Simulating the mm-wave Sky & Experiments

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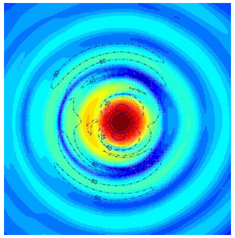
Outline

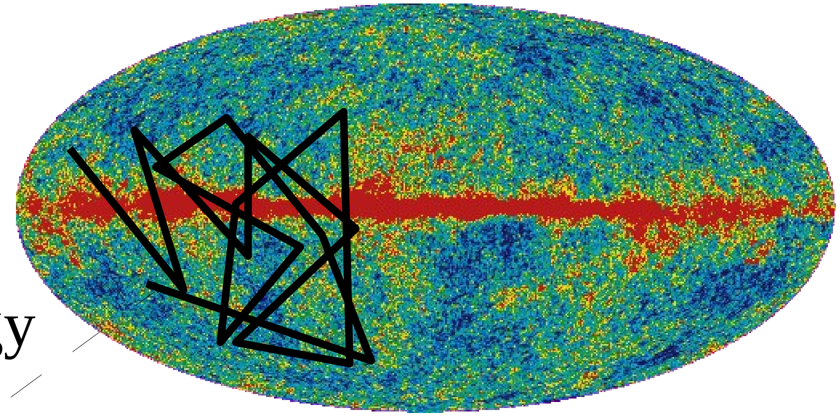
- Motivation
- Monte Carlo based power spectrum estimation
- Mechanics of simulating experiments, and some examples:
  - Propagating systematic errors
  - Planning observations

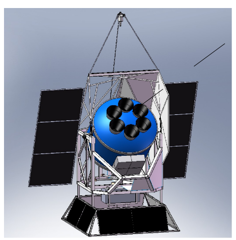
What does it mean to observe the sky?

beam



scan strategy

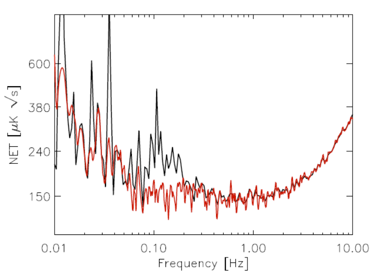




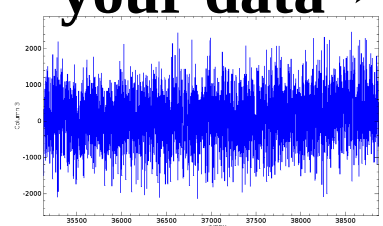
detector and readout transfer function

instrument noise

glitches (CR hits, data dropouts)



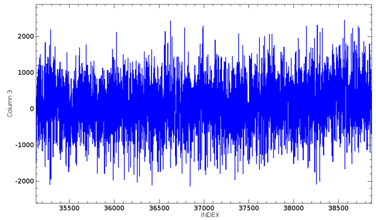
your data



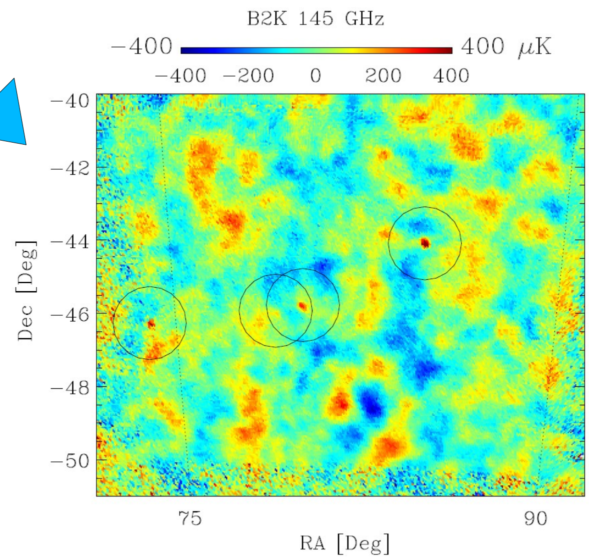
other systematics, etc..

Measuring Cl's from time ordered data

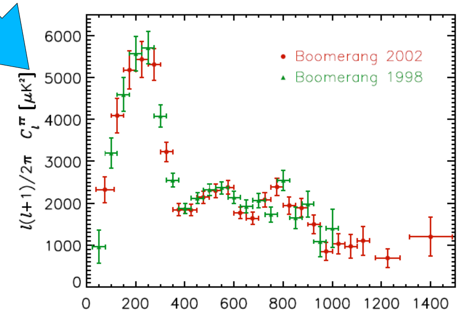
(cleaned data)



Mapmaker



Cl estimator



Observation *filters* the true sky signal

- You're trying to invert the filter to find out what the true sky is from your data
- Learn about that filter by putting in signals you already know:
  - Characterizing your instrument in the lab or with specialized observations
- Need simulations to probe beyond what you can directly characterize

Why Simulate observations?

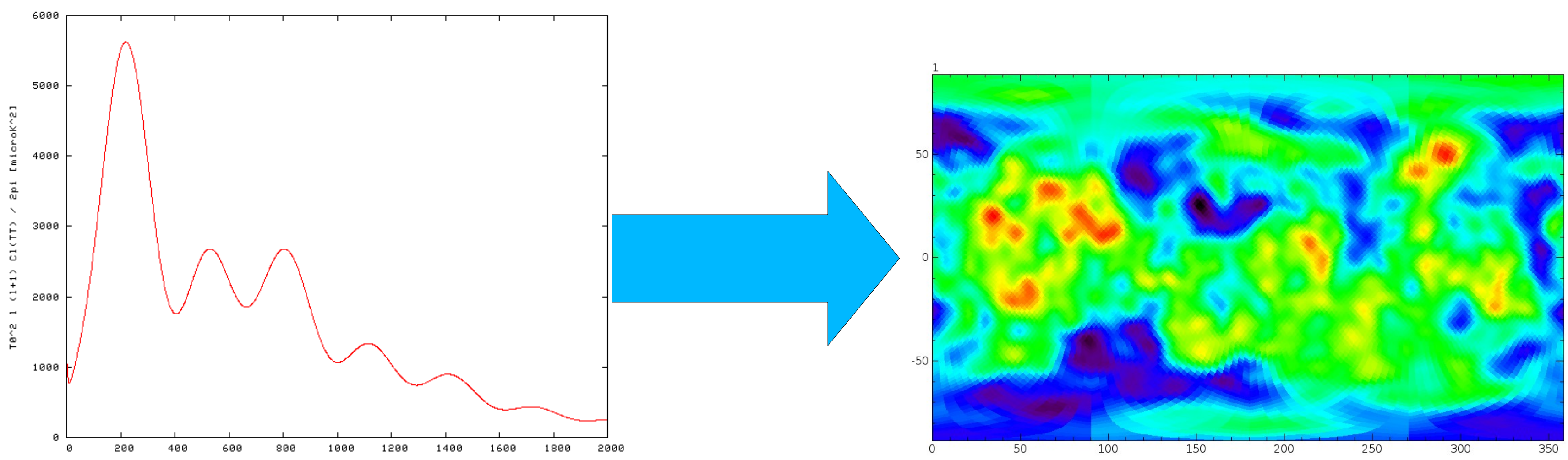
- Sims are an *essential* part of a Monte Carlo-based Cl estimation pipeline
  - calculating the experimental transfer function
  - propagating detector noise to l-space
- Estimate systematic error bars on Cls
- testing analysis software
- Plan observations

Basic idea of simulations

- Generate simulated sky
- Experimental simulator:
  - time-ordered pointing information (could be simulated)
  - “observe” fake sky with beam & pointing info --> time ordered data
  - filter with transfer function of experiment (detector, readout, etc.)
  - add noise (or other systematics) --> noisy time ordered data
- Run analysis pipeline on simulated time ordered data
  - mapmaker
  - power-spectrum estimator
- (you might want to generate something other than full TOD's)

Simulating the CMB

- alm's are Gaussian-distributed random numbers with variance Cl
- Given a set of Cl's: generate random alms at each l (numerical recipes, GSL, etc.)
- synfast: (code included with Healpix): generates alms given a power spectrum; spherical harmonic transform to real space
- If you don't need the full sky: 2D FFTs are much faster



Simulating foregrounds

- Use models to extrapolate maps to frequency of interest
- For example:
  - WMAP MEM foreground maps: lambda.gsfc.nasa.gov
  - IRAS 100 micron
    - Finkbeiner et al ApJ 524 (1999), Miville-Deschenes & Lagache ApJS 157 (2005)
- Planck Sky Model (publicly available eventually)
  - summarizes all of our knowledge of forgrounds
  - includes estimates of polarization

Monte-carlo pseudo Cl method

- Take a cut sky map, fill in the rest of the sky with zeros, take spherical harmonic transform; make power spectrum
  - do this with Healpix package: anafast
- the resulting coefficients you get are called pseudo-Cls: not really your alm's or Cl's
- The spherical harmonics are not a complete orthonormal basis on part of a sphere

Monte Carlo methods for power spectrum estimation

observed pseudo-Cl's

True Cls

$$\tilde{C}_l = M_{ll'} F_{l'} B^2_{l'} C_{l'} + N_l$$

mode coupling kernel matrix (calculated with geometry)

Experimental Transfer function: calculated with simulations

beam window function: calculated from beam measurement/optical models

Noise: propagated to l-space with simulations

$$M_{\ell\ell'} \equiv \frac{(2\ell'+1)}{4\pi} \sum_{\ell''} (2\ell''+1) \begin{pmatrix} \ell & \ell' & \ell'' \\ 0 & 0 & 0 \end{pmatrix}^2 \mathcal{W}_{\ell'}$$

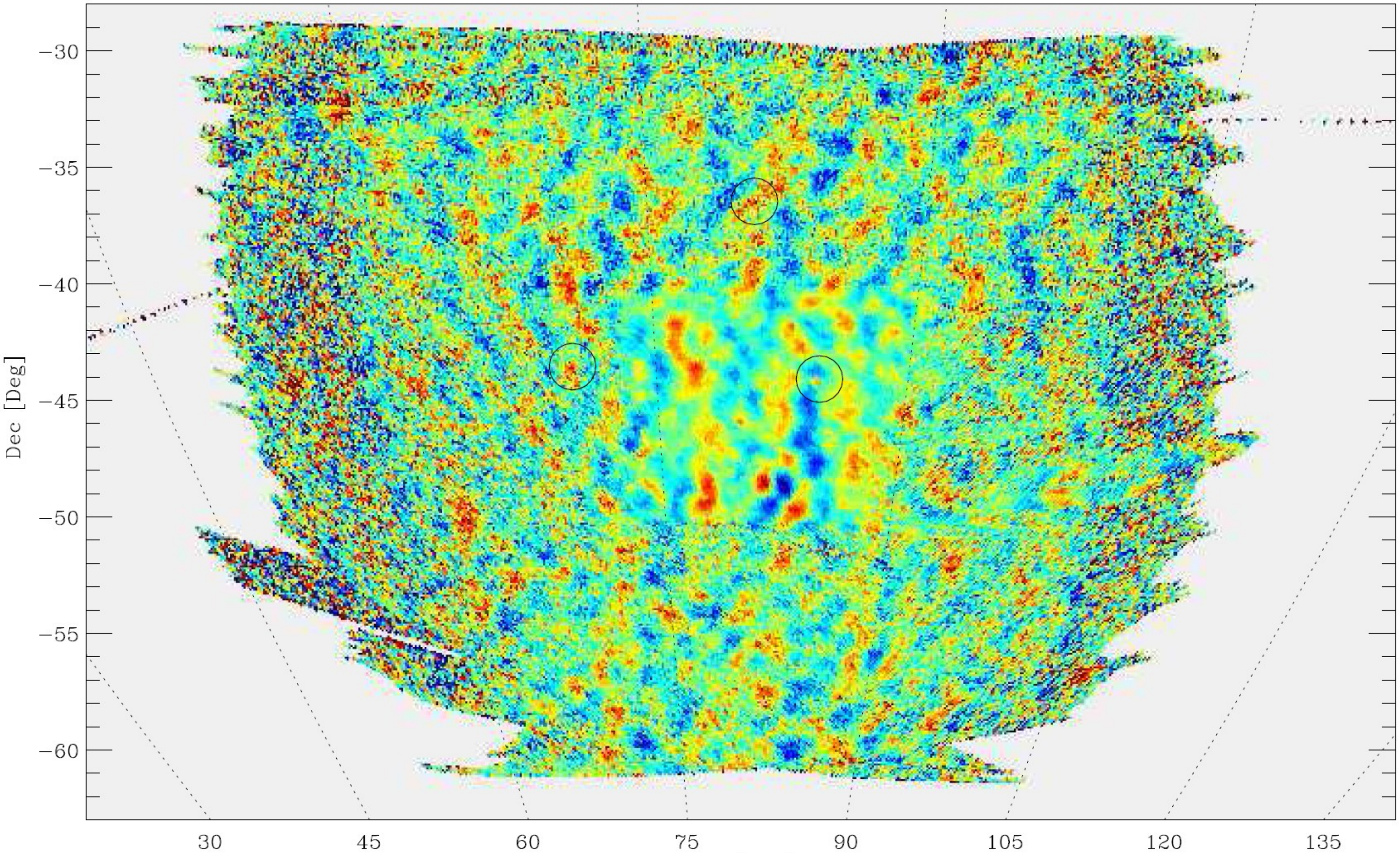
spherical harmonic transform of sky cut

(to invert: bin in multipole)

Hivon et al ApJ 567 (2002)

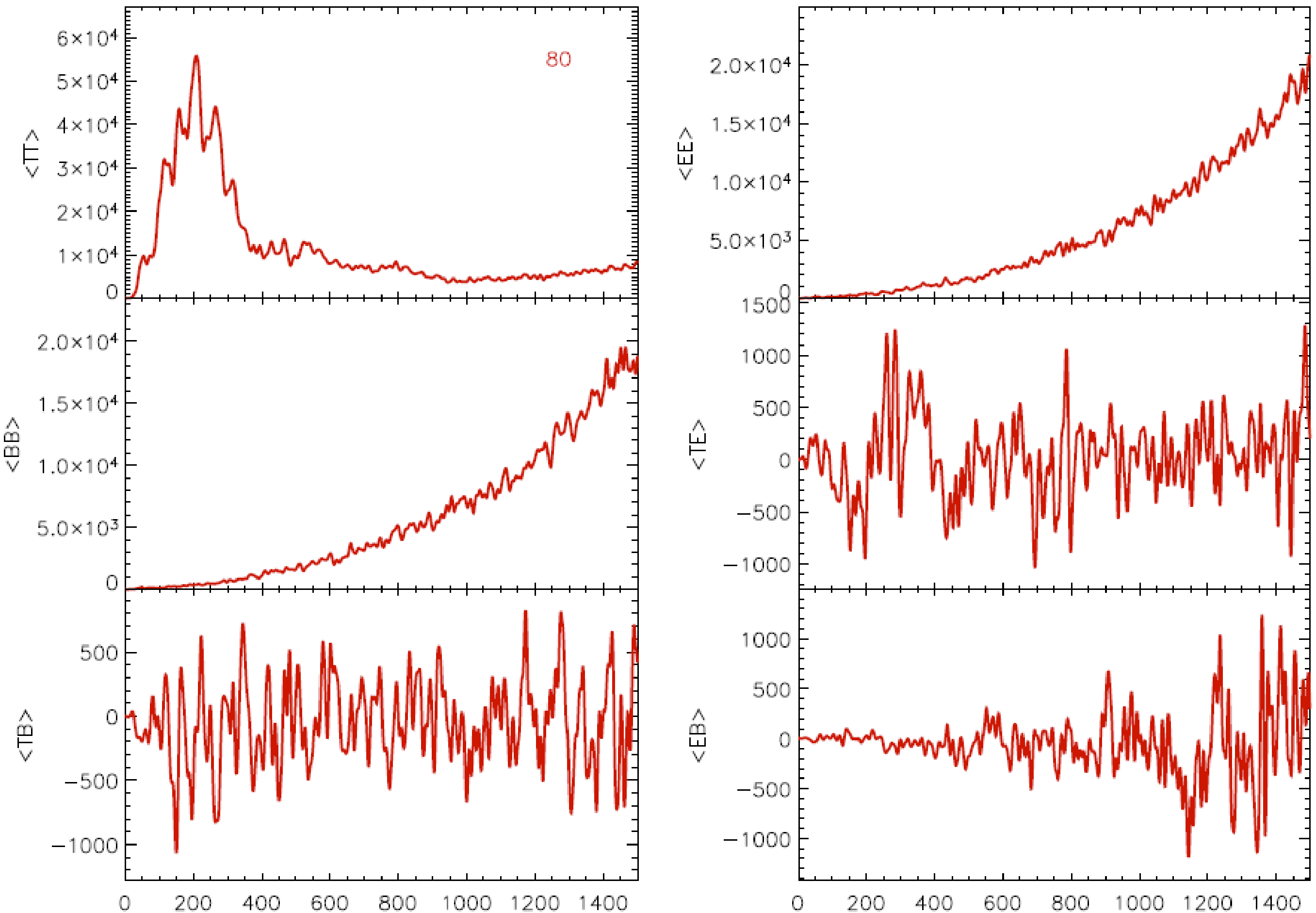
Example: Boomerang 2003 Stokes I map at 145 GHz

- Used a Generalized Least Squares iterative solver



Boomerang 2003 Pseudo-Cl power spectra

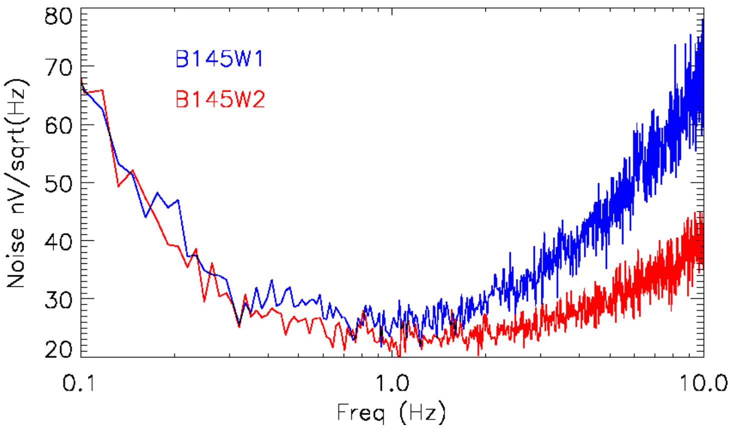
take naïve spherical harmonic transform of map:



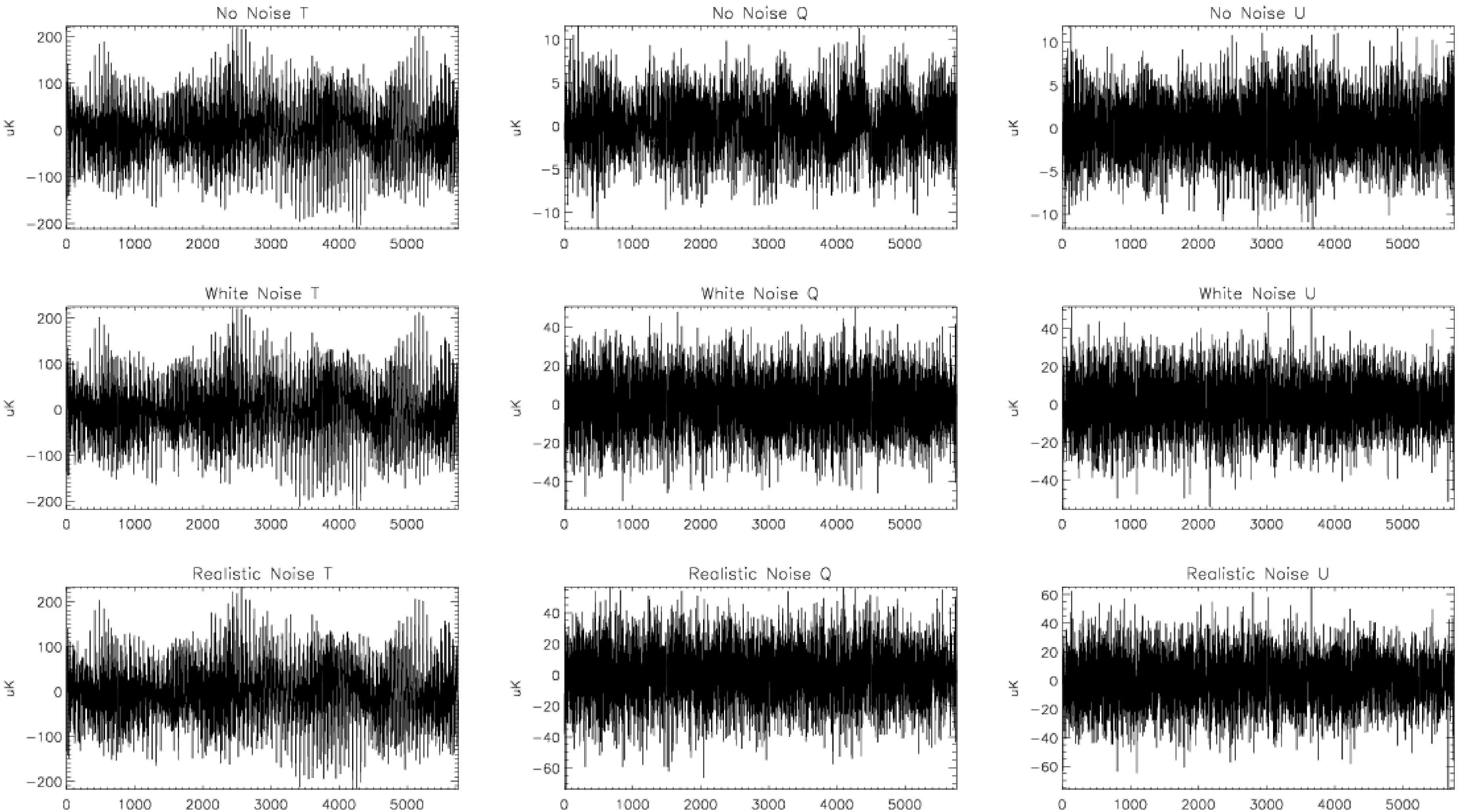
(Bill Jones' thesis – Caltech (2005))

Estimating $\langle N_l \rangle$

- **Noise-only simulation:**
  - (need to have a characterization of your detector noise)
  - generate realizations of time-ordered noise data: random phases, same power spectrum as real data
  - bin into maps
  - estimate Cl's
  - take the variance
- **Including cosmic sample variance:**
  - do simulations of noise + CMB realizations



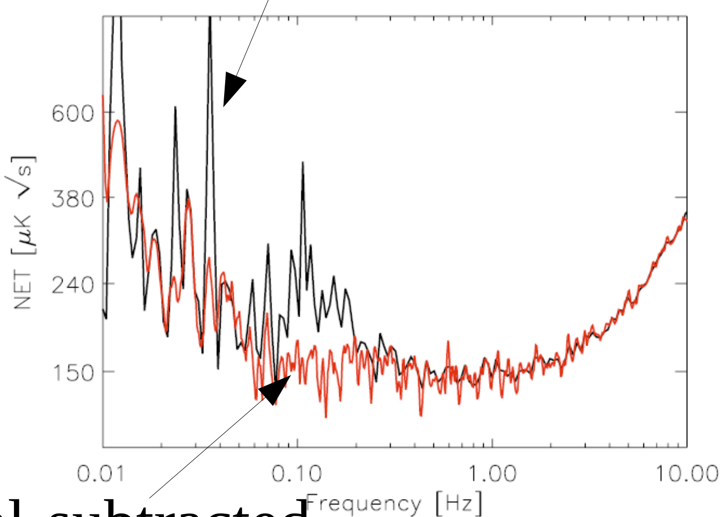
Boomerang simulated data

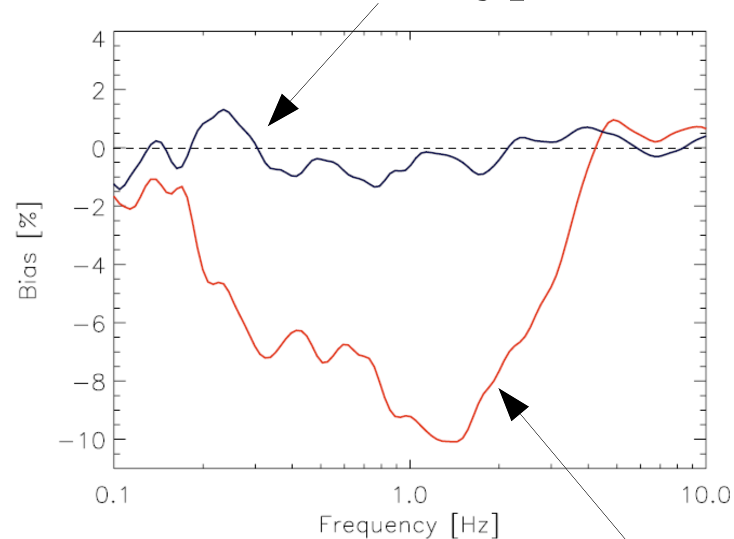


Bias in noise estimation

- **Noise estimation:**
  - **imperfect signal subtraction gives a bias in estimated noise**
- **Bias can be calculated with an ensemble of simulated noise estimations**

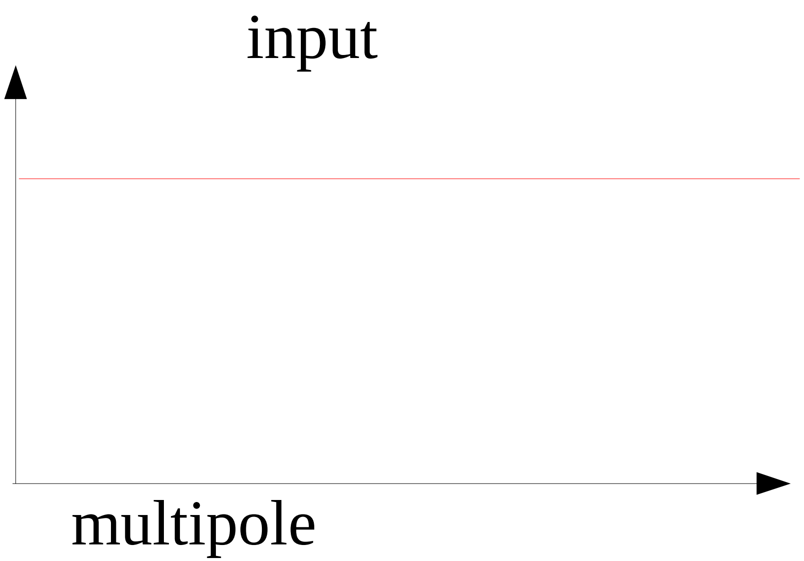
$$\tilde{n} = s + n - A\tilde{m} = n - \hat{n}$$



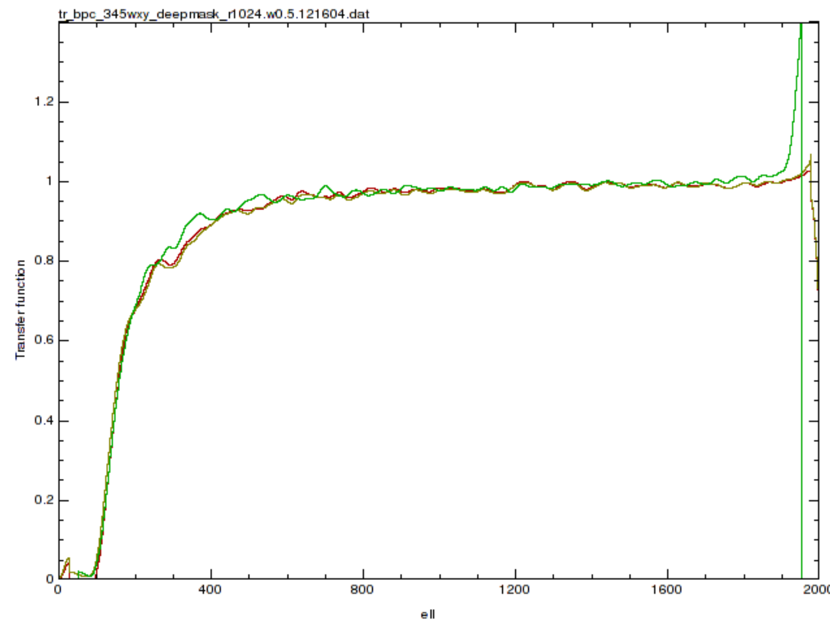


Measuring transfer function

- Want to figure out how the observation strategy (and analysis code!) filters the true signal
- Generate an ensemble of signal-only simulations
- Output power spectrum divided by input power spectrum = transfer function
- No need to use a CMB-like spectrum here; any will do



<output>/input

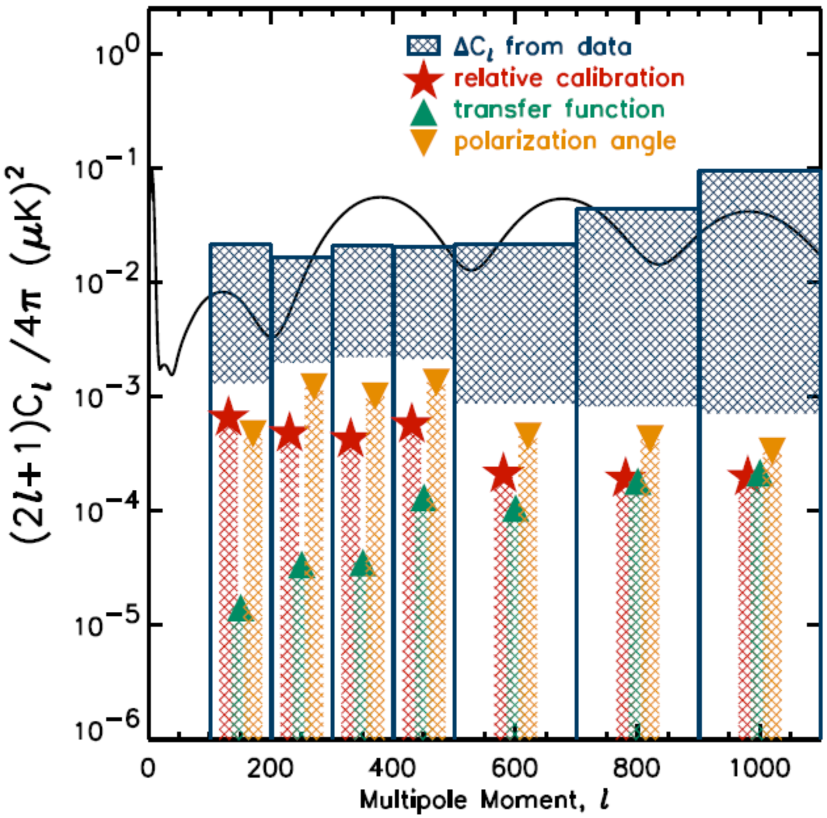


Estimating power spectrum error bars due to systematics

- Example from Boomerang-03: How do uncertainties in polarization parameters propagate into <EE> measurement?
- A single polarization-sensitive bolometer sees this signal:

$$d_i \simeq \frac{s}{2} \int \mathrm{d}\nu \, \lambda^2 F_\nu \iint \mathrm{d}\Omega \left[I + \gamma \mathcal{P} \left(Q \cos 2\psi_i + U \sin 2\psi_i \right) \right]$$

- Generate ensemble of signal-only simulations with randomly tweaked instrumental parameters:
  - estimate power spectrum

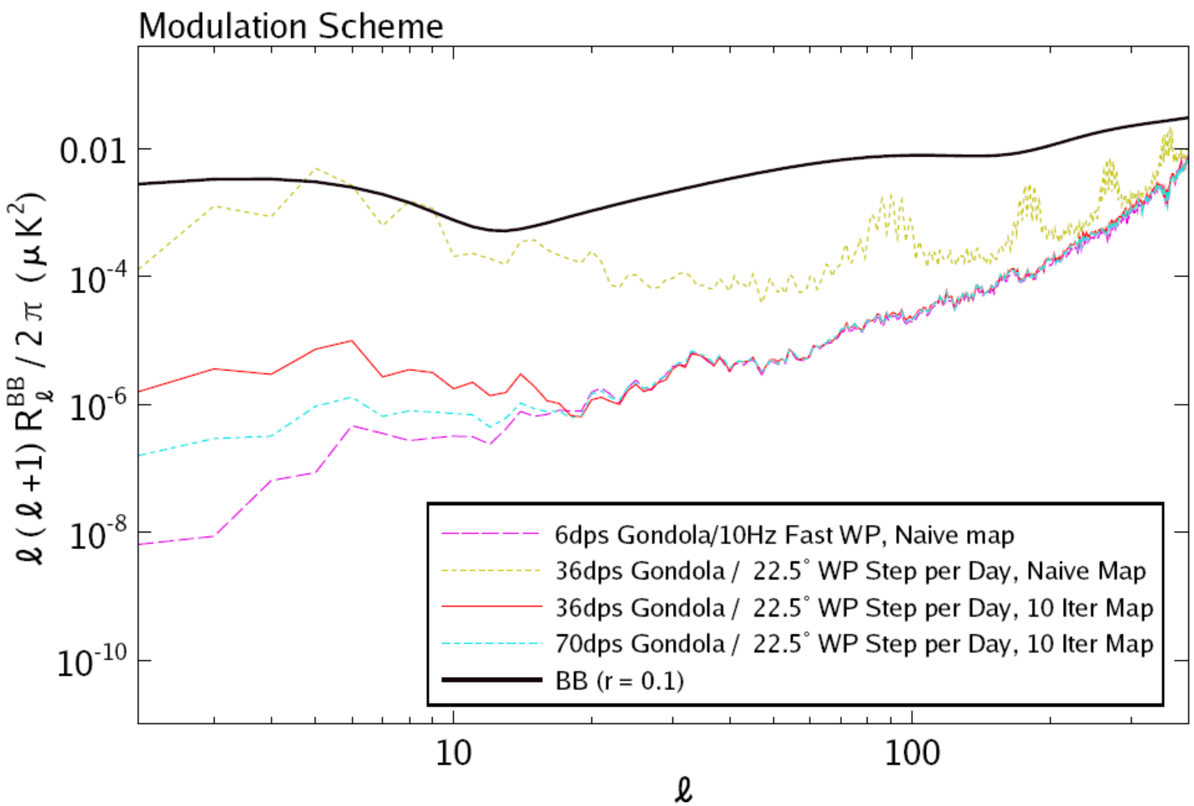


- relative calibration known to 0.8%
- polarization angle known to 2°
- bolometer time constant known to 10%
- Expected systematics are much less than the instrumental noise

Montroy et al 2005 ApJ 647 (2006)

Planning Observations

- MacTavish et al (astro-ph/0710.0375) for an example with SPIDER
- Calculate half-wave plate specifications; scan strategy specifications

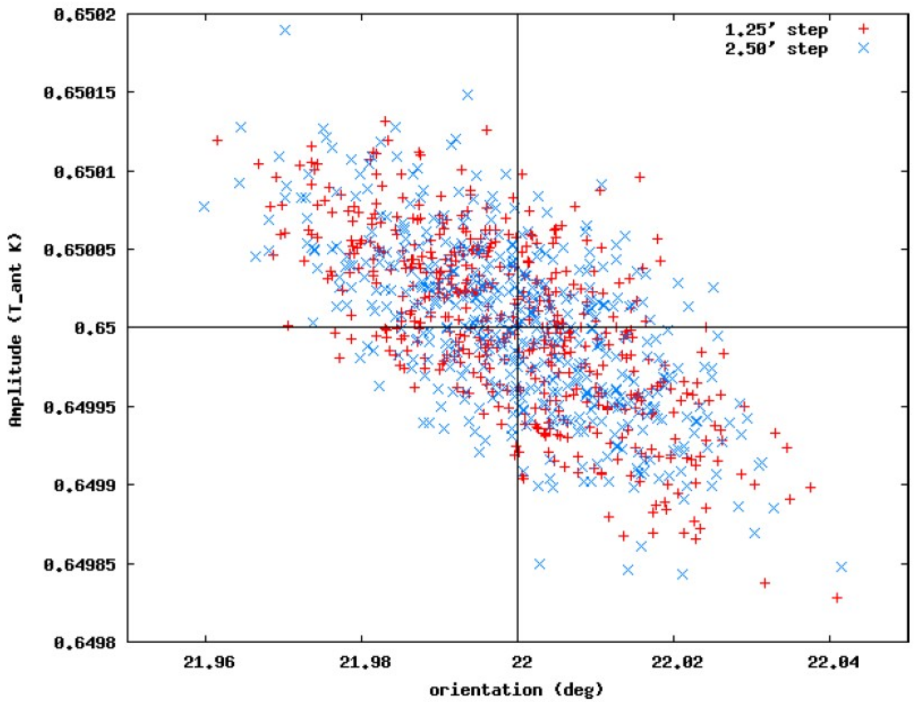


Simulations for Planck

- Level S: a simulation package for Planck
  - generates spacecraft pointing
  - fast convolution of map on the sphere with arbitrary beam shapes
  - generate simulated time ordered data including 1/f noise, glitches, dipole, whatever...

Investigating Beam reconstruction with Planck

- **Specialized fast beam parametric fit pipeline**
- **rapid simulation of realizations of Planck pointing, CMB, 1/f noise, and planet observations --> fit to parametric model (such as Elliptical Gaussian)**
- **get measurements of correlations between parameters**



Huffenberger et al (in prep)

Some References

- Healpix:
  - http://healpix.jpl.nasa.gov/
  - Gorski et al ApJ 622 (2005)
- Level S:
  - Reinecke et al A&A 445 (2006)
- Polarization measurements with bolometers
  - Jones et al A&A 470 (2007)
- Monte Carlo Cl estimation
  - Hivon et al ApJ 567 (2002)
- Boomerang theses:
  - http://cmb.phys.cwru.edu/boomerang