Detector Sensitivity

- If I have a detector that averages n photons per second, and observes for t seconds, what is the fractional uncertainty on n?

- I get a total of nt photons, which are (probably) Poisson distributed. Variance is nt, so $\sigma=\sqrt{(nt)}$.

- Fractional error is then $\delta n/n = 1/\sqrt{(nt)}$.

- If I want more accuracy, I can either observe longer, or increase photon rate. Larger telescopes are good!

How low can we go

- Is there a limit to how high I can push photon rate *n*?
- At some point, photons start to overlap. What *n* would I need for optical wavelengths?
- If wavelength ~500 nm, need C/λ~6e14 photons/s.
- Could pack in $(1\text{m}/500\text{ nm})^2$ detectors/m^2=4e12. So, would need 4e12*6e14=2.4e27 photons/m^2/s.
- Energy/photon=hv, or 4e-19 joules. Total power 4e-19*2.4e27= 1GW/m^2. Camera will melt first.

What Happens When Saturate?

- In limit of many overlapping photons, best I can do is measure electric field continuously.
- How often do I get a new electric field measurement?
- If I have signal up to some ν_{max}, correlation length goes like $1/\nu_{max}$. We call this the *bandwidth* B.
- # of independent samples is Bt, so fractional error is just $1/\sqrt{n\_samples}$.
- Usually refer to temperature (instead of count rate), which gives $\delta T/T=1/\sqrt{(Bt)}$ (radiometer equation)

Shot noise vs. continuous

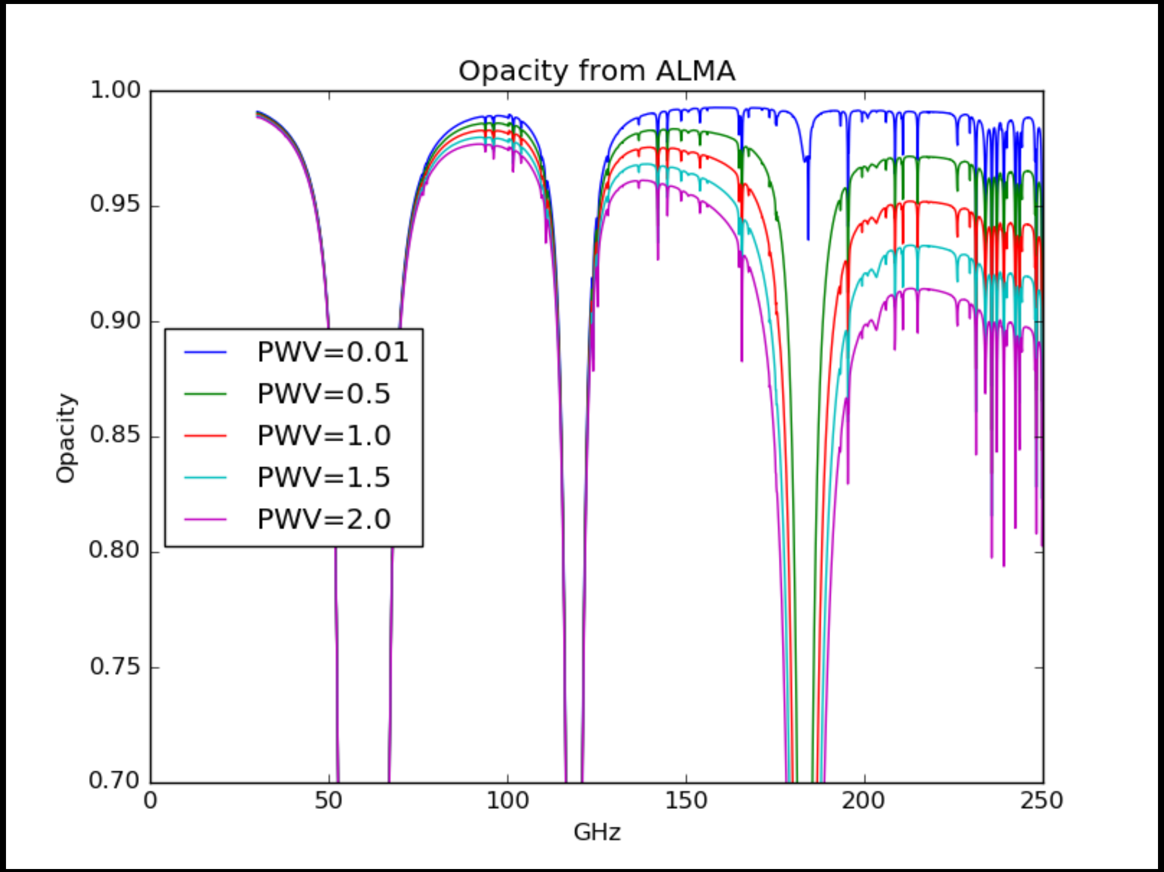
- As I crank up intensity, fractional sensitivity increases until I saturate at continuous limit.
- Shot noise absolute error: $\delta n = n/\sqrt{nt} \sim n^{1/2}$. If I want to measure a star (fixed δn) and add noise, my error on star goes like sqrt(added noise)
- Continuous: $\delta T = T/\sqrt{(Bt)} \sim T$. If I increase noise power, my error scales linearly (not as sqrt).

Comparison to Black Body

- Where will we transition?
- If staring at black-body radiation, $B_\nu=2h\nu^3/c^2(\exp(x)-1)$, where $x=h\nu/kT$.
- Photon occupation number is $1/(\exp(x)-1)$, so far to left of BB peak, we will be in continuous, and far to right shot noise.
- For CMB, $x=1$ at $\nu=50$ GHz. Radio always in continuous limit.

Ground-based CMB

- At typical CMB frequencies, O_2 and H_20 block some wavelengths.
- Oxygen lines can't do much about. Water can be avoided -> go high, and dry. South Pole, Chilean Atacama best places so far. (Tibet, Greenland…)
- Plot at right shows opacity from ALMA site as function of precipitable water vapor. What frequencies would you use?



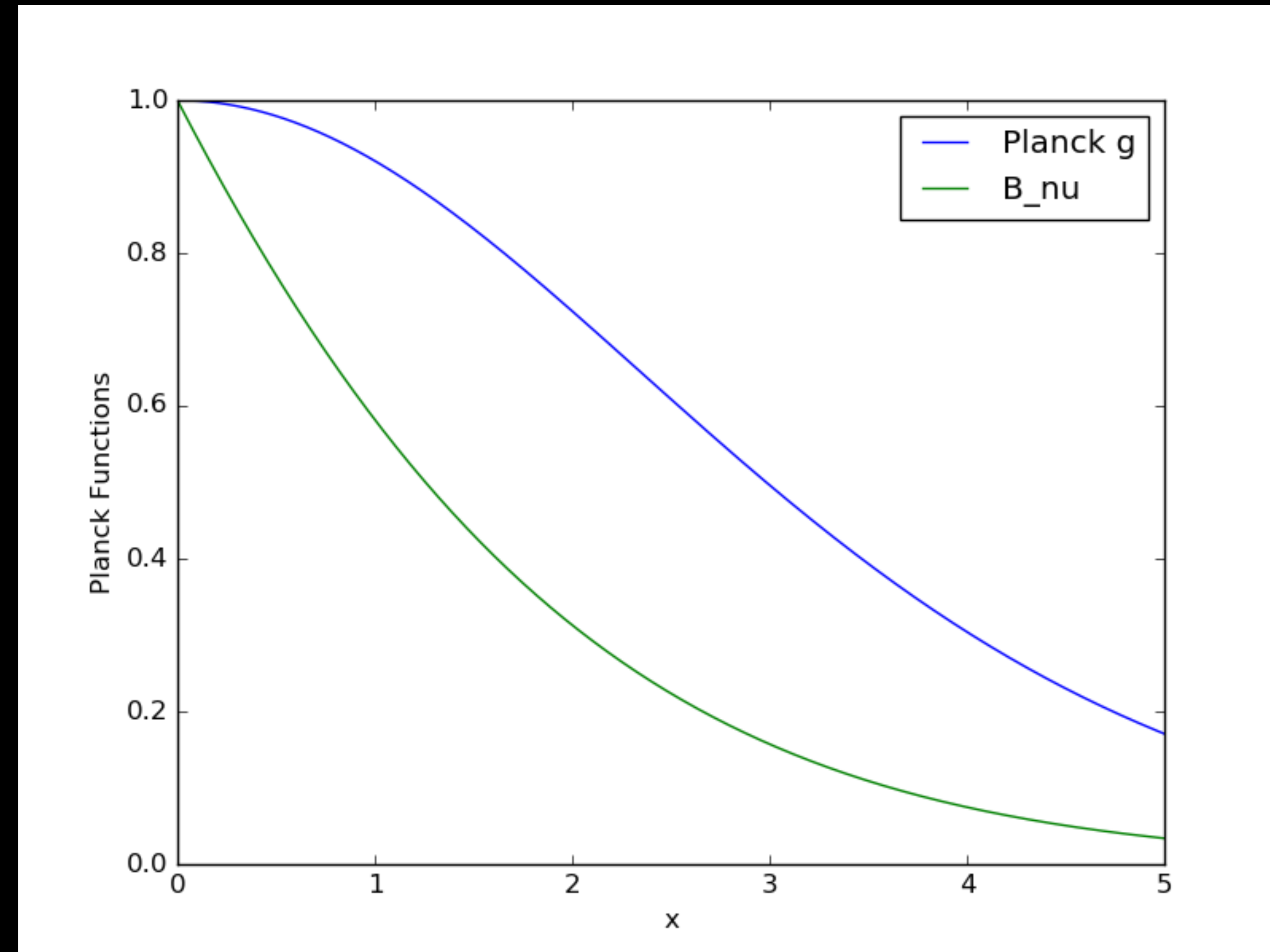
Ground-based Sensitivity

- Let's pick 90 GHz window. Have 30 GHz window width.
- For PWV=1mm (decent day in Chile), opacity is 0.025.
- Call temperature 270K - emission equivalent to 0.025*270=7K + 3K CMB ~ 10K noise signal.
- For 1sec, δT=10K/sqrt(30e9)=6e-5=60 μK.
- However… x=1.6, pushes noise to~80 μK (Planck g function).
- Other sources of noise contribute, plus CMB not in full continuous limit. Typical ground-based limit more like 200-300 μK (RJ).

Planck g function

- CMB is made up of temperature fluctuations. In one direction, it might be 2.725K, in another, 2.72507K. How does intensity vary?
- $B_\nu = 2h\nu^3/c^2(\exp(h\nu/kT)-1)$, or $2\nu^2kT/c^2\ x/\exp(x-1)$
- Rayleigh Jeans - $h\nu/kT \ll 1$, $B_\nu \to 2h\nu^3/c^2\ kT/h\nu = 2\nu^2kT/c^2$
- But, intensity from temp change is $d(B_\nu)/dT\ \delta T$.
- Works out to $2\nu^2k\delta T/c^2\ x^2\exp(x)/(\exp(x)-1)^2$.
- Ratio is called Planck g, is $x^2\exp(x)/(\exp(x)-1)^2$.
- Planck g tends to be much closer to 1 than B_ν.

Planck g ctd.




```
at  30  GHz, x is  0.528919026725  Planck function is  0.758745451691  an Planck g is  0.977009566303
at  90  GHz, x is  1.58675708018  Planck function is  0.408129946138  an Planck g is  0.8141731346
at  150  GHz, x is  2.64459513363  Planck function is  0.202221045781  an Planck g is  0.575686144945
at  220  GHz, x is  3.87873952932  Planck function is  0.0818934996164  an Planck g is  0.324350099436
at  270  GHz, x is  4.76027124053  Planck function is  0.0411156509351  an Planck g is  0.197412147434
at  350  GHz, x is  6.17072197846  Planck function is  0.0129221263007  an Planck g is  0.0799058301206
```

For CMB, we want to know δT_{CMB}, which is down relative to RJ by Planck g. So, noise in CMB units is RJ noise over g. Our 200-300 μK (RJ) goes to more like 300-500 μK (CMB), with 300 quite optimistic from ground. Typical balloon limit ~150 μK, space ~50 μK (CMB)0

CMB Detectors

- Transition edge sensors (TES) are standard these days. Essentially glorified thermometers.
- Work by keeping an absorber on edge of superconducting transition, then measuring change in resistance as temperature changes.
- Readout is hard! Typical ground-based incident powers in picowatts. What would noise in that power be? Readout noise has to be smaller.
- Also need to read out thousands of detectors without heating detectors up. Dobbs an expert in this.

ACBAR Noise (Runyan Thesis)

Frequency (GHz)	150	220	280
$\Delta\nu$ (GHz)	30	30	50
η (%)	40	32	30
$FWHM$ (′)	4.8	3.9	3.9
Q_{total} (pW)	12.8	9.6	26.4
T_{RJ} (K)	39	36	64
R (MΩ)	7.1	7.7	7.3
T_{bolo} (mK)	359	351	355
$G(T)$ (pW/K)	470	485	760
S ($\times 10^8$ V/W)	-2.4	-2.6	-1.9
$NEP_{\gamma\ counting} \times 10^{17}$ $(W/\sqrt{Hz})$	5.0	5.3	9.9
$NEP_{\gamma\ bose} \times 10^{17}$ $(W/\sqrt{Hz})$	7.4	5.5	11.8
$NEP_J \times 10^{17}$ $(W/\sqrt{Hz})$	2.5	2.4	3.4
$NEP_G \times 10^{17}$ $(W/\sqrt{Hz})$	4.5	4.5	5.8
$NEP_A \times 10^{17}$ $(W/\sqrt{Hz})$	1.2	1.2	1.6
$NEP_{total\ w/o\ bose} \times 10^{17}$ $(W/\sqrt{Hz})$	7.3	7.4	12.1
$NEP_{total\ w/\ bose} \times 10^{17}$ $(W/\sqrt{Hz})$	10.4	9.3	16.9
$NEP_{achieved} \times 10^{17}$ $(W/\sqrt{Hz})$	9.4	7.9	14.6
NET_{CMB} $(\mu K\sqrt{s})$	345	640	1400
NET_{RJ} $(\mu K\sqrt{s})$	200	210	250
$NEFD$ (mJy $\sqrt{s}$)	290	530	890

“Table 3.8: Average bolometer parameters and noise budget for all three frequencies based on telescope noise data taken with the chopper stopped and a load curve performed at EL=60○ ; both on 06/14/02. The amplifier and FET voltage noise contribution is estimated to be 3 × 10–9 V/√ Hz at 10 Hz and is scaled to NEPA by dividing by the responsivity, S. The total NEP is the quadrature sum of all noise components listed. The achieved NEPs are determined from the average calibrated noise power spectra between 10 and 20 Hz.”

From Last Week

doi:xyz

BICEP2 / *Keck Array* X: Constraints on Primordial Gravitational Waves using *Planck*, WMAP, and New BICEP2/*Keck* Observations through the 2015 Season

Keck Array and BICEP2 Collaborations: P. A. R. Ade,[1] Z. Ahmed,[2] R. W. Aikin,[3] K. D. Alexander,[4] D. Barkats,[4] S. J. Benton,[5] C. A. Bischoff,[6] J. J. Bock,[3,7] R. Bowens-Rubin,[4] J. A. Brevik,[3] I. Buder,[4] E. Bullock,[8] V. Buza,[4,9] J. Connors,[4] J. Cornelison,[4] B. P. Crill,[7] M. Crumrine,[10] M. Dierickx,[4] L. Duband,[11] C. Dvorkin,[9] J. P. Filippini,[12,13] S. Fliescher,[10] J. Grayson,[14] G. Hall,[10] M. Halpern,[15] S. Harrison,[4] S. R. Hildebrandt,[3,7] G. C. Hilton,[16] H. Hui,[3] K. D. Irwin,[14,2,16] J. Kang,[14] K. S. Karkare,[4,17] E. Karpel,[14] J. P. Kaufman,[18] B. G. Keating,[18] S. Kefeli,[3] S. A. Kernasovskiy,[14] J. M. Kovac,[4,9] C. L. Kuo,[14,2] N. A. Larsen,[17] K. Lau,[10] E. M. Leitch,[17] M. Lueker,[3] K. G. Megerian,[7] L. Moncelsi,[3] T. Namikawa,[19] C. B. Netterfield,[20,21] H. T. Nguyen,[7] R. O'Brient,[3,7] R. W. Ogburn IV,[14,2] S. Palladino,[6] C. Pryke,[10,8,*] B. Racine,[4] S. Richter,[4] A. Schillaci,[3] R. Schwarz,[10] C. D. Sheehy,[22] A. Soliman,[3] T. St. Germaine,[4] Z. K. Staniszewski,[3,7] B. Steinbach,[3] R. V. Sudiwala,[1] G. P. Teply,[3,18] K. L. Thompson,[14,2] J. E. Tolan,[14] C. Tucker,[1] A. D. Turner,[7] C. Umiltà,[6] A. G. Vieregg,[23,17] A. Wandui,[3] A. C. Weber,[7] D. V. Wiebe,[15] J. Willmert,[10] C. L. Wong,[4,9] W. L. K. Wu,[17] H. Yang,[14] K. W. Yoon,[14,2] and C. Zhang[3]

"We present results from an analysis of all data taken by the BICEP2/ Keck CMB polarization experiments up to and including the 2015 observing season. This includes the first Keck Array observations at 220 GHz and additional observations at 95 & 150 GHz. The Q/U maps reach depths of 5.2, 2.9 and 26 μK_{cmb}-arcmin at 95, 150 and 220 GHz respectively over an effective area of ≈ 400 square degrees."

With 500 μK-rt(s) detectors, how many detector years would this take?

With 500 μK-rt(s) detectors, how many detector years would this take?

- Need $(500/2.9)^2$ = 30,000 seconds per patch
- 3600 arcmin^2 per square degree, 1.4 million patches.
- Total time=30,000*1.4e6 = 4.3e10 detector seconds
- Or, about 1,400 detector-years. Need to build large cameras to constrain r
- Improving by order of magnitude will take tens of thousands of detectors.

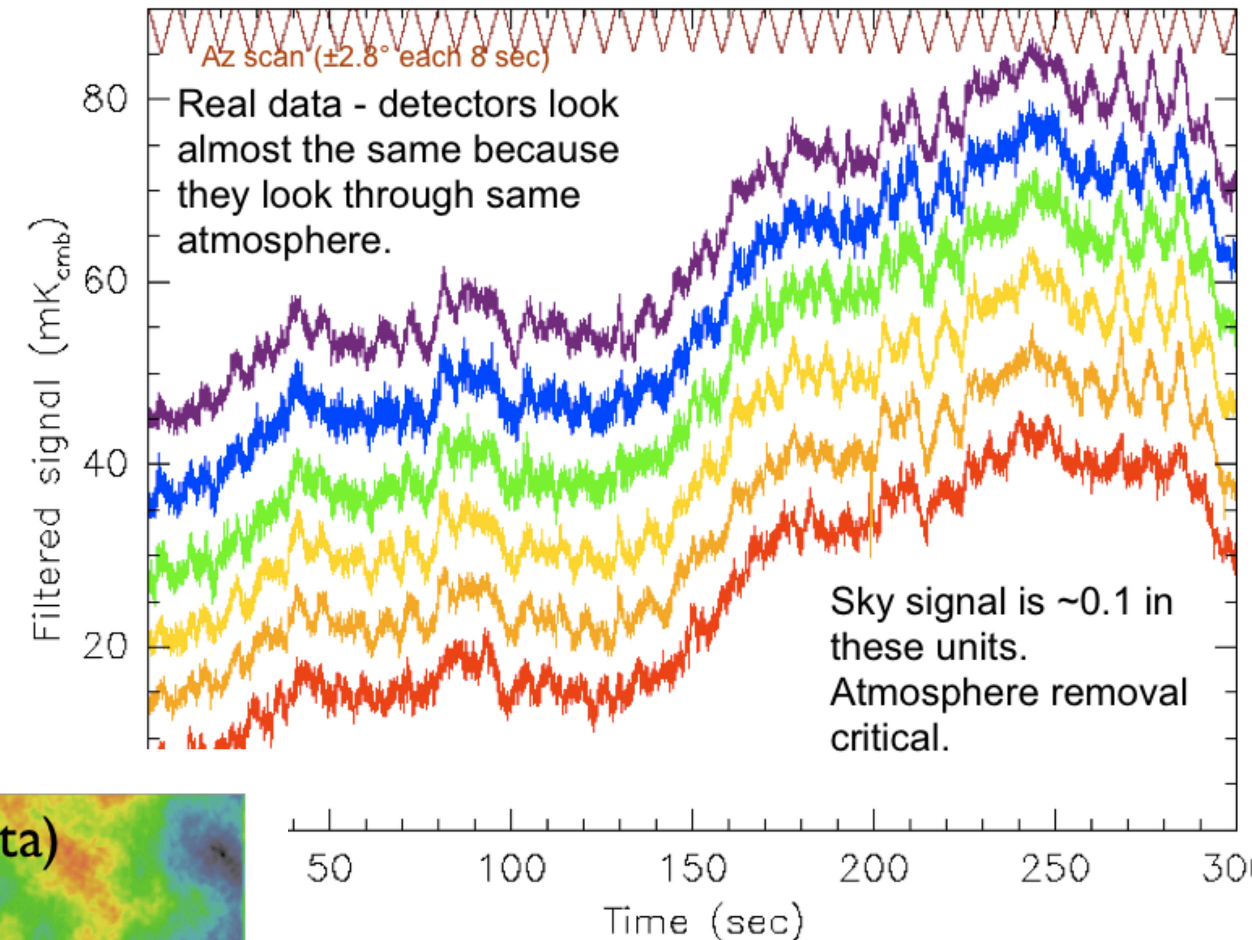
1/f Noise

- Unfortunately, detectors have 1/f noise. Some is intrinsic to detector drifts. Index often not exactly -1, but still called 1/f colloquially.
- From ground, even more challenging is that noise is correlated. All detectors see a cloud in front of telescope!
- From ground, almost everything we see comes from correlated 1/f noise.

ACT: Data Challenge

Go from

to



Unbiased estimate of all modes from *ell* ~ 100 - 10000

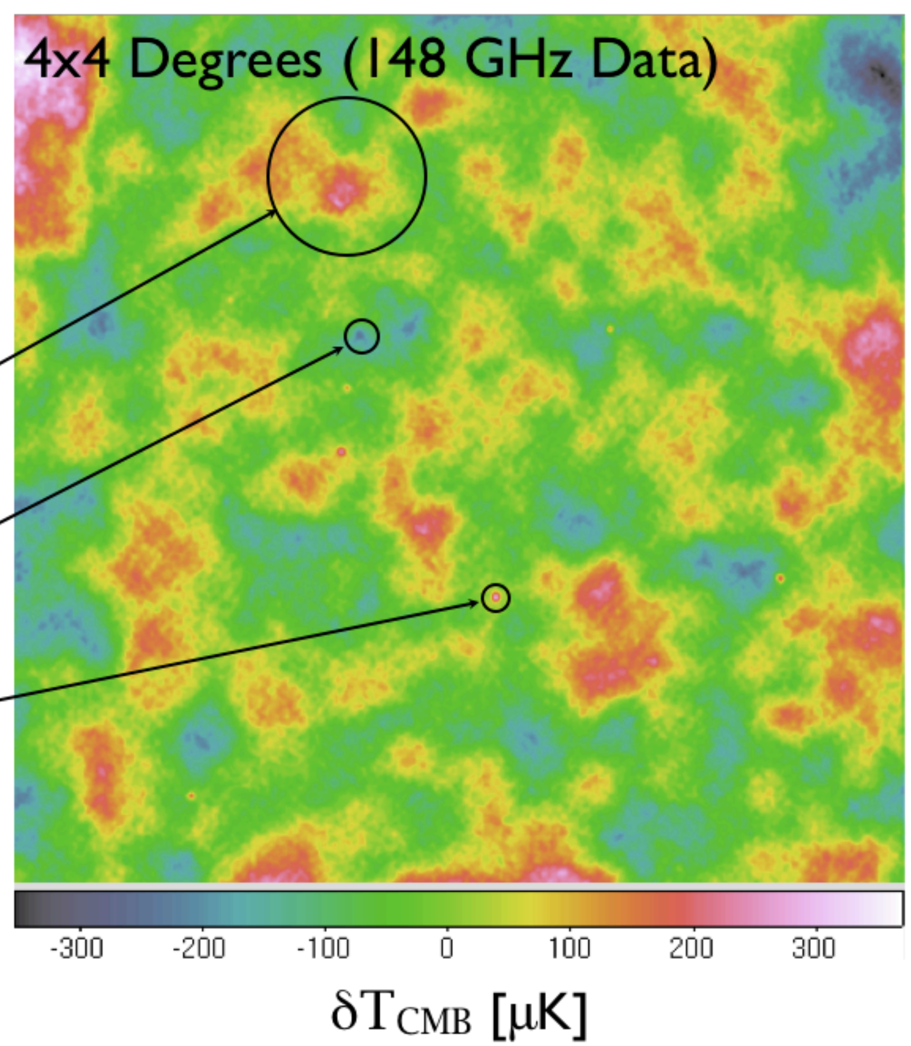
Atmosphere: 2 deg
(Filtered Here)

CMB: 1 deg

Clusters*: (>1.4')-4'

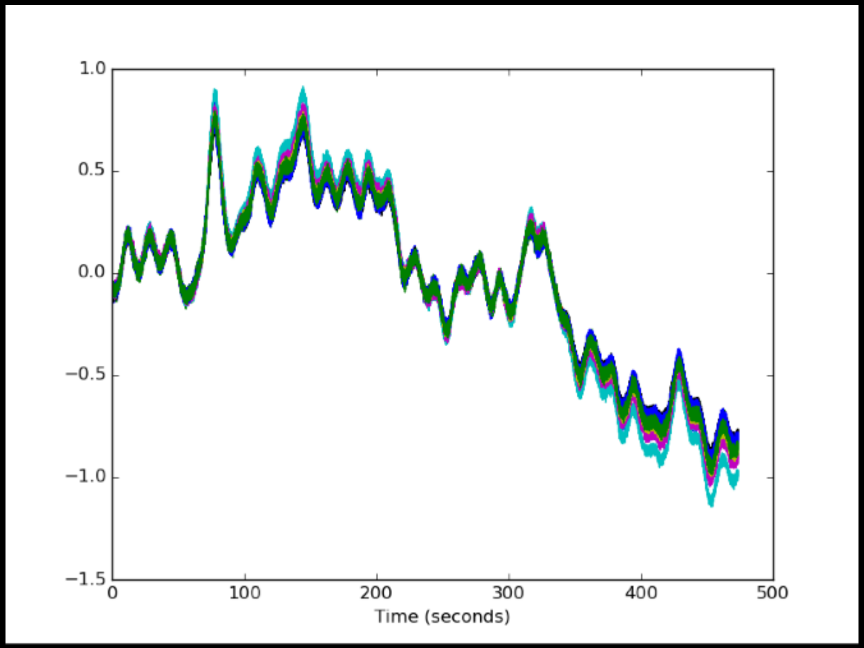
Sources*: 1.4'

* Minimum size set by beam

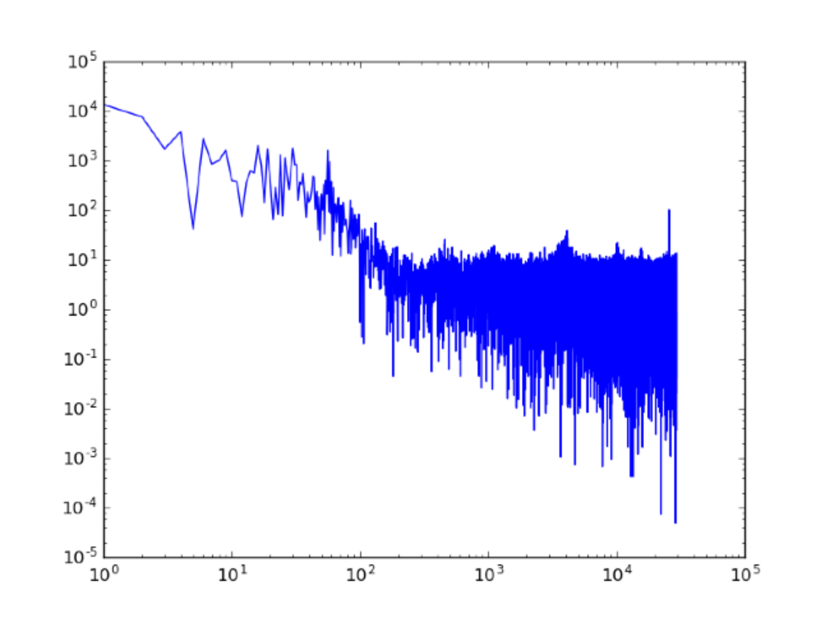


Requirements: Unbiased sky estimate (need ~1% signal accuracy). Optimal (data is precious). Ability to handle complex noise. Fast - 7 years of WMAP=hours of ACT data, all of Planck=~2 weeks. 200 GB/ night

So... How do we make a map out of stuff



- Top: examples of several detectors from same observation.
- Bottom: power spectrum.
- Can I point my CMB camera at a patch of sky, leave it there, and average what comes out?
- Let's say I was looking for a signal - what frequencies would I like that signal to be at?



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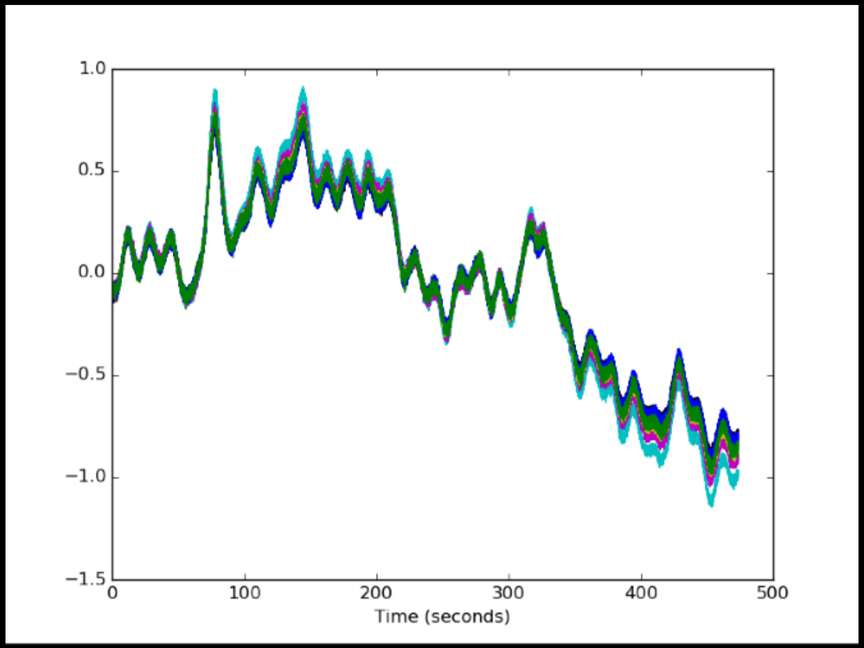
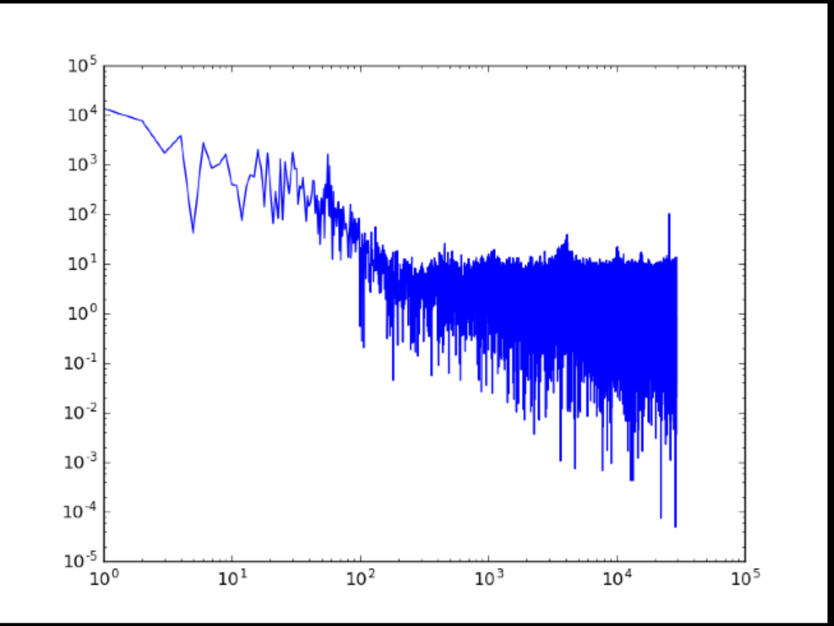


- Top: examples of several detectors from same observation.
- Bottom: power spectrum.
- Can I point my CMB camera at a patch of sky, leave it there, and average what comes out?
    - No - all I'll see are those big drifts.
- Let's say I was looking for a signal - what frequencies would I like that signal to be at?
    - Signal ideally sits in white part, above bend. In this case, above ~1 Hz. Generally, atmosphere moves faster than telescope (so knee frequency doesn't depend on scan speed), so given what you're looking for make sure to move telescope fast enough to push signal to white part.



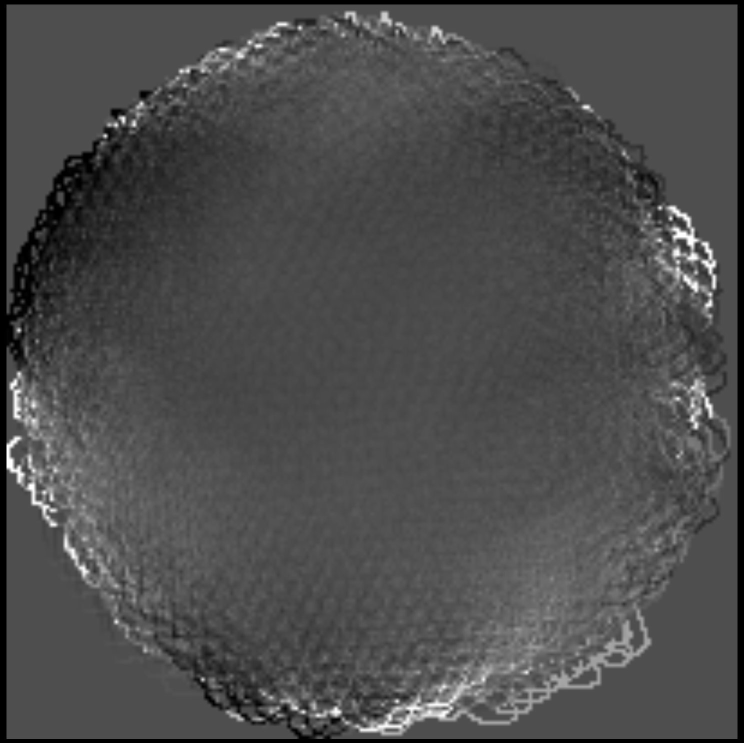
Naive maps

- What would happen if we made a map, and just averaged the data points that fell in each map pixel?

- This is called a “naive” map. It’s the right thing to do for white noise, but horribly wrong for typical ground-based noise.

- Scale: +/- 1

- What you’re seeing is the streaking from the low-frequency correlated 1/f noise in the data.



Well, where do you start if you're looking for a signal in data?

- Minimize χ^2!
- Let's look a bit at mapmaking equation again: $A^TN^{-1}Am=A^TN^{-1}d$
- What are we doing? Right hand side, we weight the data, then project onto our model.
- Solution is the thing that when turned into predicted data, gives the same noise-weighted, projected model as the real data.
- What might various models look like?

Usual A/Solution

- Want <d>=Am. If m is a (pixellized) map of the sky, then A is often called the "pointing matrix".
- We can sensibly solve for a map that minimizes χ^2, called an "optimal" or "maximum likelihood" map.
- Alternative is to make $A^T N^{-1} d$, then run a bunch of sims, trying to guess the effects of $A^T N^{-1} A$. "Divide" by your guess, to give a map.
- Same data! Noise 30x lower, can see SZ cluster with point source in it quite clearly.
- Will see next time how to go about solving for χ^2.