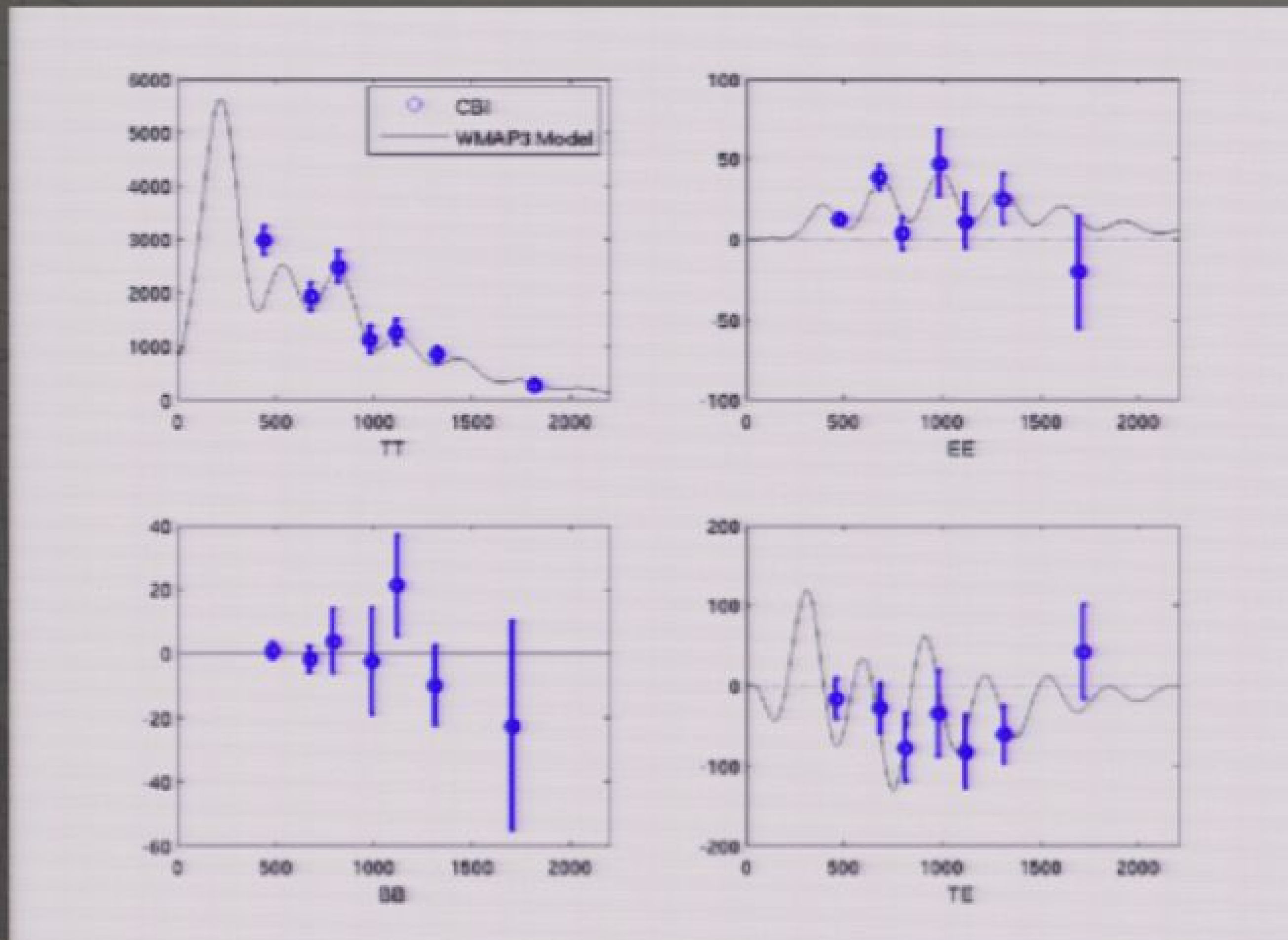


(One of two CBI datasets to be combined.)

Very Clean Exp't

CBI polarization. Required virtually no filtering/ cleaning. Note axes on EE/BB 50-100x smaller than TT. Black curves *prediction* from WMAP TT.

Amplitude vs. (all) TT prediction:
TT=1.12+/-0.05
EE=1.02+/-0.14
TE=1.02+/-0.24
BB=0.22+/-1.55
(BB=μK)



JLS et al.

Combining CBI Datasets

Have 2 datasets. Partly overlap, observing strategy very different.

Make matrix that maps CMB sky (Fourier plane version thereof) to data for each dataset. (code written by Steve Myers)

Glue matrices together, then outer product gives correlated expected signal.

Feed signal into maximum likelihood pipeline, get optimal spectrum.

Run on CITA Sunnyvale beowulf cluster. Takes 2 hrs to do signals, 20 min to then get spectrum. (1600 Core-2 cores, 800 GB RAM, cost 400K)

(pipeline also being used for 21cm reionization)

Main Challenge at 30 GHz: Discrete Source Foreground

- ~5000 NVSS sources in CBI fields
- Detected at 30 GHz (OVRO 40m/CBI)

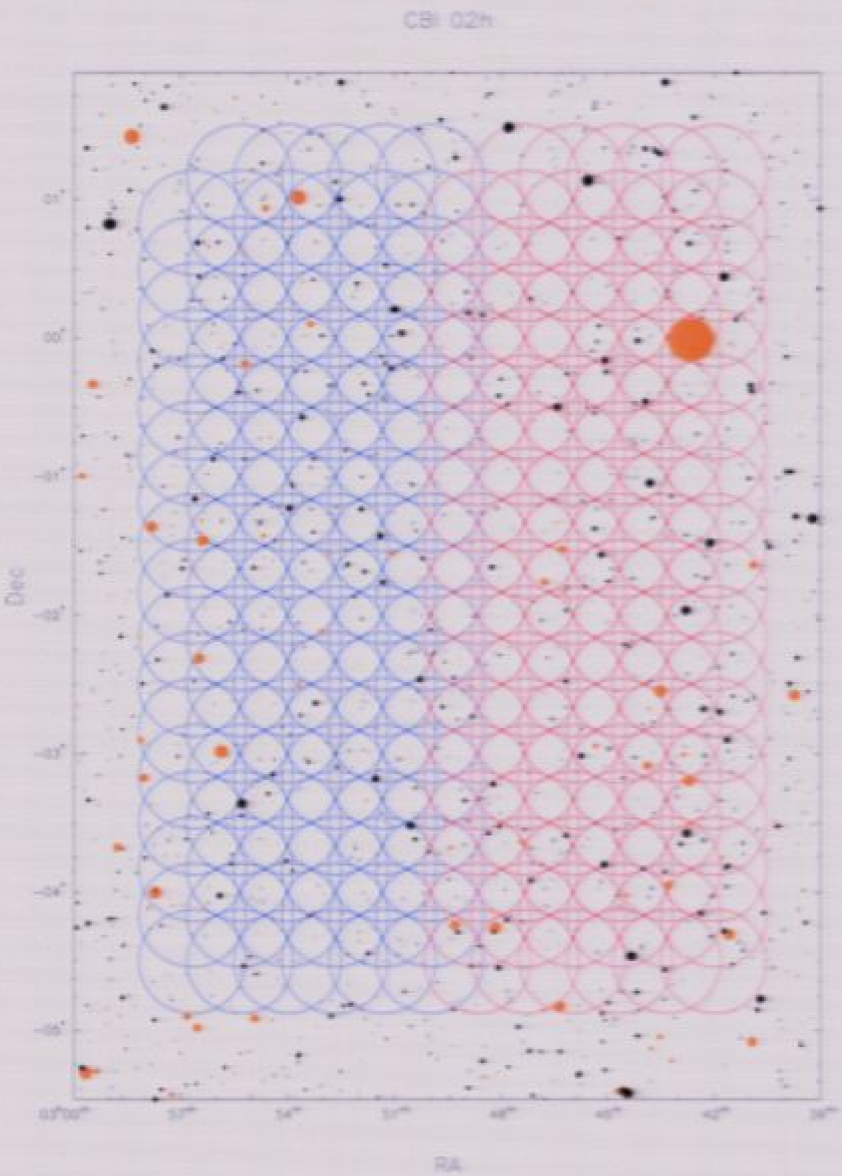
STRATEGY:

- Project out all reliably detected low-frequency sources (NVSS: S_1.4 GHz > 3.4 mJy)

  LOSS OF SENSITIVITY

- Calculate the power contributed by sources below our cut for projection

  SIGNIFICANTLY UNCERTAIN



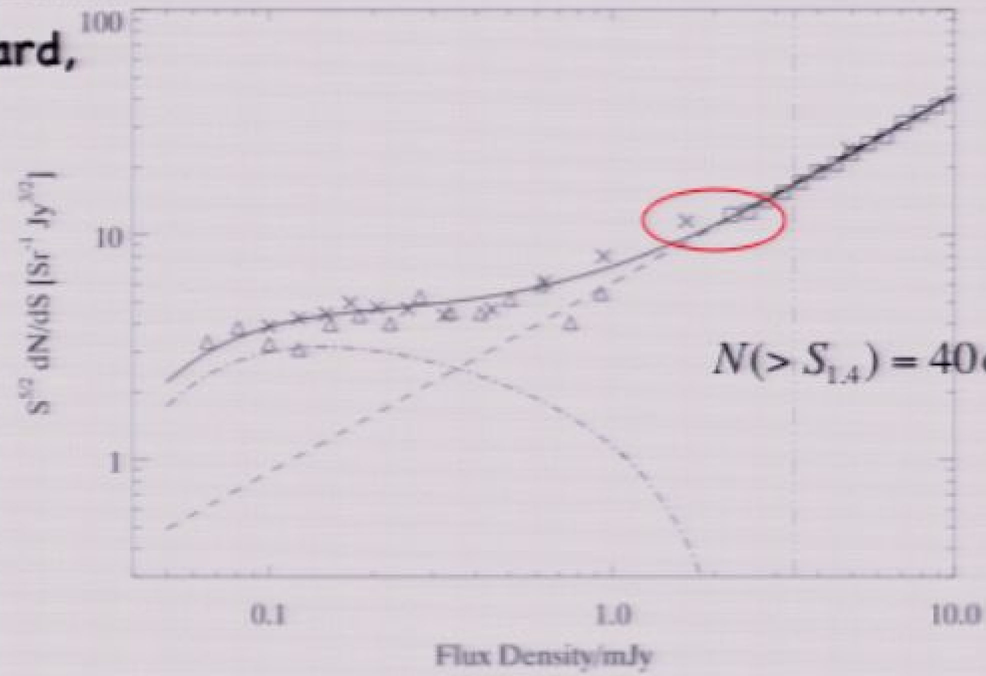
Most variance comes

from

Right under projection

Threshold: standard,

mJy level AGN



$$N(>S_{1.4}) = 40\deg^{-2}\left(\frac{S_{1.4}}{3mJy}\right)^{-0.7}$$

Fig. 12.— 1.4 GHz source counts. The solid line is the model of Hopkins et al. (2003) and triangles are their measurements in the Phoenix Deep Field; x's are the source counts from the COSMOS field (Bondi et al. 2008); and squares are source counts from FIRST (White et al. 1997). The dashed line is a power-law fit to the FIRST source counts at flux densities fainter than 100 mJy and the dot-dash line is the excess of the full source counts over the power law form. The vertical dash-triple-dot line is the CBI projection threshold: the sources of interest are those to the left of this line. The power law behavior persists up to 100 mJy.

Main Challenge at 30 GHz: Discrete Source Foreground

- ~5000 NVSS sources in CBI fields
- Detected at 30 GHz (OVRO 40m/ CBI)

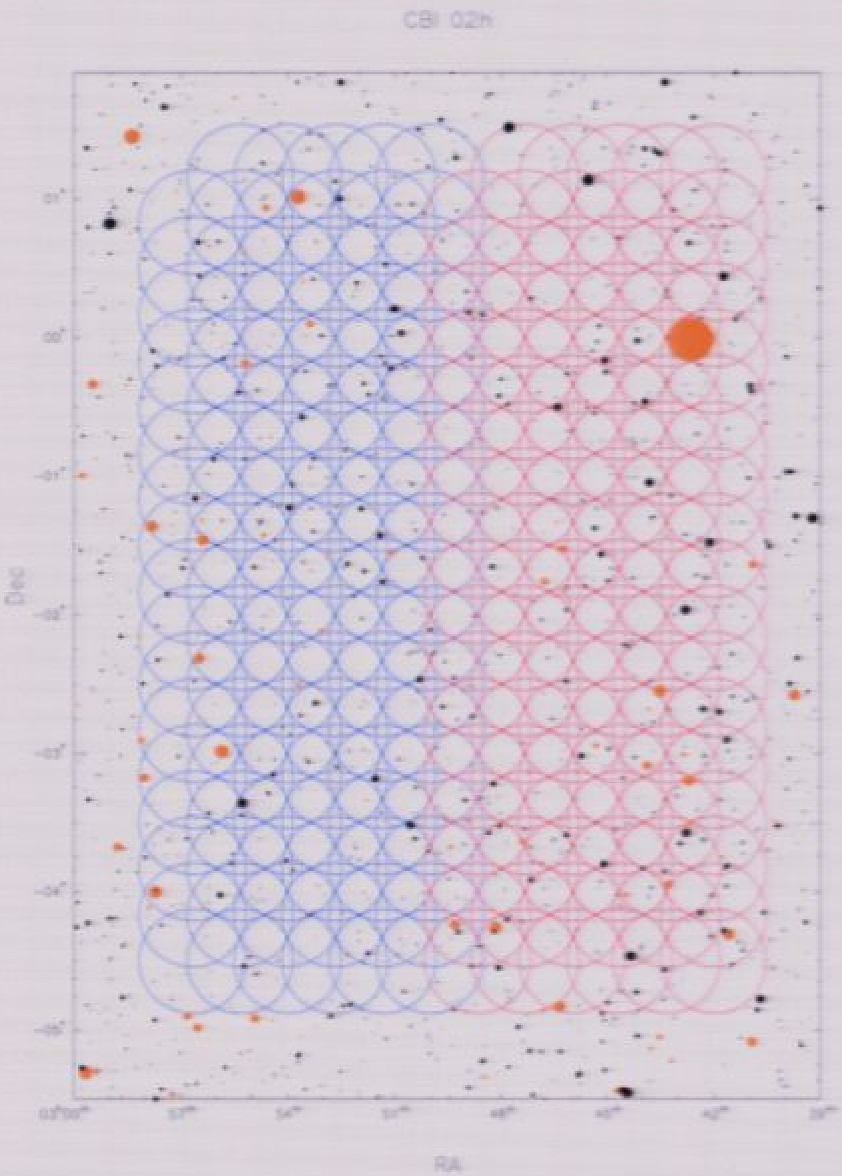
STRATEGY:

- Project out all reliably detected low-frequency sources (NVSS: S_1.4 GHz > 3.4 mJy)

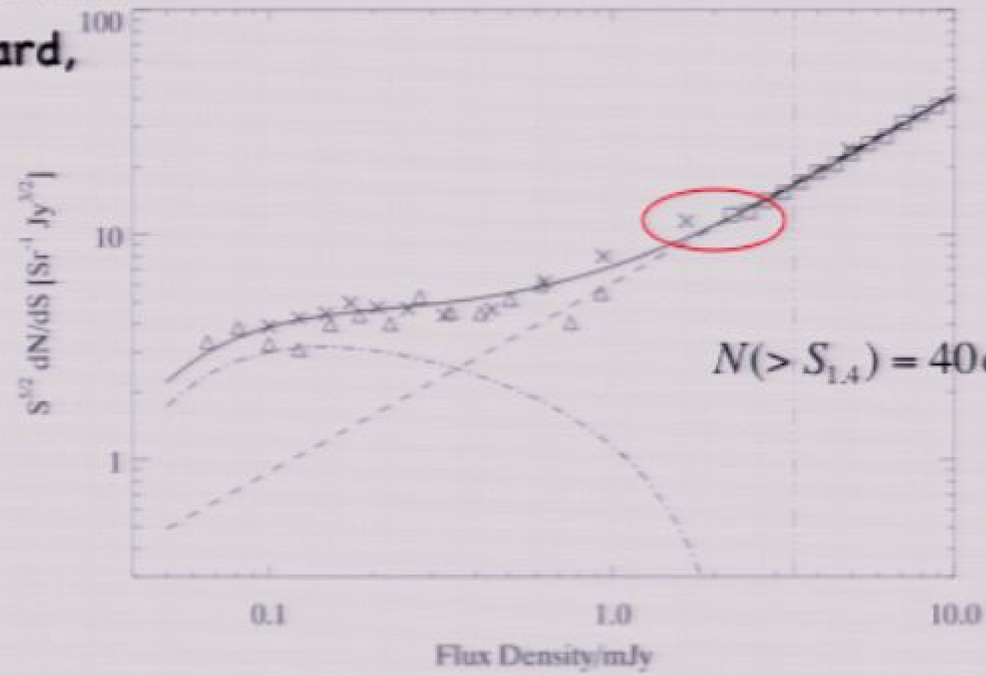
  LOSS OF SENSITIVITY

- Calculate the power contributed by sources below our cut for projection

  SIGNIFICANTLY UNCERTAIN



Most variance comes
from
Right under projection
Threshold: standard,
mJy level AGN



$$N(>S_{1.4}) = 40\deg^{-2}\left(\frac{S_{1.4}}{3mJy}\right)^{-0.7}$$

Fig. 12.— 1.4 GHz source counts. The solid line is the model of Hopkins et al. (2003) and triangles are their measurements in the Phoenix Deep Field; x's are the source counts from the COSMOS field (Bondi et al. 2008); and squares are source counts from FIRST (White et al. 1997). The dashed line is a power-law fit to the FIRST source counts at flux densities fainter than 100 mJy and the dot-dash line is the excess of the full source counts over the power law form. The vertical dash-triple-dot line is the CBI projection threshold: the sources of interest are those to the left of this line. The power law behavior persists up to 100 mJy.

GBT Survey

GOALS

- Reduce loss of sensitivity due to "nulled" pixels
- Reduce uncertainty in the statistical contribution due to faint, unknown sources

Data collected in 2005/2006

170 Hours GBT Time

4574 NVSS sources in the CBI Fields Observed

Individual, 70 second observations of each.

Data Filters

- Wind < 5 m/s
- Median Absolute Deviation Measurement noise (+/-20 min) < 1.0 mJy
- Preceding Peak/Focus succeeded (30-45 min)

2125 NVSS Sources In Final Dataset -- Typical Noise level 0.4 mJy

Caltech:
Larry Weintraub
Tim Pearson
Martin Shepherd
Tony Readhead

CITA:
Jon Sievers
Dick Bond

Green Bank:
Randy McCullough
Melinda Mello
Galen Watts

Key Players and warm optics (100-meter Robert C. Byrd Telescope in Green Bank, WV)

~2000 NVSS sources w/GBT @0.5 mJy

GBT Survey

GOALS

- Reduce loss of sensitivity due to "nulled" pixels
- Reduce uncertainty in the statistical contribution due to faint, unknown sources

Data collected in 2005/2006

170 Hours GBT Time

4574 NVSS sources in the CBI Fields Observed

Individual, 70 second observations of each.

Data Filters

- Wind < 5 m/s
- Median Absolute Deviation Measurement noise (+/-20 min) < 1.0 mJy
- Preceding Peak/Focus succeeded (30-45 min)

2125 NVSS Sources In Final Dataset -- Typical Noise level 0.4 mJy

Caltech:
Larry Weintraub
Tim Pearson
Martin Shepherd
Tony Readhead

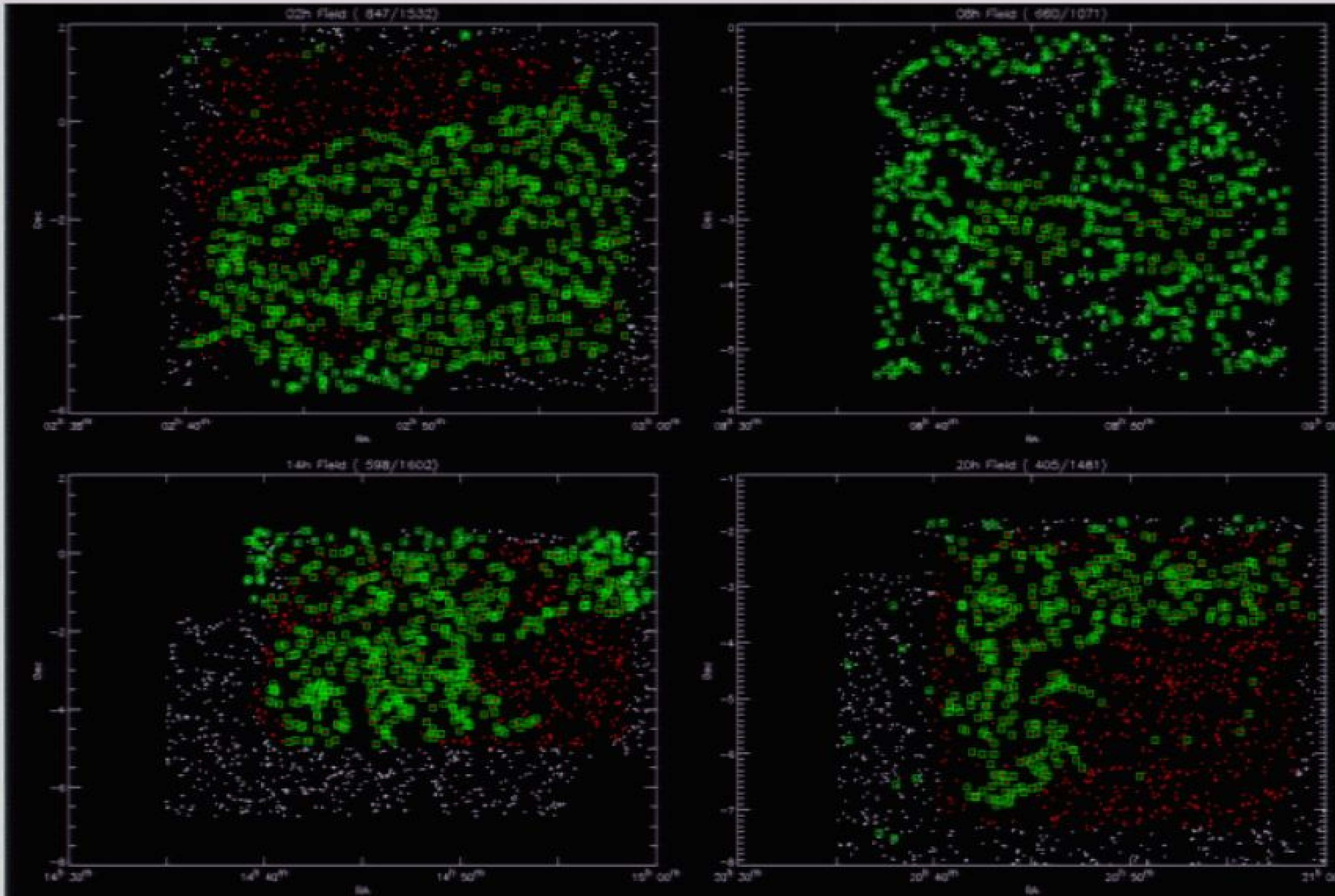
CITA:
Jon Sievers
Dick Bond

Green Bank:
Randy McCullough
Melinda Mello
Galen Watts

Key Players and warm optics (100-meter Robert C. Byrd Telescope in Green Bank, WV)

~2000 NVSS sources w/GBT @0.5 mJy

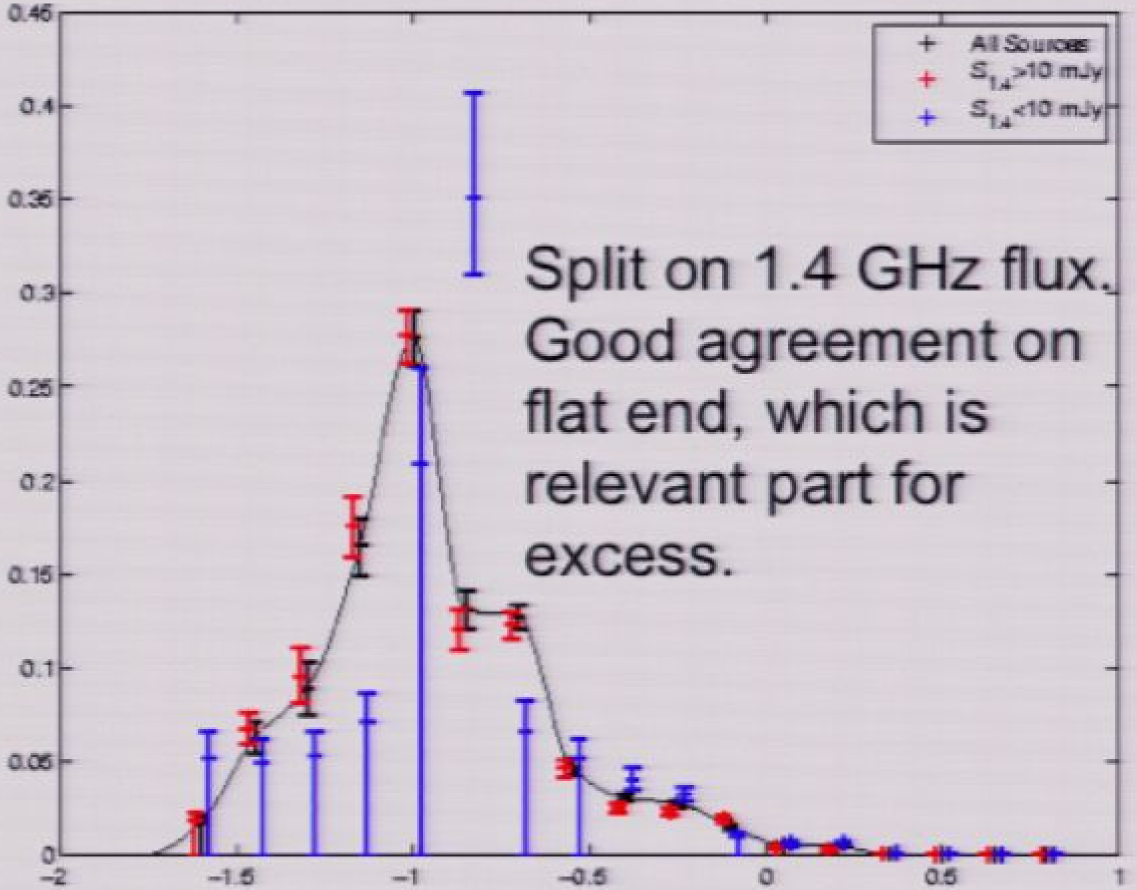
GBT Survey Snapshot



Measuring dn/dS

- Take 1.4 GHz fluxes, 30 GHz measurements. Fold all measurements into Maximum Likelihood code.
- Describe PDF as interpolation between points in index, then use modified CosmoMC to measure constraints.
- We split at 12 mJy @1.4 GHz, find properties in flat end consistent between subsamples.
- Convolve 1.4->30 flux ration distribution w/ 1.4 GHz source counts to get 30 GHz dn/dS (from NVSS-type sources).

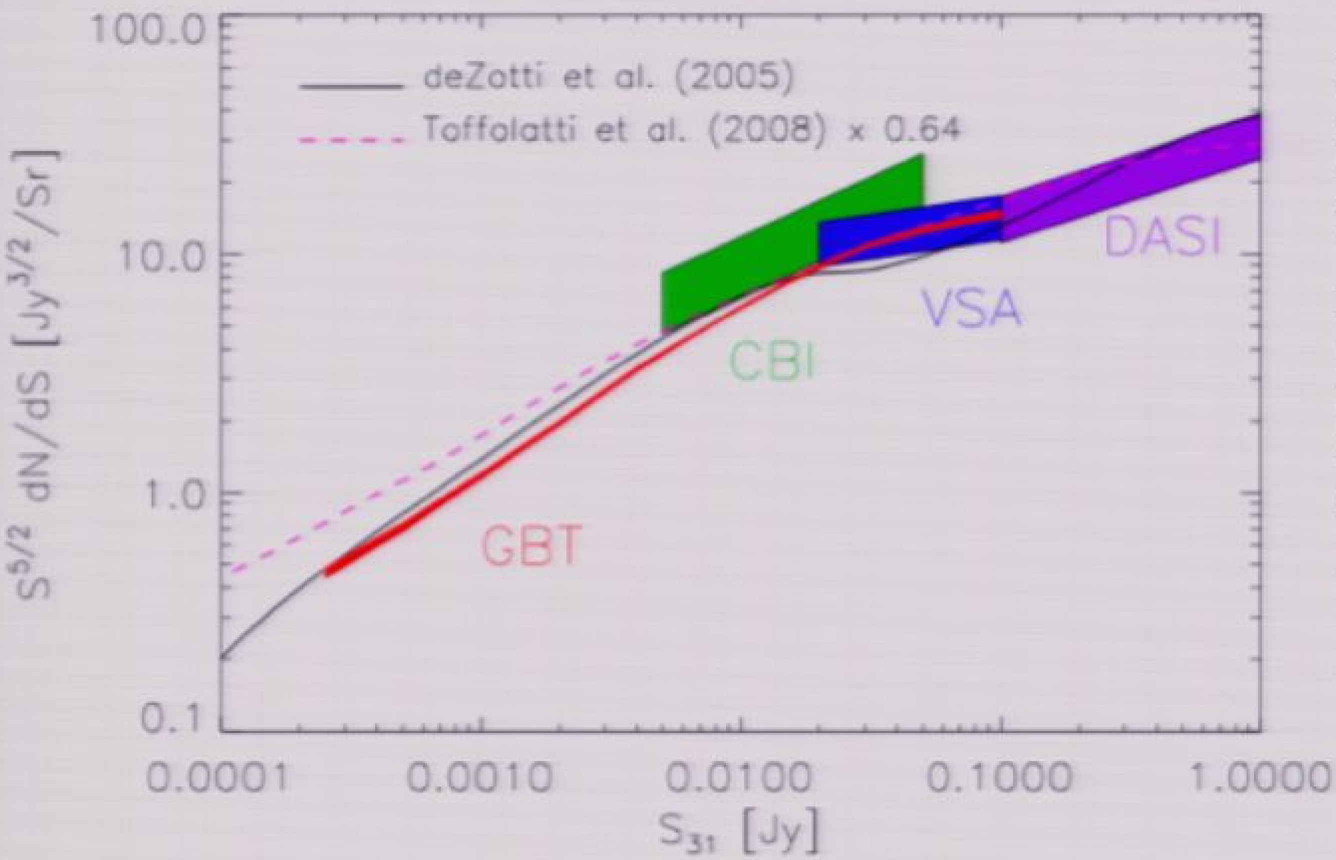
Spectral Indices



Split on 1.4 GHz flux. Good agreement on flat end, which is relevant part for excess.

Developed max. likelihood pipeline to get source properties, dealing with varying noises, selection effects, non-detections...

dN/dS



30 GHz dN/dS from Mason et al. Big remaining uncertainty is behavior of sources below 1 mJy @ 1.4 GHz.

NB - does not include 1.4 counts uncertainty (10%).

22

Sources cont'd:

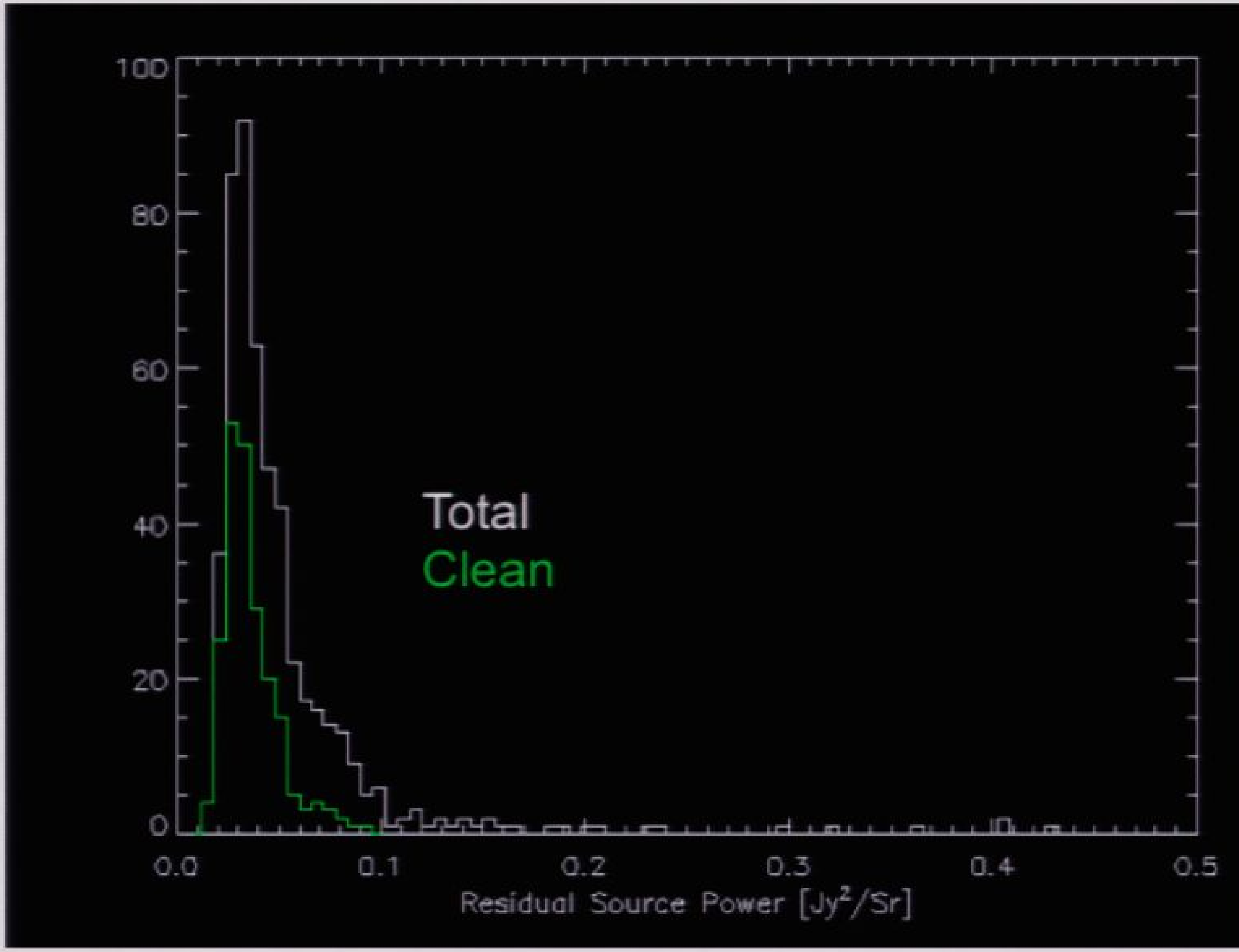
- GBT/OVRO survey gives us very good handle on AGN-type sources (dominate above ~1.5 mJy @1.4).
- Second population of star-forming galaxies dominate counts @1.4 below ~1.5 mJy.
- Have gotten some data on these faint sources @30 GHz, they are consistent with similarity to brighter ones.
- Run full pipeline sims to estimate faint source contributions and NG distribution of power.

23

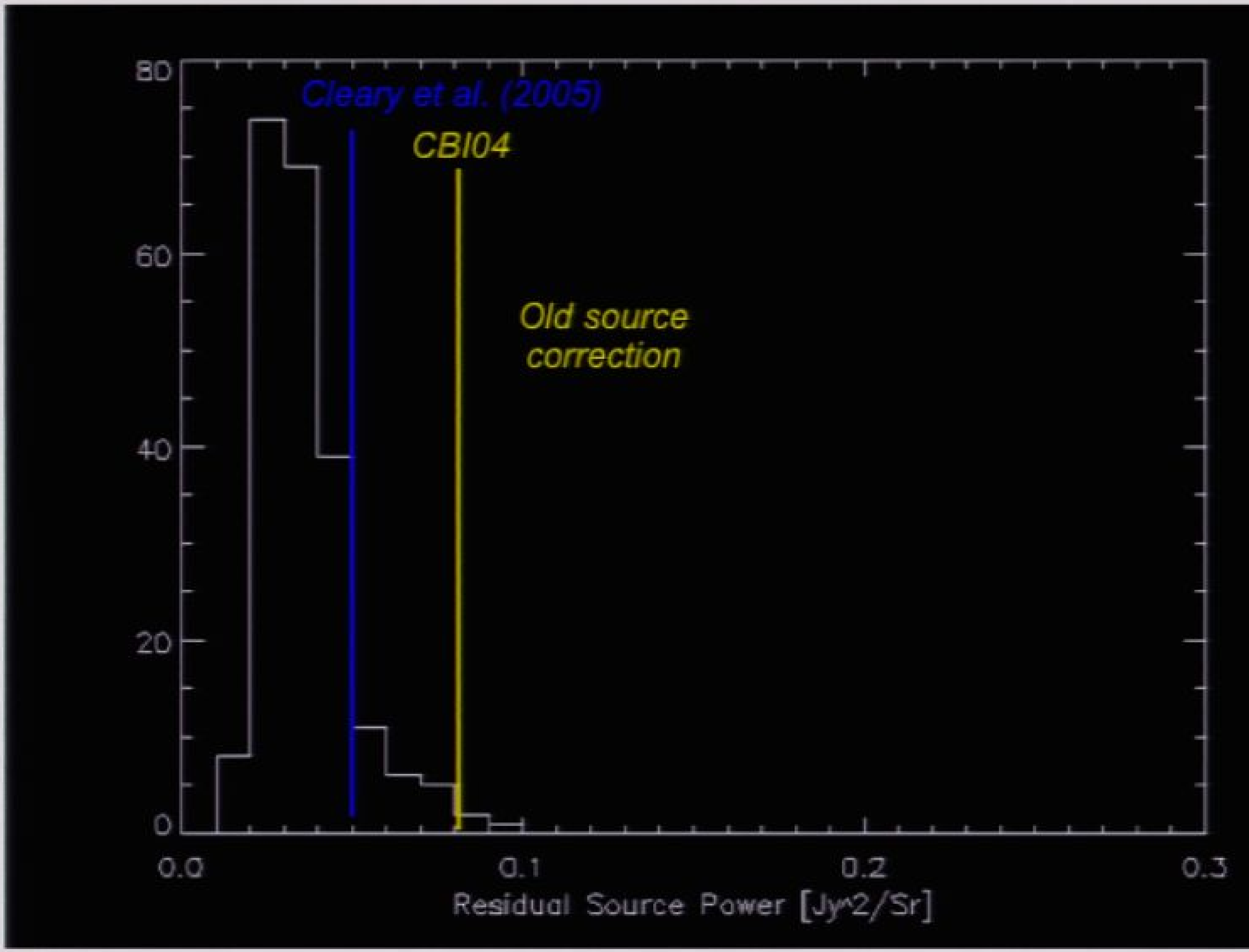
CBI Source Estimation

- Two inputs: ML spectral index distribution, no non-NVSS sources seen in CBI maps.
- Draw source realizations from ML dist. Add noise, CMB. Did we see a non-NVSS source?
- Yes? (pseudo) observe w/ GBT. Still there? Call sim dirty.
- Not there? Call sim possible realization of CBI sources.
- Make hundreds of sims, run full pipeline on them.
- Mean of clean/dirty sims similar, but dirty has tail to high power. Due mainly to Poisson statistics, a few faint sources stacking up in one beam.
- Method also serves to constrain bins where ML has no detection. Poisson effect dominant, though.

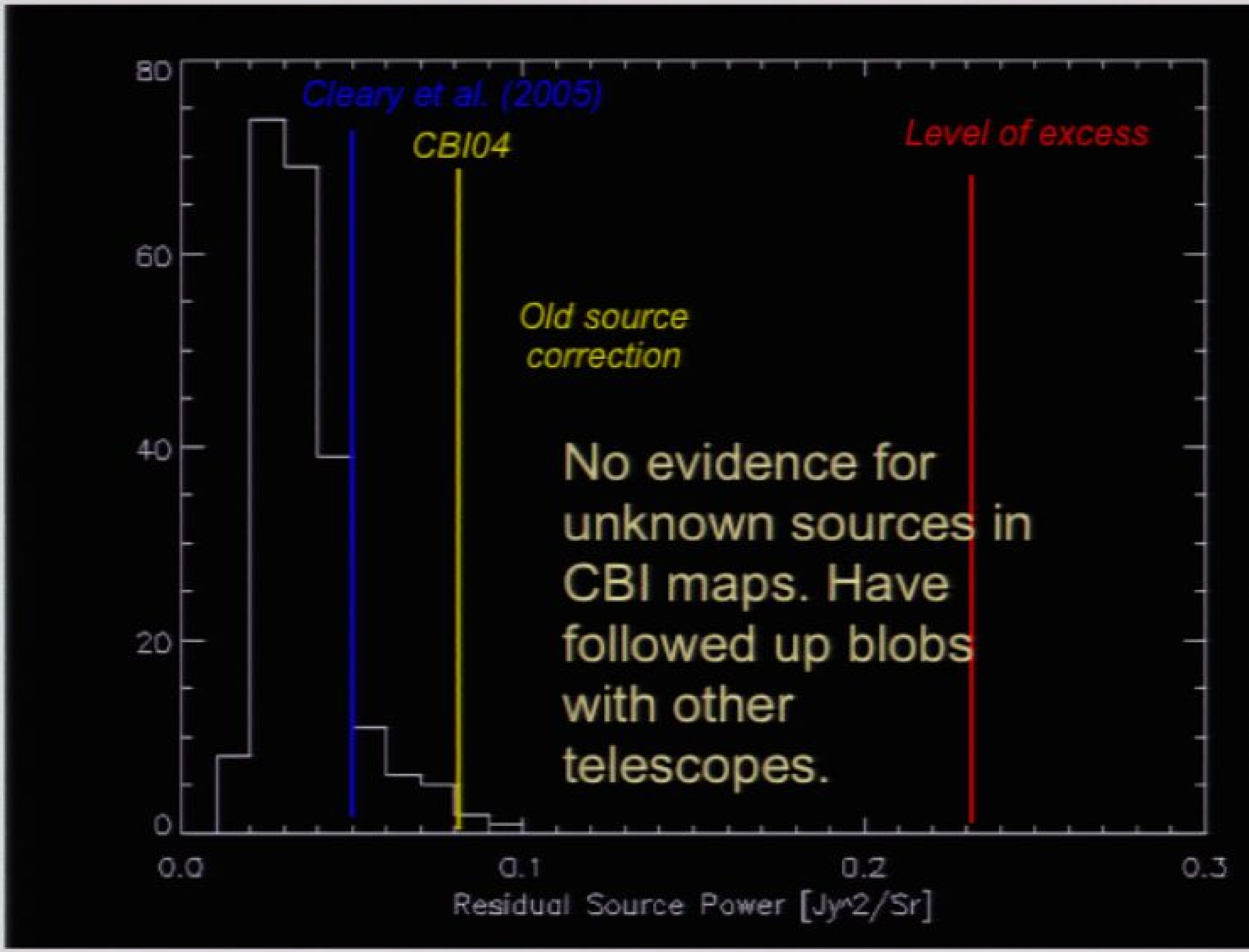
CBI Power From Source Sims.



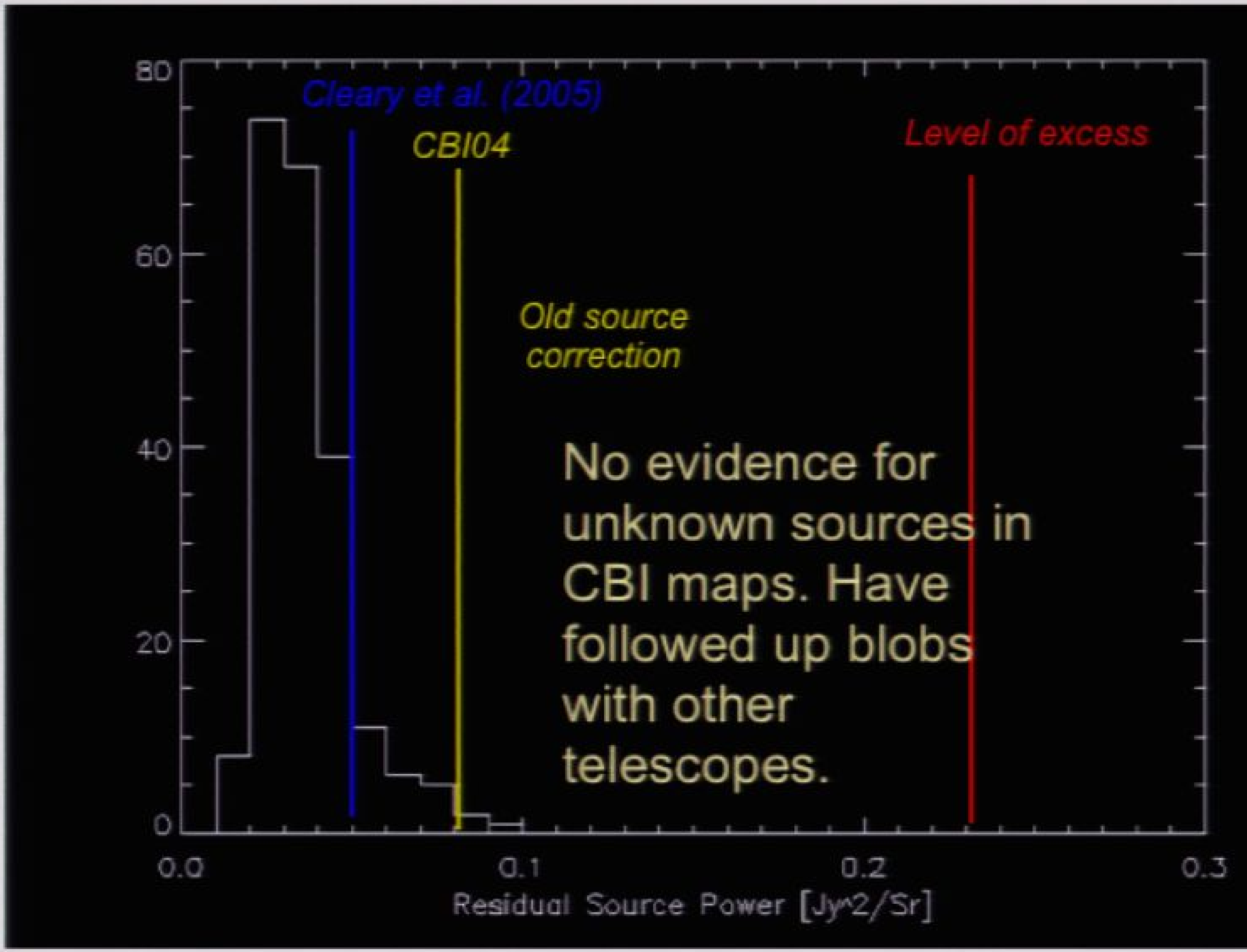
GBT + OVRO 30 GHz: Residual Source Contamination



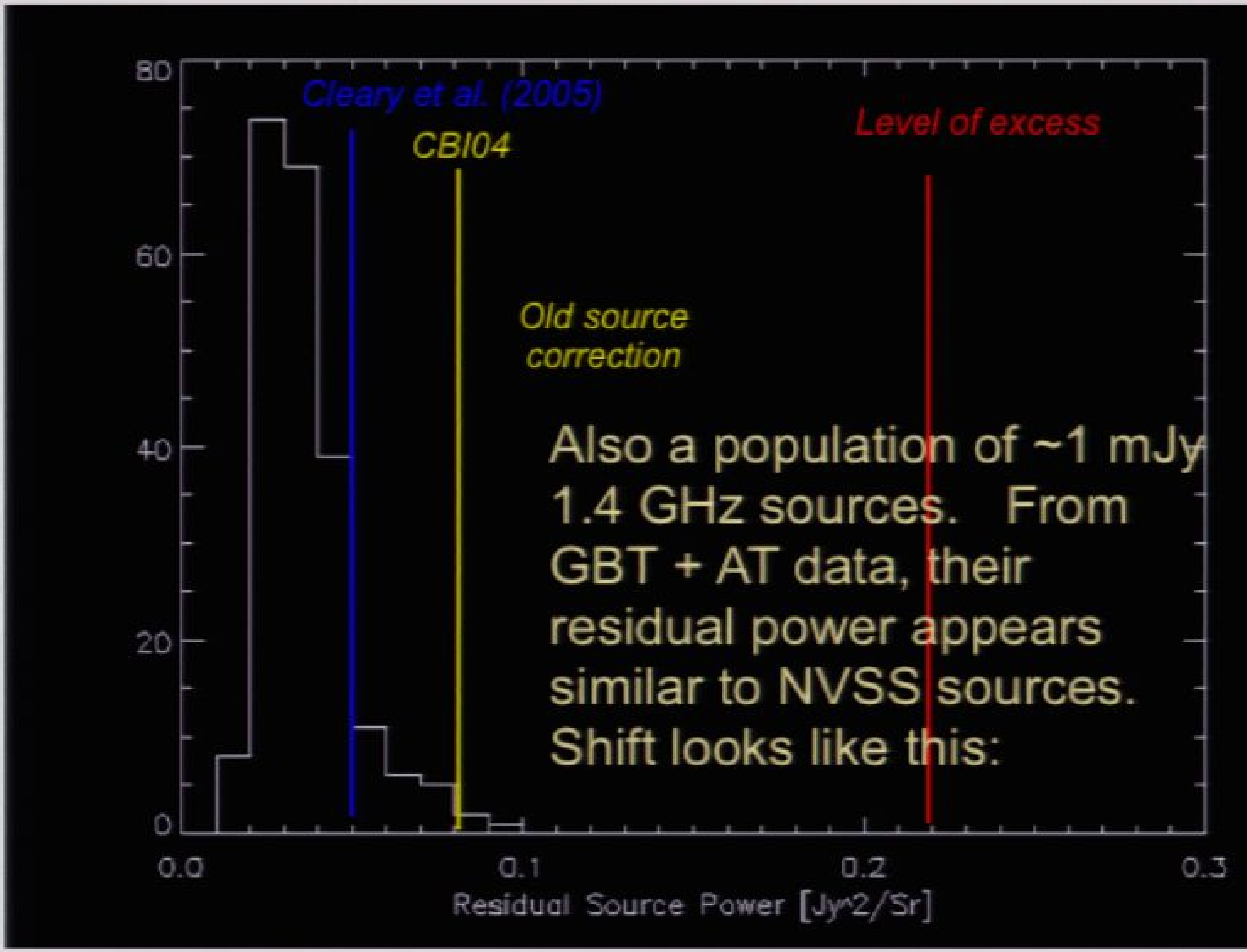
GBT + OVRO 30 GHz: Residual Source Contamination



GBT + OVRO 30 GHz: Residual Source Contamination

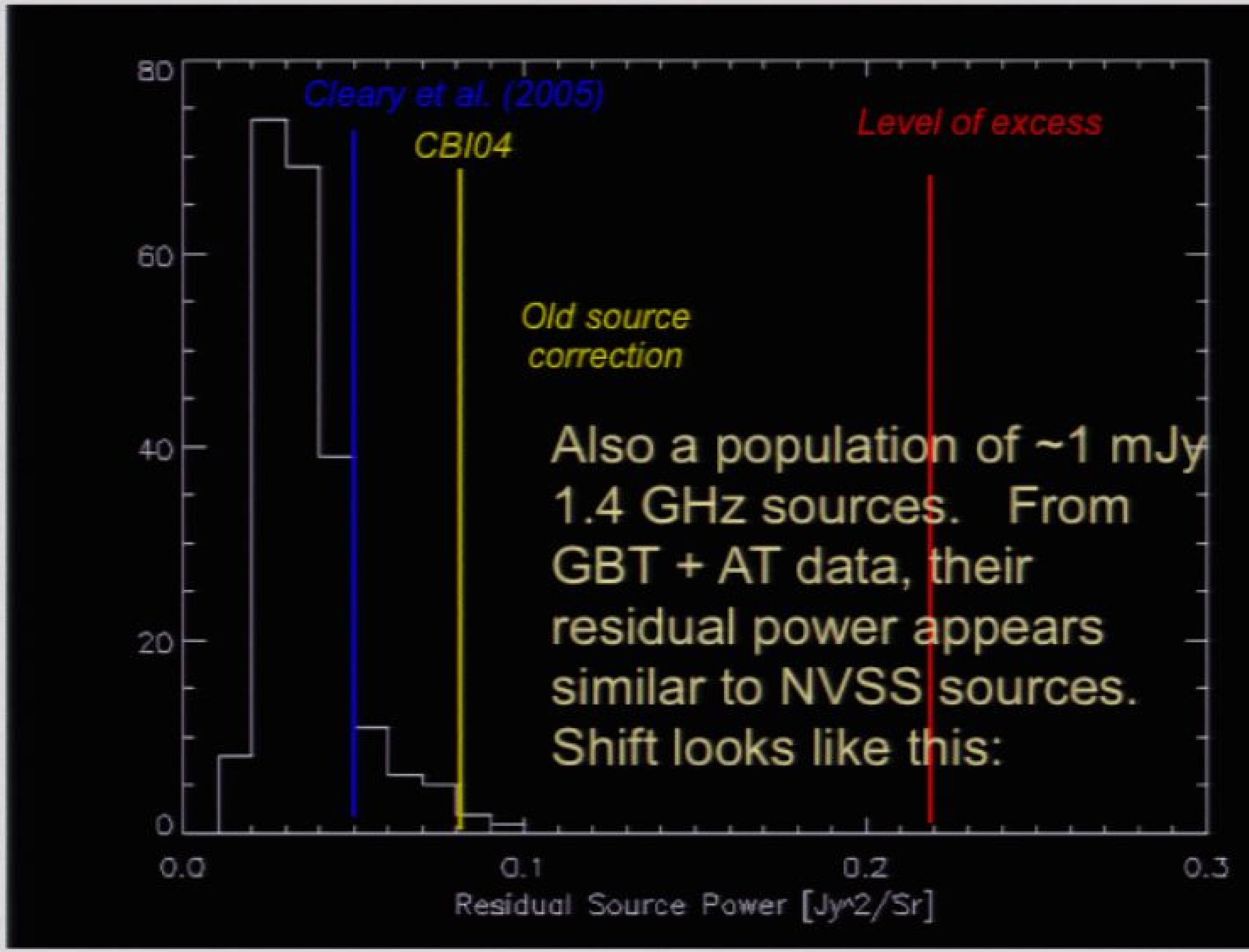


GBT + OVRO +AT 30 GHz: Faint 1.4 GHz sources

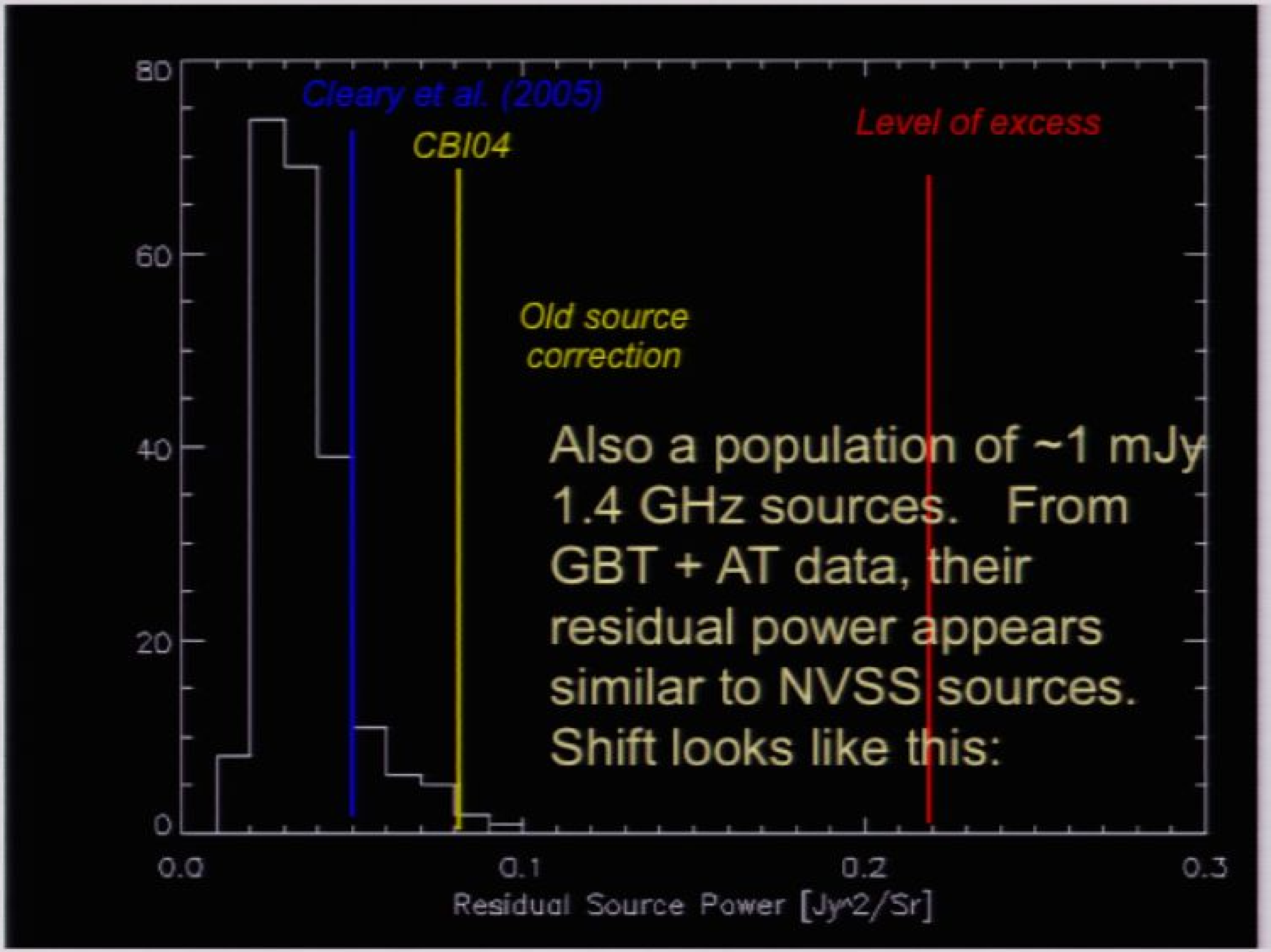


Also a population of ~1 mJy 1.4 GHz sources. From GBT + AT data, their residual power appears similar to NVSS sources. Shift looks like this:

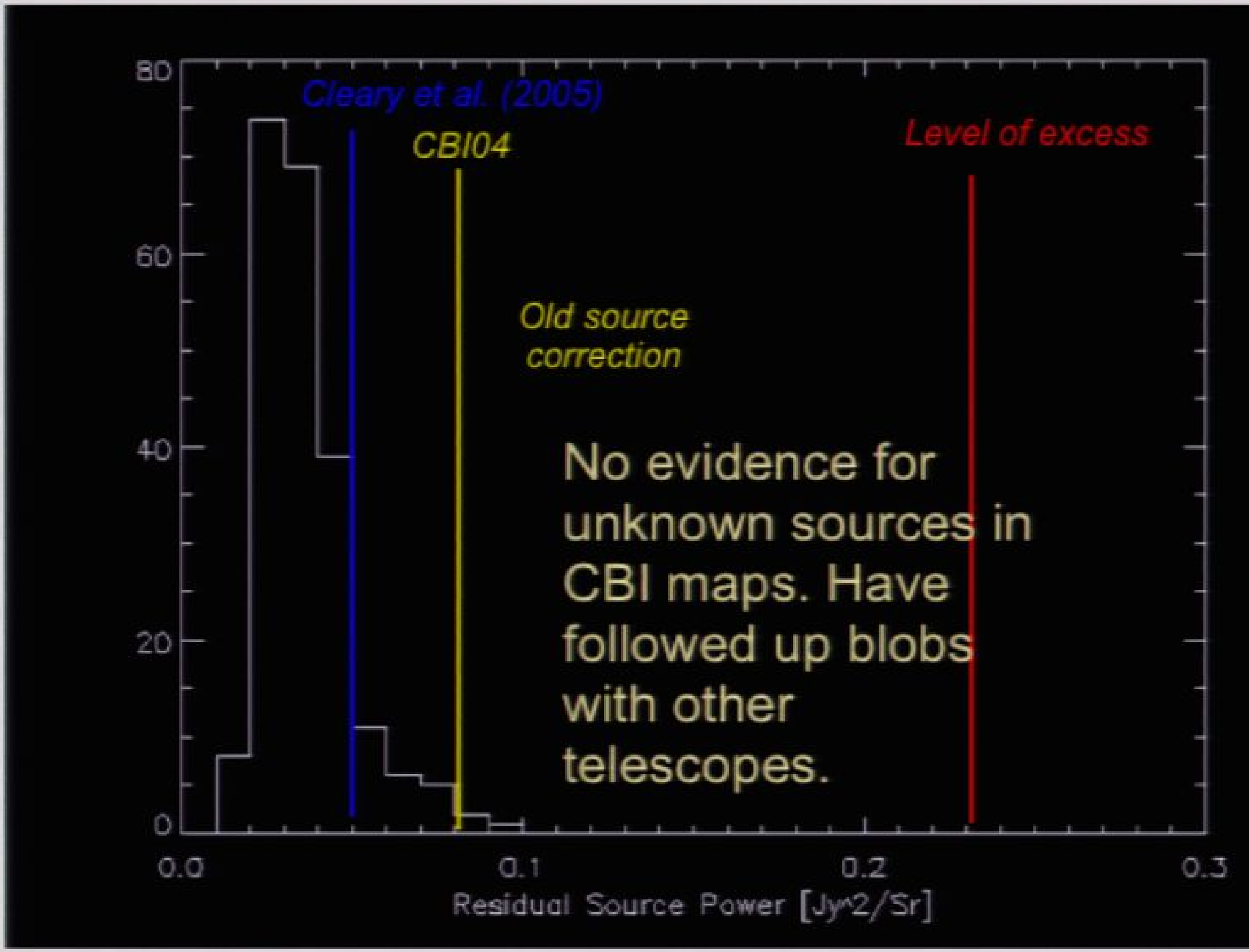
GBT + OVRO +AT 30 GHz: Faint 1.4 GHz sources



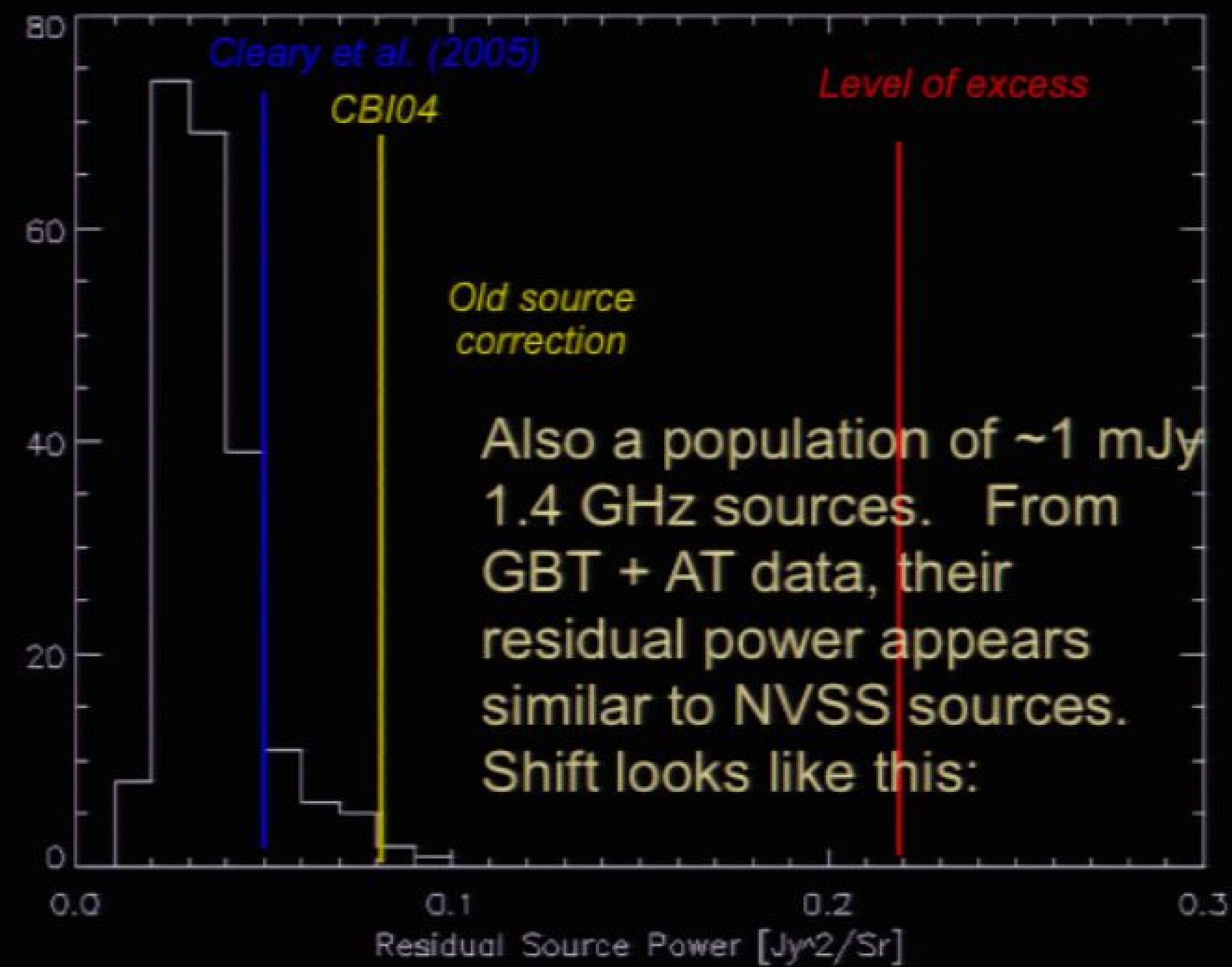
GBT + OVRO +AT 30 GHz: Faint 1.4 GHz sources



GBT + OVRO 30 GHz: Residual Source Contamination

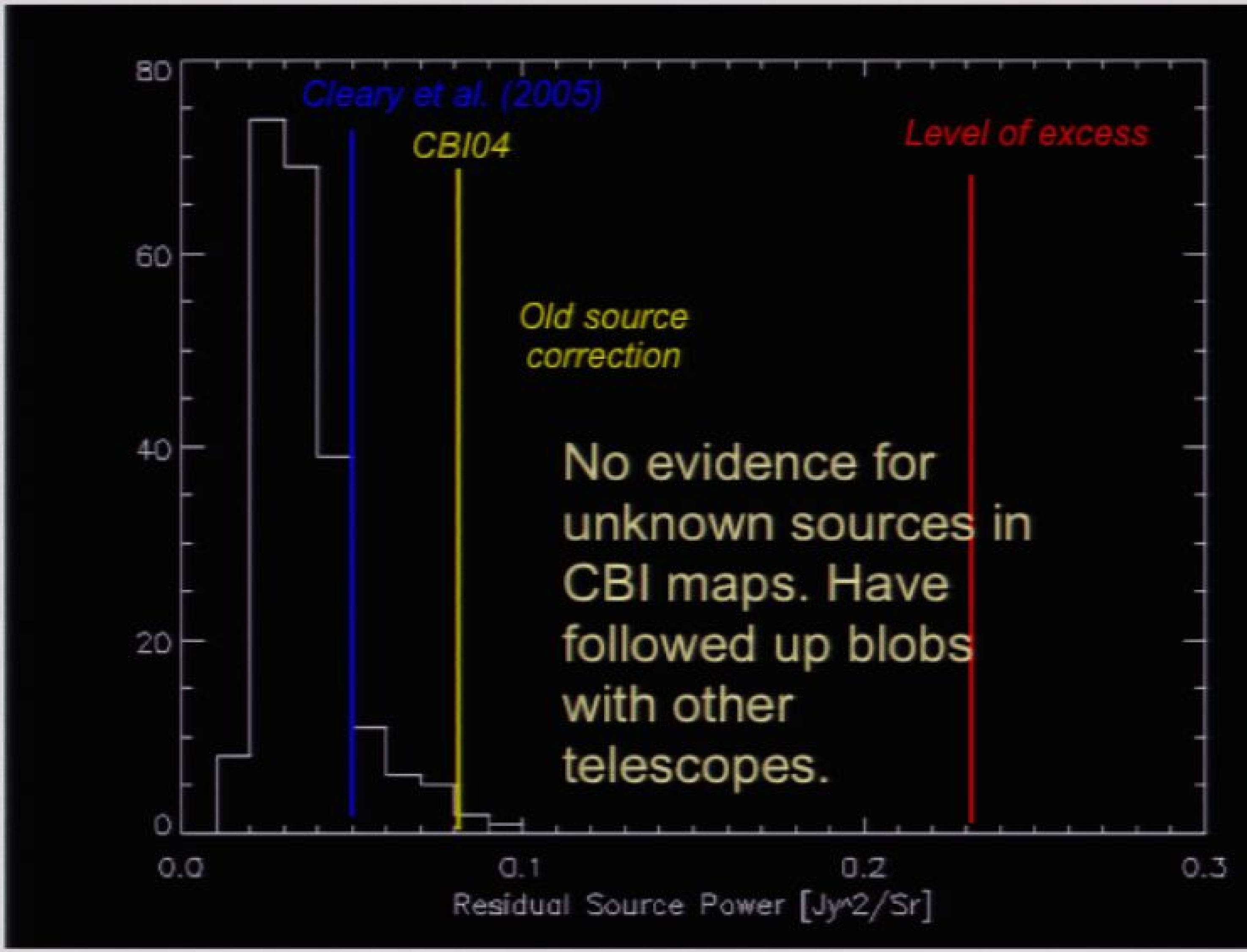


GBT + OVRO +AT 30 GHz: Faint 1.4 GHz sources

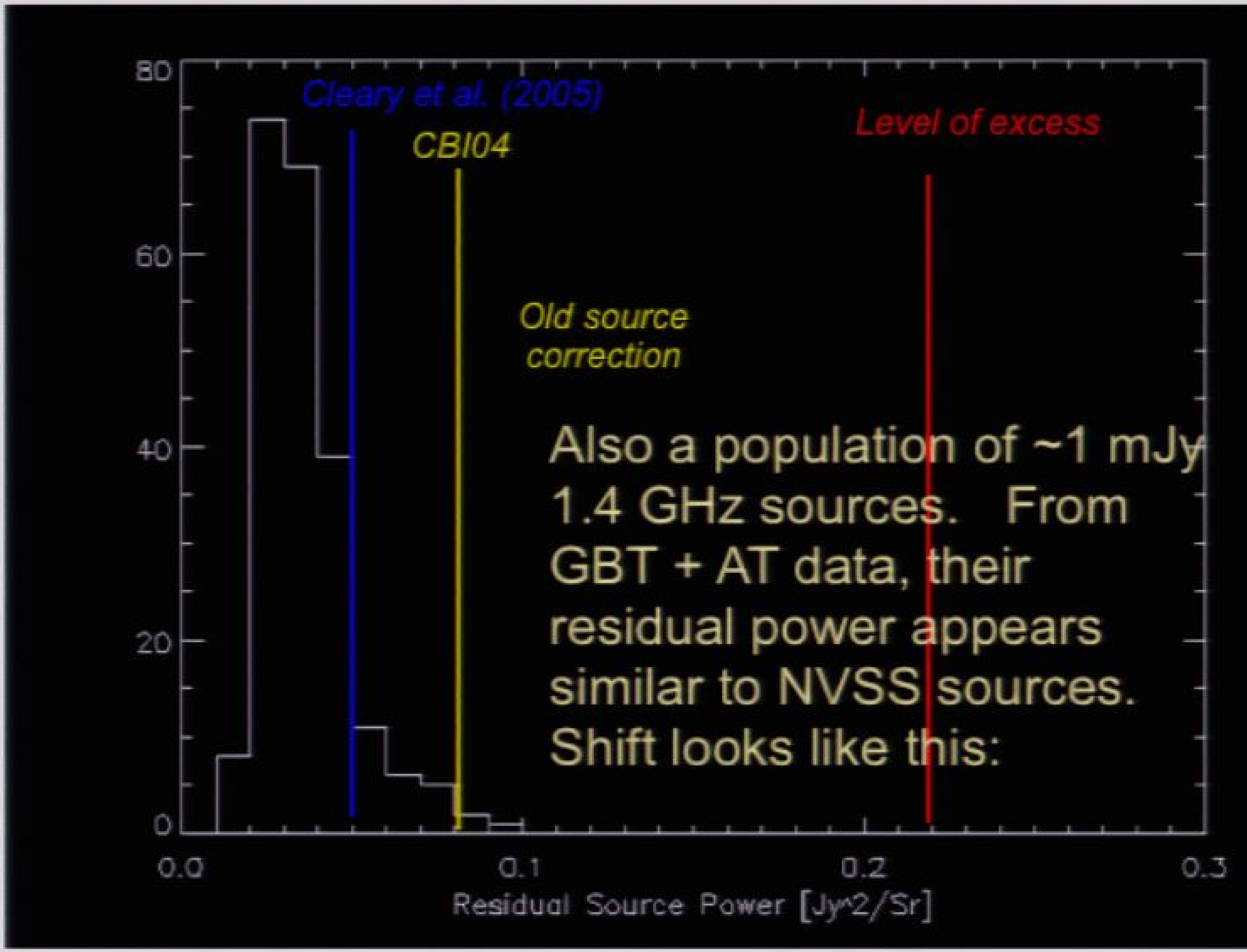


Also a population of ~1 mJy 1.4 GHz sources. From GBT + AT data, their residual power appears similar to NVSS sources. Shift looks like this:

GBT + OVRO 30 GHz: Residual Source Contamination

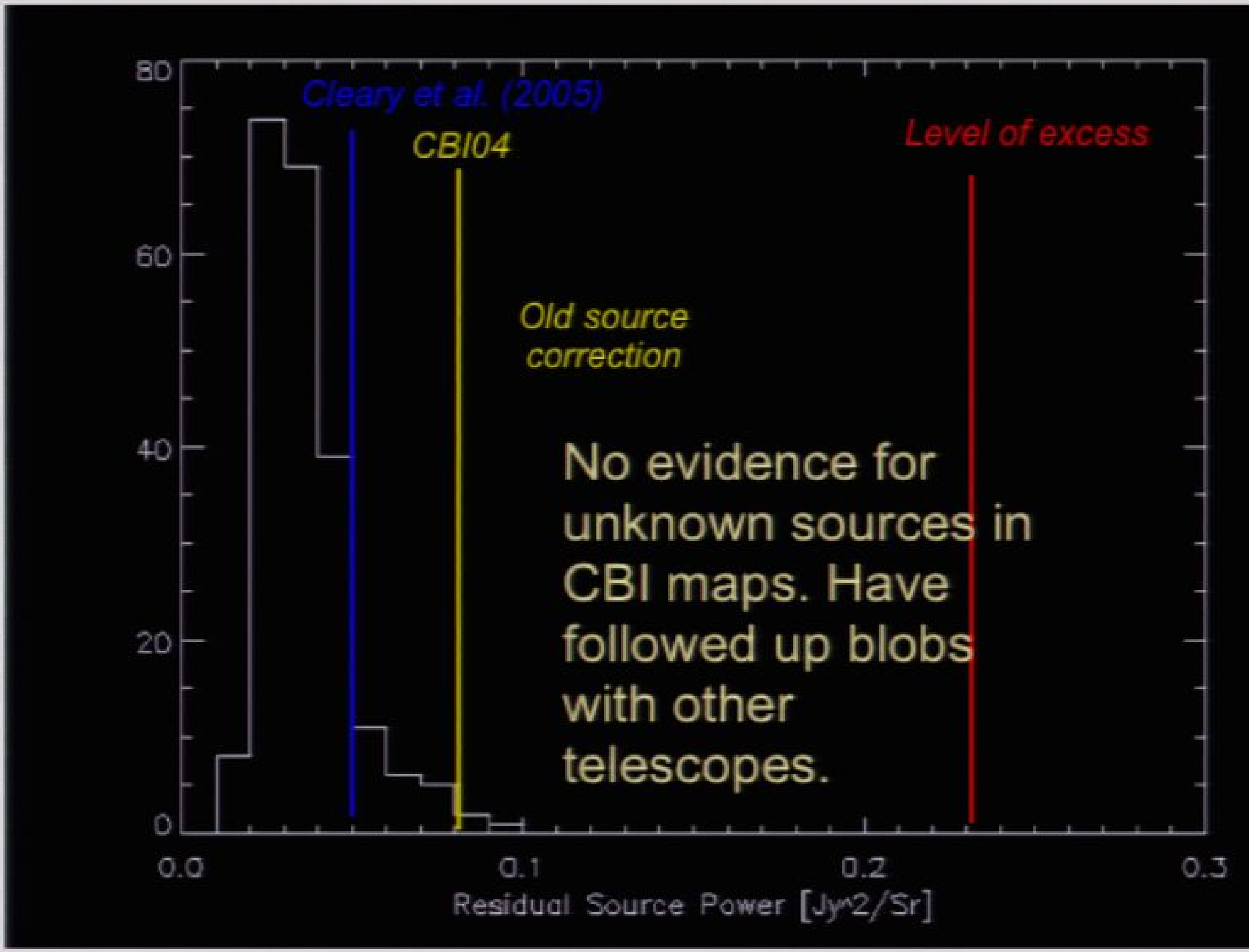


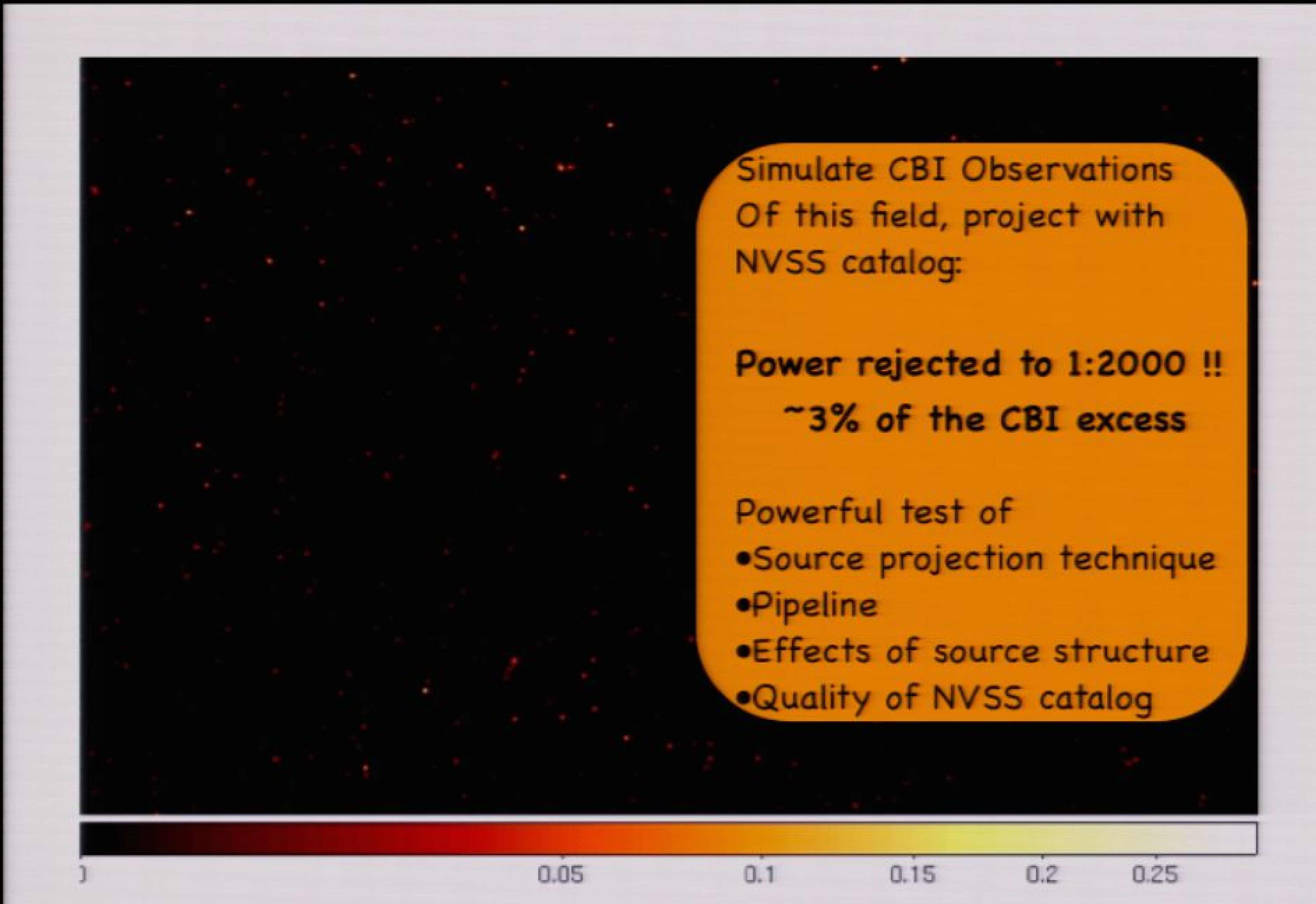
GBT + OVRO +AT 30 GHz: Faint 1.4 GHz sources



Also a population of ~1 mJy 1.4 GHz sources. From GBT + AT data, their residual power appears similar to NVSS sources. Shift looks like this:

GBT + OVRO 30 GHz: Residual Source Contamination

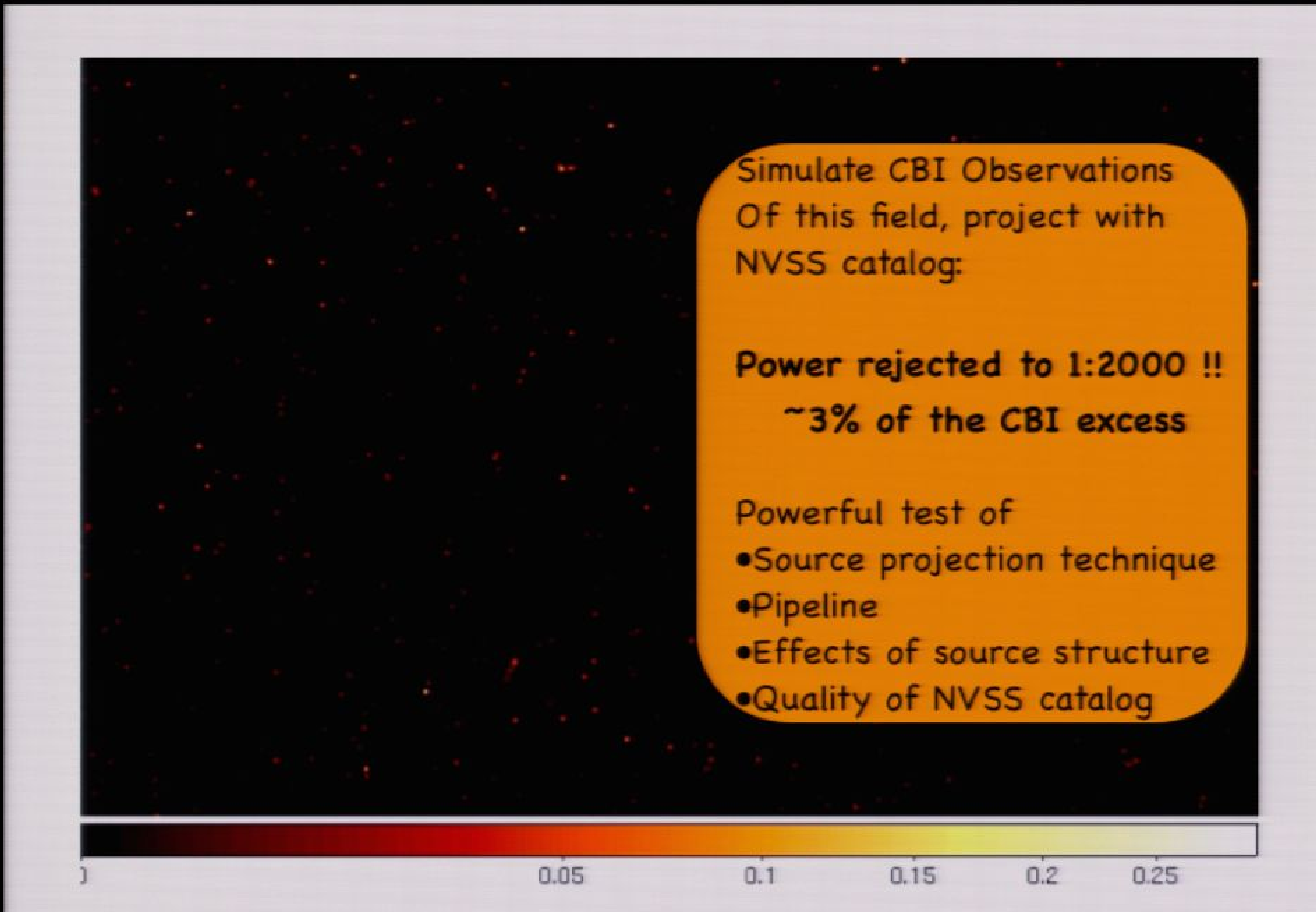



Simulate CBI Observations
Of this field, project with
NVSS catalog:
Power rejected to 1:2000 !!
~3% of the CBI excess
Powerful test of
•Source projection technique
•Pipeline
•Effects of source structure
•Quality of NVSS catalog
0.05
0.1
0.15
0.2
0.25

SZA Source Comp.

- We think SZA level for CBI is ~0.11-0.13 Jy^2/sr
- Using *total* simulation sample, we get 0.066±0.056 Jy^2/sr.
- Scatter dominated by sources falling in the same beam, CBI map constraints (no non-NVSS sources) are a statement of *particular* CBI fields.
- Maximum Likelihood fills up unconstrained bins up to amout allowed by data. Map test important for constraining (potentially arbitrary) tail.
- Don't know of any inconsistencies between SZA/ CBI source counts. Direct comparison slightly tricky due to SZA selecting at higher frequency.

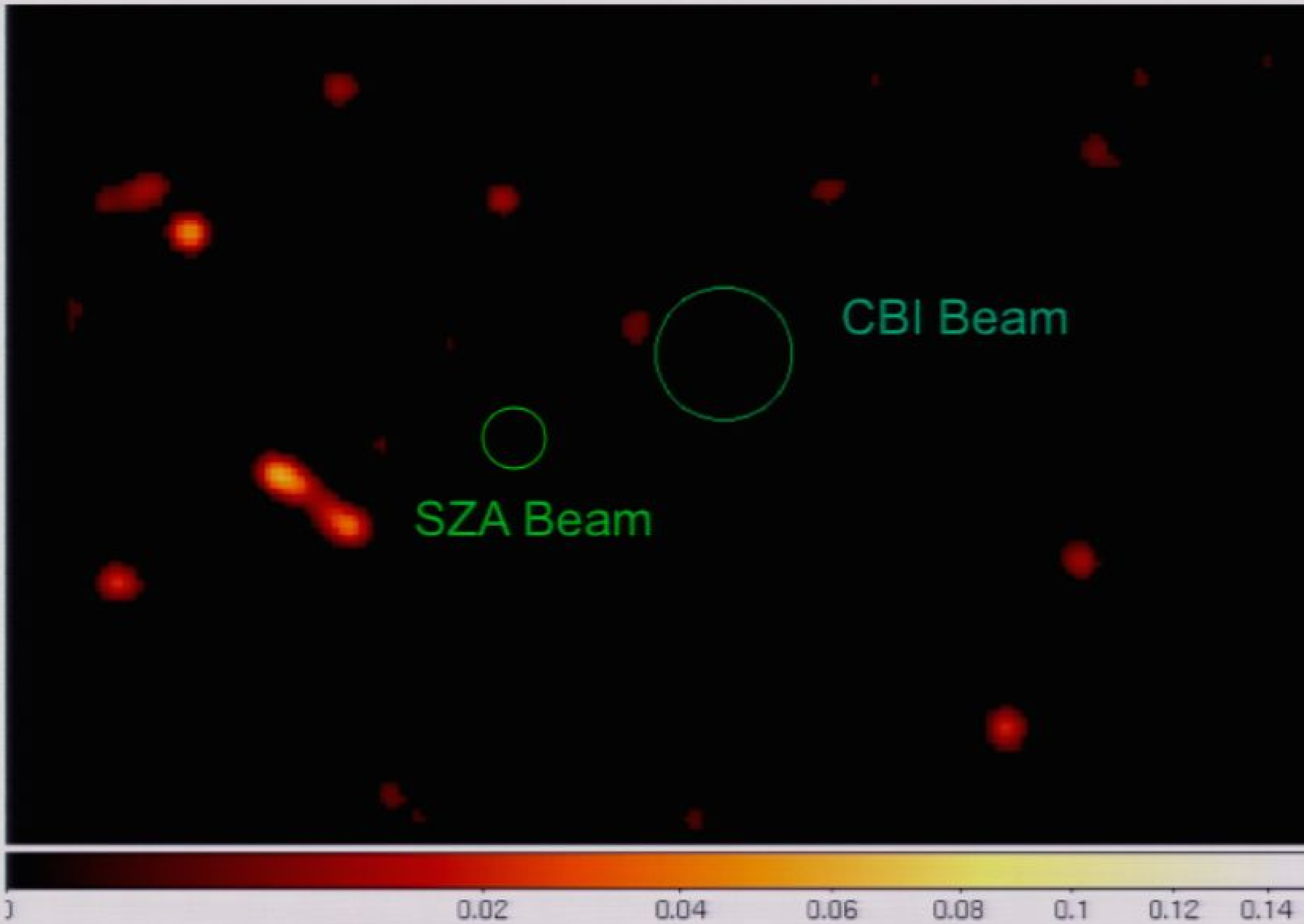
31


Simulate CBI Observations
Of this field, project with
NVSS catalog:
Power rejected to 1:2000 !!
~3% of the CBI excess
Powerful test of
•Source projection technique
•Pipeline
•Effects of source structure
•Quality of NVSS catalog
0
0.05
0.1
0.15
0.2
0.25

SZA Source Comp.

- We think SZA level for CBI is ~0.11-0.13 Jy^2/sr
- Using *total* simulation sample, we get 0.066 ± 0.056 Jy^2/sr.
- Scatter dominated by sources falling in the same beam, CBI map constraints (no non-NVSS sources) are a statement of *particular* CBI fields.
- Maximum Likelihood fills up unconstrained bins up to amout allowed by data. Map test important for constraining (potentially arbitrary) tail.
- Don't know of any inconsistencies between SZA/ CBI source counts. Direct comparison slightly tricky due to SZA selecting at higher frequency.

NVSS Map Zoom



SZA->CBI - different beams mean src struct. different impact.

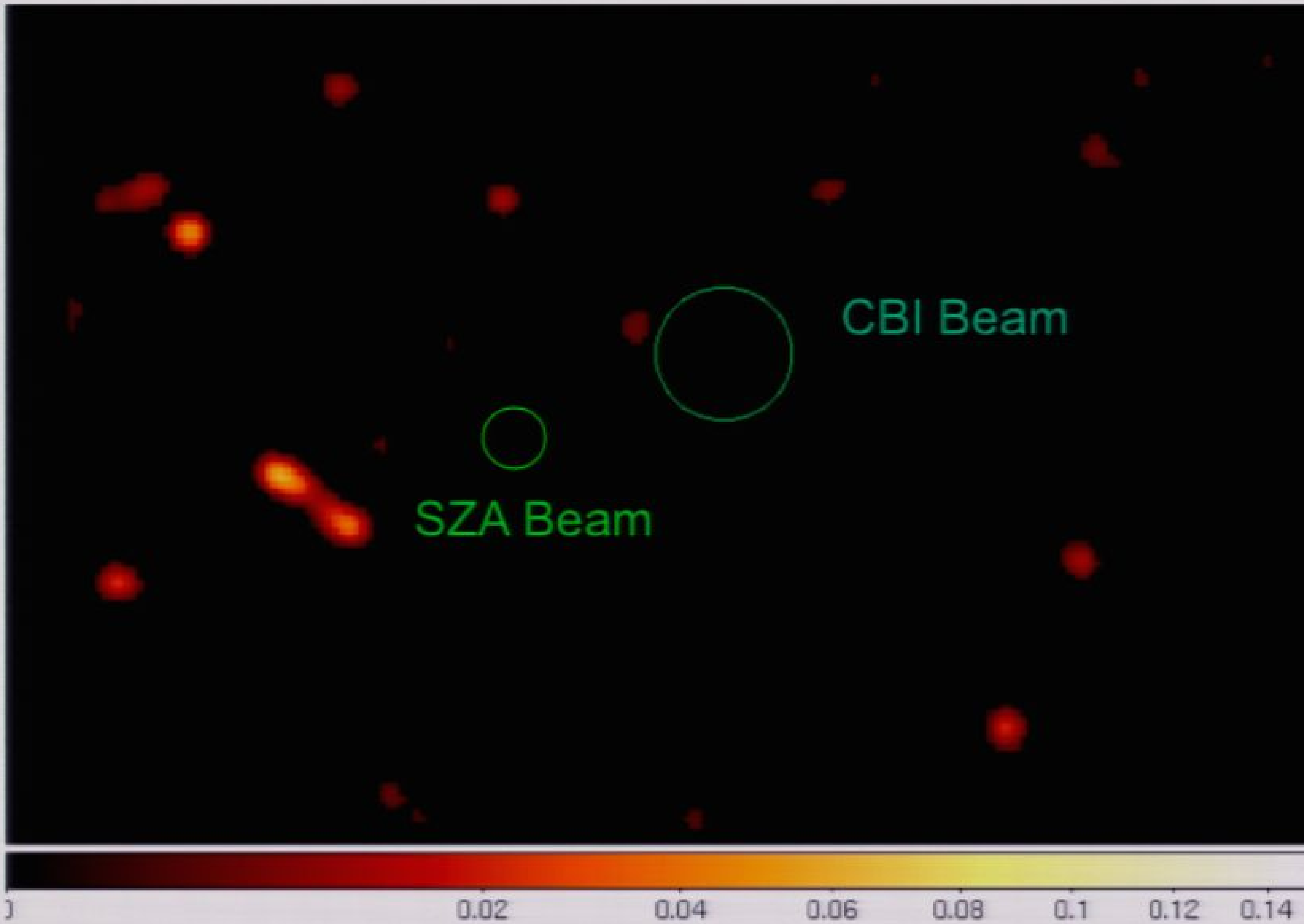
Other Possible Systematics

- Noise wrong? No. Can split data in two, measure noise + spectrum simultaneously.
- Pointing errors on bright sources? No. Simulate pointing errors - small. Also measure spectrum removing fields near bright sources - unchanged.
- Individual dish misalignment errors? No. Few uK^2
- Beam errors coupled to bright sources? No. Few uK^2 using Gaussian vs. measured beam for projection.
- Spectral index errors in projection? No. Tiny.
- Pipeline funnies? Works on all sims. Rewrote to not invert ill-conditioned matrices. (Raises damping tail by ~1/2 sigma, though highest ell unchanged).

Other Possible Systematics

- Noise wrong? No. Can split data in two, measure noise + spectrum simultaneously.
- Pointing errors on bright sources? No. Simulate pointing errors - small. Also measure spectrum removing fields near bright sources - unchanged.
- Individual dish misalignment errors? No. Few uK^2
- Beam errors coupled to bright sources? No. Few uK^2 using Gaussian vs. measured beam for projection.
- Spectral index errors in projection? No. Tiny.
- Pipeline funnies? Works on all sims. Rewrote to not invert ill-conditioned matrices. (Raises damping tail by ~1/2 sigma, though highest ell unchanged).

NVSS Map Zoom



SZA->CBI - different beams mean src struct. different impact.

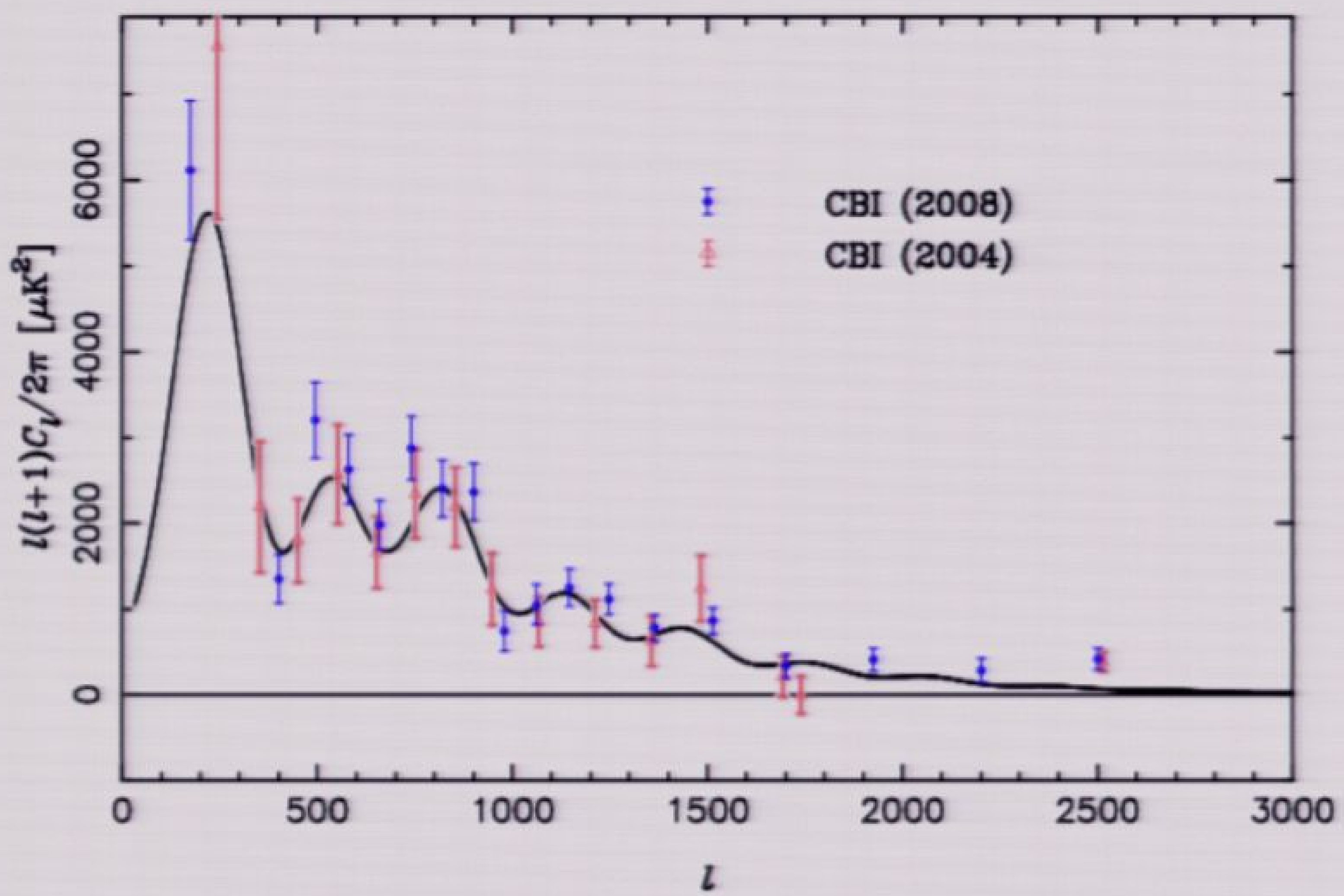
Other Possible Systematics

- Noise wrong? No. Can split data in two, measure noise + spectrum simultaneously.
- Pointing errors on bright sources? No. Simulate pointing errors - small. Also measure spectrum removing fields near bright sources - unchanged.
- Individual dish misalignment errors? No. Few uK^2
- Beam errors coupled to bright sources? No. Few uK^2 using Gaussian vs. measured beam for projection.
- Spectral index errors in projection? No. Tiny.
- Pipeline funnies? Works on all sims. Rewrote to not invert ill-conditioned matrices. (Raises damping tail by ~1/2 sigma, though highest ell unchanged).

Other Possible Systematics

- Noise wrong? No. Can split data in two, measure noise + spectrum simultaneously.
- Pointing errors on bright sources? No. Simulate pointing errors - small. Also measure spectrum removing fields near bright sources - unchanged.
- Individual dish misalignment errors? No. Few uK^2
- Beam errors coupled to bright sources? No. Few uK^2 using Gaussian vs. measured beam for projection.
- Spectral index errors in projection? No. Tiny.
- Pipeline funnies? Works on all sims. Rewrote to not invert ill-conditioned matrices. (Raises damping tail by ~1/2 sigma, though highest ell unchanged).

New CBI Spectrum

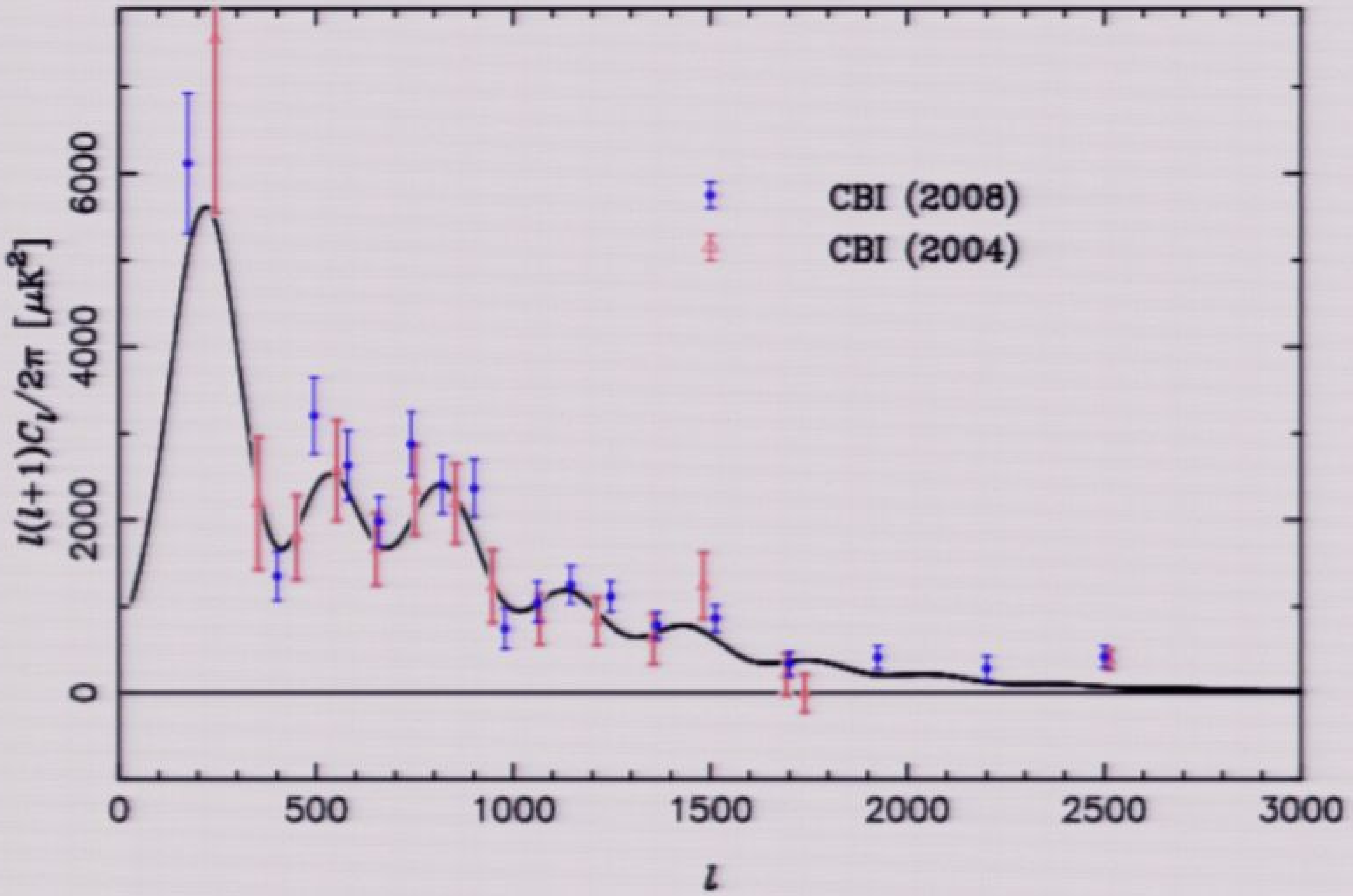


JLS et al., arXiv:0901.4540

Other Possible Systematics

- Noise wrong? No. Can split data in two, measure noise + spectrum simultaneously.
- Pointing errors on bright sources? No. Simulate pointing errors - small. Also measure spectrum removing fields near bright sources - unchanged.
- Individual dish misalignment errors? No. Few uK^2
- Beam errors coupled to bright sources? No. Few uK^2 using Gaussian vs. measured beam for projection.
- Spectral index errors in projection? No. Tiny.
- Pipeline funnies? Works on all sims. Rewrote to not invert ill-conditioned matrices. (Raises damping tail by ~1/2 sigma, though highest ell unchanged).

New CBI Spectrum



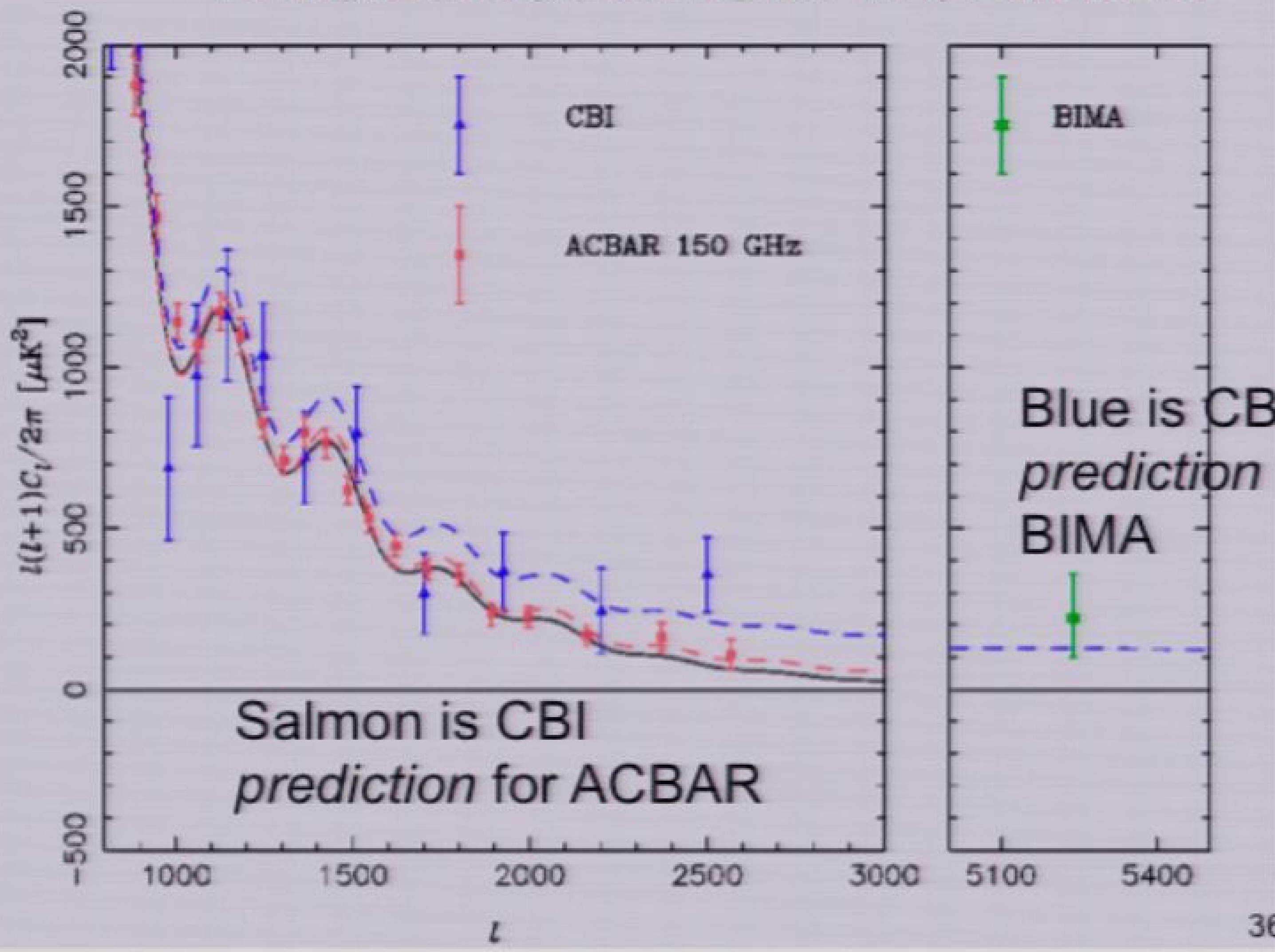
JLS et al., arXiv:0901.4540

High-ℓ Excess

- Fit 3 component model directly to CBI data (not to power spectrum).
- 2 CMB components (ell<400, ell>400) and an SZ template (Bond et al. or KS). Full parameter search, CBI sees 2.6+/-1 times KS template @σ_8=0.8 over primary.
- Each field sees at least KS expected level, all consistent with mean.
- Broad consistency among high-ℓ experiments - CBI, ACBAR@150, BIMA@30, SZA@30, QUaD @100,150 (2 pipelines).

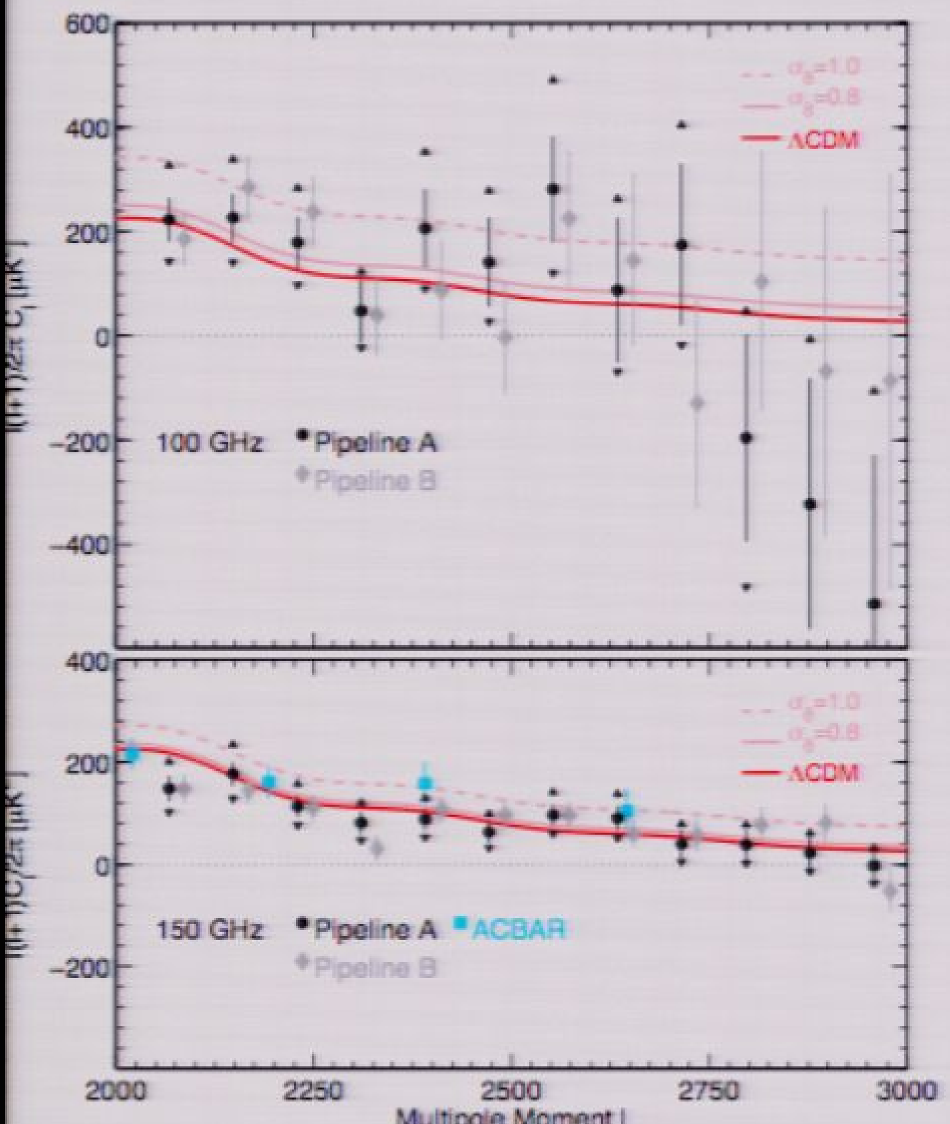
35

High-ell Zoom
What about ACBAR/BIMA?



36

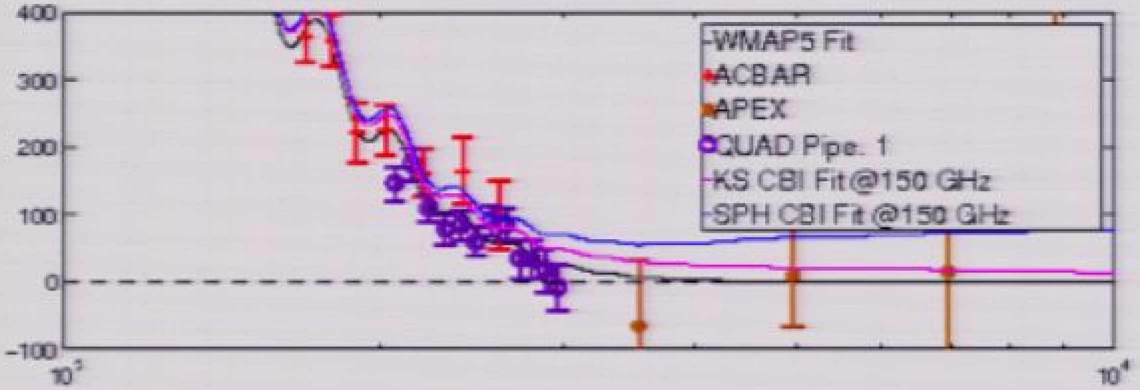
CBI Predictions, New QUaD

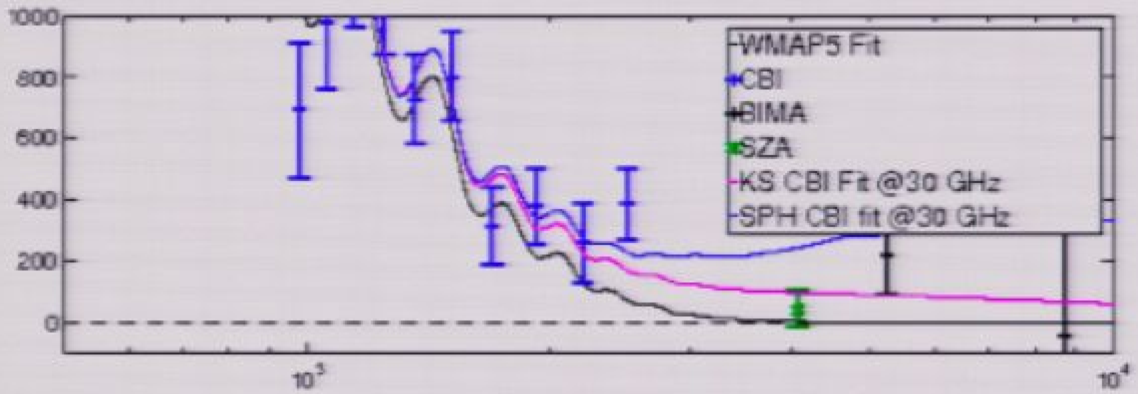


ℓ	30 GHz KS	100 GHz KS	150 GHz KS
500	48.6 ± 18.5	29.0 ± 11.0	11.6 ± 4.4
1000	73.3 ± 27.9	43.6 ± 16.6	17.4 ± 6.6
1500	87.8 ± 33.4	52.3 ± 19.9	20.9 ± 8.0
2000	94.2 ± 35.9	56.1 ± 21.4	22.4 ± 8.5
2500	96.2 ± 36.6	57.3 ± 21.8	22.9 ± 8.7
3000	96.2 ± 36.7	57.3 ± 21.8	22.9 ± 8.7
4000	92.4 ± 35.2	55.1 ± 21.0	22.0 ± 8.4
5000	86.2 ± 32.8	51.4 ± 19.6	20.5 ± 7.8
6000	80.3 ± 30.6	47.9 ± 18.2	19.1 ± 7.3
8000	67.4 ± 25.7	40.1 ± 15.3	16.0 ± 6.1

30 GHz SPH	100 GHz SPH	150 GHz SPH
24.3 ± 8.3	14.5 ± 4.9	5.8 ± 2.0
52.5 ± 17.8	31.3 ± 10.6	12.5 ± 4.2
94.2 ± 32.0	56.1 ± 19.1	22.4 ± 7.6
138.2 ± 46.9	82.3 ± 28.0	32.9 ± 11.2
151.8 ± 51.5	90.4 ± 30.7	36.1 ± 12.3
189.3 ± 64.3	112.8 ± 38.3	45.0 ± 15.3
232.9 ± 79.1	138.8 ± 47.1	55.4 ± 18.8
280.4 ± 95.2	167.0 ± 56.7	66.7 ± 22.7
294.0 ± 99.9	175.2 ± 59.5	70.0 ± 23.8
316.9 ± 107.6	188.8 ± 64.1	75.4 ± 25.6

Zoom W/SZA, others





SZA has recently released PS @ell~4000, 30 GHz. No detection of power, but consistent with CBI at 1-sigma (green point).

APEX last night (brown).

Black now CMB, magenta CMB+KS SZ from CBI+WMAP5, full MCMC runs.

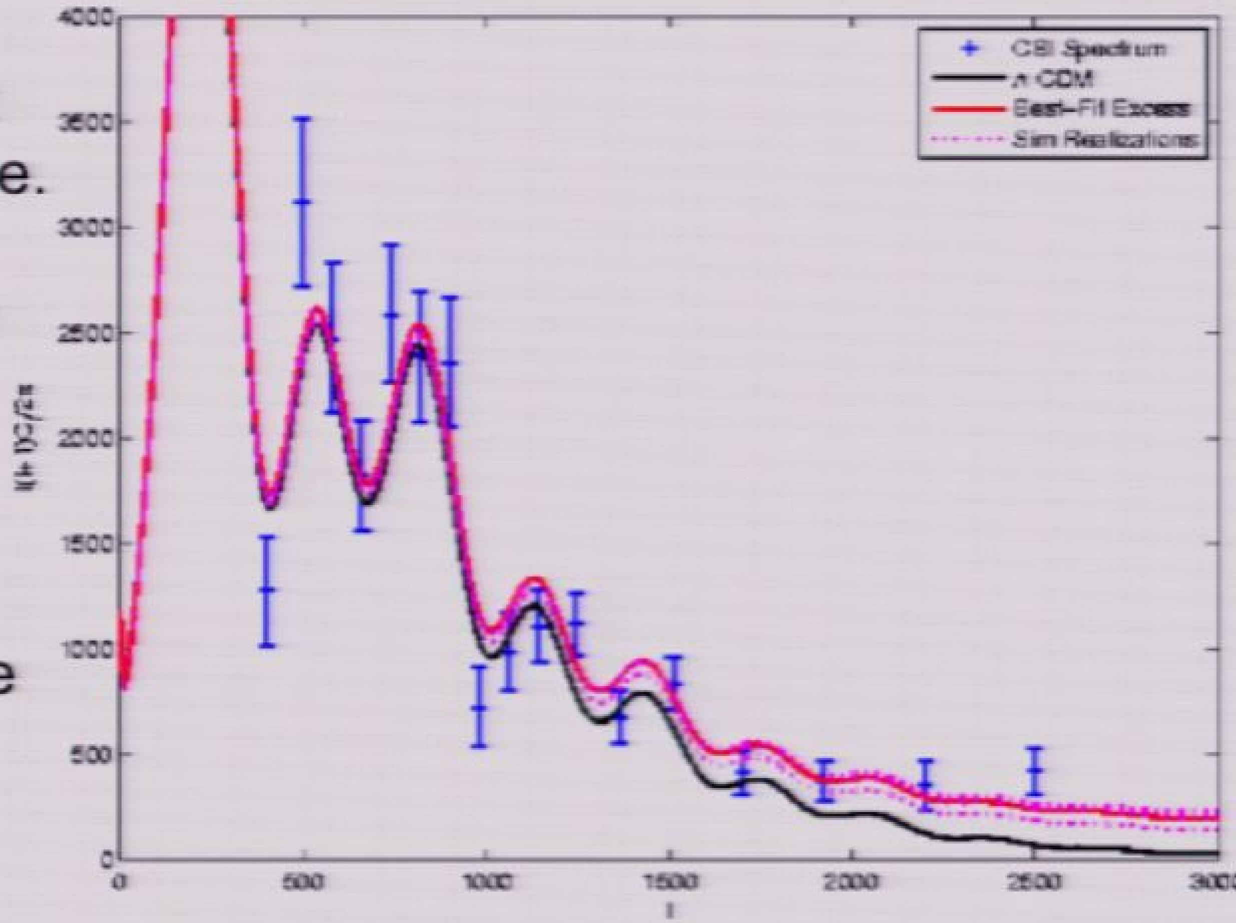
Proper Comparison Needs NG

- Most everything non-Gaussian at high-ℓ.
- Point sources are Poisson - CBI uncertainty ~1/3, dominated by Poisson nature of sources.
- Clusters also NG. NG SZ scatter in CBI ~20% (~100 sq. degrees @s8=1.0) vs. ~4% if Gaussian. SZA level uncertain by 50%!
- Consistency checks presented use Gaussian errors, overemphasizes.

Non-Gaussianity of Cluster Signal

Run 10 10 degree n-body sims by White et al. through CBI pipeline. Scatter is 20%, to be folded into uncertainty converting excess amplitude to σ_8.

Sims run with $\sigma_8 = 1.0$, so underestimates true scatter.



Better sims shortly, alas not done for this talk.
Need large areas to cover CBI fields.

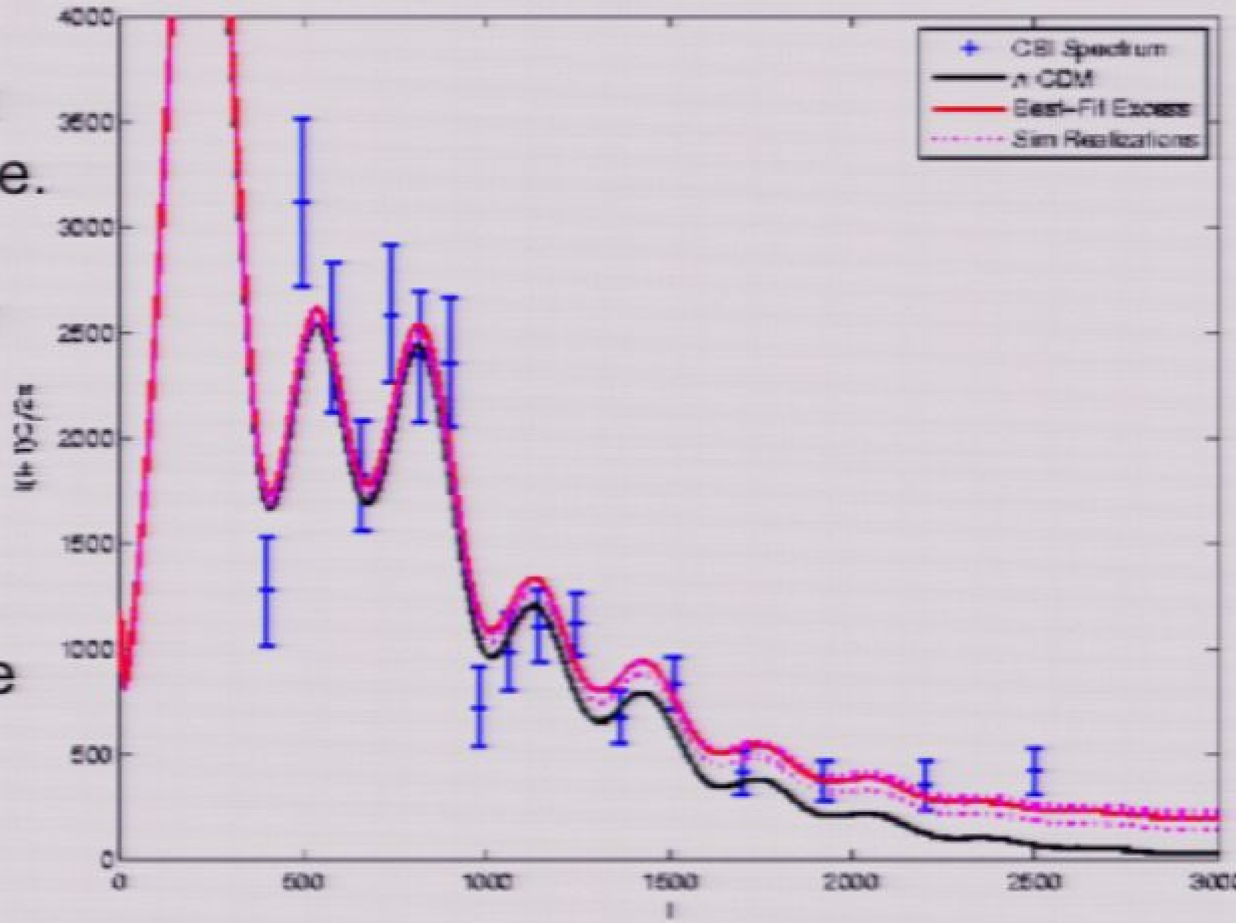
Proper Comparison Needs NG

- Most everything non-Gaussian at high-ℓ.
- Point sources are Poisson - CBI uncertainty ~1/3, dominated by Poisson nature of sources.
- Clusters also NG. NG SZ scatter in CBI ~20% (~100 sq. degrees @s8=1.0) vs. ~4% if Gaussian. SZA level uncertain by 50%!
- Consistency checks presented use Gaussian errors, overemphasizes.

Non-Gaussianity of Cluster Signal

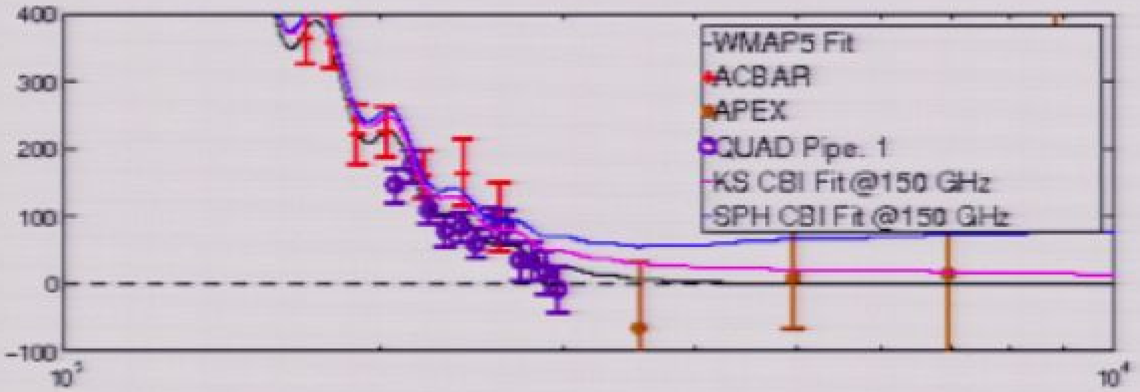
Run 10 10 degree n-body sims by White et al. through CBI pipeline. Scatter is 20%, to be folded into uncertainty converting excess amplitude to σ_8.

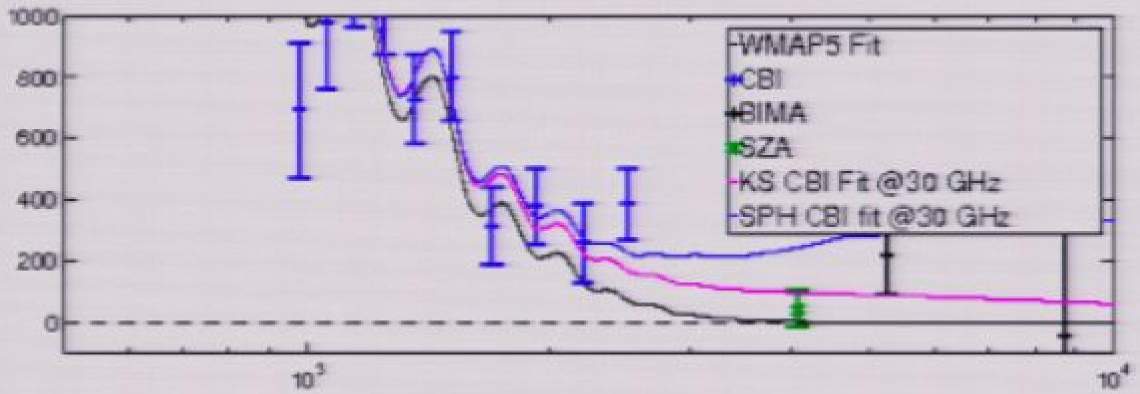
Sims run with $\sigma_8 = 1.0$, so underestimates true scatter.



Better sims shortly, alas not done for this talk.
Need large areas to cover CBI fields.

Zoom W/SZA, others





SZA has recently released PS @ell~4000, 30 GHz. No detection of power, but consistent with CBI at 1-sigma (green point).

APEX last night (brown).

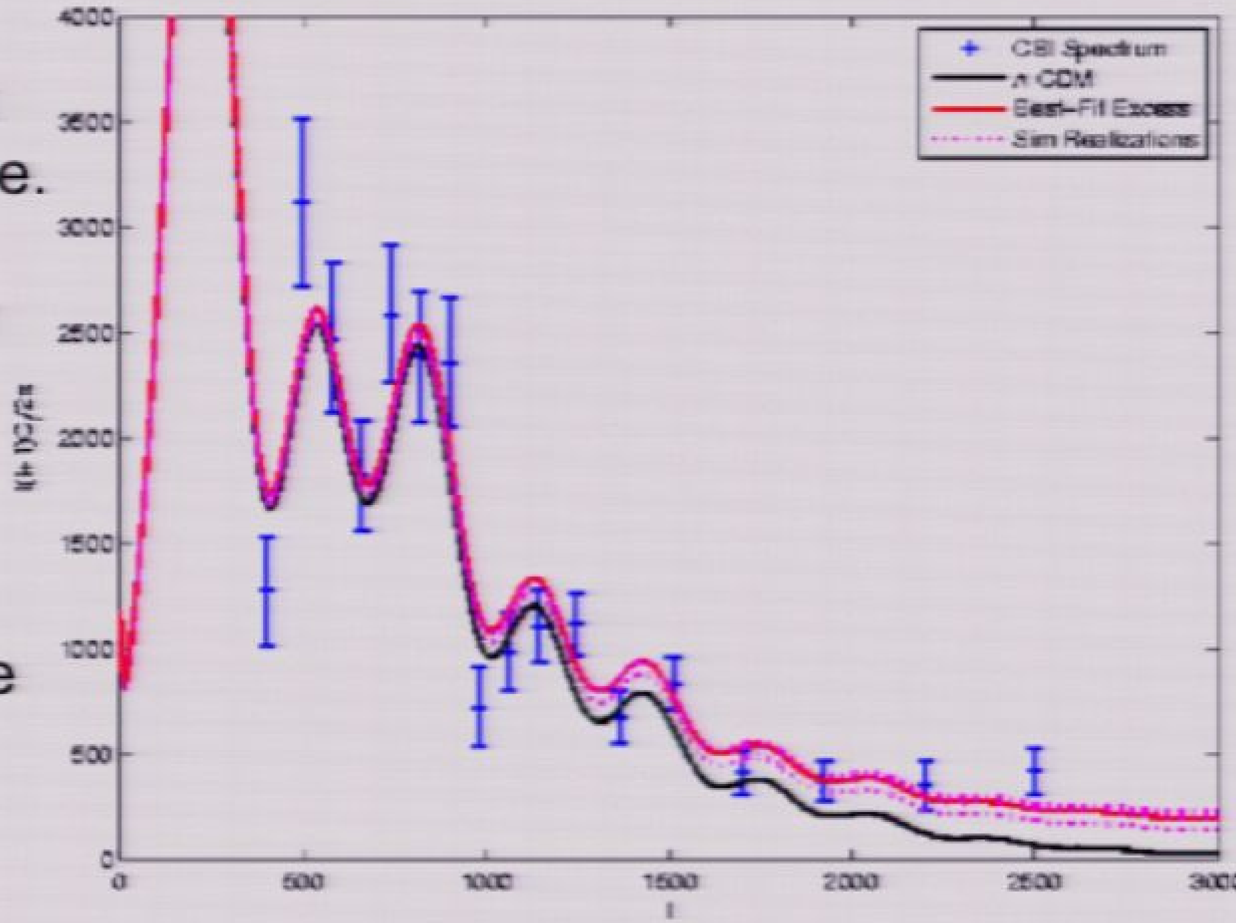
Black now CMB, magenta CMB+KS SZ from CBI+WMAP5, full MCMC runs.

38

Non-Gaussianity of Cluster Signal

Run 10 10 degree n-body sims by White et al. through CBI pipeline. Scatter is 20%, to be folded into uncertainty converting excess amplitude to σ_8.

Sims run with $\sigma_8 = 1.0$, so underestimates true scatter.

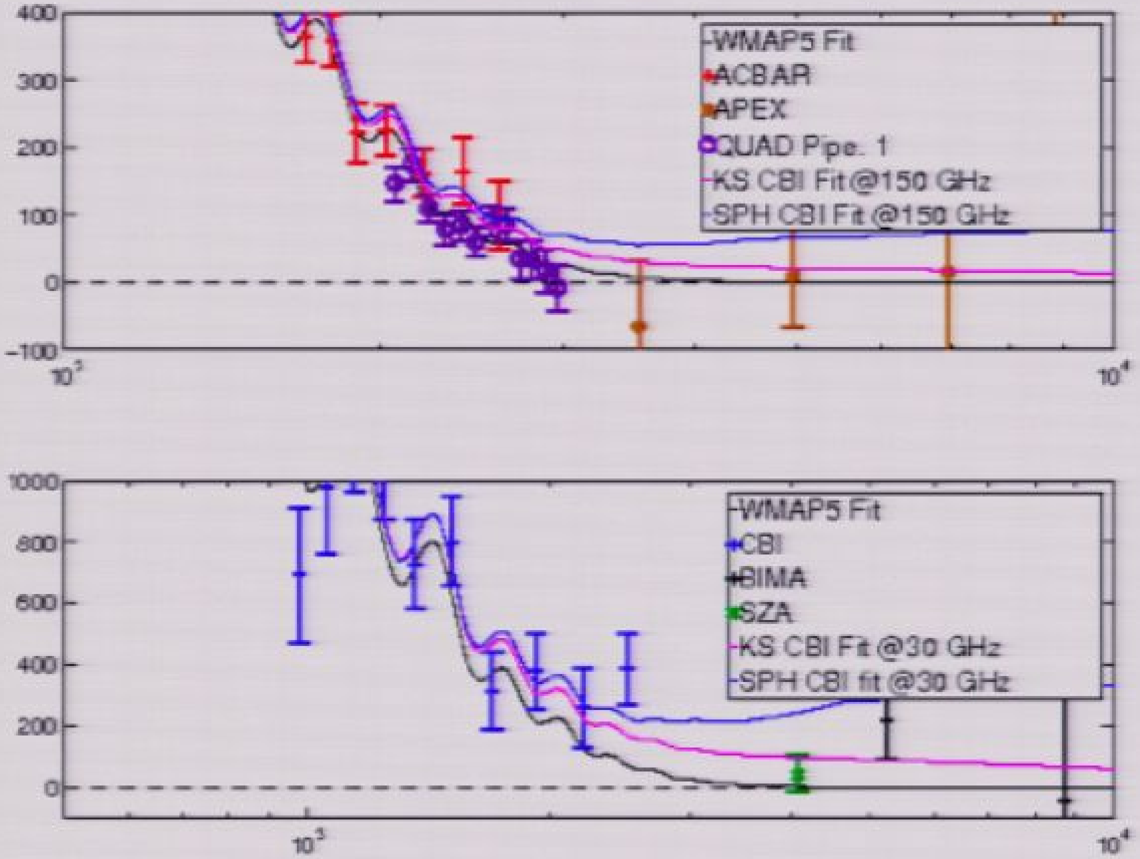


Better sims shortly, alas not done for this talk.
Need large areas to cover CBI fields.

Proper Comparison Needs NG

- Most everything non-Gaussian at high-ℓ.
- Point sources are Poisson - CBI uncertainty ~1/3, dominated by Poisson nature of sources.
- Clusters also NG. NG SZ scatter in CBI ~20% (~100 sq. degrees @s8=1.0) vs. ~4% if Gaussian. SZA level uncertain by 50%!
- Consistency checks presented use Gaussian errors, overemphasizes.

Zoom W/SZA, others

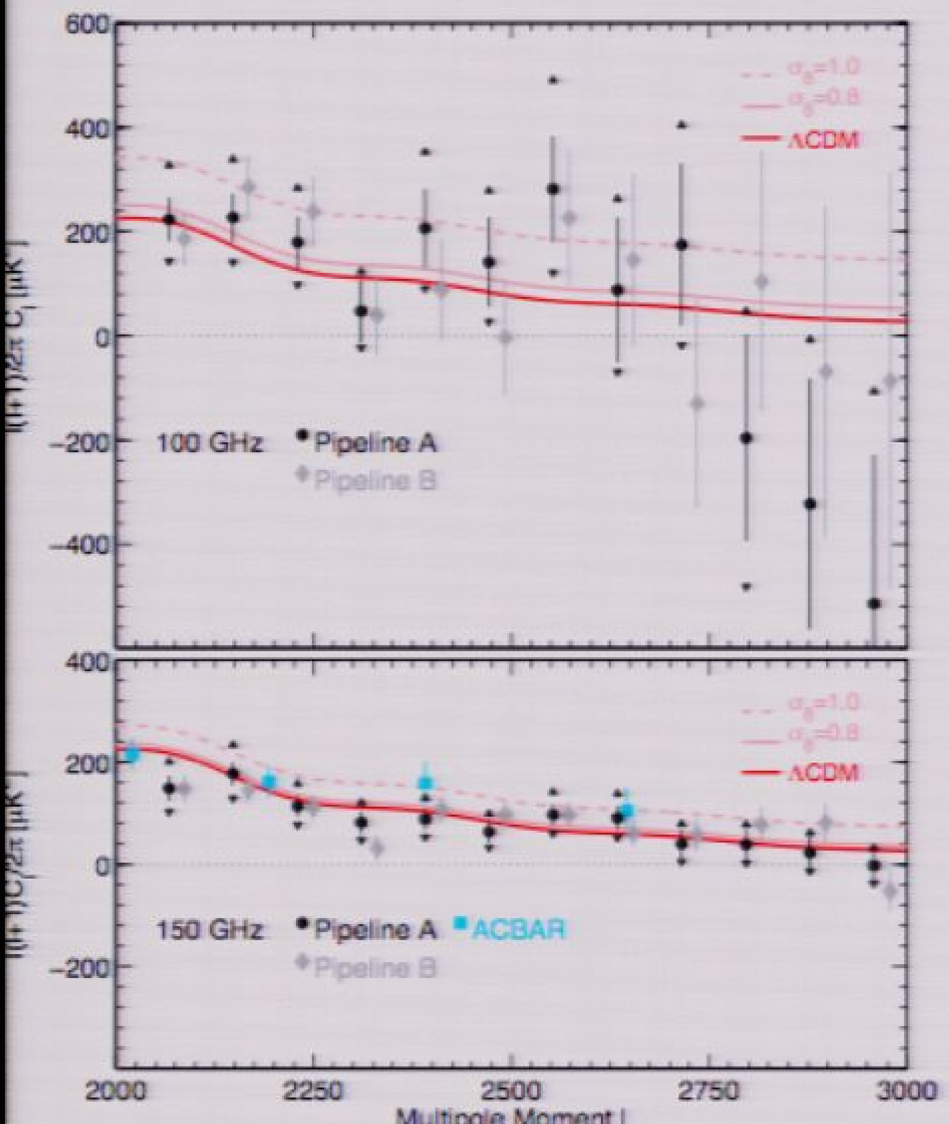


SZA has recently released PS @ell~4000, 30 GHz. No detection of power, but consistent with CBI at 1-sigma (green point).

APEX last night (brown).

Black now CMB, magenta CMB+KS SZ from CBI+WMAP5, full MCMC runs.

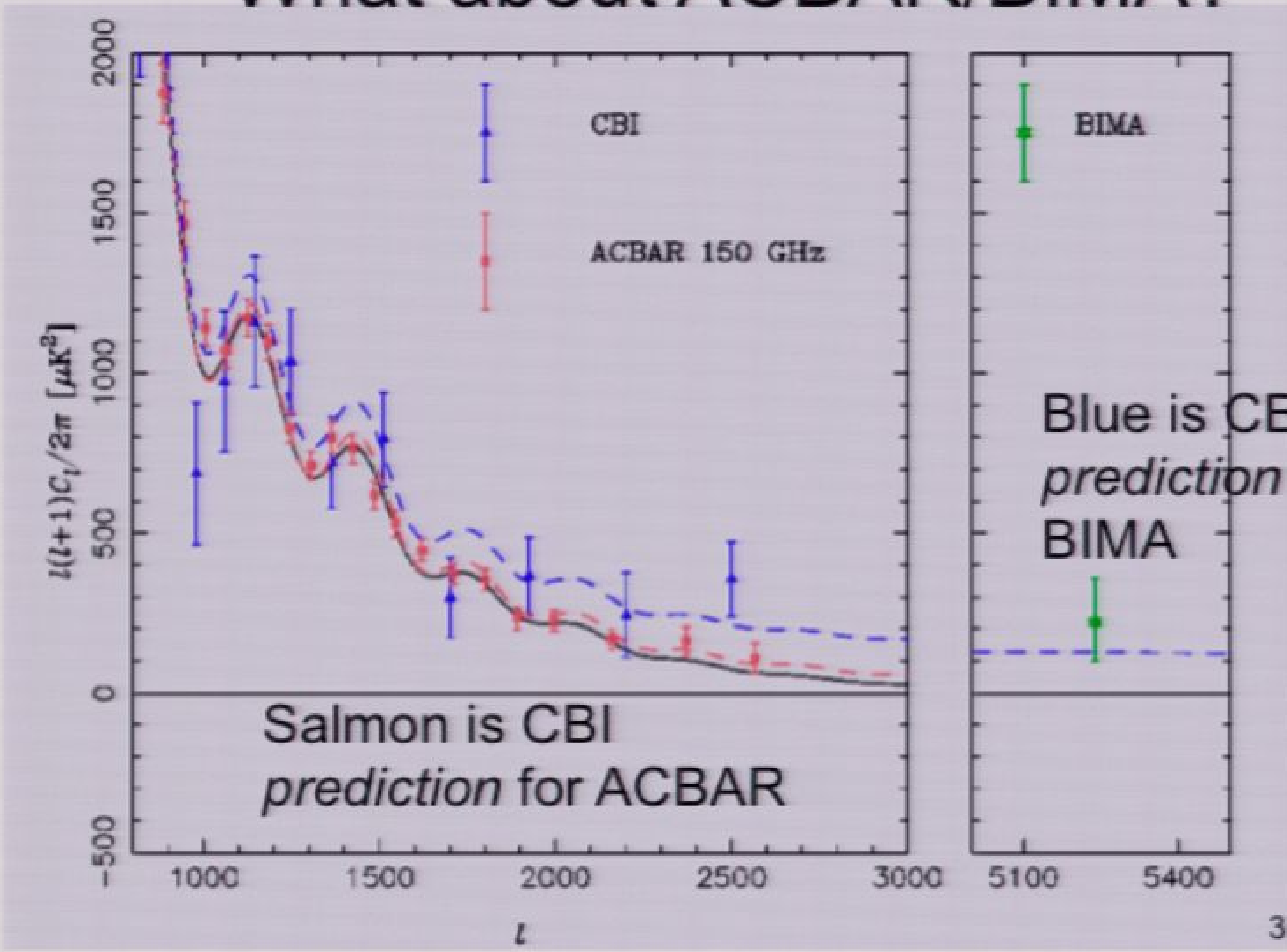
CBI Predictions, New QUaD



ℓ	30 GHz KS	100 GHz KS	150 GHz KS
500	48.6 ± 18.5	29.0 ± 11.0	11.6 ± 4.4
1000	73.3 ± 27.9	43.6 ± 16.6	17.4 ± 6.6
1500	87.8 ± 33.4	52.3 ± 19.9	20.9 ± 8.0
2000	94.2 ± 35.9	56.1 ± 21.4	22.4 ± 8.5
2500	96.2 ± 36.6	57.3 ± 21.8	22.9 ± 8.7
3000	96.2 ± 36.7	57.3 ± 21.8	22.9 ± 8.7
4000	92.4 ± 35.2	55.1 ± 21.0	22.0 ± 8.4
5000	86.2 ± 32.8	51.4 ± 19.6	20.5 ± 7.8
6000	80.3 ± 30.6	47.9 ± 18.2	19.1 ± 7.3
8000	67.4 ± 25.7	40.1 ± 15.3	16.0 ± 6.1

30 GHz SPH	100 GHz SPH	150 GHz SPH
24.3 ± 8.3	14.5 ± 4.9	5.8 ± 2.0
52.5 ± 17.8	31.3 ± 10.6	12.5 ± 4.2
94.2 ± 32.0	56.1 ± 19.1	22.4 ± 7.6
138.2 ± 46.9	82.3 ± 28.0	32.9 ± 11.2
151.8 ± 51.5	90.4 ± 30.7	36.1 ± 12.3
189.3 ± 64.3	112.8 ± 38.3	45.0 ± 15.3
232.9 ± 79.1	138.8 ± 47.1	55.4 ± 18.8
280.4 ± 95.2	167.0 ± 56.7	66.7 ± 22.7
294.0 ± 99.9	175.2 ± 59.5	70.0 ± 23.8
316.9 ± 107.6	188.8 ± 64.1	75.4 ± 25.6

High-ell Zoom
What about ACBAR/BIMA?

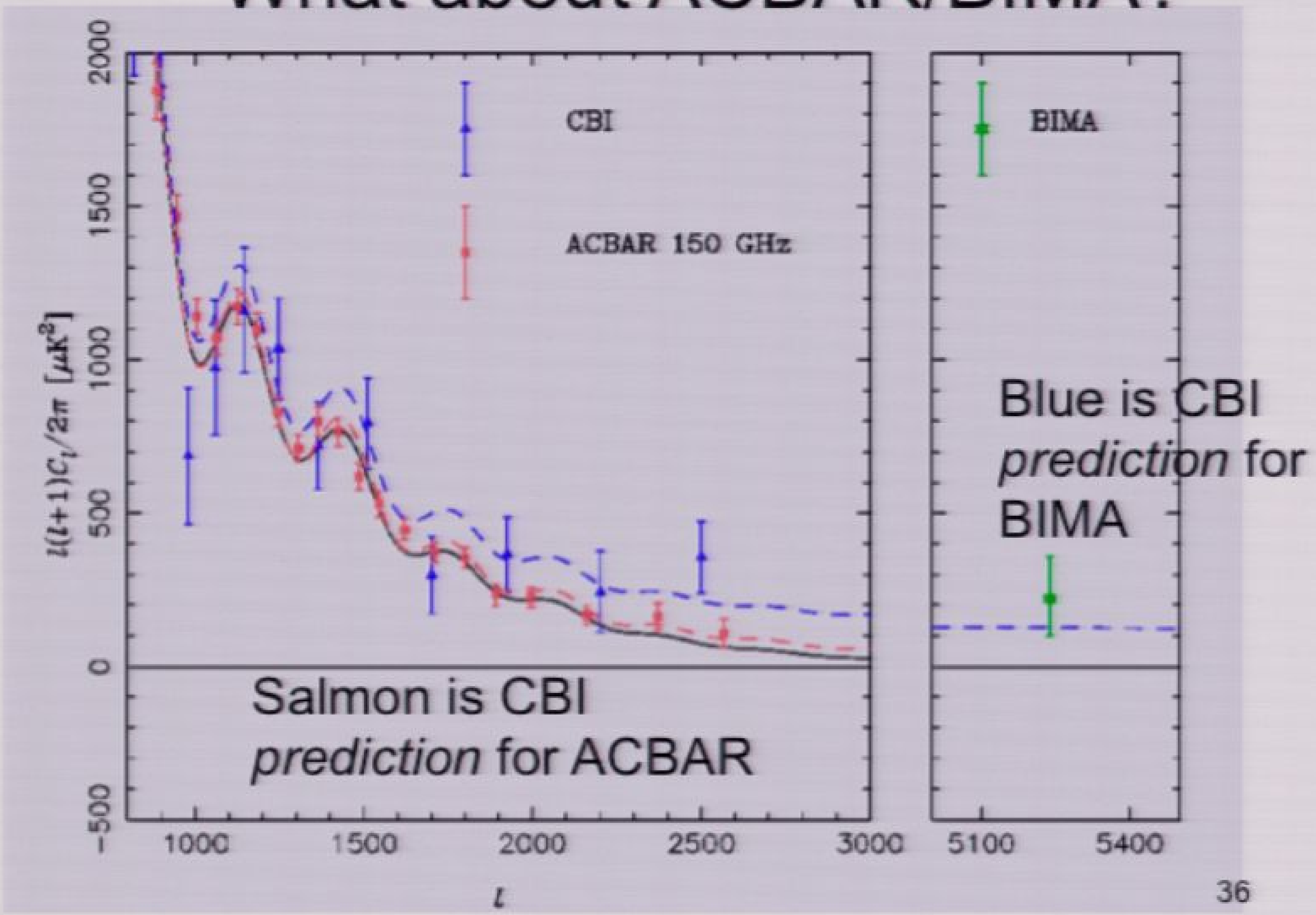


36

High-ℓ Excess

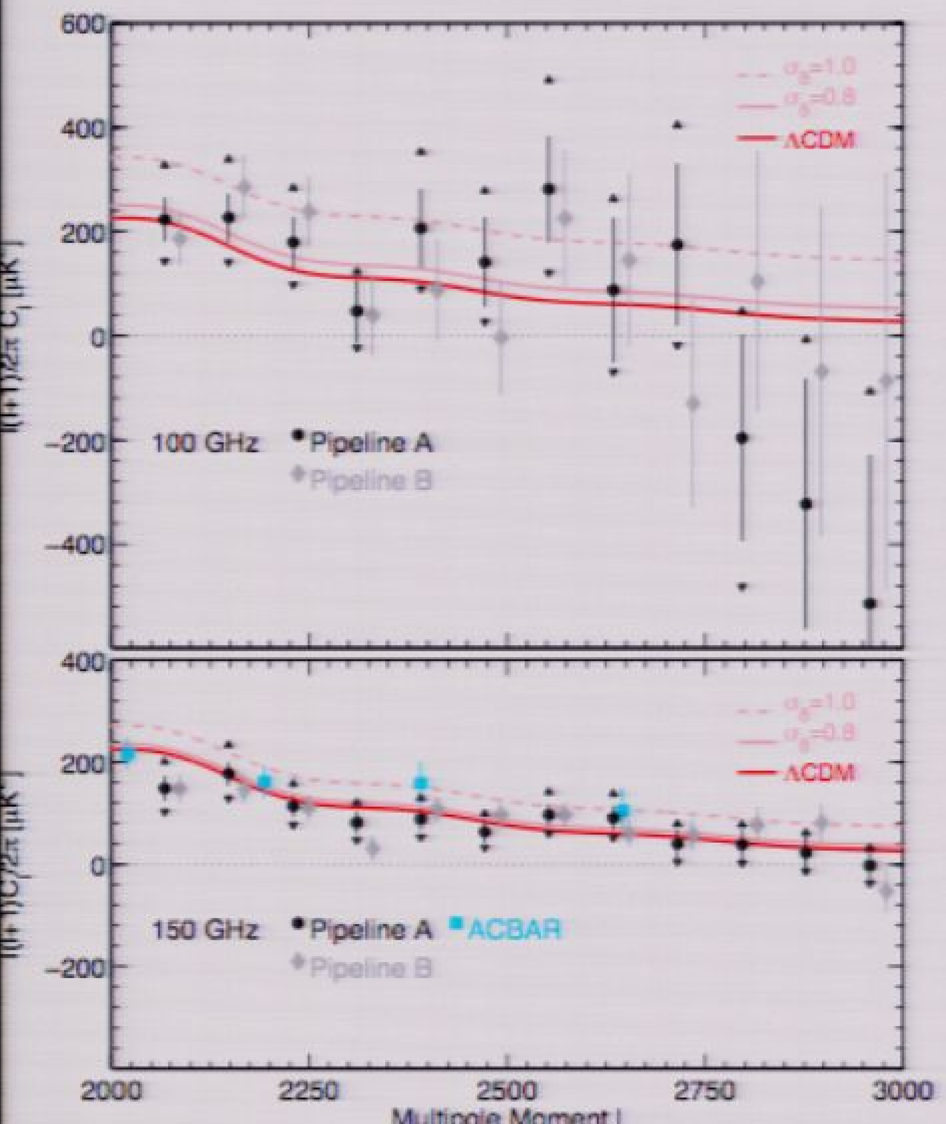
- Fit 3 component model directly to CBI data (not to power spectrum).
- 2 CMB components (ell<400, ell>400) and an SZ template (Bond et al. or KS). Full parameter search, CBI sees 2.6+/-1 times KS template @σ_8=0.8 over primary.
- Each field sees at least KS expected level, all consistent with mean.
- Broad consistency among high-ℓ experiments - CBI, ACBAR@150, BIMA@30, SZA@30, QUaD @100,150 (2 pipelines).

High-ell Zoom
What about ACBAR/BIMA?



36

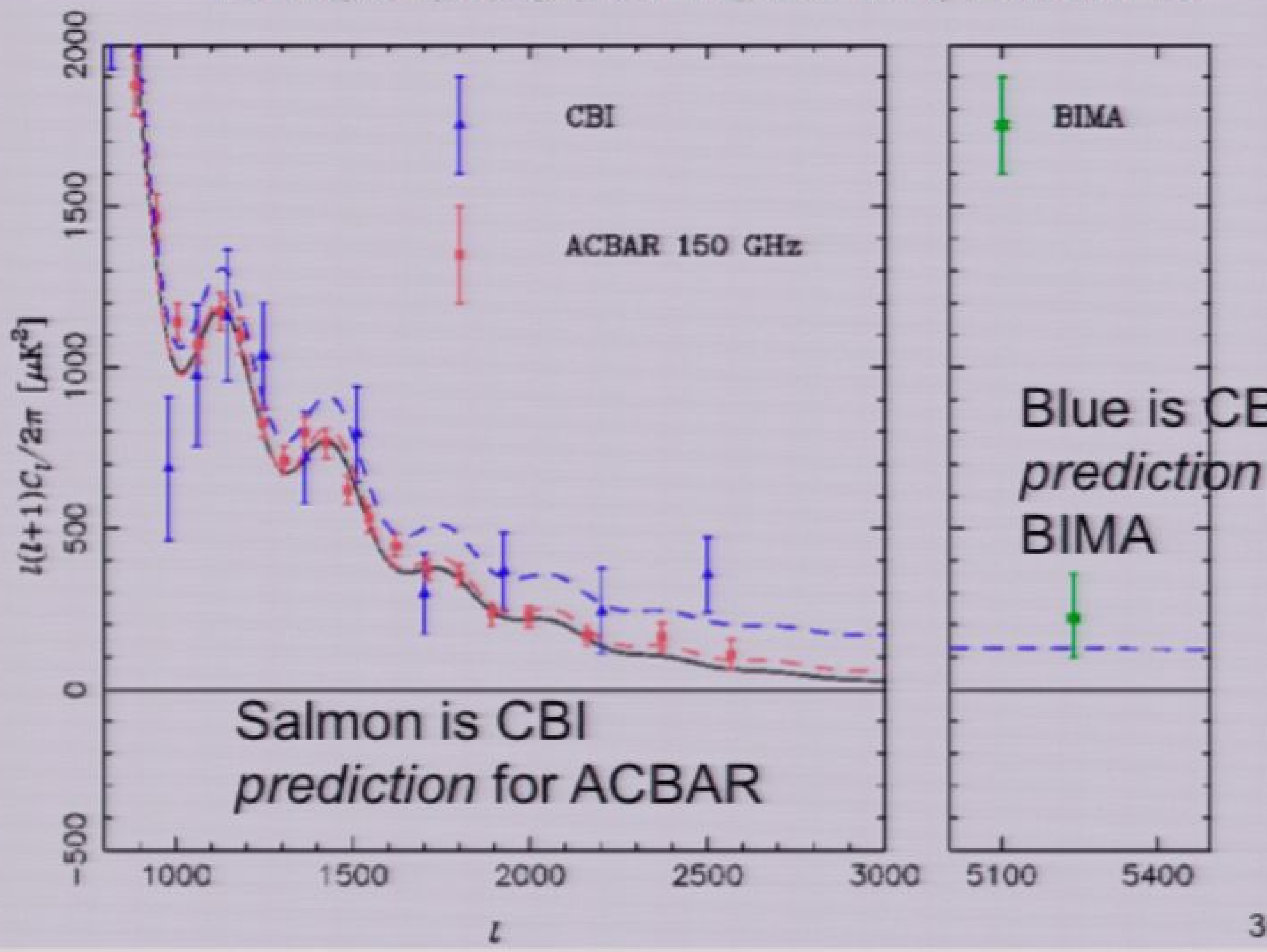
CBI Predictions, New QUaD



ℓ	30 GHz KS	100 GHz KS	150 GHz KS
500	48.6 ± 18.5	29.0 ± 11.0	11.6 ± 4.4
1000	73.3 ± 27.9	43.6 ± 16.6	17.4 ± 6.6
1500	87.8 ± 33.4	52.3 ± 19.9	20.9 ± 8.0
2000	94.2 ± 35.9	56.1 ± 21.4	22.4 ± 8.5
2500	96.2 ± 36.6	57.3 ± 21.8	22.9 ± 8.7
3000	96.2 ± 36.7	57.3 ± 21.8	22.9 ± 8.7
4000	92.4 ± 35.2	55.1 ± 21.0	22.0 ± 8.4
5000	86.2 ± 32.8	51.4 ± 19.6	20.5 ± 7.8
6000	80.3 ± 30.6	47.9 ± 18.2	19.1 ± 7.3
8000	67.4 ± 25.7	40.1 ± 15.3	16.0 ± 6.1

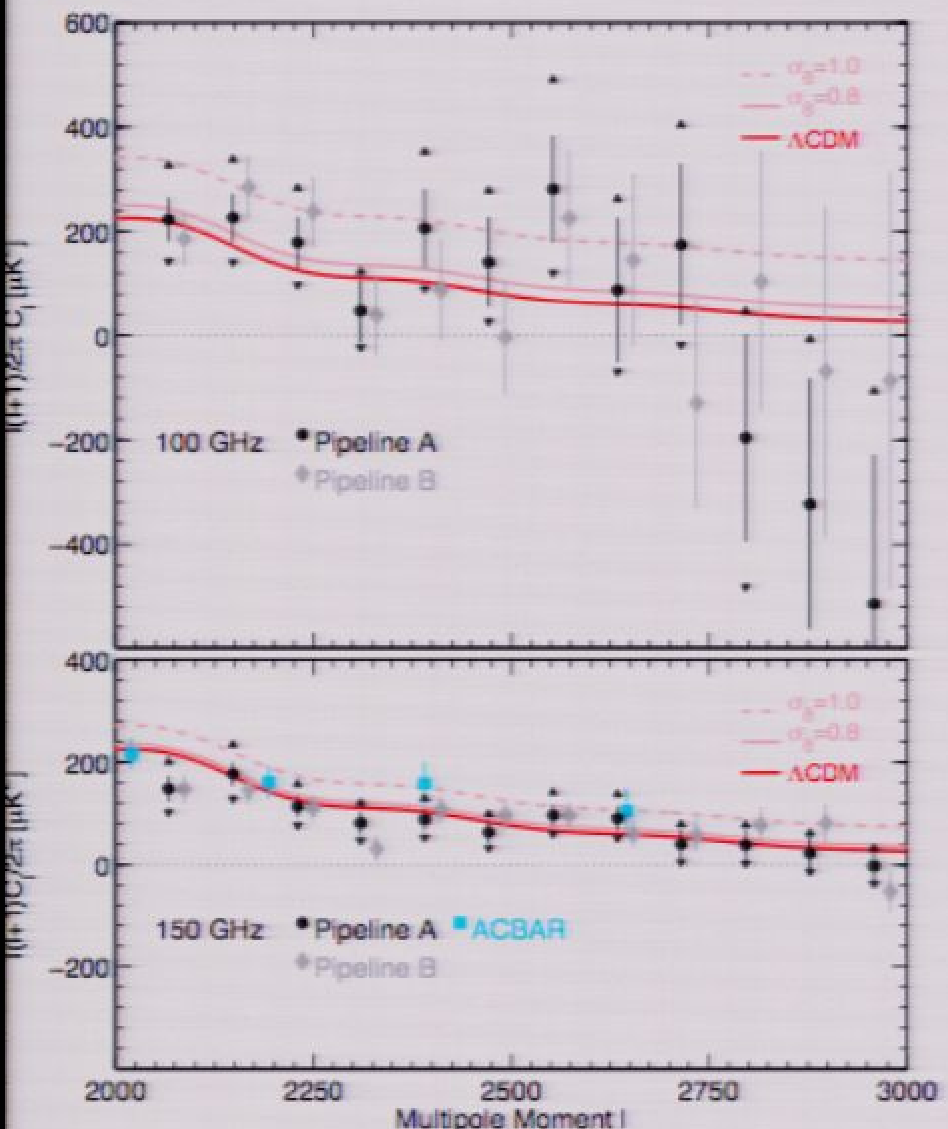
30 GHz SPH	100 GHz SPH	150 GHz SPH
24.3 ± 8.3	14.5 ± 4.9	5.8 ± 2.0
52.5 ± 17.8	31.3 ± 10.6	12.5 ± 4.2
94.2 ± 32.0	56.1 ± 19.1	22.4 ± 7.6
138.2 ± 46.9	82.3 ± 28.0	32.9 ± 11.2
151.8 ± 51.5	90.4 ± 30.7	36.1 ± 12.3
189.3 ± 64.3	112.8 ± 38.3	45.0 ± 15.3
232.9 ± 79.1	138.8 ± 47.1	55.4 ± 18.8
280.4 ± 95.2	167.0 ± 56.7	66.7 ± 22.7
294.0 ± 99.9	175.2 ± 59.5	70.0 ± 23.8
316.9 ± 107.6	188.8 ± 64.1	75.4 ± 25.6

High-ell Zoom
What about ACBAR/BIMA?



36

CBI Predictions, New QUaD



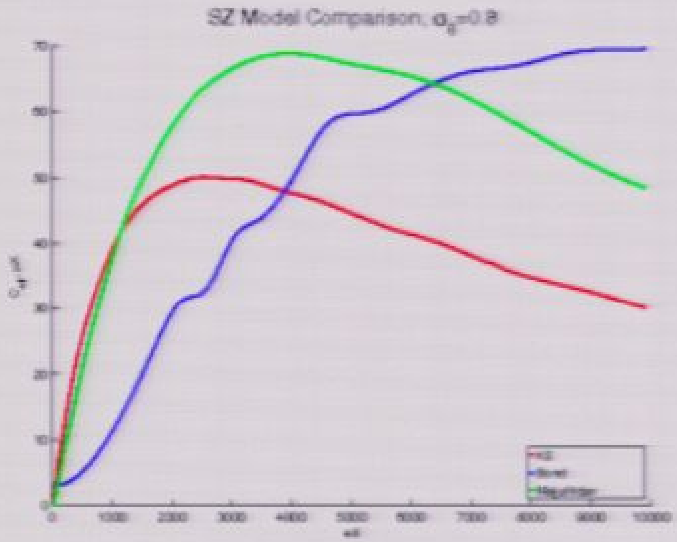
ℓ	30 GHz KS	100 GHz KS	150 GHz KS
500	48.6 ± 18.5	29.0 ± 11.0	11.6 ± 4.4
1000	73.3 ± 27.9	43.6 ± 16.6	17.4 ± 6.6
1500	87.8 ± 33.4	52.3 ± 19.9	20.9 ± 8.0
2000	94.2 ± 35.9	56.1 ± 21.4	22.4 ± 8.5
2500	96.2 ± 36.6	57.3 ± 21.8	22.9 ± 8.7
3000	96.2 ± 36.7	57.3 ± 21.8	22.9 ± 8.7
4000	92.4 ± 35.2	55.1 ± 21.0	22.0 ± 8.4
5000	86.2 ± 32.8	51.4 ± 19.6	20.5 ± 7.8
6000	80.3 ± 30.6	47.9 ± 18.2	19.1 ± 7.3
8000	67.4 ± 25.7	40.1 ± 15.3	16.0 ± 6.1

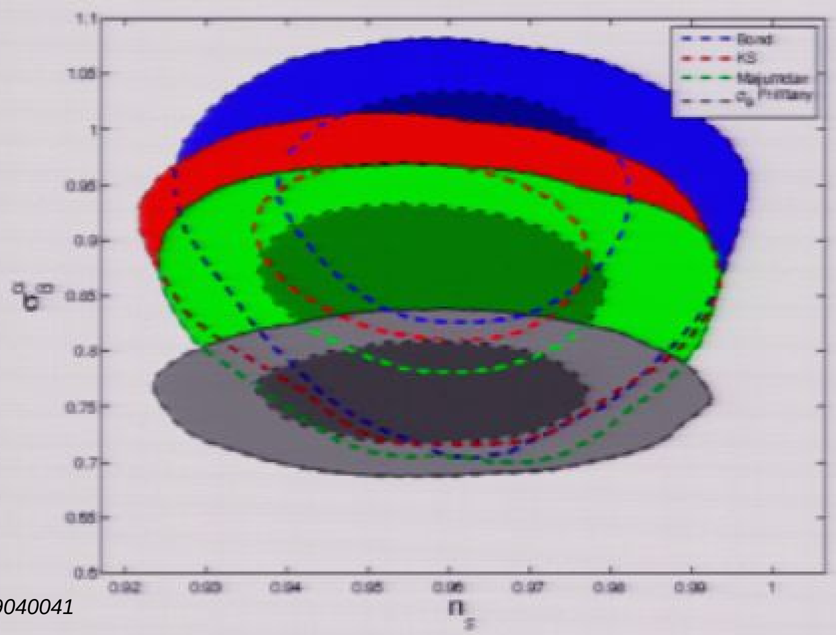
30 GHz SPH	100 GHz SPH	150 GHz SPH
24.3 ± 8.3	14.5 ± 4.9	5.8 ± 2.0
52.5 ± 17.8	31.3 ± 10.6	12.5 ± 4.2
94.2 ± 32.0	56.1 ± 19.1	22.4 ± 7.6
138.2 ± 46.9	82.3 ± 28.0	32.9 ± 11.2
151.8 ± 51.5	90.4 ± 30.7	36.1 ± 12.3
189.3 ± 64.3	112.8 ± 38.3	45.0 ± 15.3
232.9 ± 79.1	138.8 ± 47.1	55.4 ± 18.8
280.4 ± 95.2	167.0 ± 56.7	66.7 ± 22.7
294.0 ± 99.9	175.2 ± 59.5	70.0 ± 23.8
316.9 ± 107.6	188.8 ± 64.1	75.4 ± 25.6

What *Should* We See?

- Predicting rough power spectrum from SZ is easy. Signal from one cluster proportional to electron pressure. By virial theorem, proportional to cluster binding energy. Can read off from sims.
- Detailed very tricky - much baryon physics. Where are all the baryons? How hot are outer regions? No cooling flows - why, and how does that impact SZ? Energy input and feedback?
- Very important to get this nailed down. Will shortly be in regime where dominant uncertainty is theory, not data.
- For example - three different templates on following page (Bond et al. from sims, Komatsu & Seljak semi-analytic, Majumdar similar to KS but matching current SZ scaling).

Template Uncertainty





Considerable uncertainty in converting SZ power spectrum to σ_8. Green=σ_8 from Majumdar, red=σ_8 from KS, blue=σ_8 from sims.

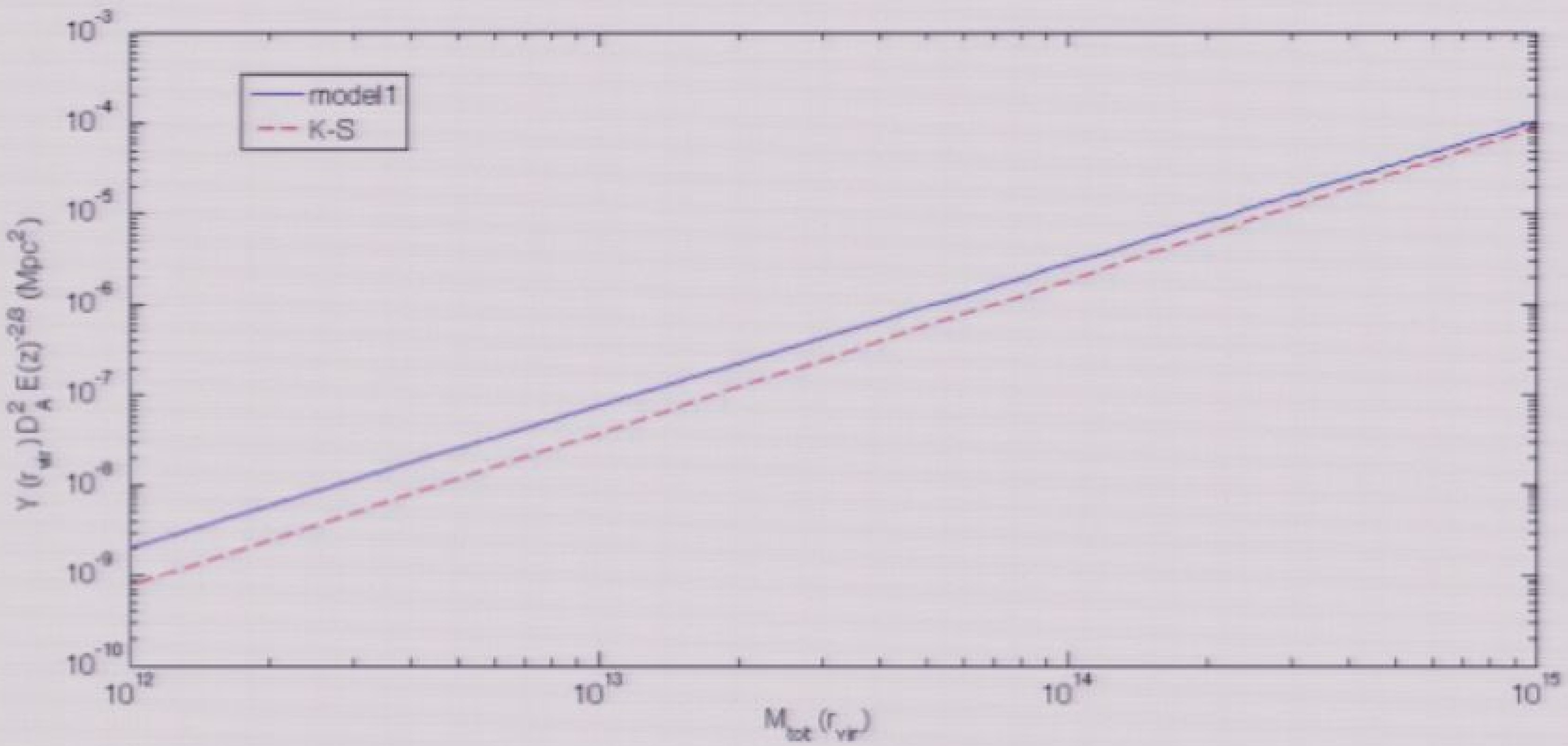
Complicated physics in outer parts of clusters, hard to see in X-rays.

Low mass clusters hotter than expected?

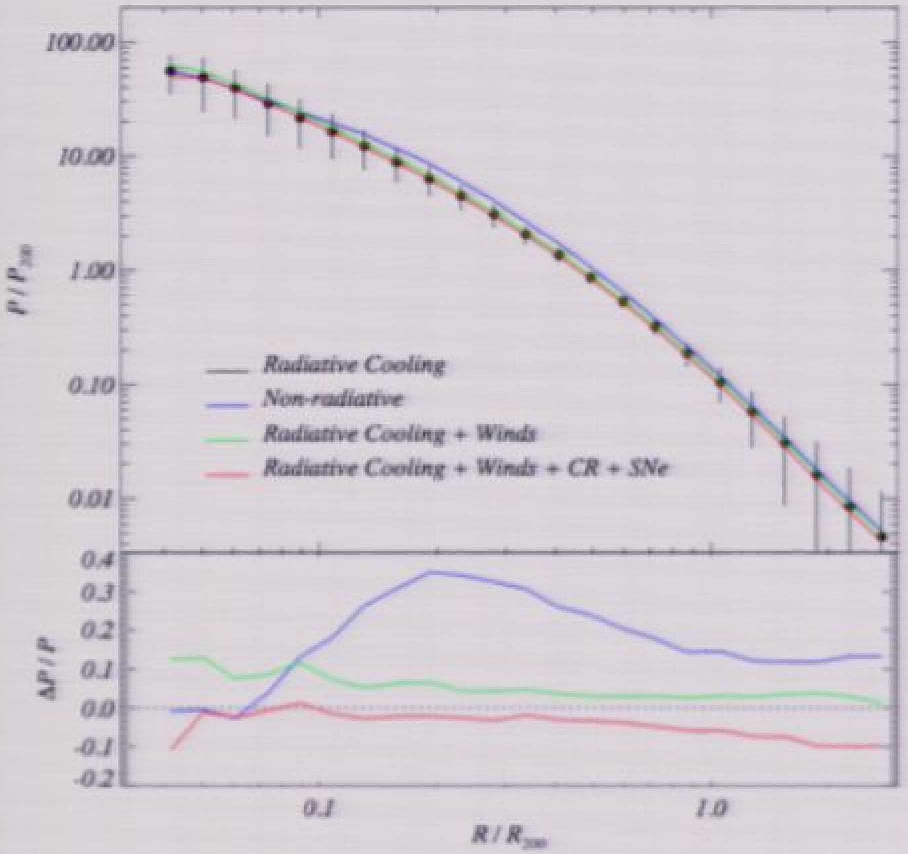
NB - Primary σ_8 pushed down by higher SZ at third peak.

From Subha

Question yesterday: Looked like Subha below KS in pressure, yet power spectrum higher. Plot was for R_{2500}. For R_{vir}, Subha pressure above KS.



On the Way to Better Models



With Battaglia, Pfrommer, and Bond. Do high-resolution cluster sims with as much physics as possible. Get average (in power) pressure form factor of cluster as function of mass, redshift.

Once form factor settled, can integrate over expected cluster counts & Hubble volume to get power spectrum, NG scatter (as function of mass cuts...)

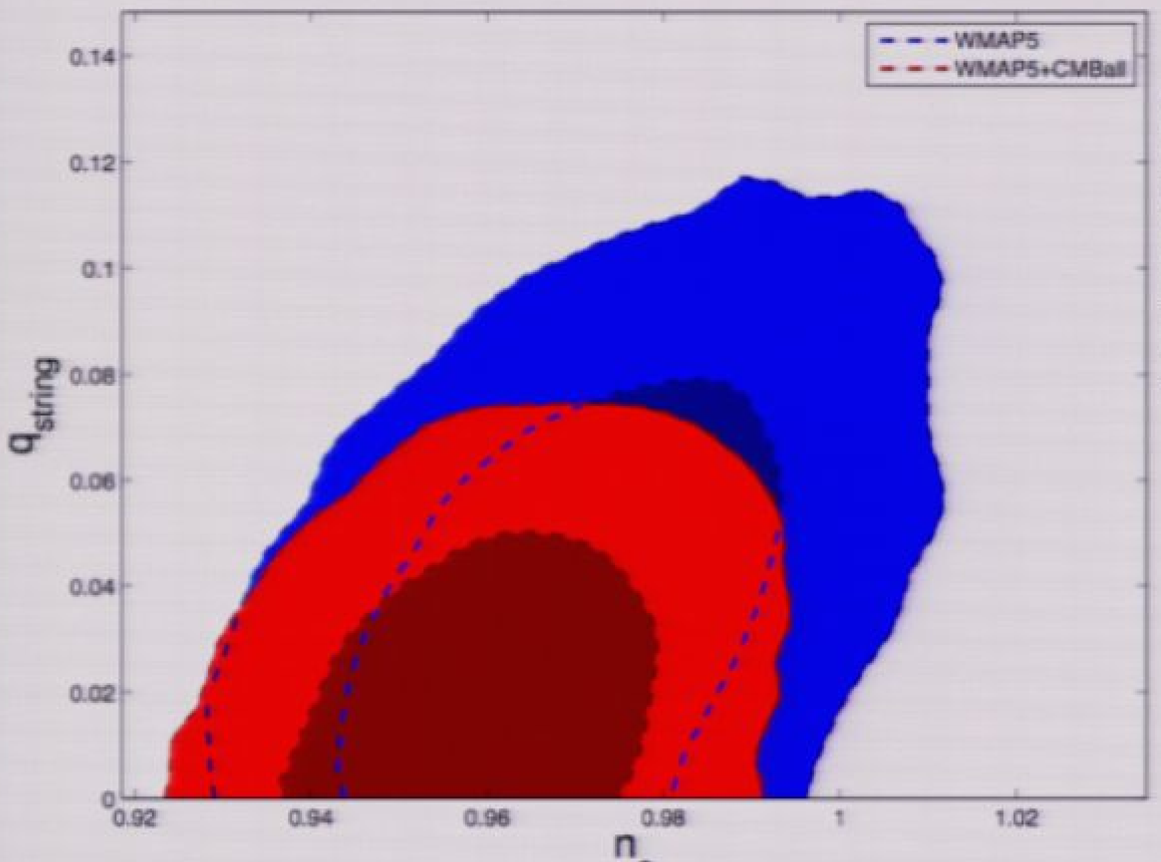
PRELIMINARY (i.e. chains still running): Varying physics gives s8~0.89-0.99 ±~0.06 for our models.

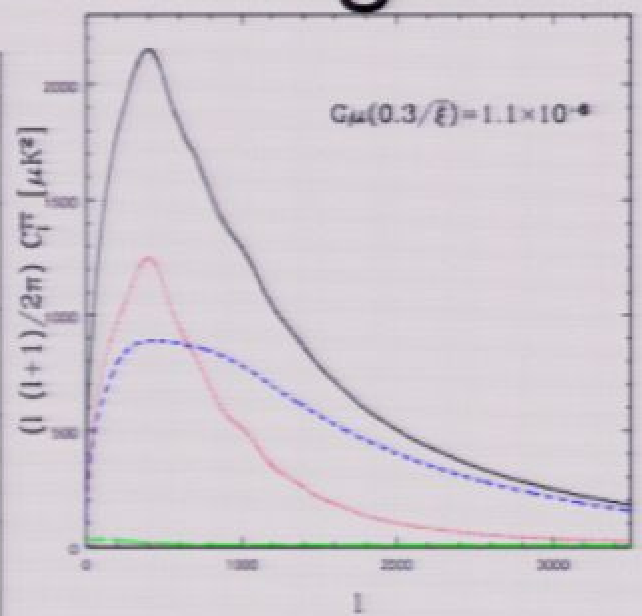
Why Else Should a Theorist Care

(If you think the origin of the high-ℓ signal is boring)

- Can learn qualitatively new things from CMB if can push out to higher ell.
- Must clean SZ, etc. from spectrum to get to fundamentals.
- If so, can constrain cosmic strings, spectral index running, etc.
- Some examples...

Fun With Cosmic Strings





String template from Pogosian et al. for Gμ=1.1e-6 (0804.0810)

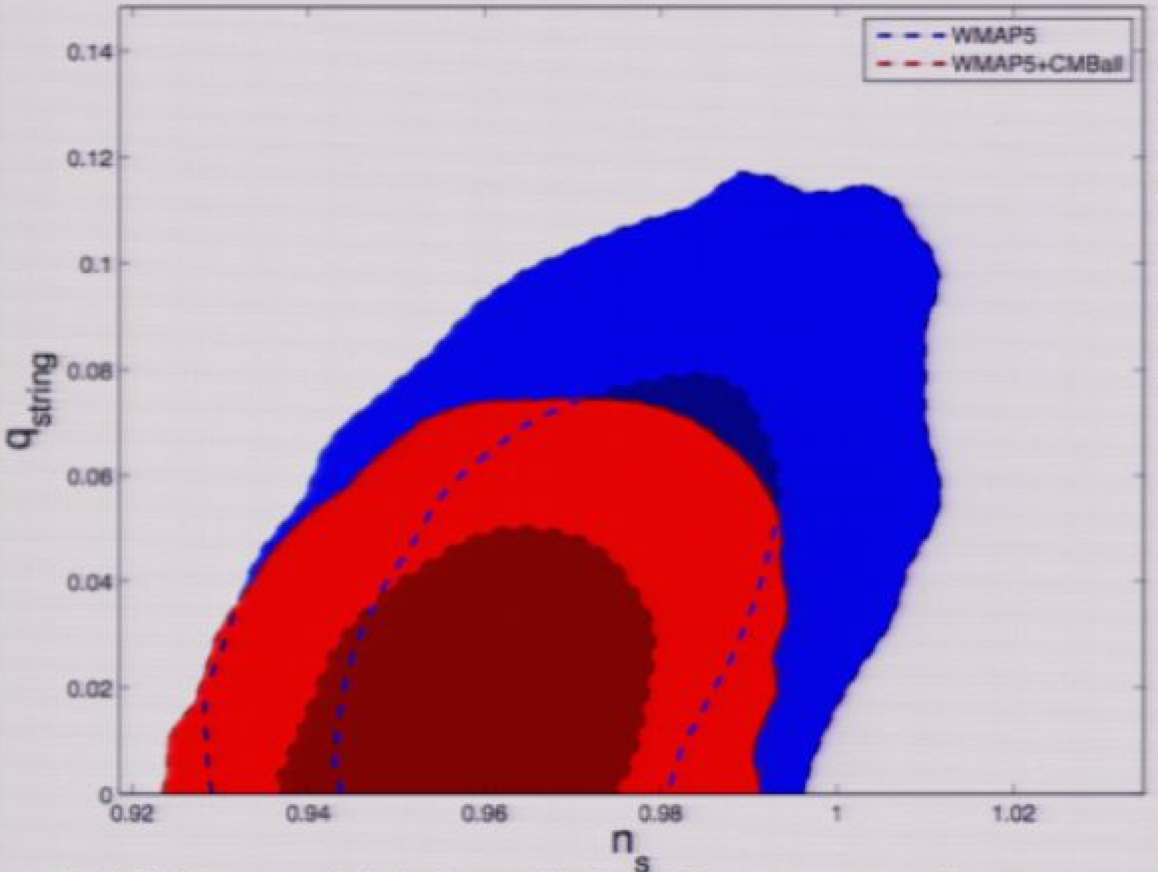
Addition of high-ell CMB constrains string amplitude, helps break string-n_s degeneracy.

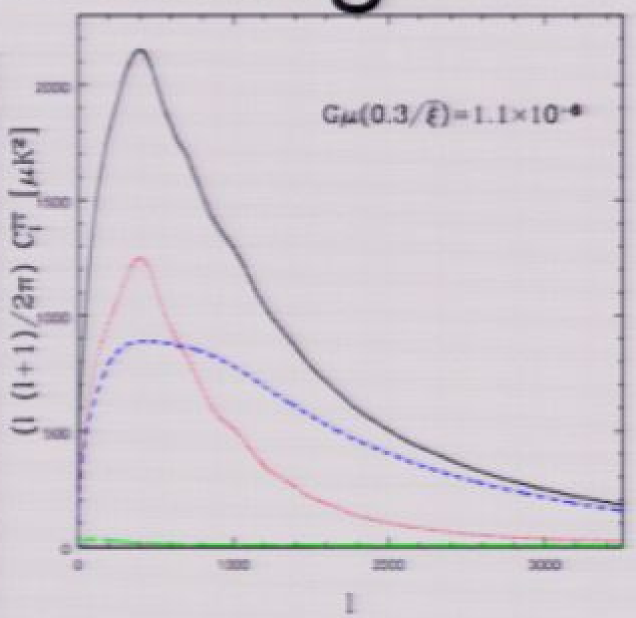
Why Else Should a Theorist Care

(If you think the origin of the high-ℓ signal is boring)

- Can learn qualitatively new things from CMB if can push out to higher ell.
- Must clean SZ, etc. from spectrum to get to fundamentals.
- If so, can constrain cosmic strings, spectral index running, etc.
- Some examples...

Fun With Cosmic Strings





String template from Pogosian et al. for Gμ=1.1e-6 (0804.0810)

Addition of high-ell CMB constrains string amplitude, helps break string-n_s degeneracy.

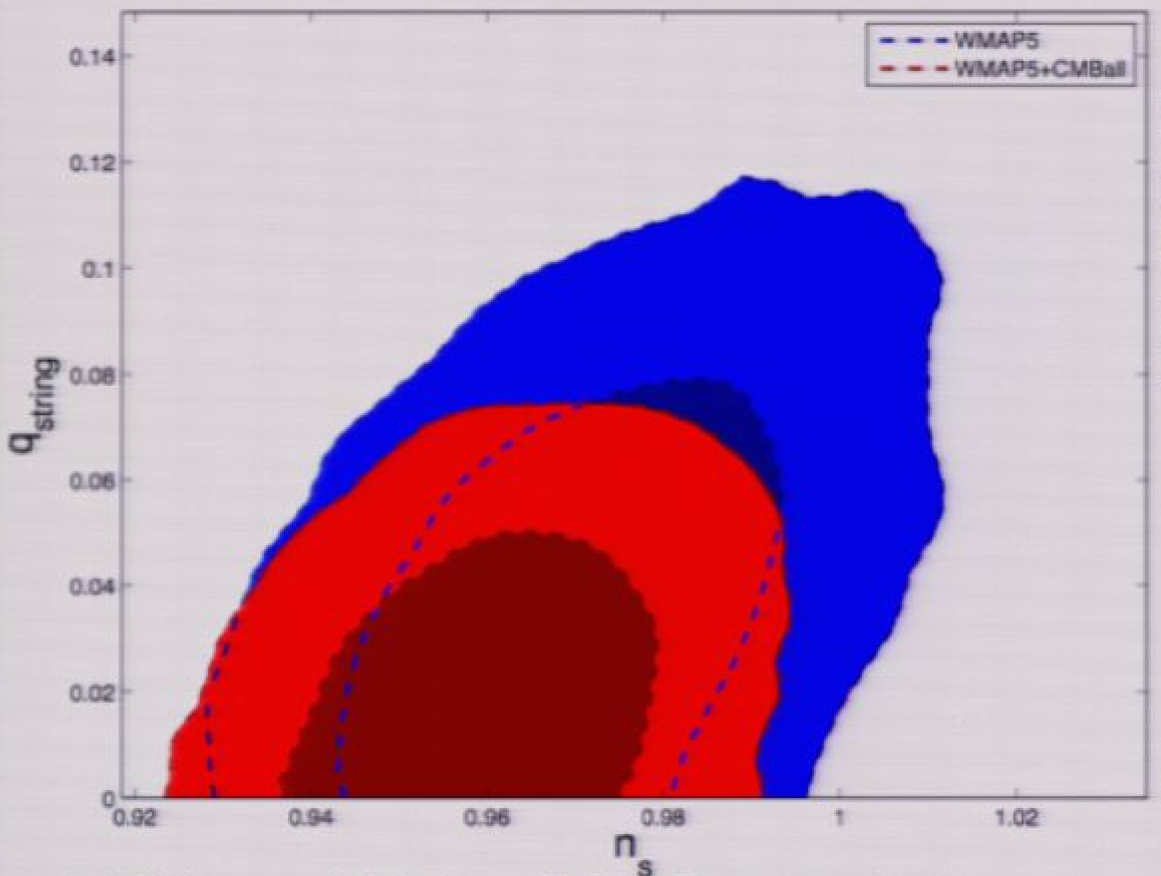
Why Else Should a Theorist Care

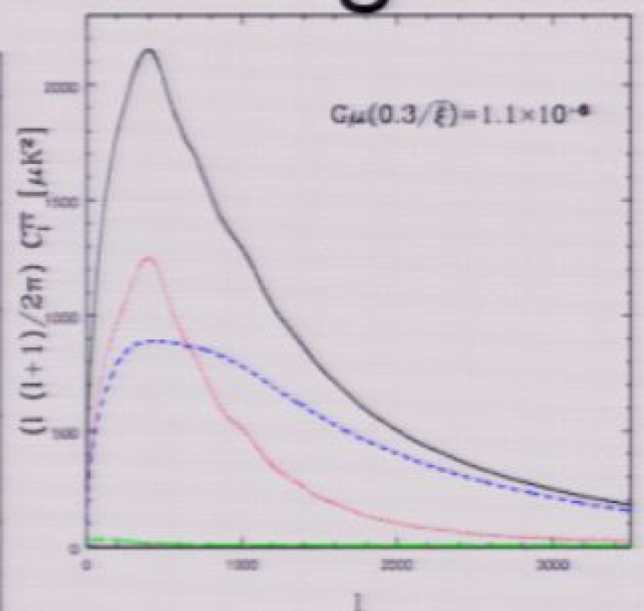
(If you think the origin of the high-ℓ signal is boring)

- Can learn qualitatively new things from CMB if can push out to higher ell.
- Must clean SZ, etc. from spectrum to get to fundamentals.
- If so, can constrain cosmic strings, spectral index running, etc.
- Some examples...

45

Fun With Cosmic Strings



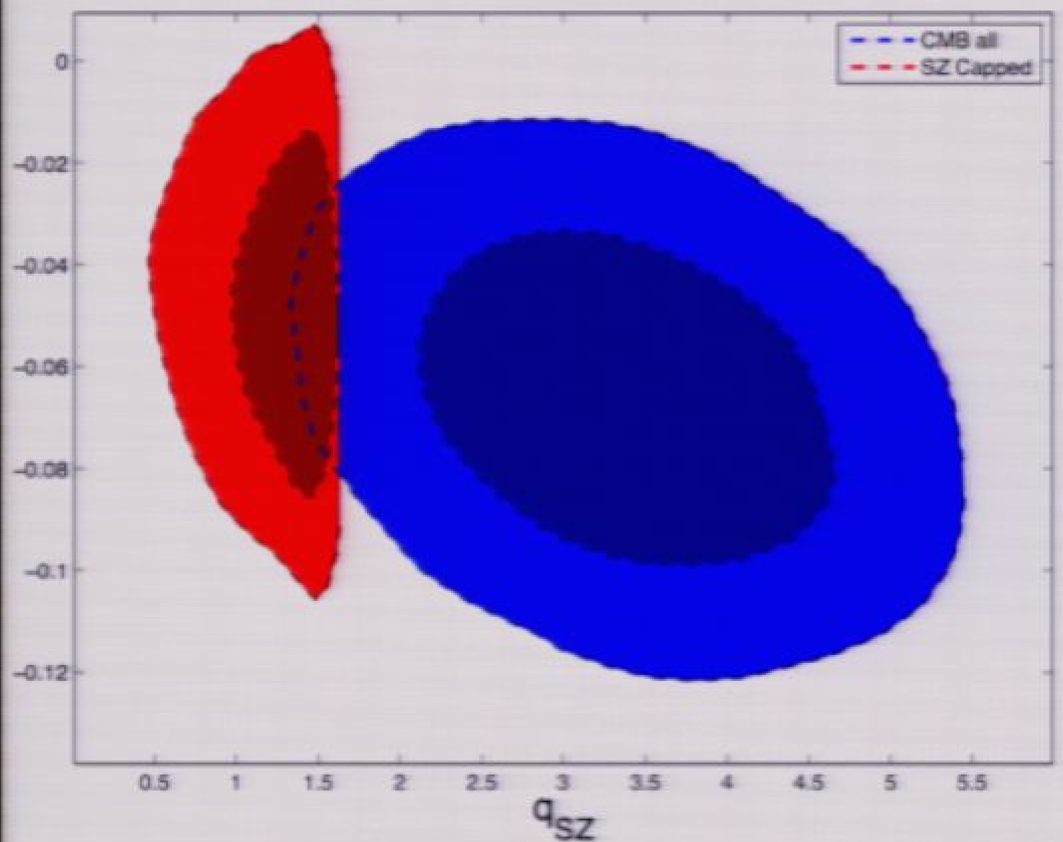


String template from Pogosian et al. for Gμ=1.1e-6 (0804.0810)

Addition of high-ell CMB constrains string amplitude, helps break string-n_s degeneracy.

46

n_{run}



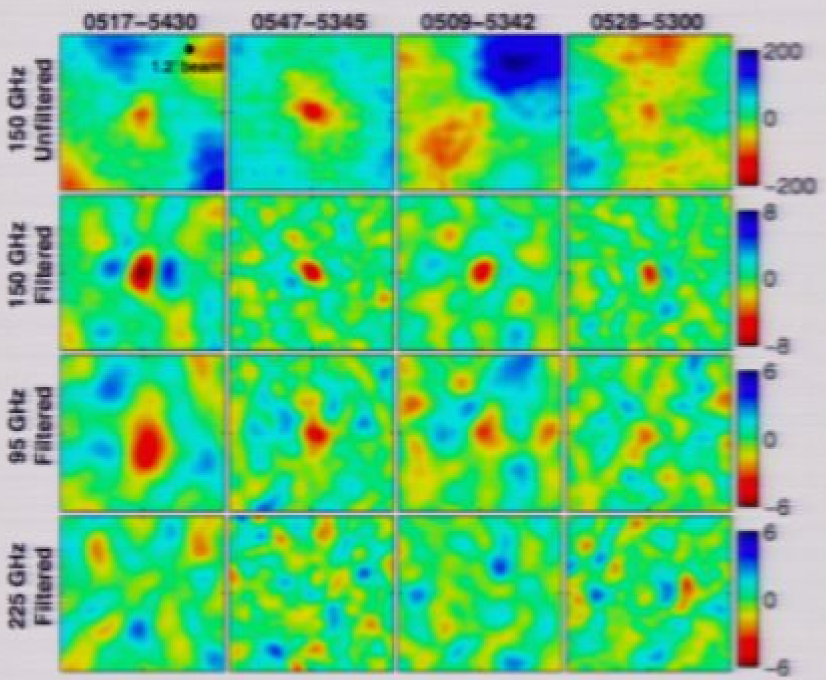
Running of the spectral index is rather correlated with high-ell signal. Getting high-ell. Red contours have SZ contribution capped, blue allow it to float freely.

Future

- Next generation experiments either on-line or about to be.
- Improvement in PS will be dramatic - more sky area, better sensitivity.
- Critically, next-gen expts. have multiple frequency bands. Will help tremendously splitting SZ from CMB from point sources.
- kSZ always a pain (thermal spectrum).

South Pole Telescope

SPT has 960 bolometers on a 10m telescope at South Pole. Have released paper with clusters discovered in SZ.

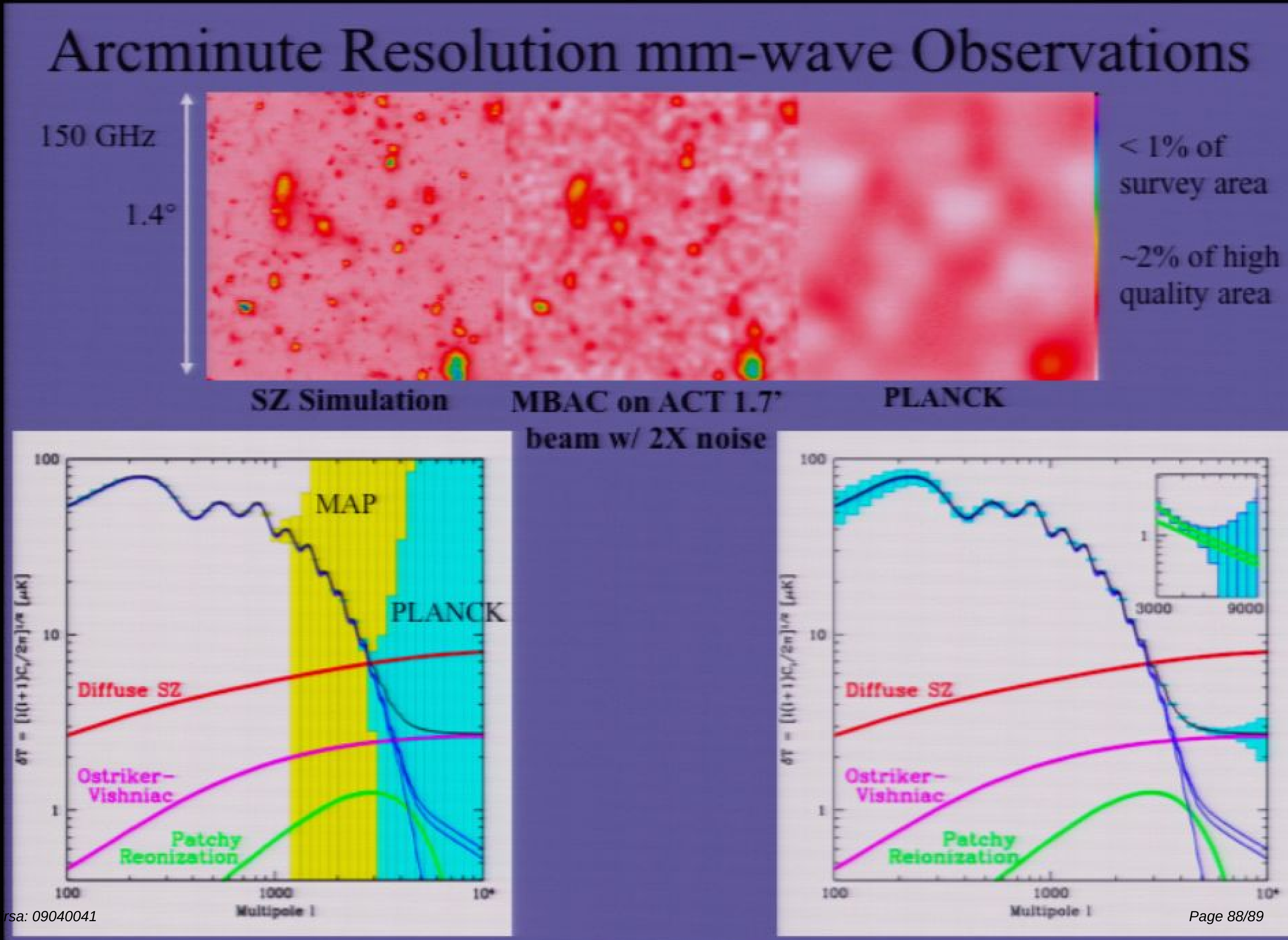


49

Atacama Cosmology Telescope

3000 Bolometer 3-frequency (150,220,270) in Atacama desert in Chile (just down the road from CBI). 6m telescope, so better than 1.5' resolution.

51


Arcminute Resolution mm-wave Observations
150 GHz
1.4°
< 1% of survey area
~2% of high quality area
SZ Simulation
MBAC on ACT 1.7' beam w/ 2X noise
PLANCK
MAP
PLANCK
Diffuse SZ
Ostriker–Vishniac
Patchy Reonization
Diffuse SZ
Ostriker–Vishniac
Patchy Reionization
Multipole l
Multipole l
3000
9000

Summary

- CBI sees power somewhat higher than expected at ell>2000 in CMB.
- High-ell signal consistent with other experiments if from SZ.
- Much theory remains to be done on SZ prediction, field developing rapidly.
- High-ell primary well constrained by standard ΛCDM, but very valuable for extended parameters.
- High-ell will be nailed soon - SZA, QUAD have just released. SPT, ACT going, Planck launches in two months.