Title: Optimal Filtering: A Real-World Example

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Abstract: Extracting compact sources from maps contaminated with noise and unwanted astrophysical signals is a well-studied problem. In anticipation of the now-current generation of large-scale SZ surveys, many authors arrived at the conclusion that a simple multi-scale spatial/spectral filter would be the optimal way to find galaxy clusters in data from these surveys. I will briefly present the basics of the spatial/spectral optimal filter and then show in some detail how this has been implemented in one real-world case, namely in data from the South Pole Telescope (SPT) survey.

Optimal Filtering: A Real-World Example

Tom Crawford, UChicago/KICP

People I Steal Ideas From

Published:

- Haehnelt & Tegmark 96, Tegmark & de Oliveira-Costa 01, Melin et al. 05/06, ...

Conversations:

- Laurie Shaw, J.B. Melin, Gil, ...

Chewing on the data:

- Laurie, Keith Vanderlinde, Zak Staniszewski

Where to start?

Assume the following:

- Timestream data from all detectors at a given observing frequency has been fully processed, calibrated, co-added, and made into a single sky map. (E.g., for the example of SPT, that we have one map each at 90GHz, 150GHz, and 220GHz.)
- We understand the signal and noise properties in each of these maps.

I wonder if Laurie can see this

Two steps to clusters

1. Combine maps at different frequencies into synthesized thermal SZ map.
2. Find objects in that synthesized map.

- OR: these steps can be combined into a single spatial-spectral filter (e.g. Tegmark 2000, Herranz et al. 2002, Melin et al. 2006).

Making the synthesized tSZ map

- Treating anything that isn't thermal SZ as noise, make linear combo of maps that maximizes sensitivity to tSZ:

$$T_{\rm SZ}(\vec{\theta}) = \sum_a \lambda_a T(\vec{\theta}, \nu_a)$$

(Inverse) band-band noise covariance

Frequency dependence of thermal SZ

$$\lambda_a = \frac{\sum_b N_{ab}^{-1} f(\nu_b)}{\sum_{a,b} f(\nu_a) N_{ab}^{-1} f(\nu_b)}$$

Making the synthesized tSZ map

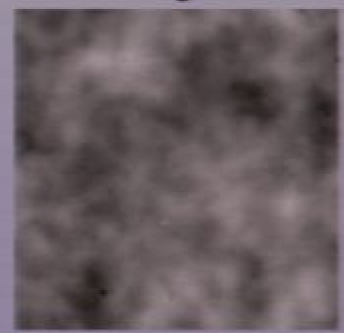
- Band-band noise covariance has terms from instrument noise, atmosphere, primary CMB, and point sources.
  - In general, the relative amplitude of these sources varies with spatial frequency, so coefficients of synthesized tSZ map are functions of spatial frequency:

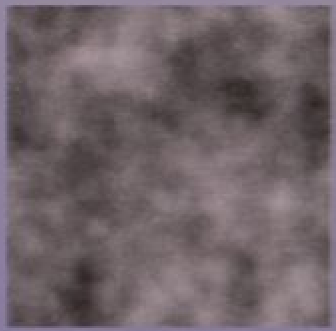
$$\lambda_a \rightarrow \lambda_a(\ell) = \frac{\sum_b C^{-1}_{\ell,ab} f(\nu_b)}{\sum_{a,b} f(\nu_a) C^{-1}_{\ell,ab} f(\nu_b)}$$

$$C_{\ell,ab} = \left[B^2 C^{\mathrm{inst}}\right]_{\ell,ab} + C^{\mathrm{CMB}}_{\ell,ab} + C^{\mathrm{PS}}_{\ell,ab} + \dots,$$

$$\left[B^2 C^{\mathrm{inst}}\right]_{\ell,ab} = \langle B_a(\ell) n_a^{\mathrm{inst}}(\ell)\ B_b(\ell) n_b^{\mathrm{inst}}(\ell) \rangle$$

Making the synthesized tSZ map

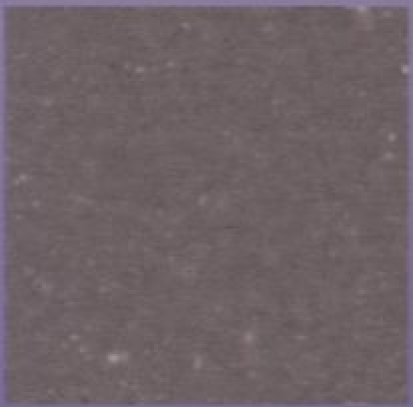




3°

150 GHz

90 GHz



220 GHz

Simulated SZ signal from Schulz & White (2003) Compton-y maps

Instrument noise levels:
90: 19 uK per 1′ pixel
150: 18 "
220: 38 "

Finding objects in the synthesized tSZ map

- If cluster profile is known, the right thing to do is obvious:
  - Filter synthesized map with Haehnelt-Tegmark-Wiener-Optimal-call-it-what-you-will:

$$\hat{T}_{\rm SZ}(\vec{\theta}) = T_{\rm SZ}(\vec{\theta}) * \Psi(\vec{\theta}) \leftrightarrow \hat{T}_{\rm SZ}(\vec{\ell}) = T_{\rm SZ}(\vec{\ell})\Psi(\vec{\ell})$$

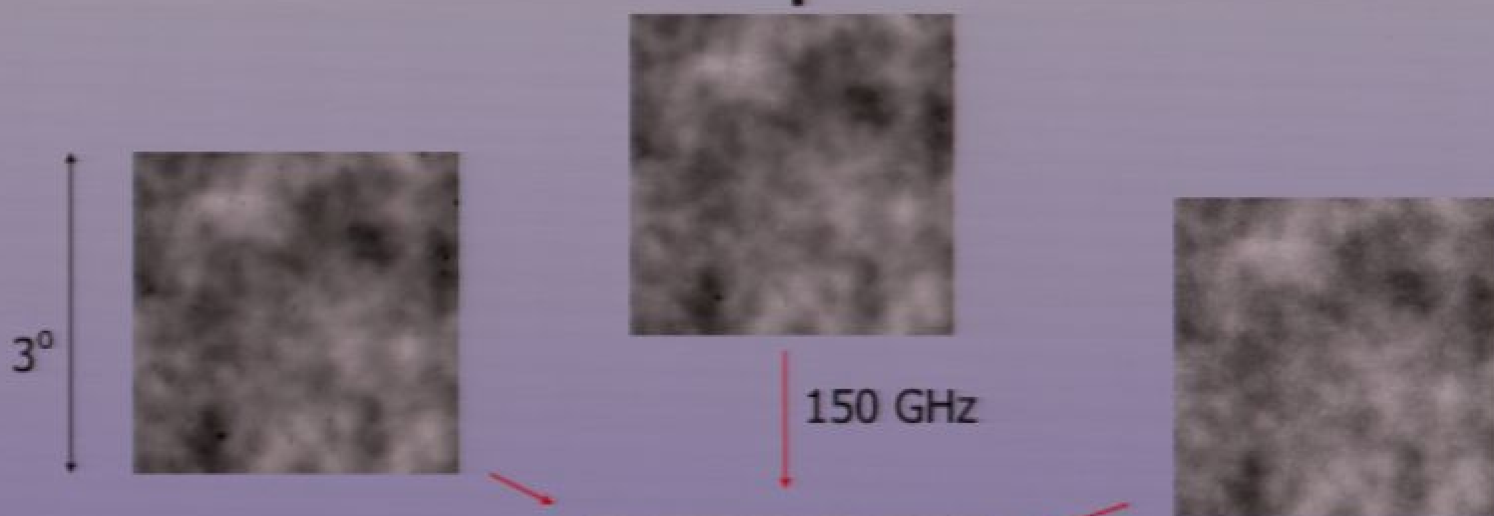
Assume everything's isotropic:

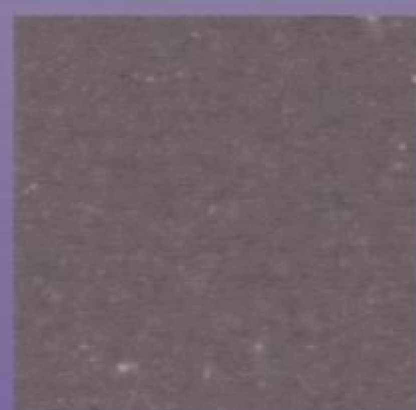
Cluster profile → $\tau(\ell)$

$$\Psi(\ell) = \frac{\tau(\ell)}{C_\ell^{\rm synth}}$$

$C_\ell^{\rm synth}$ ← Noise covariance in synthesized SZ map

Making the synthesized tSZ map





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Noise covariance in synthesized SZ map → C_ℓ^{synth}

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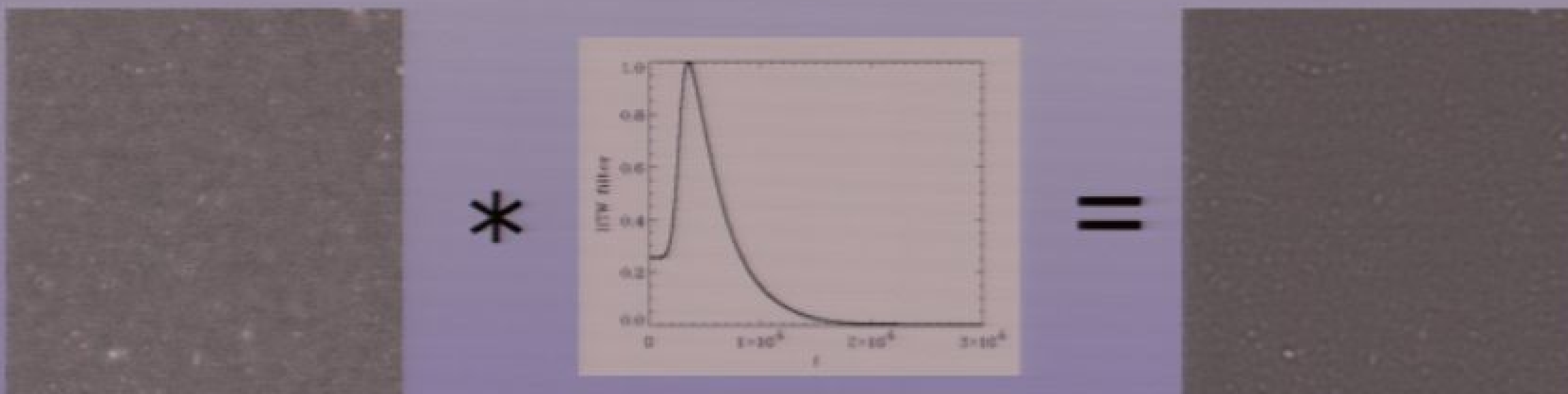
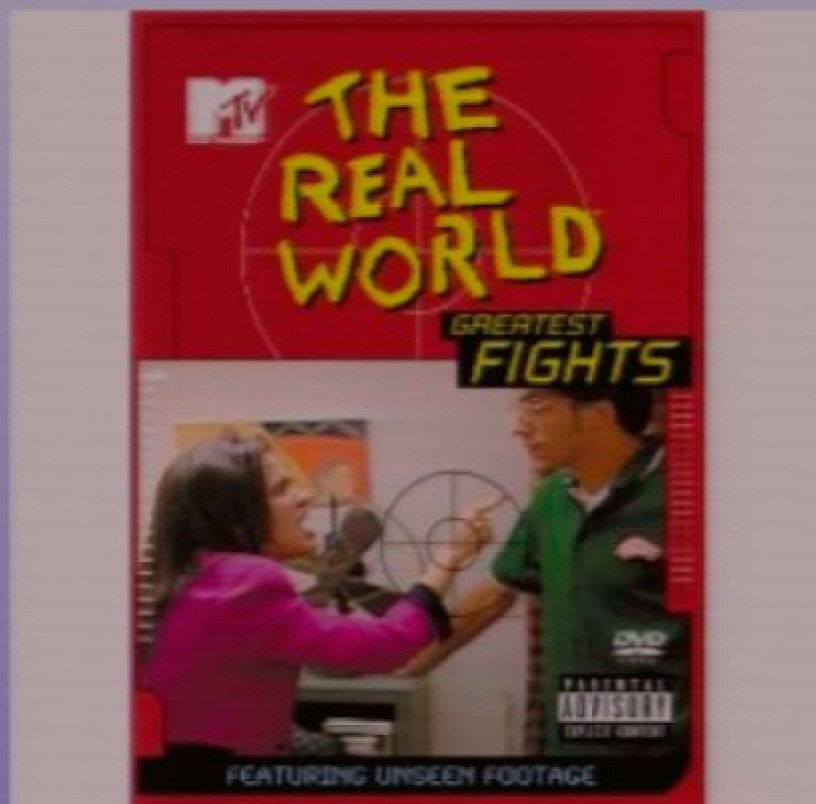


In optimally filtered map, use simple object finder (SExtractor or similar) to identify and extract peaks and their value.

Real-World Complications



Hi Laurie, how do you think the talk is going so far?

Real-World Complications

- Noise properties
- Beam properties
- Bright point sources
- Choice of cluster profile
- ......


Real-World Complications
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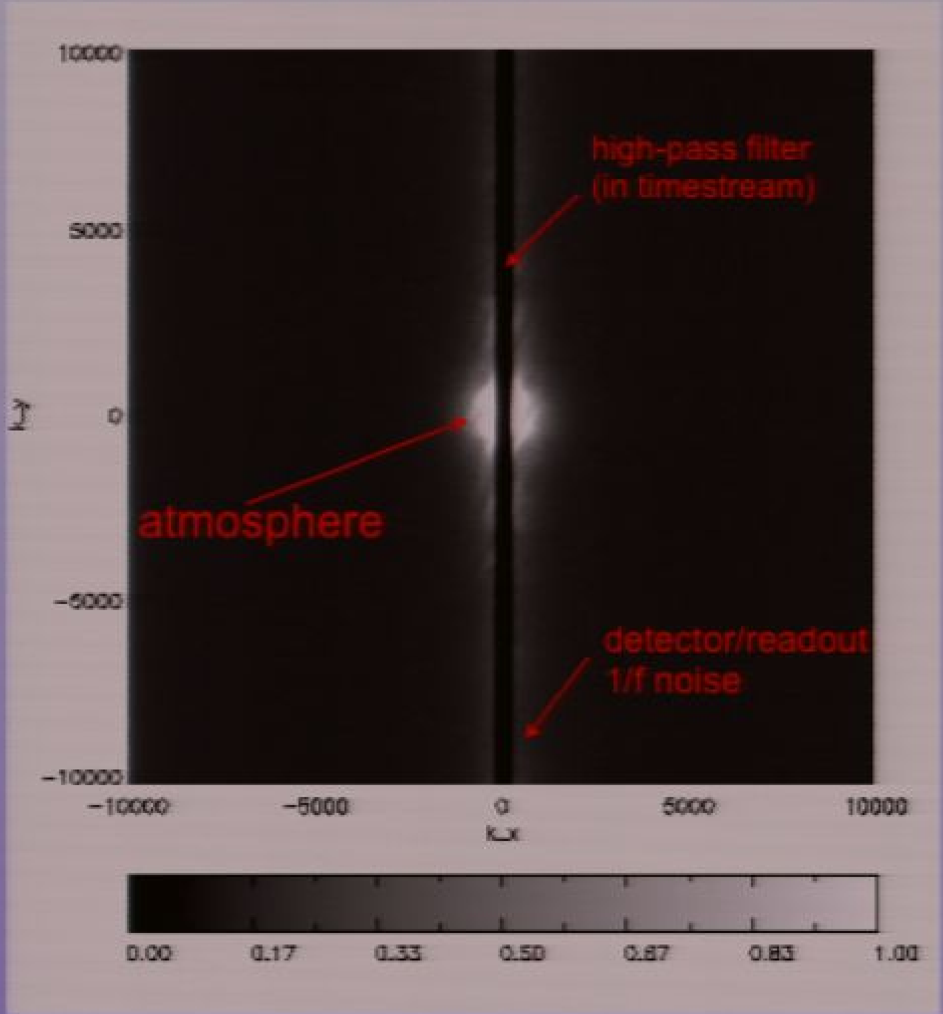
Sunyaev-Zeldovich Universe and the Future of Cluster Cosmology, Perimeter Institute for Theoretical Physics, May 1, 2009

Noise Properties

- Not (even close to) isotropic for SPT
- Still pretty close to homogeneous/ stationary (thank goodness).

Noise Estimation

- take all individual observations (100's), take sum of half minus sum of other half, calculate power spectrum, repeat many times changing who's in each half.



Real-World Complications

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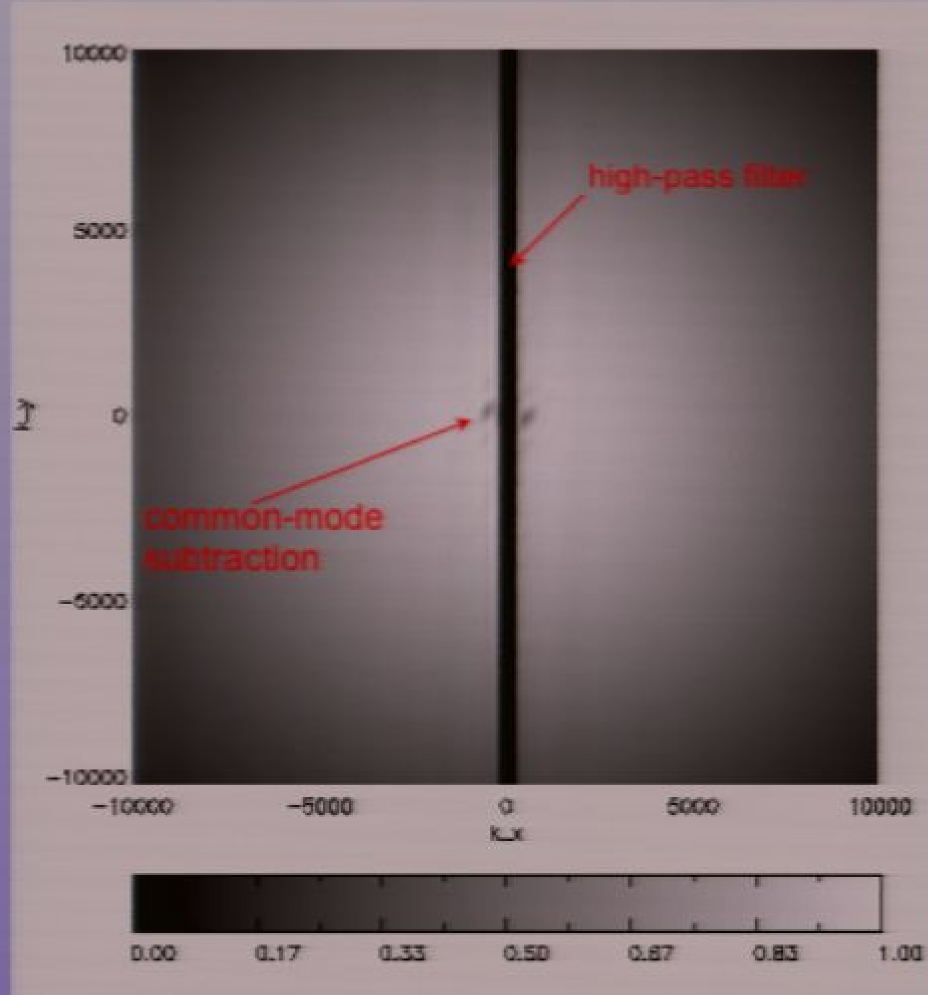
Real-World Complications

- Beam properties:
  - Really beam + all pre-map filtering
  - Also not even close to isotropic
    - well, the beam is, but the filtering isn't.

Do you think Joe Fowler would notice if I made some ACT jokes here?

Transfer Function Estimation

- place fake source in a noiseless timestream simulation, pass through filtering, measure output shape.
- only works if timestream filtering is linear in data (doesn't depend on signal).



Real-World Complications

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Bright Point Sources

- cause spurious decrements from sidelobes.
- brightest sources have different spectral behavior than background, so they don't get
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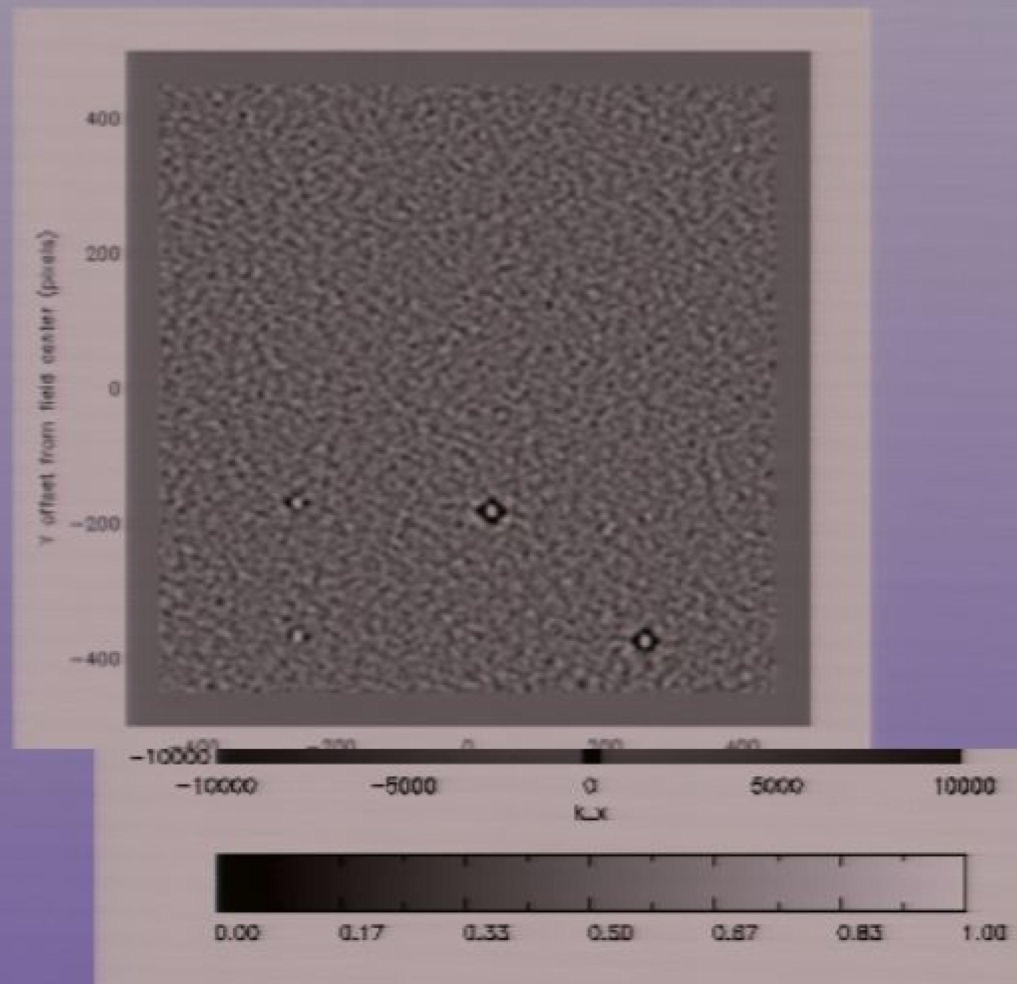

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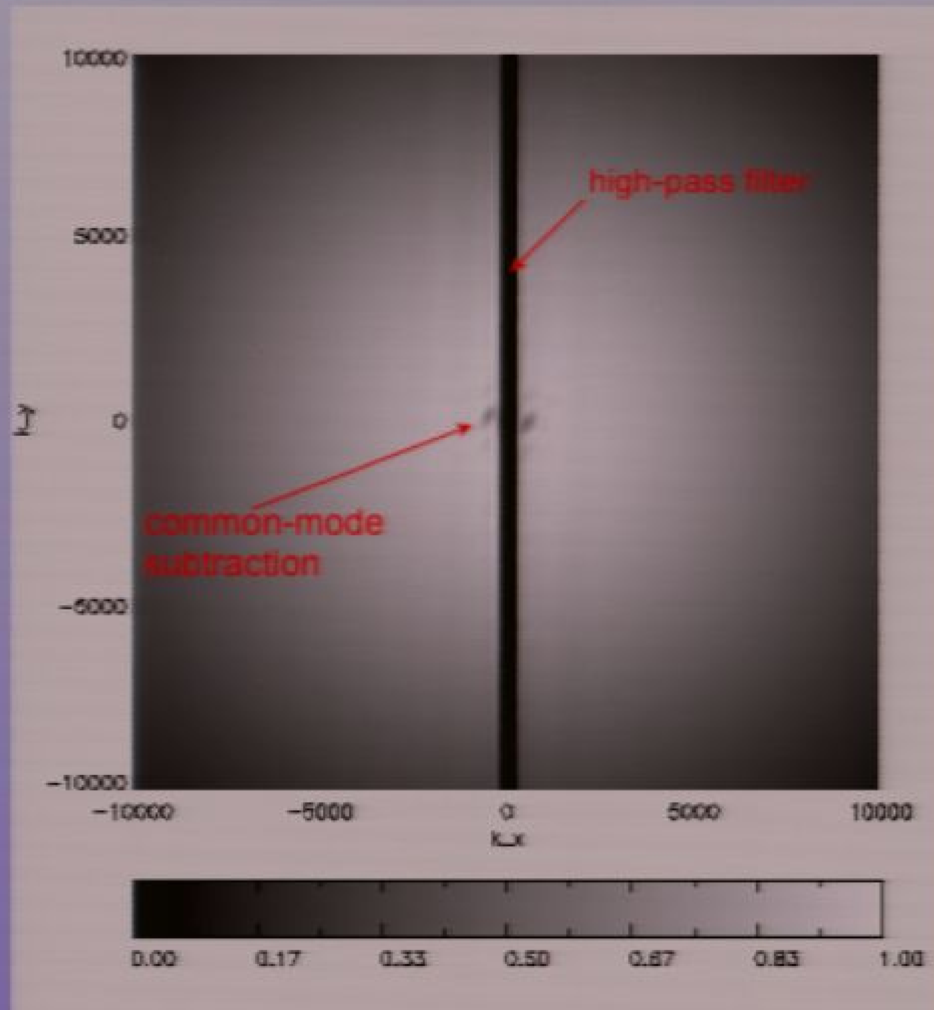

Real-World Complications

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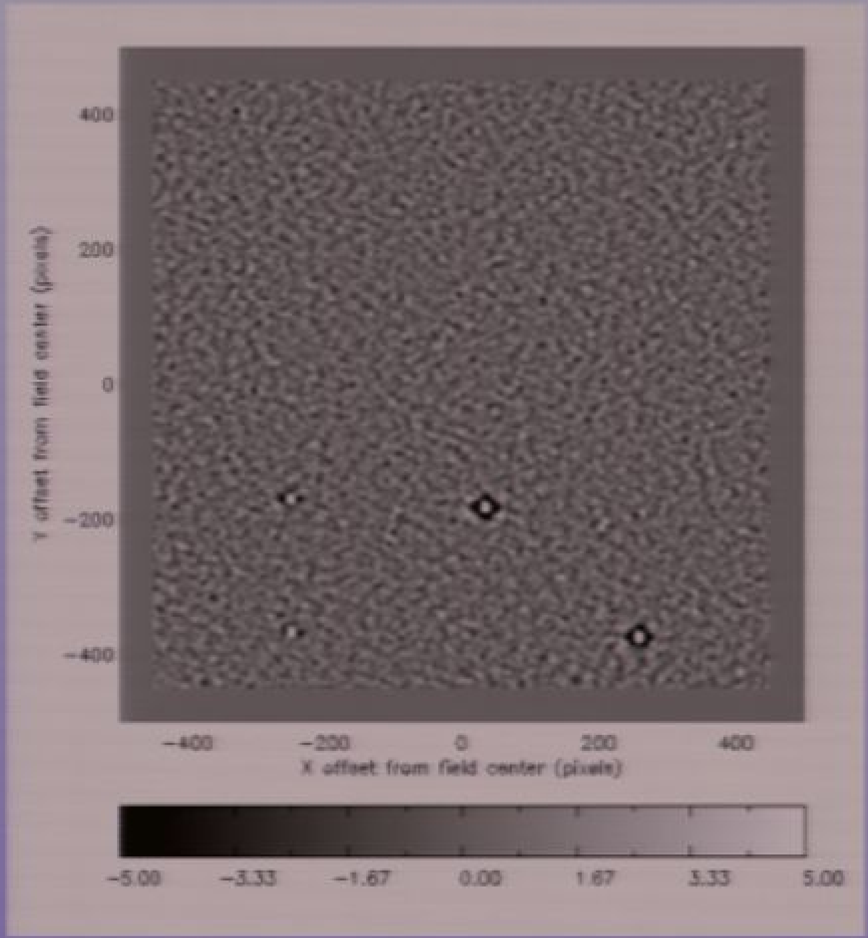

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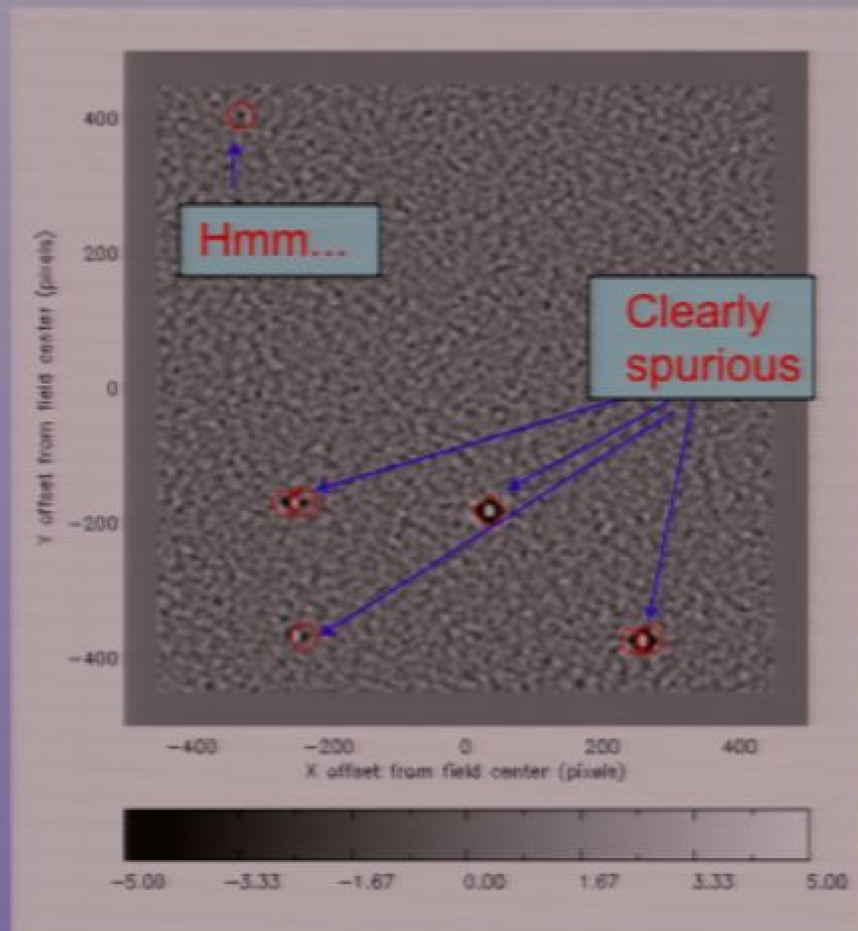

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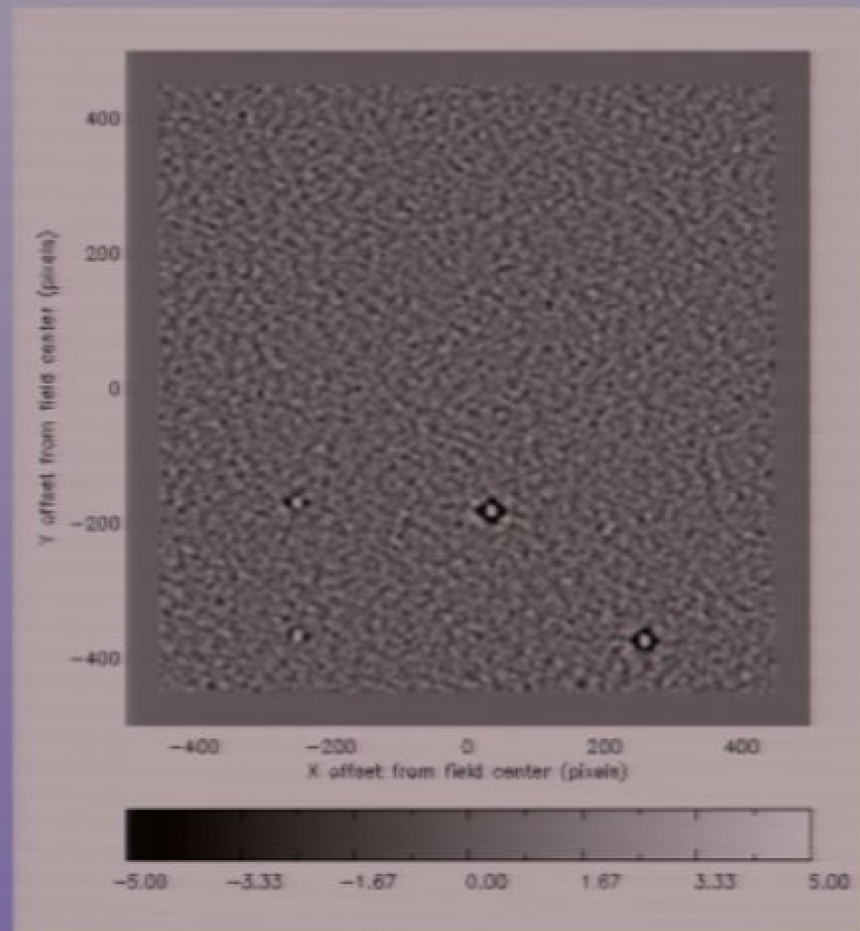

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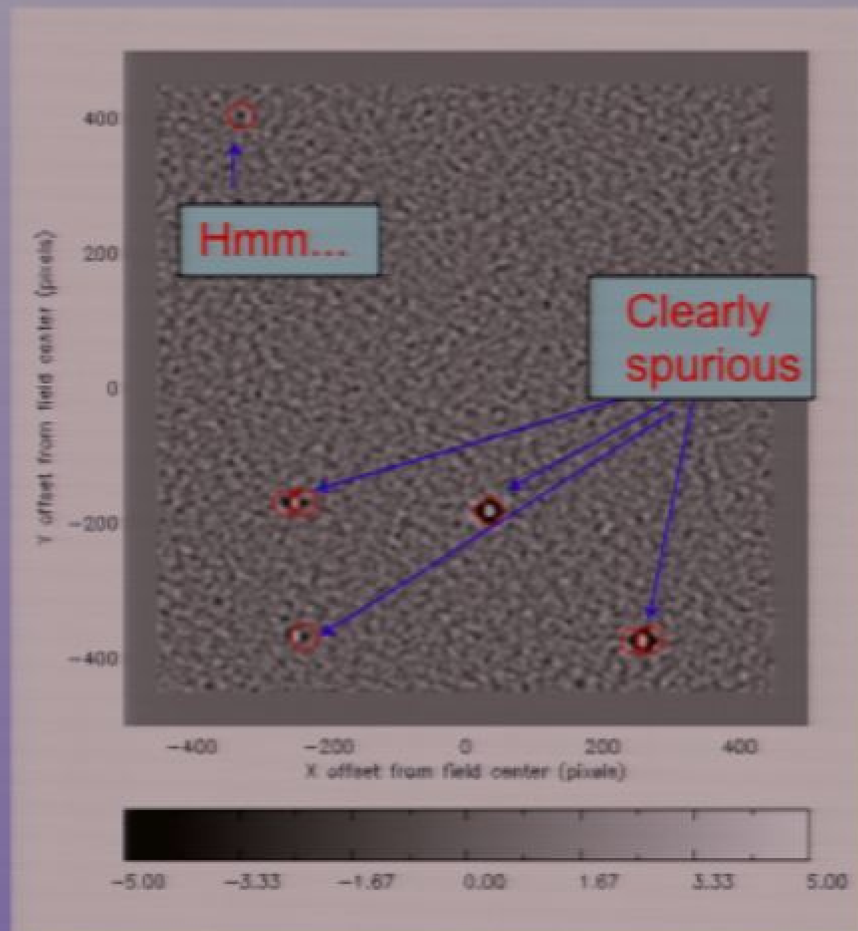
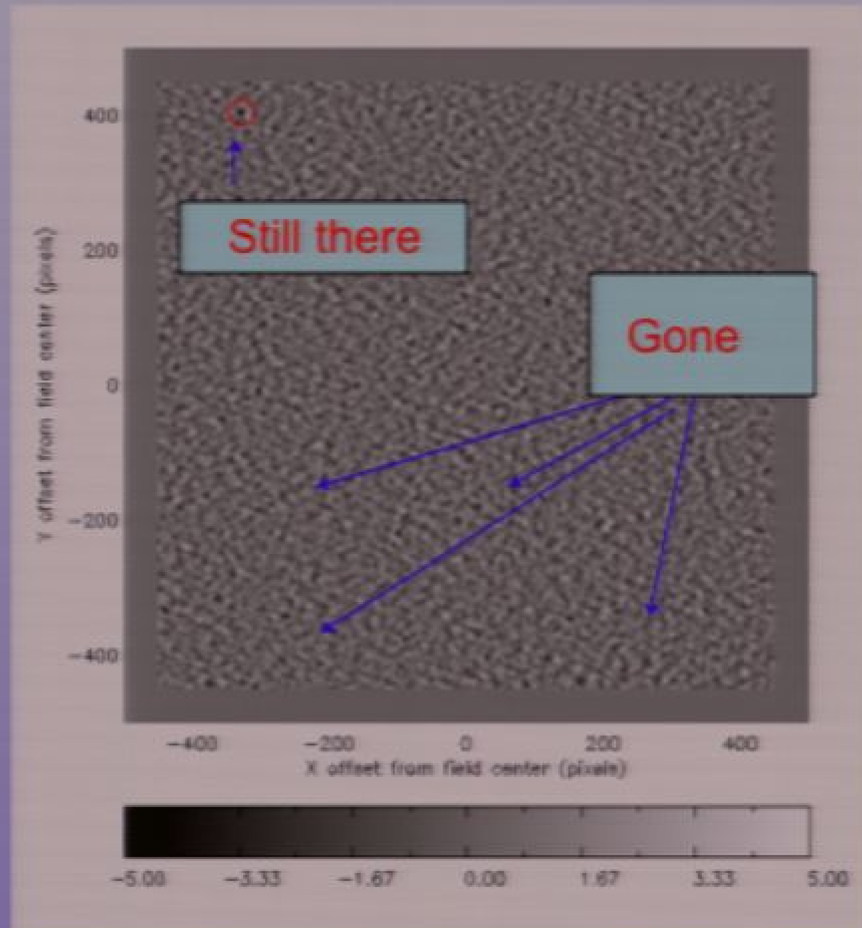
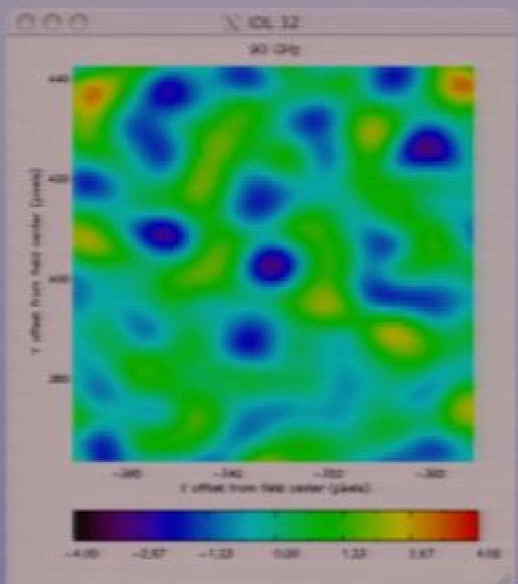


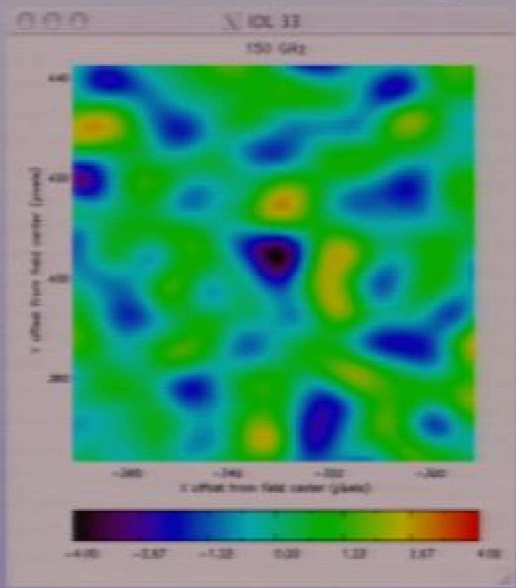
Bright Point Sources: Mitigation

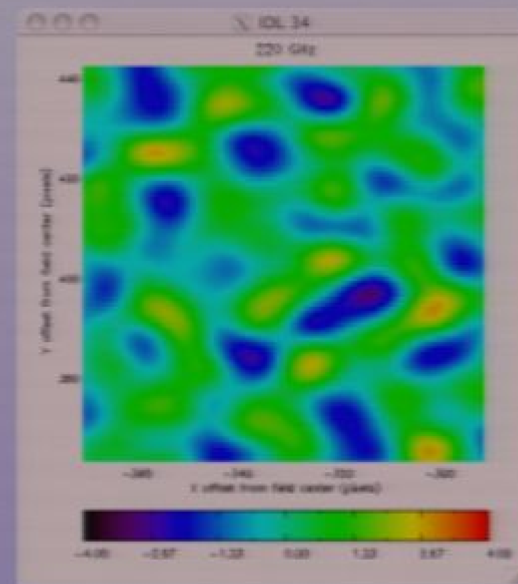
- we could subtract a model for each or just mask them.
  - but of course, the mask will cause ringing itself unless it's stitched smoothly to the rest of the map

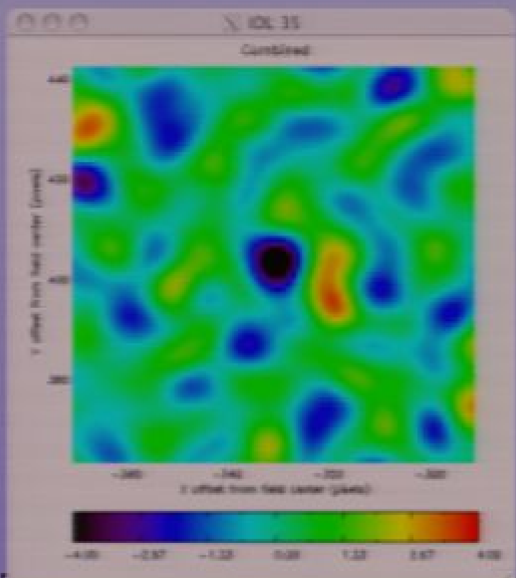


The Blackberry Cluster









- ~5.1 sigma in combined map
- ~4 sigma in 150GHz alone

Real-World Complications

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- ……

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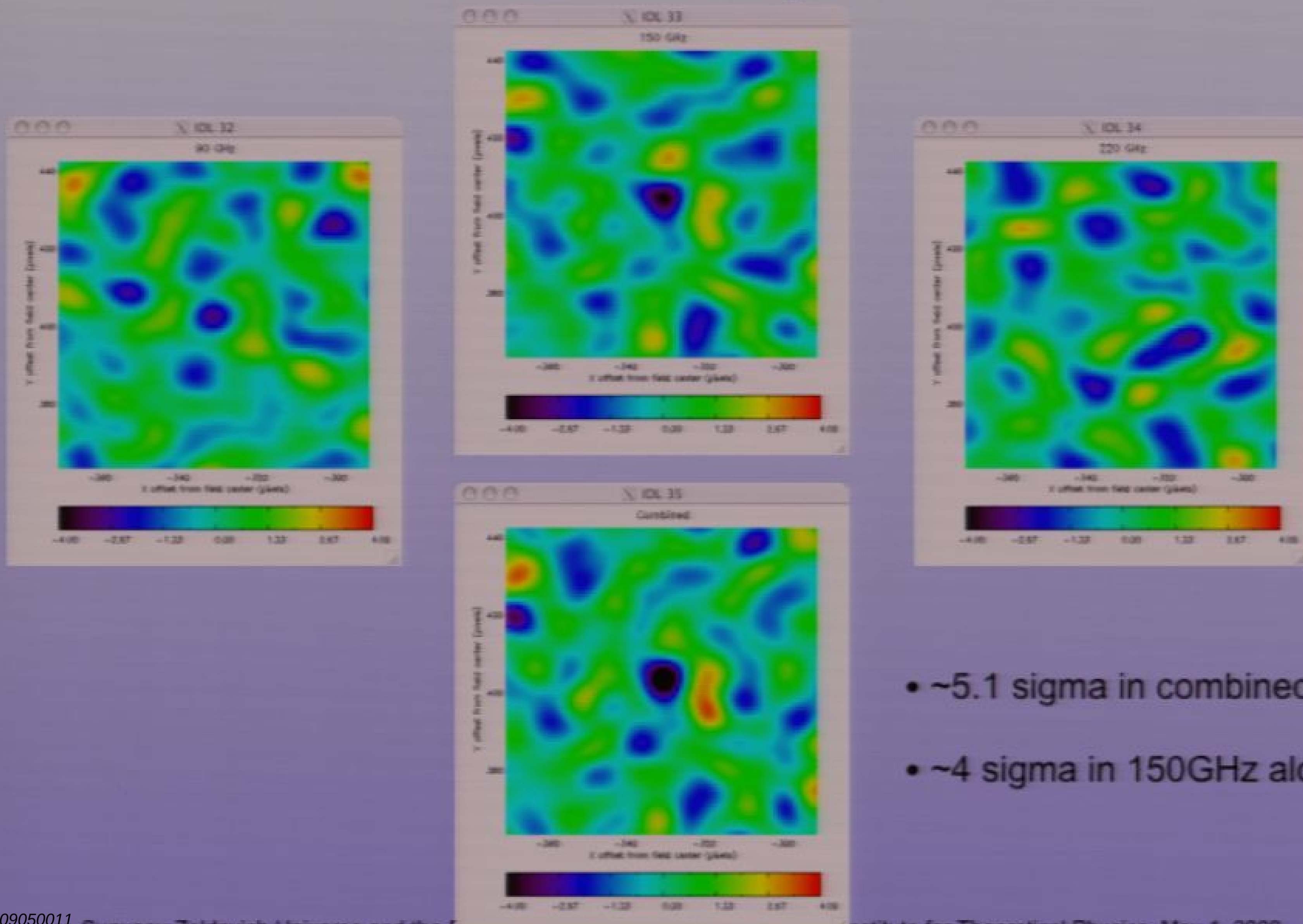

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Real-World Complications

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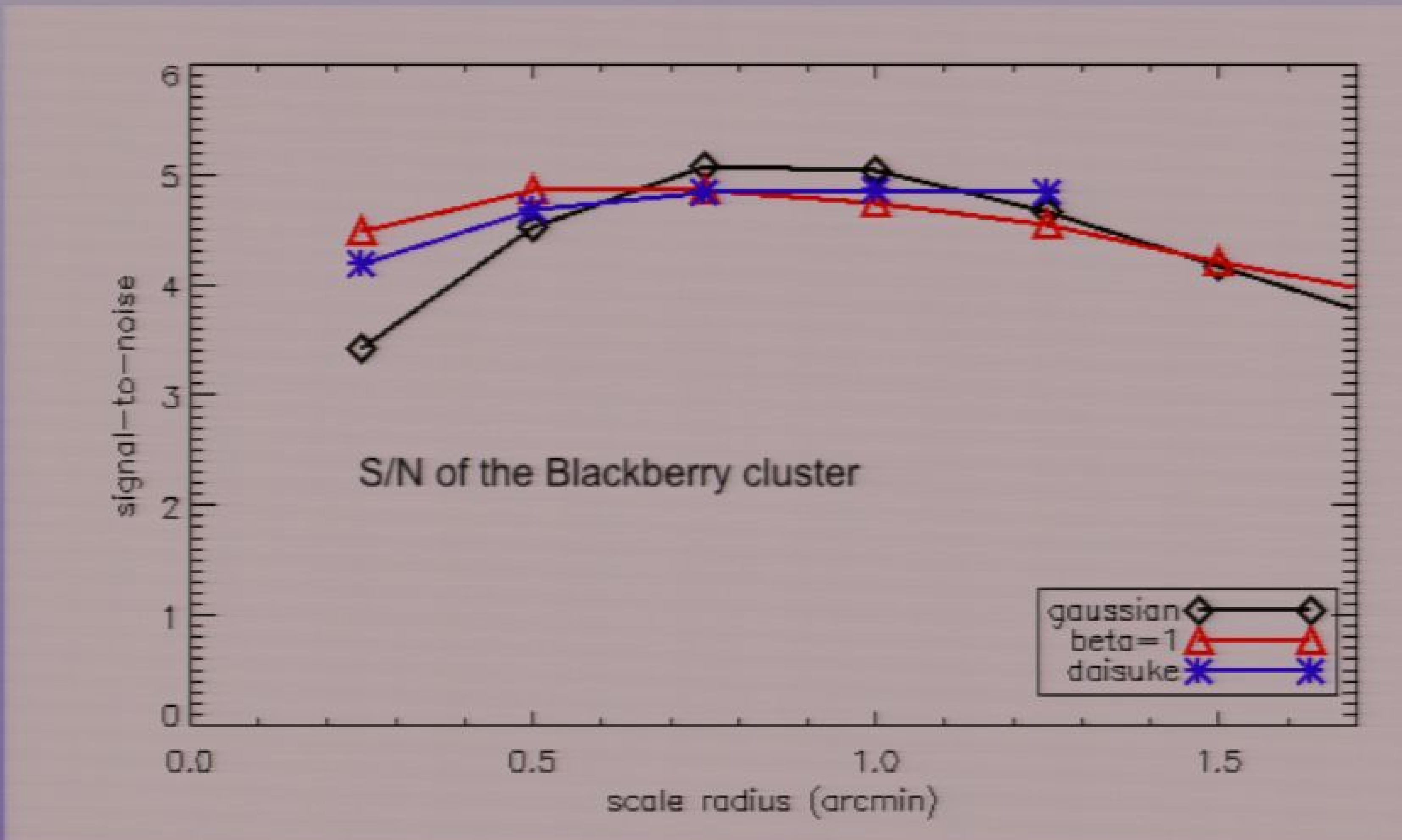
Real-World Complications

- Choice of cluster profile:
  - beta model? NFW? Daisuke's pressure profile?
  - scale radius?
- Well, obviously, you use a bunch of them and take the best detection.
- For ~5 sigma objects, the details don't matter.

Choice of Profile



Summary

- Algorithms people developed before we had data seem to work pretty well, with some complications.


Thanks!
Photo credit: Keith Vanderlinde