Map making, source finding and transient detection with ACT

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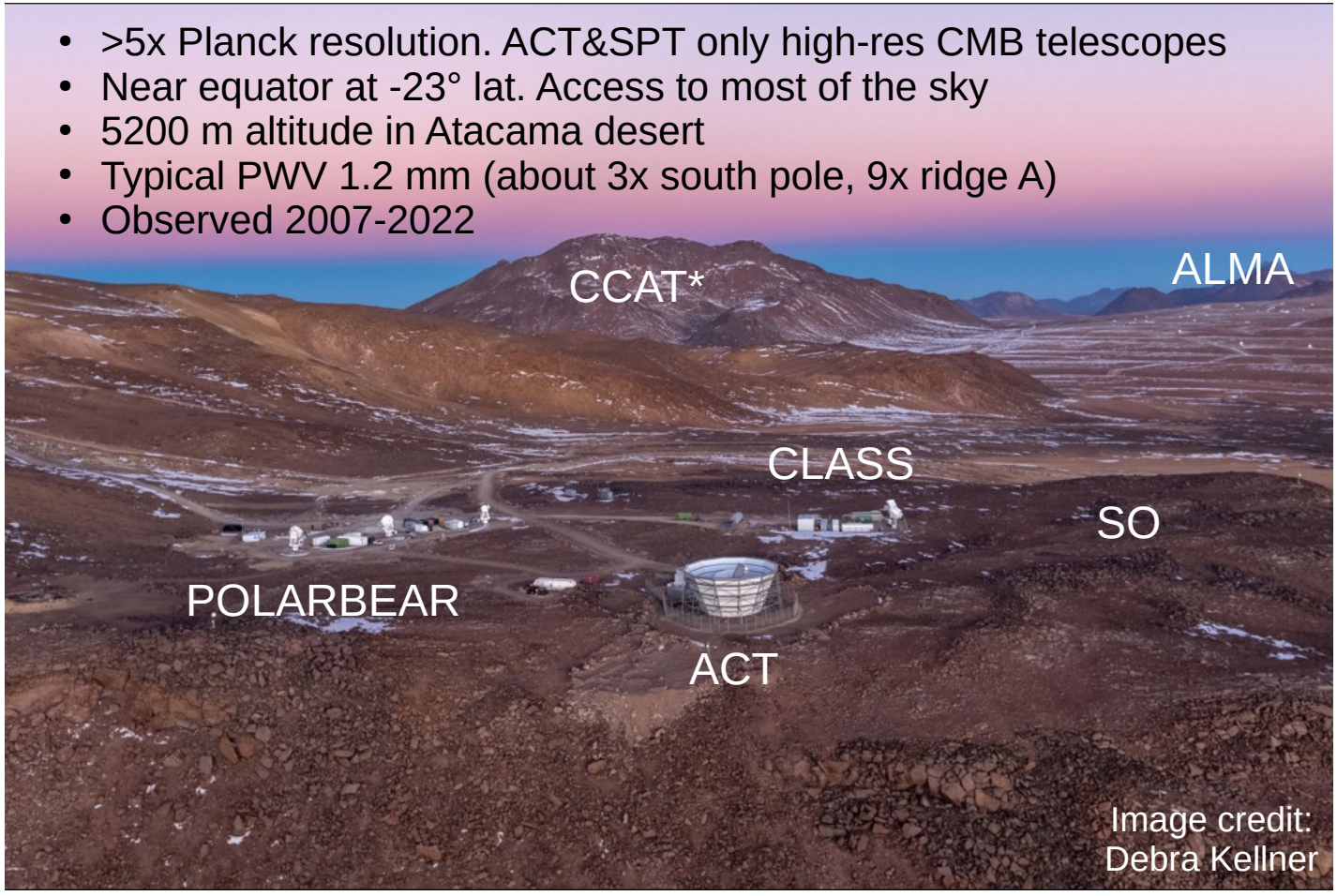
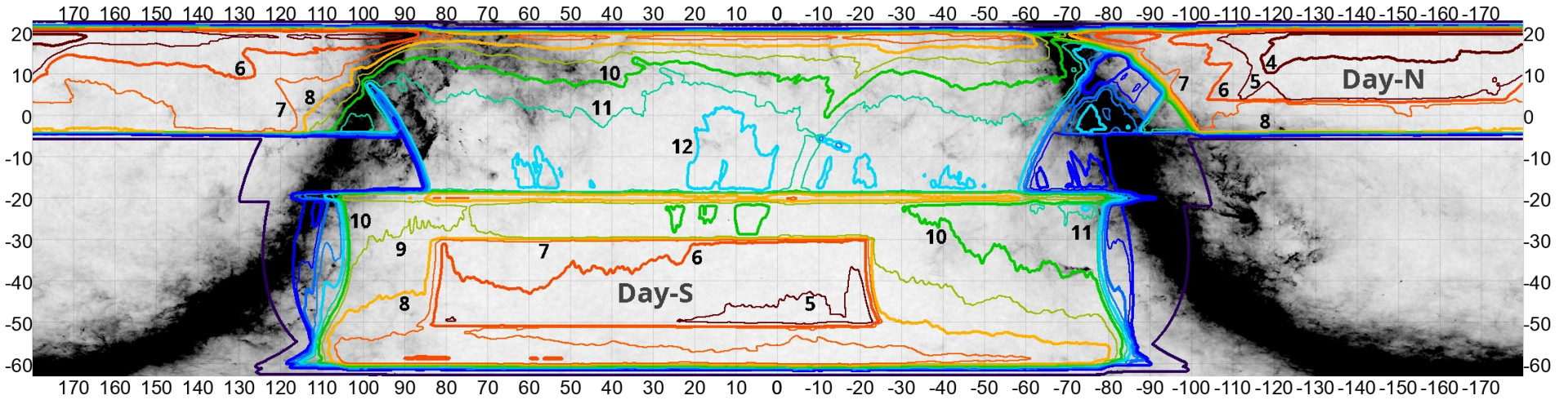
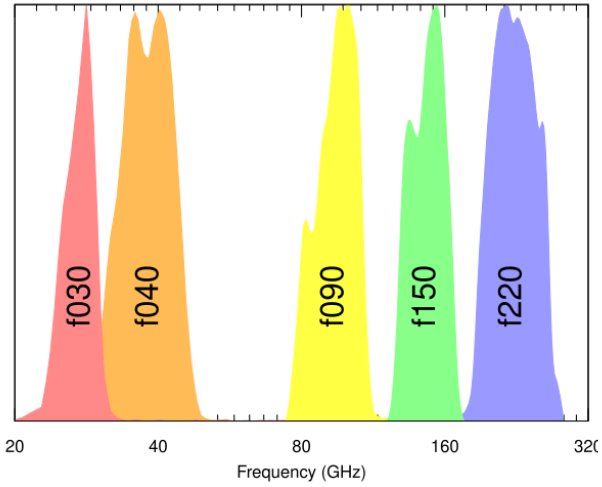
The Atacama Cosmology Telescope

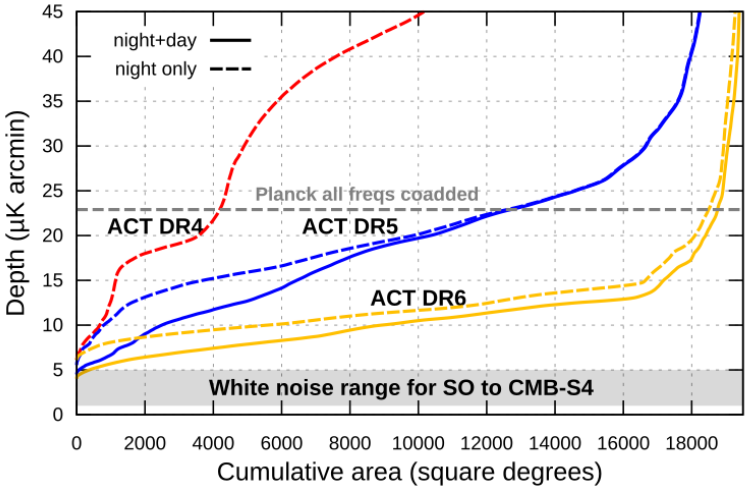
- >5x Planck resolution. ACT&SPT only high-res CMB telescopes
- Near equator at -23° lat. Access to most of the sky
- 5200 m altitude in Atacama desert
- Typical PWV 1.2 mm (about 3x south pole, 9x ridge A)
- Observed 2007-2022



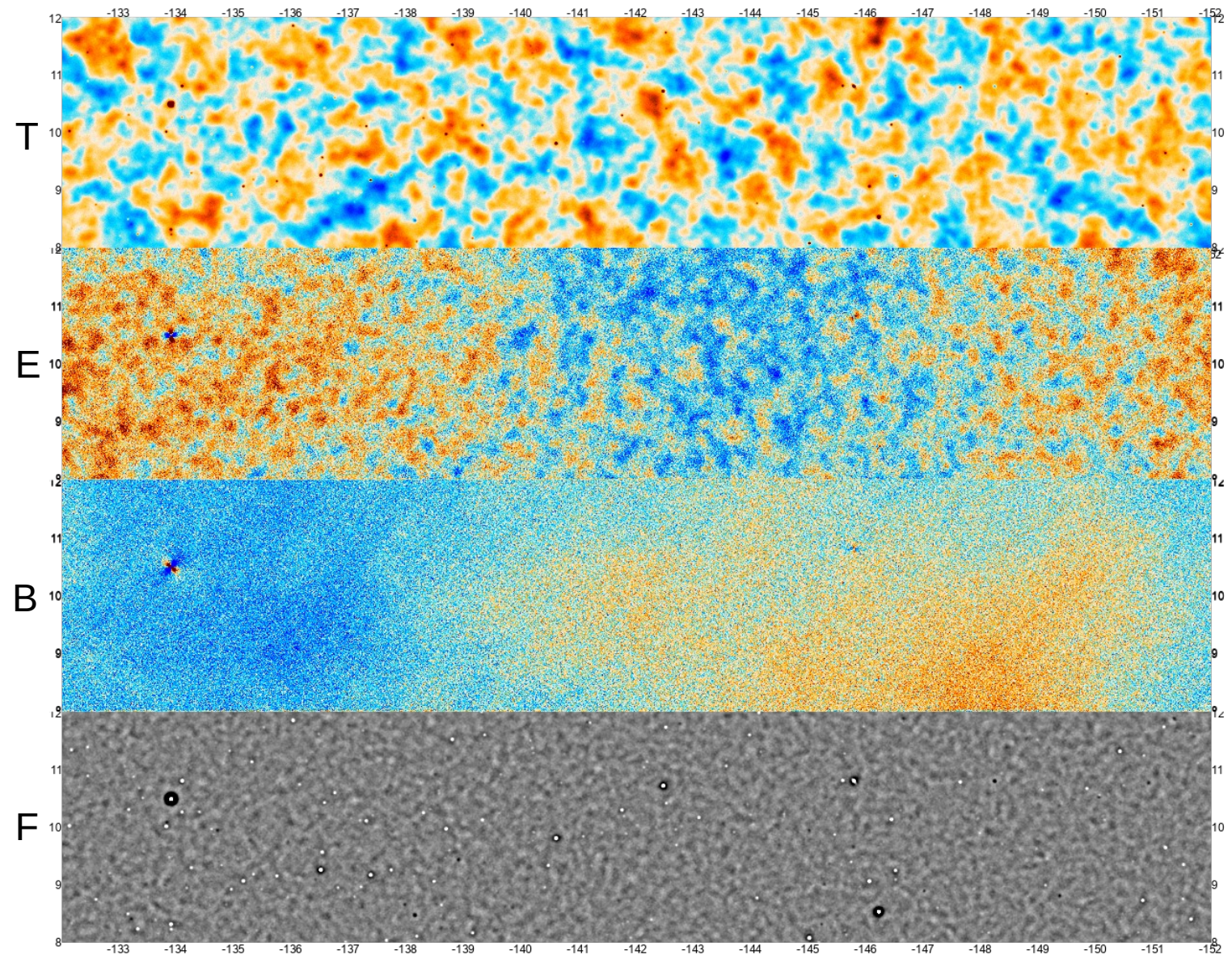
Advanced ACT







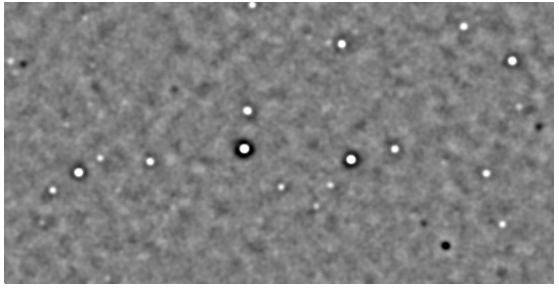
- Observed 2017-2022 in 5 bands
- Combined sensitivity of 6.1 μK√s (mostly in f090 and f150)
- ACT DR6 coming soonish
- Deeper than Planck over 19000°²
- Median depth of 10 μK arcmin
- 10x as much statistical power as DR4 (prev. cosmology release)



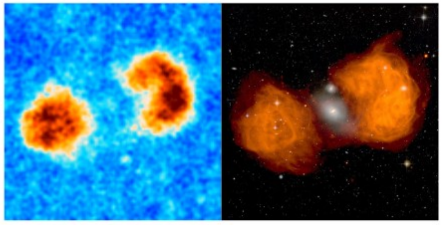
DR6 map example (from 4-5 μK arcmin region)

Much more than CMB in the maps

Point sources & clusters

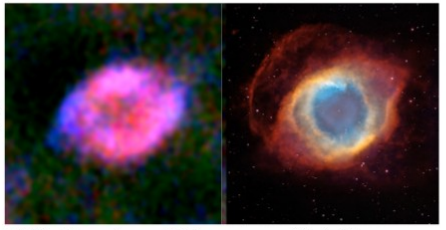


Fornax A



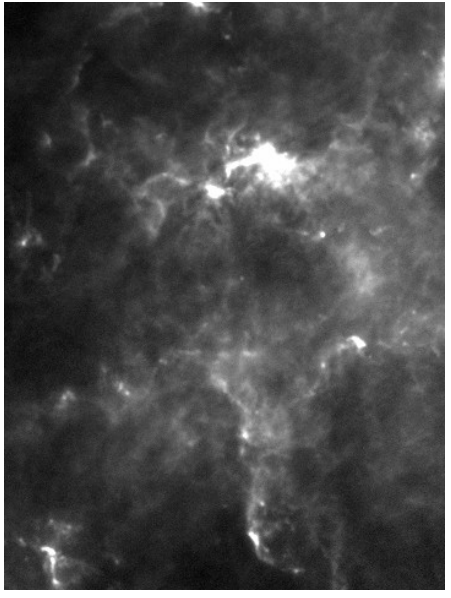
ACT+Planck f090 - f150 Radio+Optical

Helix Nebula

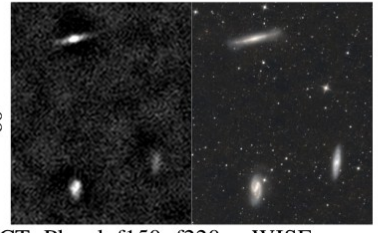


ACT+Planck multifreq Hubble

Galactic dust

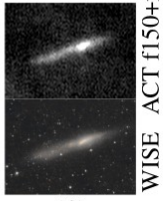


Leo Triplet



ACT+Planck f150+f220 WISE

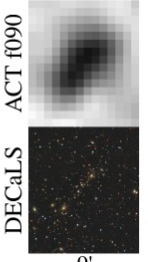
NGC 55



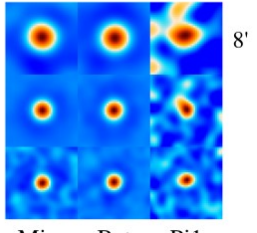
18'

NGC 253

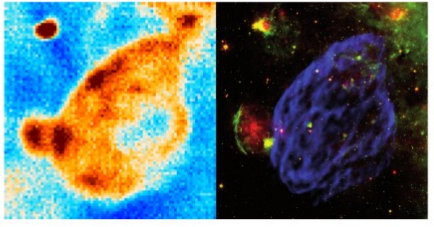
Merging clusters



Stars



Supernova remnant W44

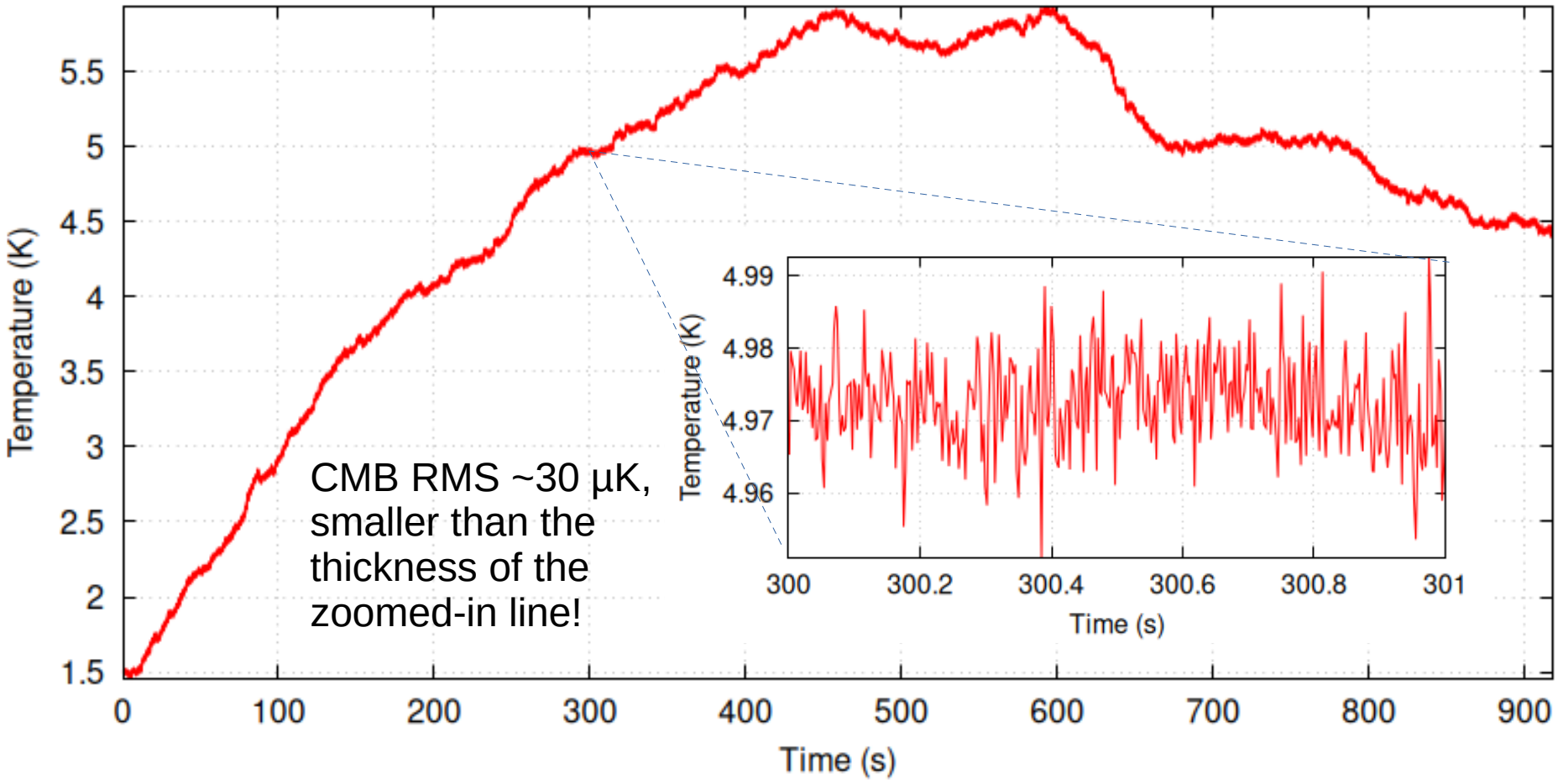


ACT+Planck f090 - f220 VLA+Spitzer

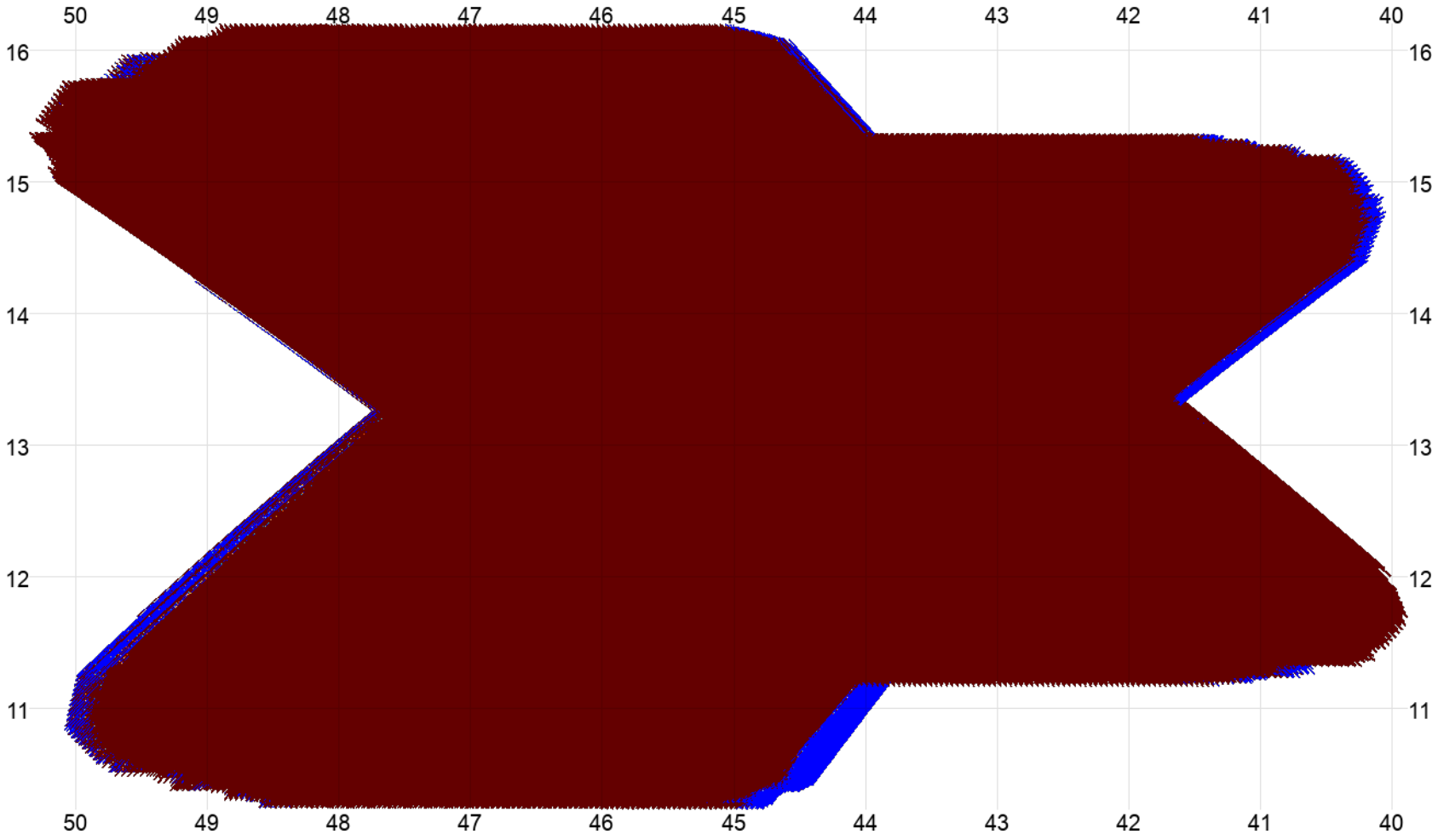
Rosette nebula

ACT+Planck multifreq IPHAS H-alpha

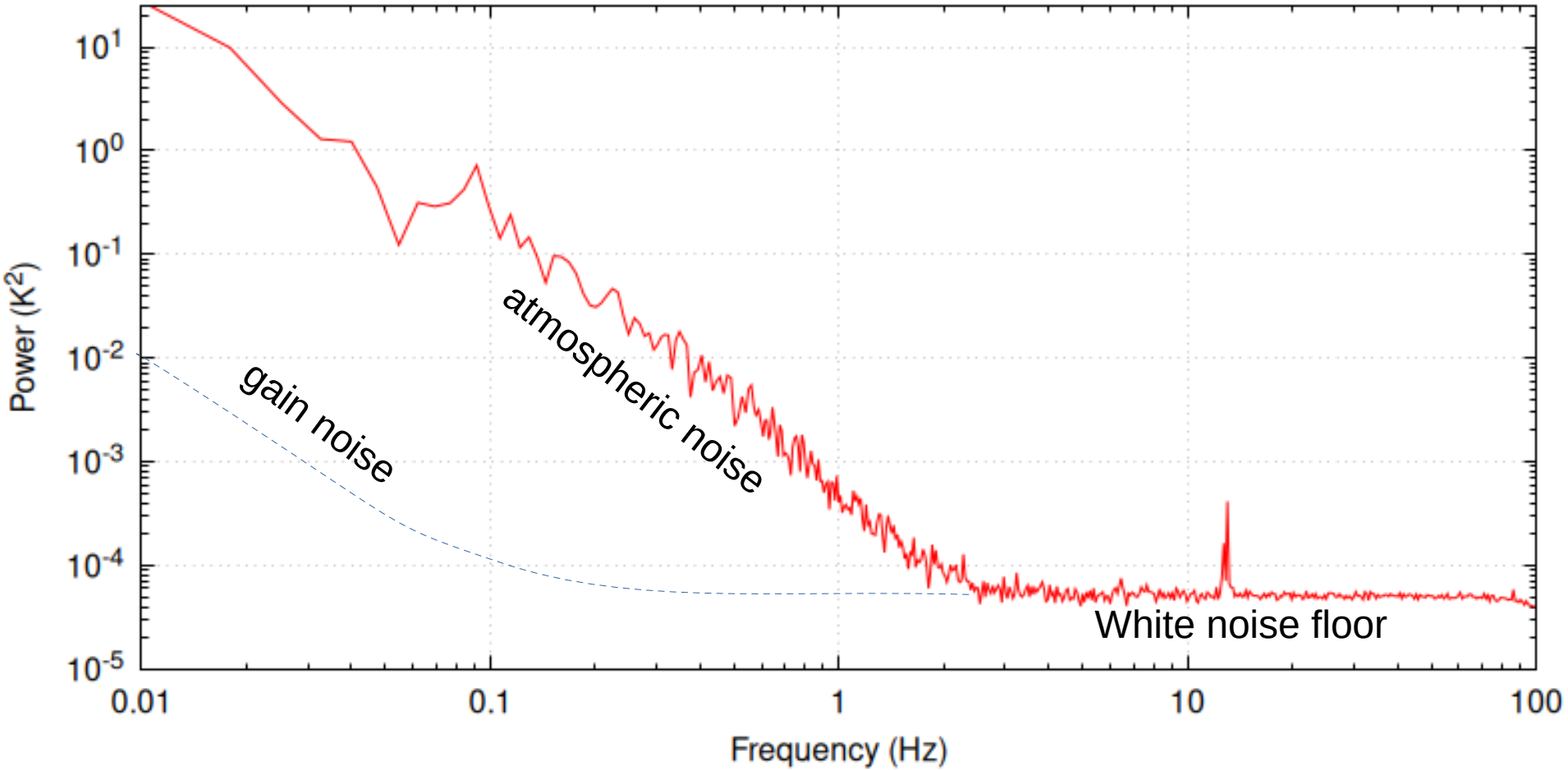
What the data actually looks like



What you get if you just try to bin this on the sky



Need to handle the correlated noise



Two main approaches

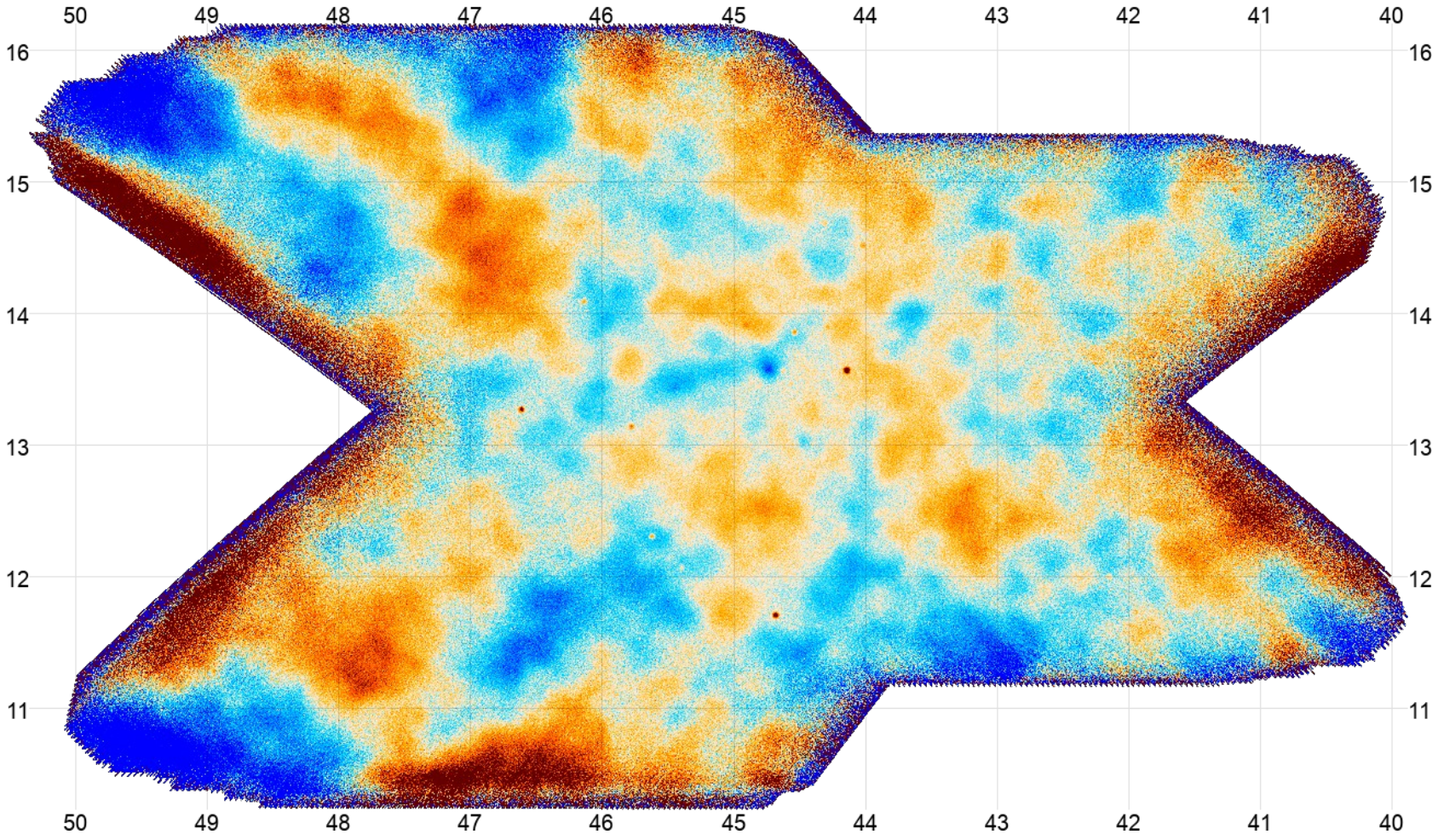
Maximum Likelihood

- Model the detector data as d=Pm+n, and solve for the least-squares map $m=(P^T N^{-1} P)^{-1} P^T N^{-1} d$
- Unbiased and optimal *if model fully describes data*
- ~100x slower than filter+bin
- Harder to deal with systematics. As little filtering as possble in the mapmaker, ideally none. Pickup dealt with via map-level filtering and/or adding it to equation system
- TOD sims expensive, but only needed to confirm biaslessness
- Majority of sims are map-based, based on data splits. Very fast, not necessarily worse than TOD-level noise sims (might be better)
- Used by e.g. WMAP, Planck, ACT. Map a primary data product

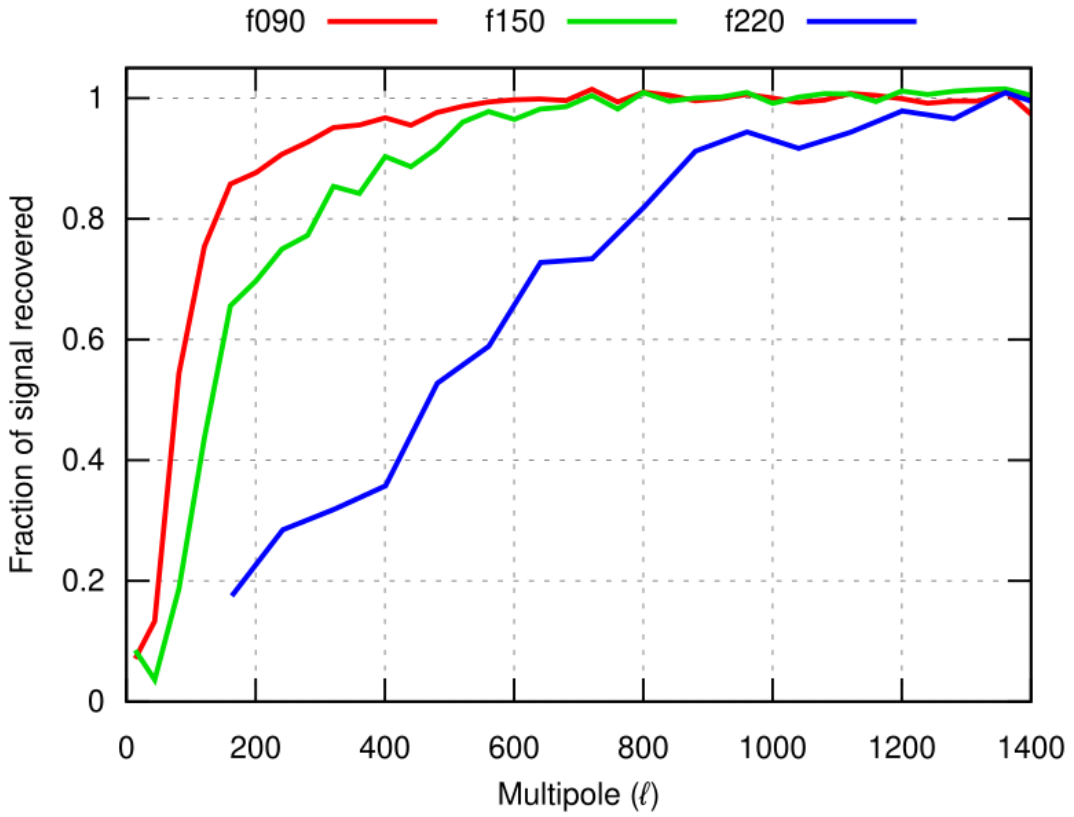
Filter+bin

- Simple and flexible: Filter the data any way you want, then average into pixels
- Need lots (10^2-10^4) of sims to characterize both bias from filtering and noise properties. All map users need these sims to interpret signal in maps. About 200 GB/sim.
- Filtering easy and done mainly in mapmaker
- Sub-maps combine linearly – easy to do large number of null tests (but heavy if combined with sims)
- Used by e.g. Bicep, SPT. Maps often regarded as implementation detail and not released

Maximum likelihood solution



Should be unbiased. But bias can sneak in



Main cause tracked down to gain mismatch between detectors. Very unintuitive!

https://arxiv.org/abs/2210.02243

Subpixel treatment also contributes.

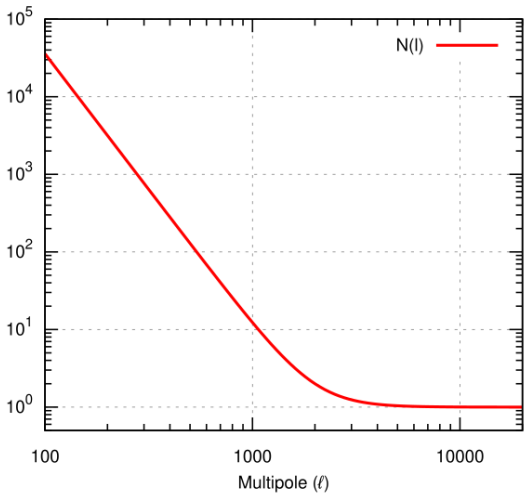
In general maximum-likelihood mapmaking only unbiased if data follows model

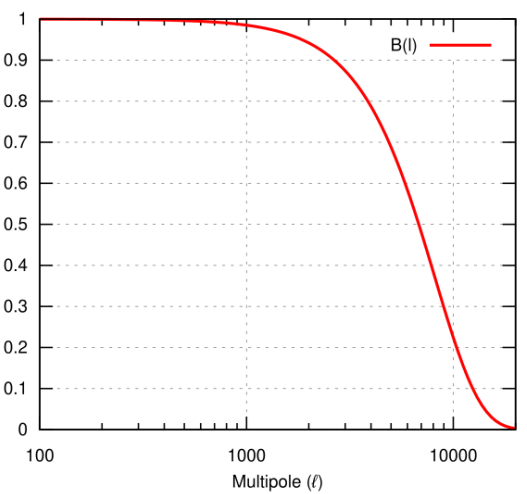
All mapmaking methods vulnerable!
Filter+bin not immune!

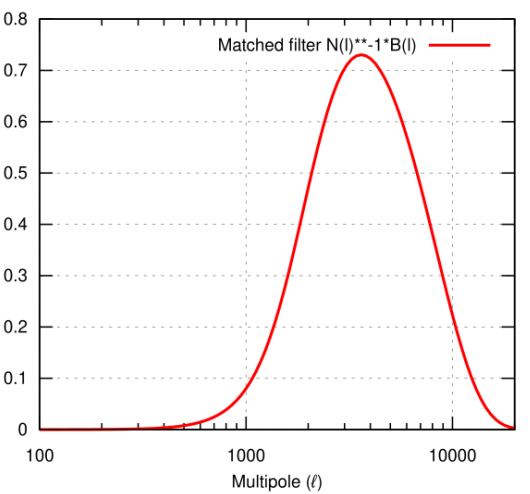
Point source detection

- Given a map with an unknown number of objects with known shape, how do we find them?
- Standard solution: Matched filter
- Simplest version is a pure harmonic filter:

$$\mathrm{map}_{\mathrm{mf}}(\ell) \propto N^{-1}(\ell) B(\ell) \mathrm{map}_{\mathrm{raw}}(\ell)$$







Inhomogeneous noise

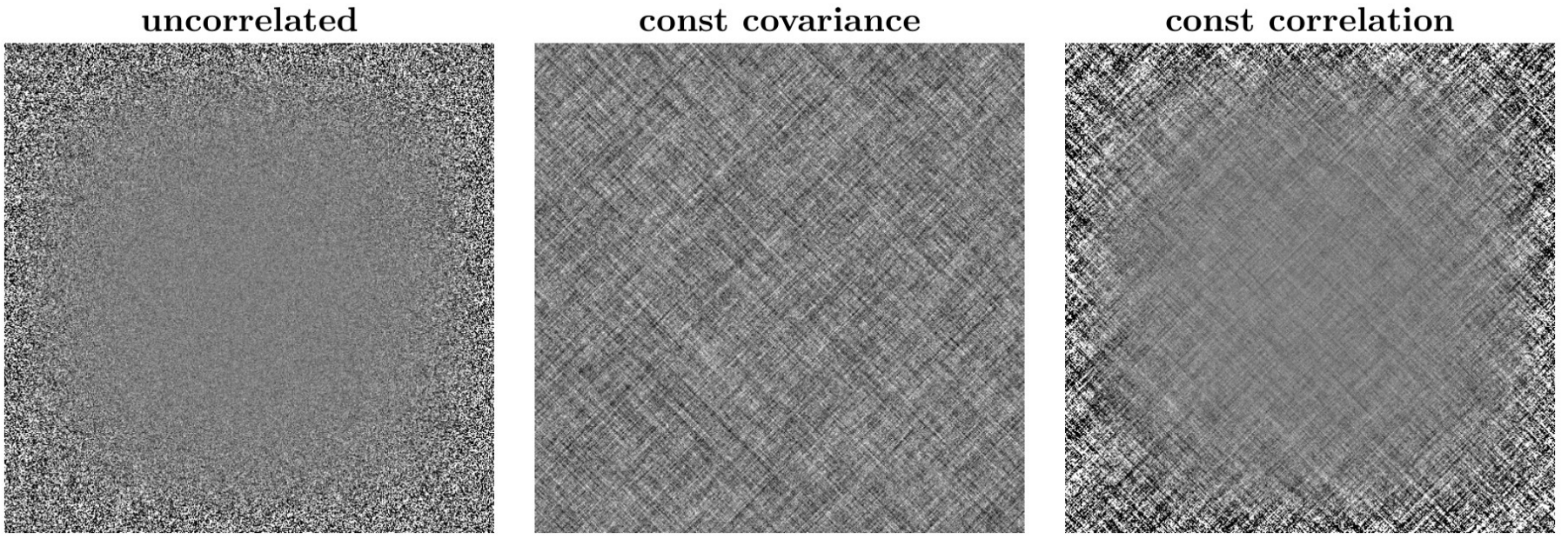
Can generalize the matched filter to

$$\rho = B^T N^{-1} m \qquad \text{flux} = \rho/\kappa$$

$$\kappa = \text{diag}(B^T N^{-1} B) \qquad \sigma_{\text{flux}} = 1/\sqrt{\kappa}$$

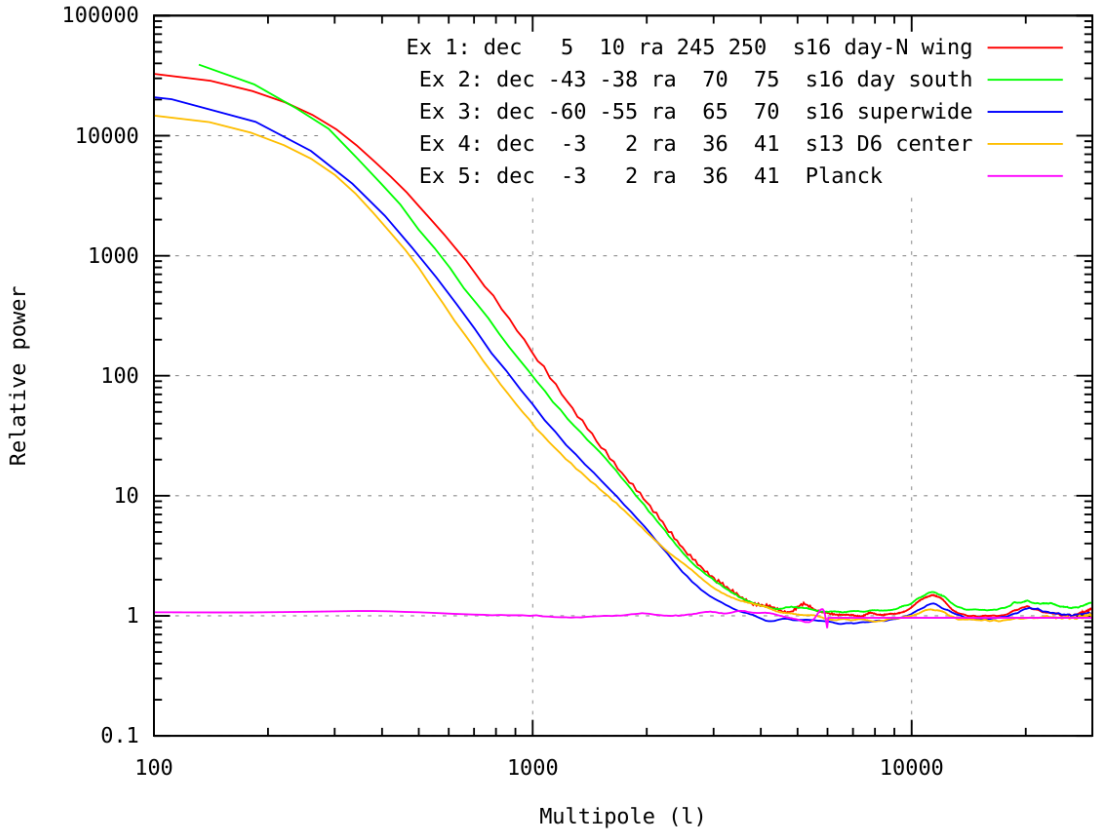
- Handles arbitrary noise properties and beams, but κ kan be tricky to compute
- I use this in ACT with a tiled "constant correlation" noise model

What does "constant correlation" mean?

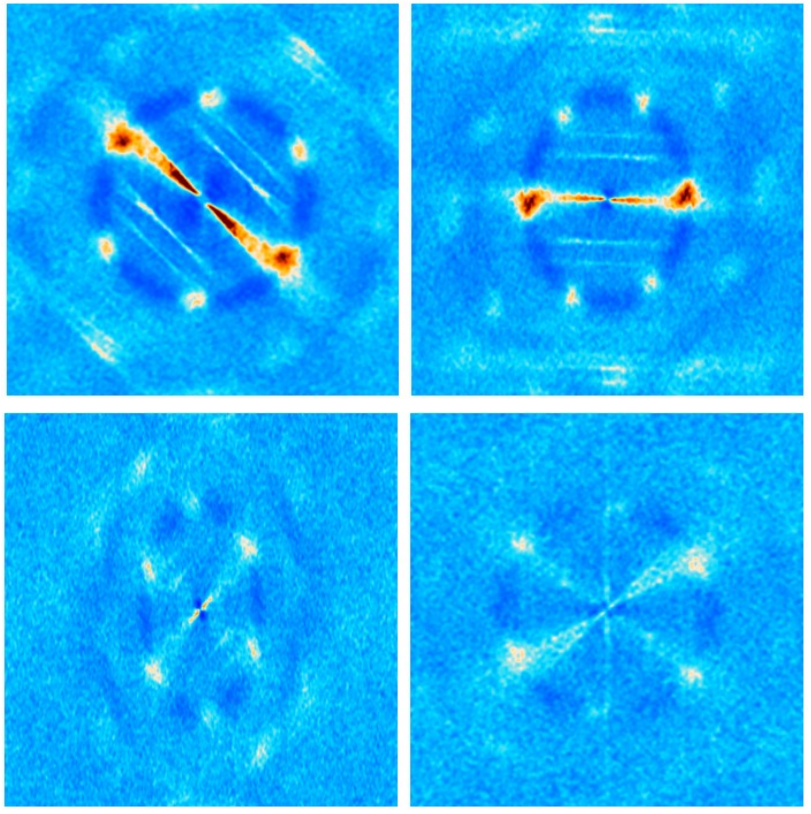


Example ACT noise correlations

Isotropic part

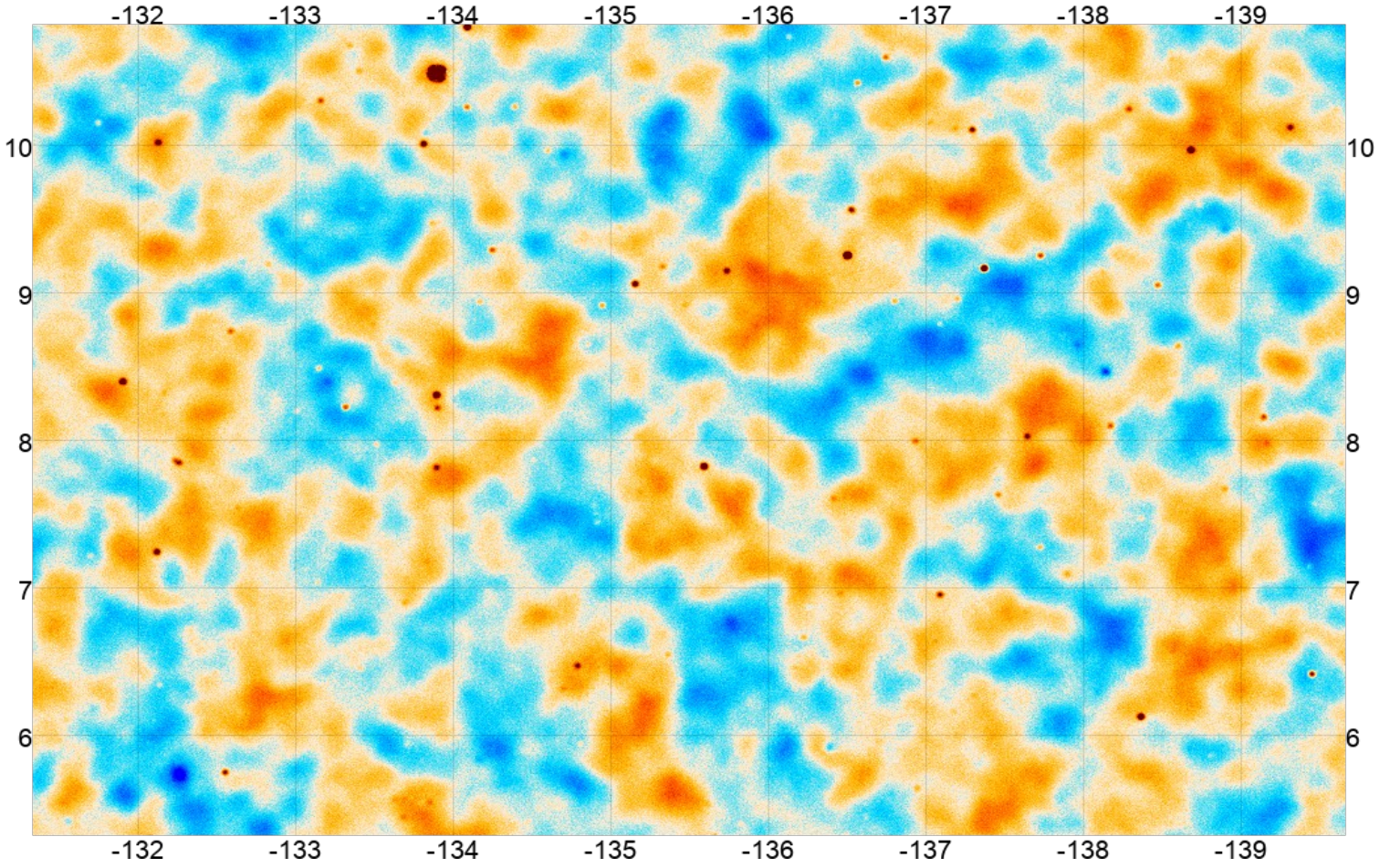


Anisotropic part



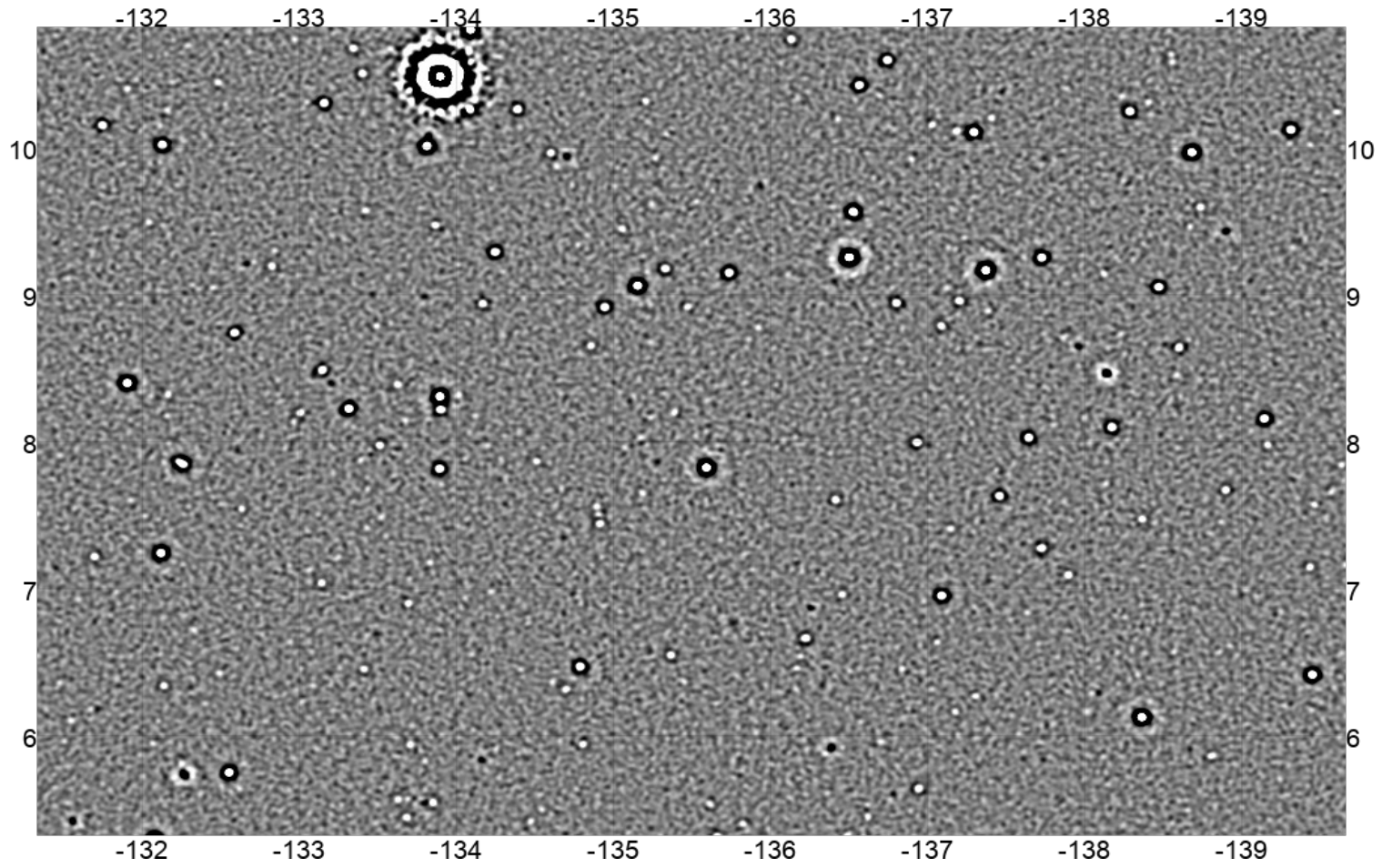
From map to catalog

Input map



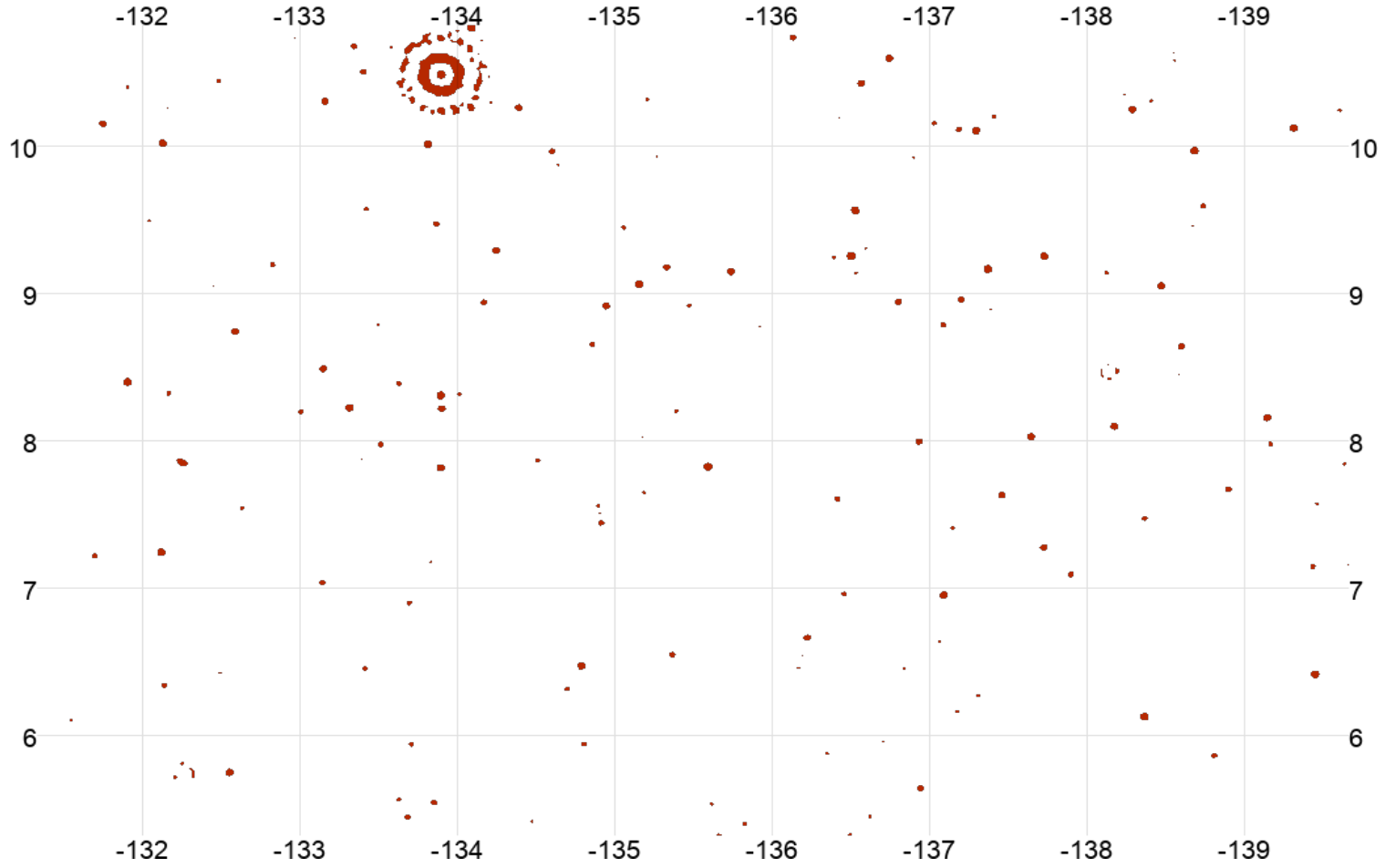
From map to catalog

Matched filtered



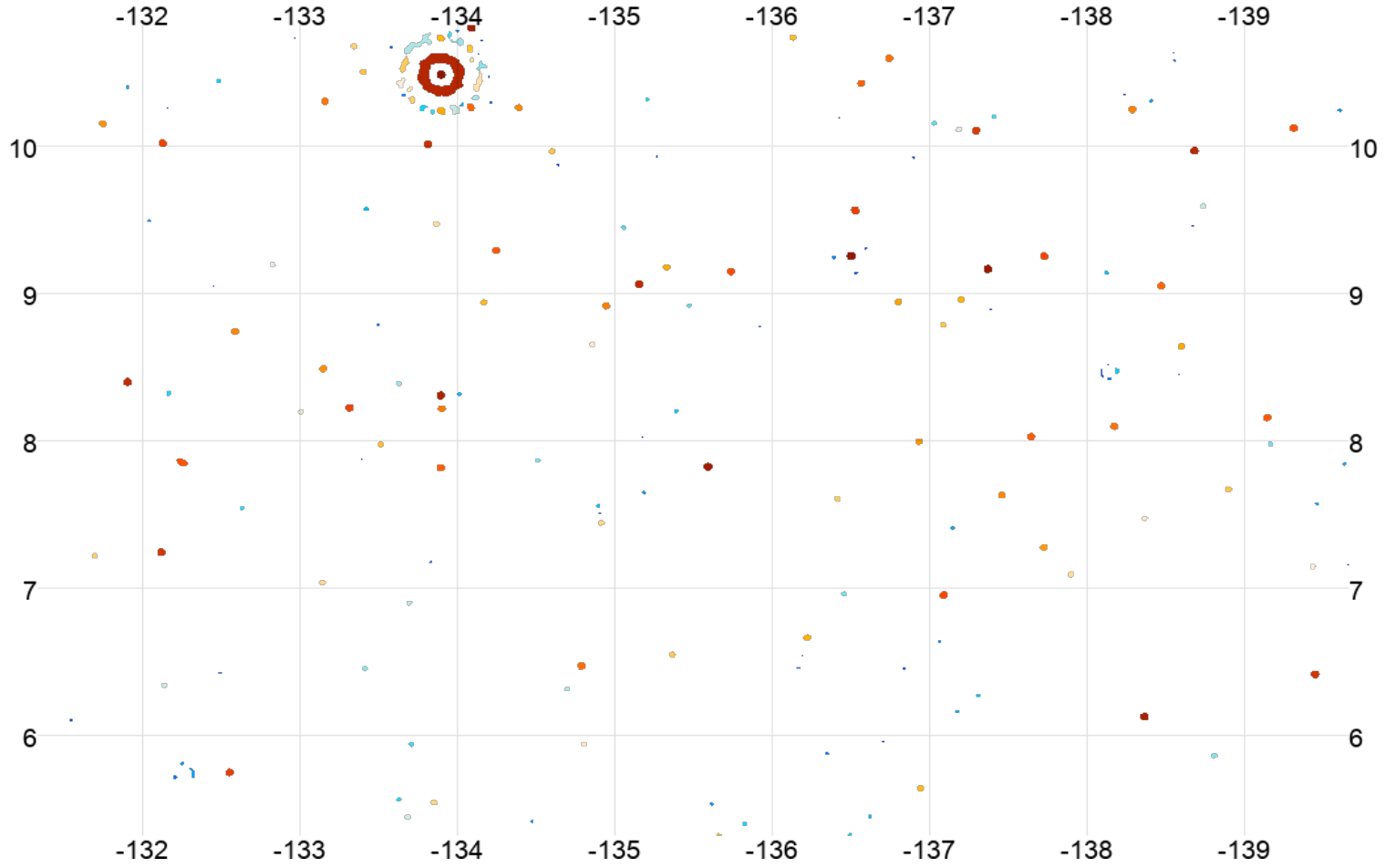
From map to catalog

`mask = snr > 5`



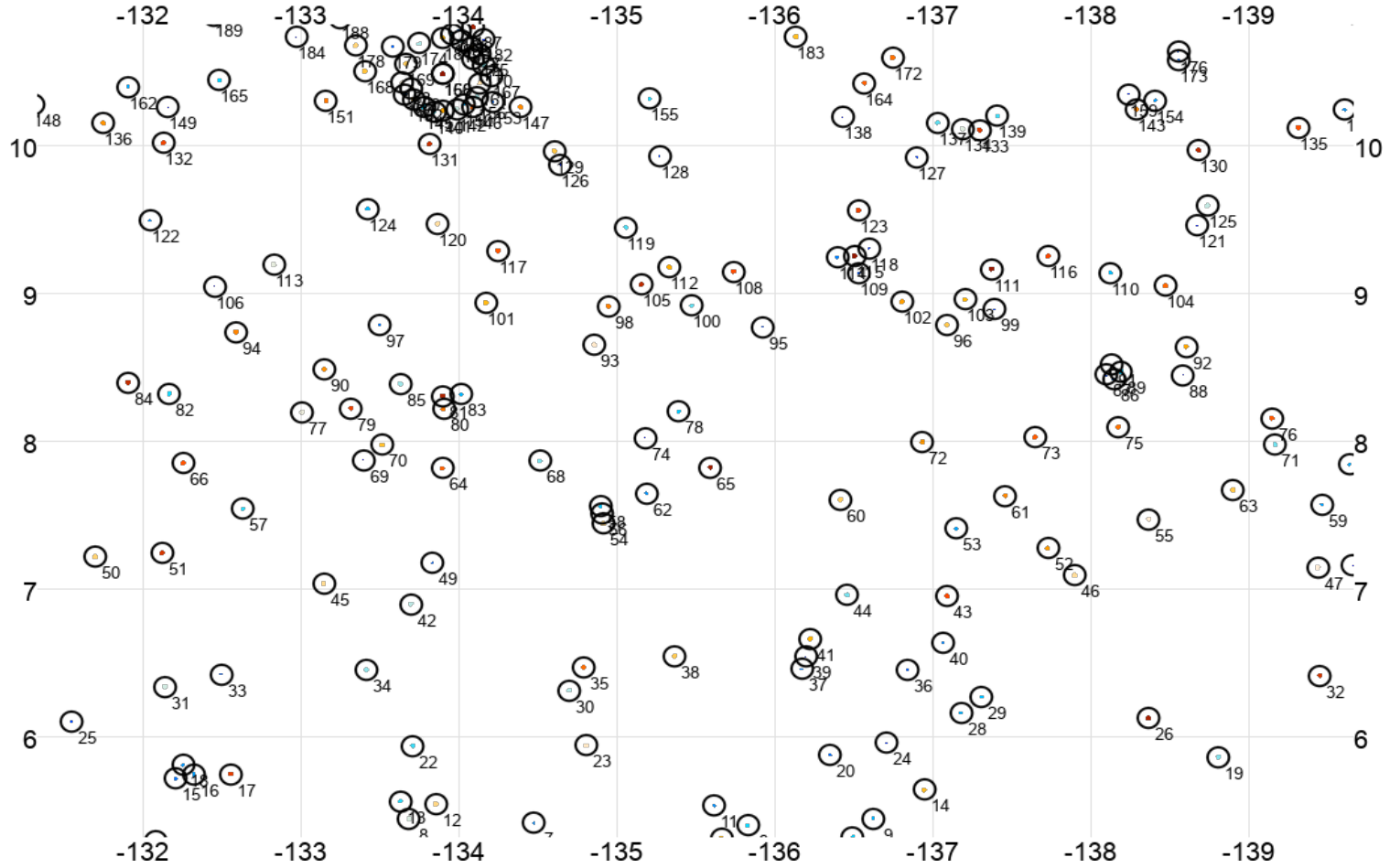
From map to catalog

`ndimage.label(mask)`

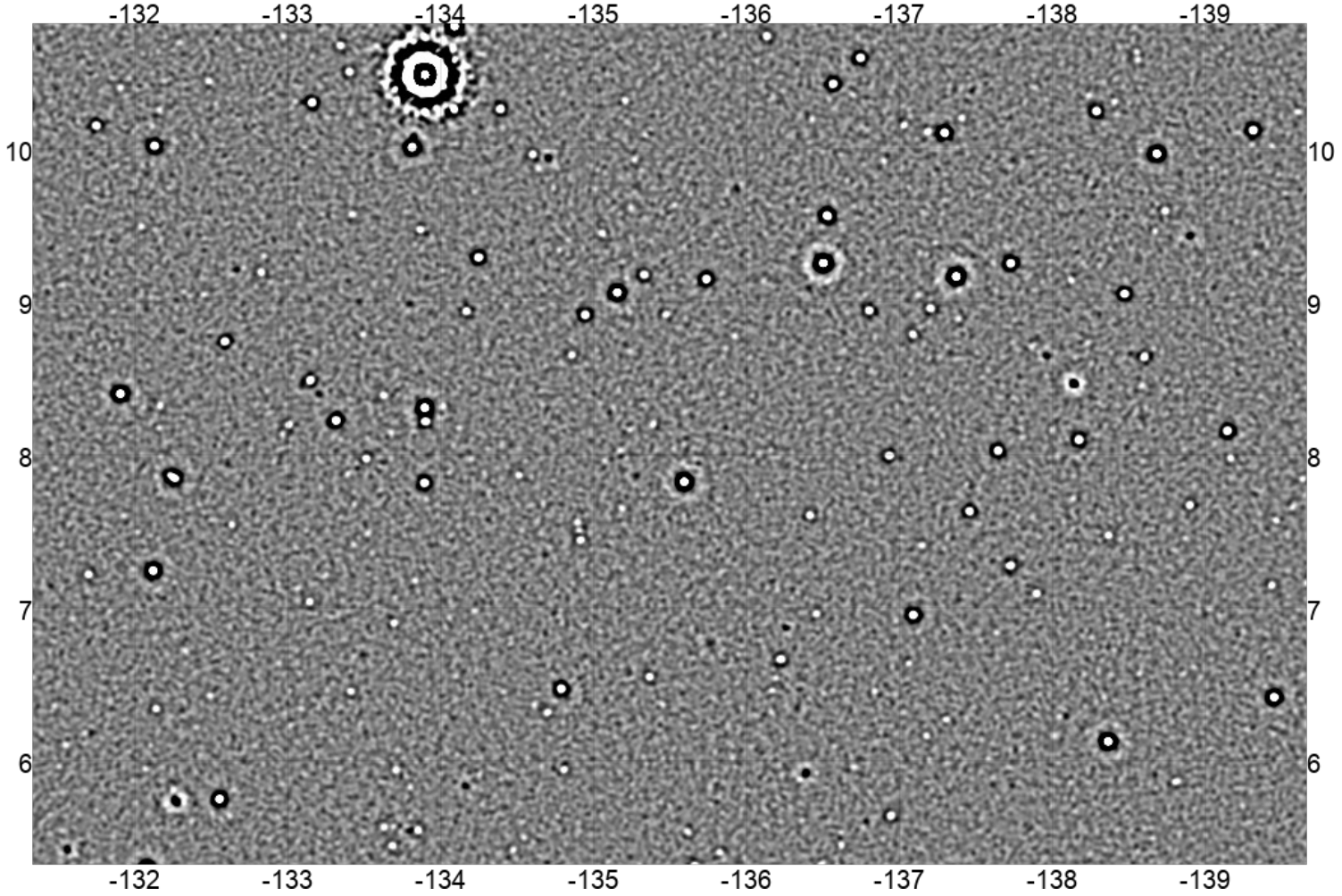


From map to catalog

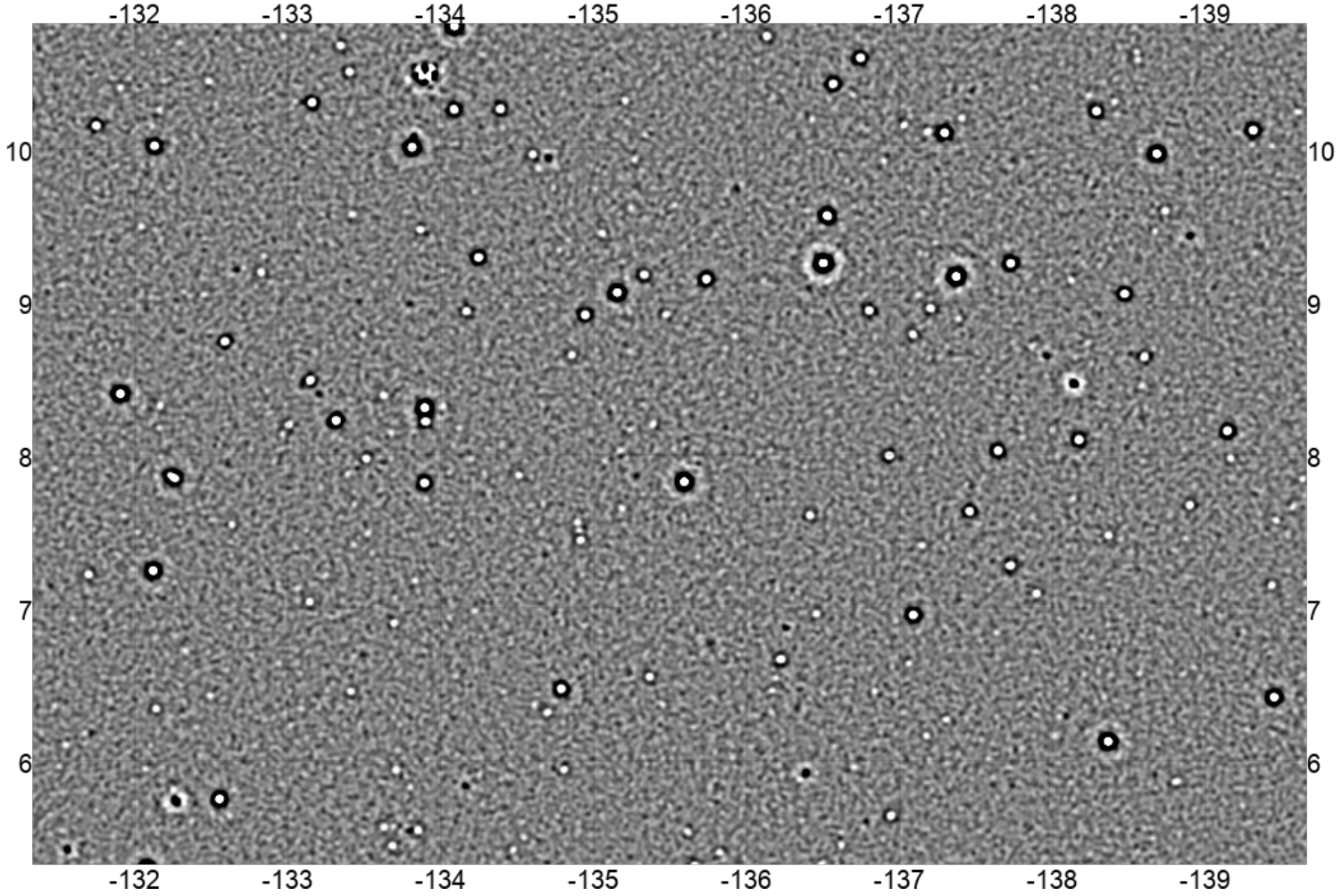
`ndimage.center_of_mass(snr**2, labels, ...)`



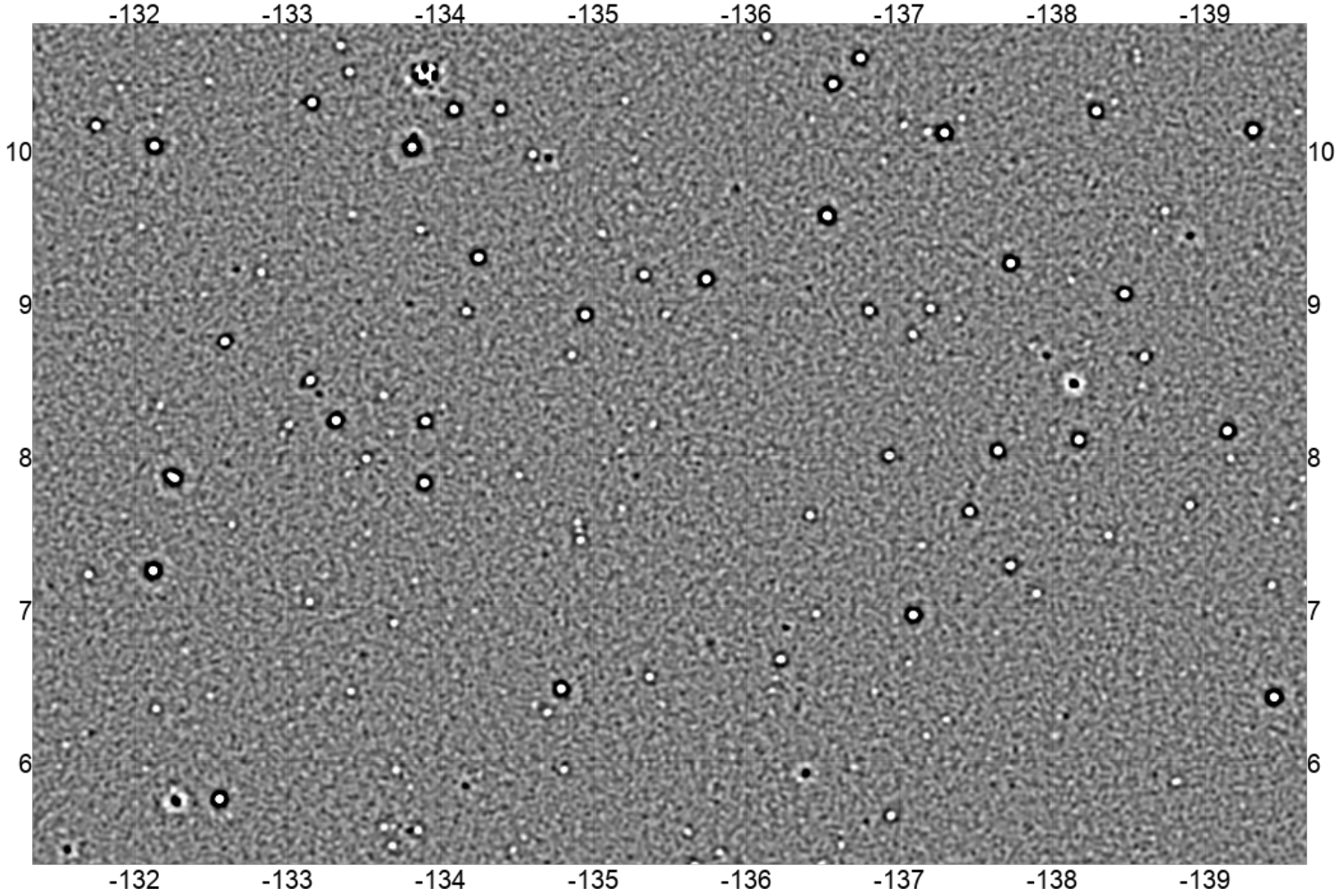
Iterative detection and subtraction



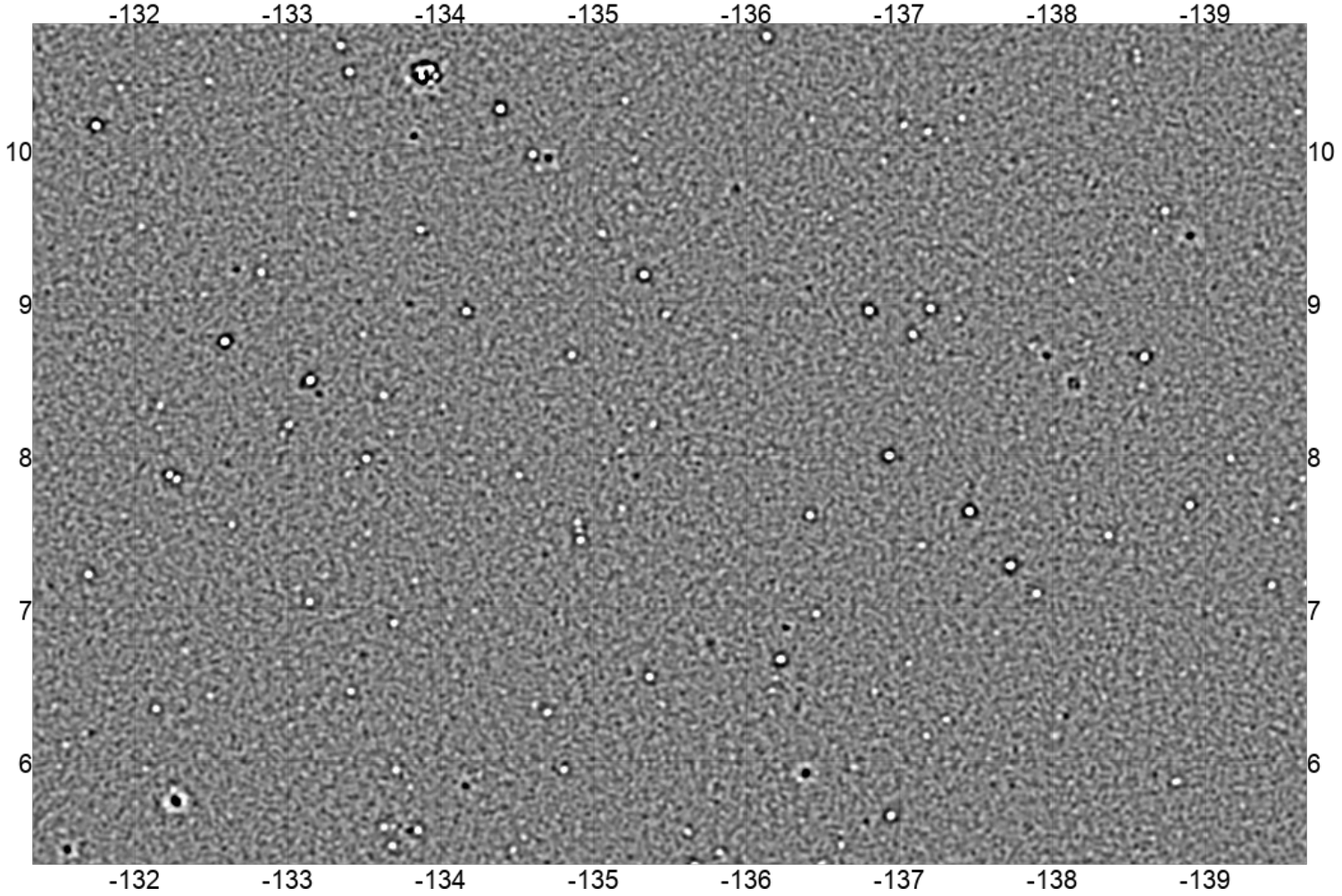
Iterative detection and subtraction



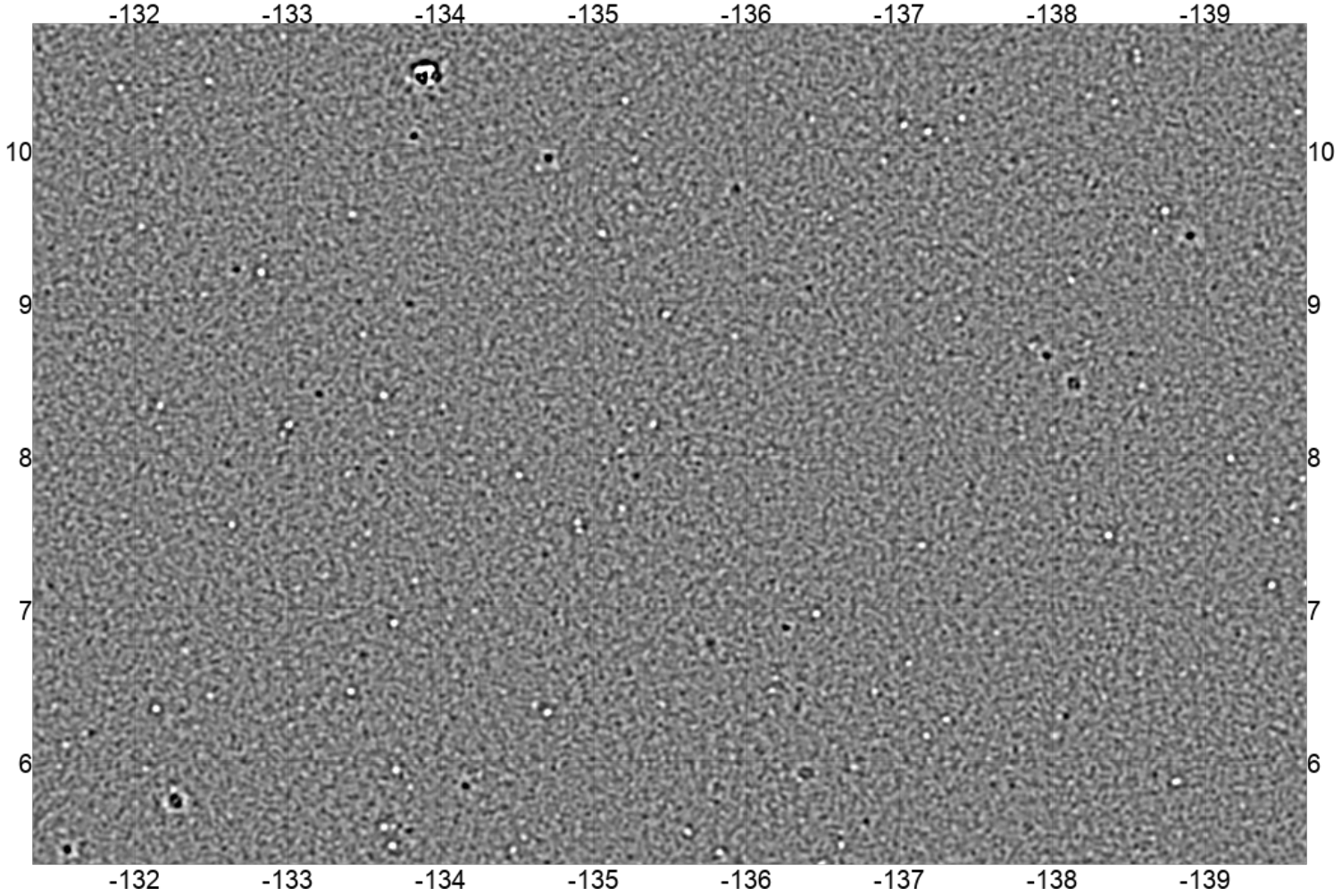
Iterative detection and subtraction



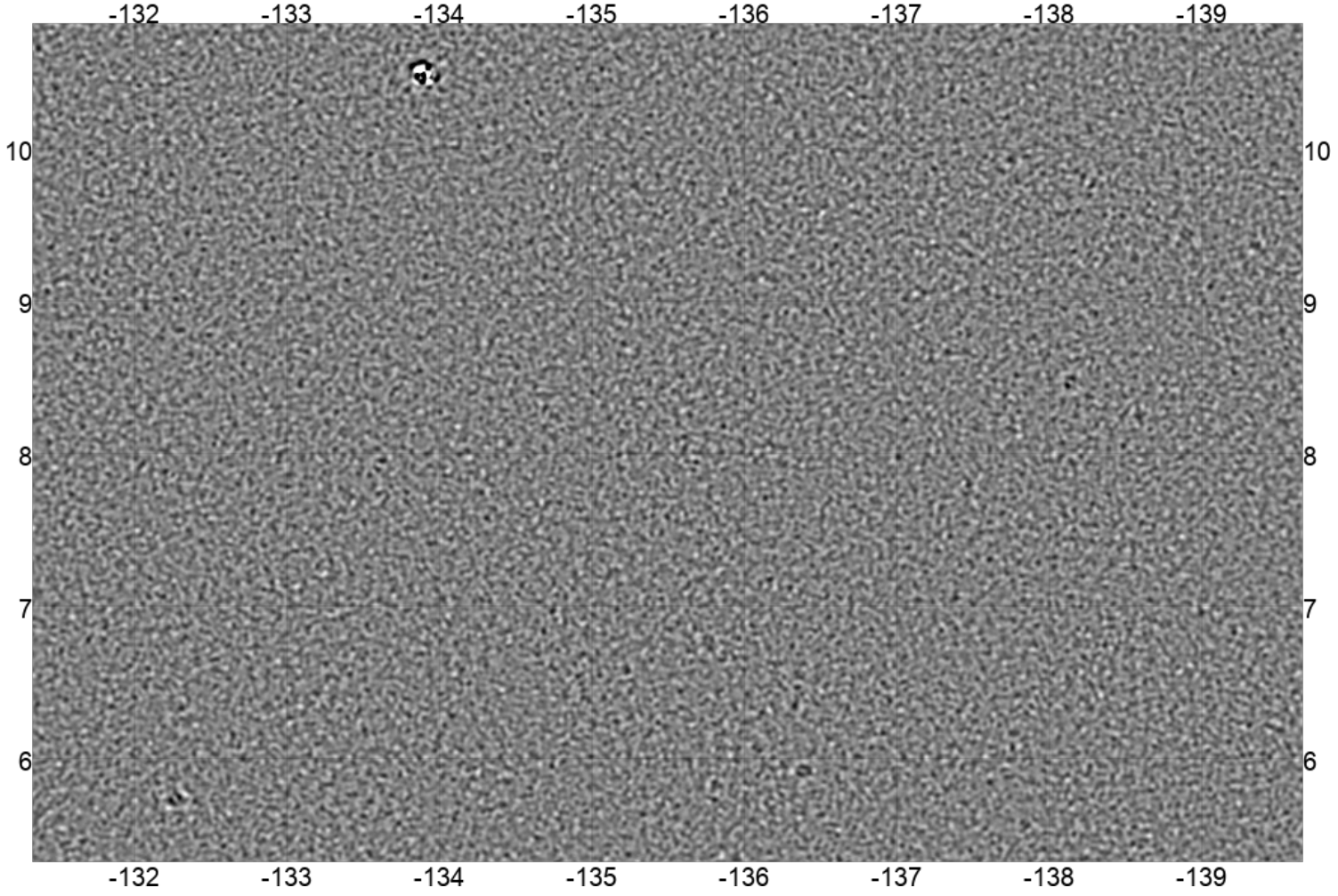
Iterative detection and subtraction



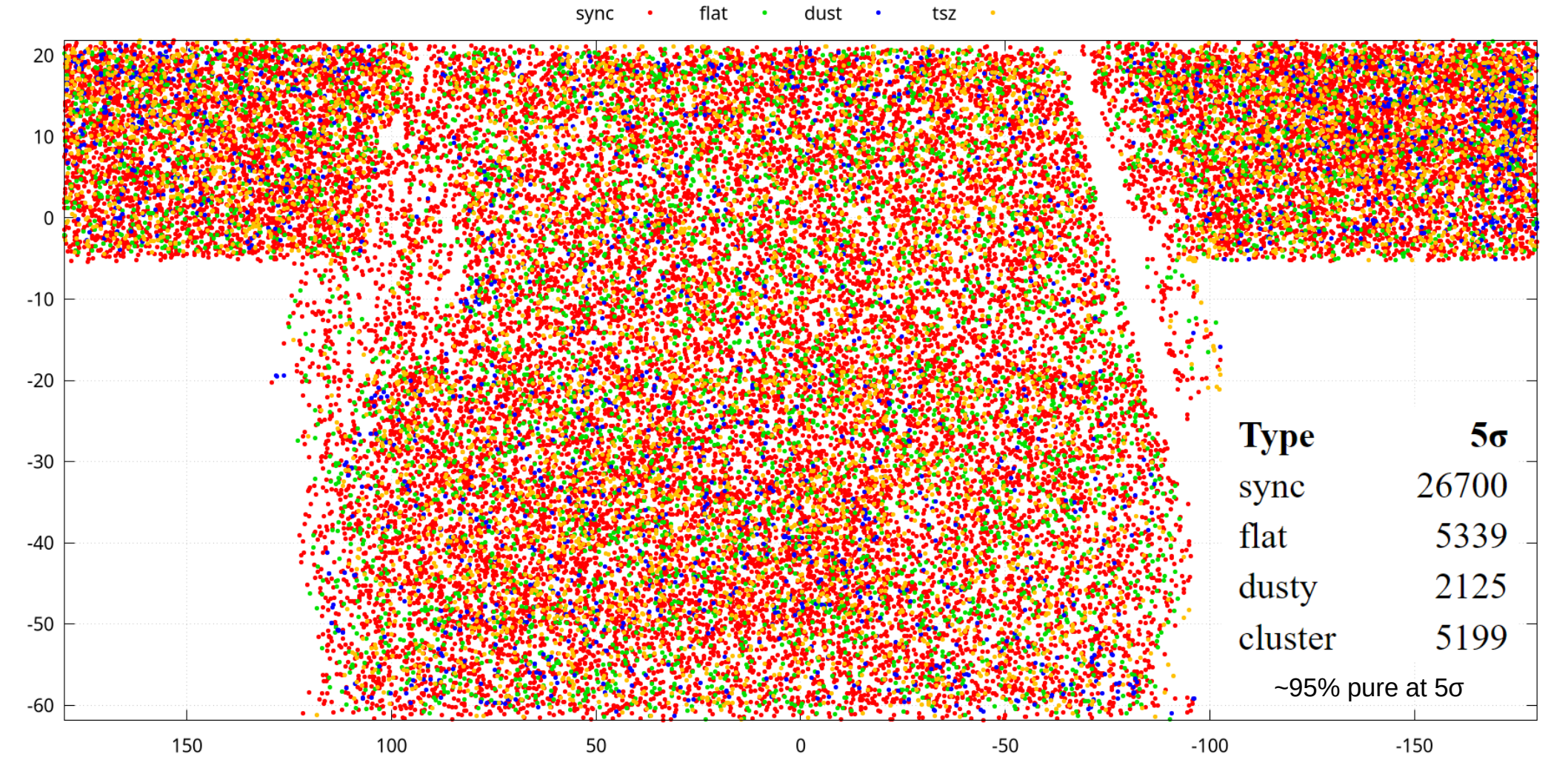
Iterative detection and subtraction



Iterative detection and subtraction

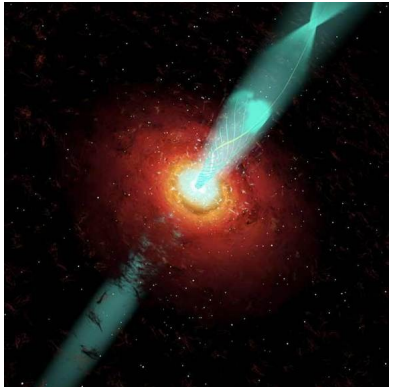


Result of a multifrequency version of this for ACT



Transients

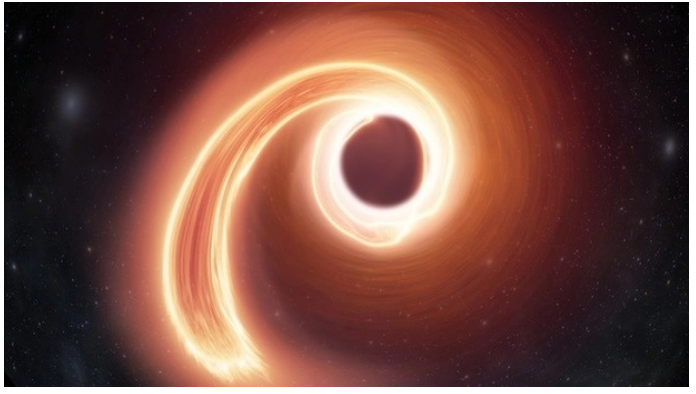
Blazar light curves



Flaring stars

Gamma-ray burst afterglows

Tidal disruption events



Solar system objects

The next galactic supernova?

Just use a matched filter again

- Objects that change on human time-scales tend to be small, and hence point sources. Have already seen that this can be handled with a matched filter.
- General approach: Split data into short subsets, map, filter and analyse
- Monthly maps? Daily maps? Would work, but can do better.

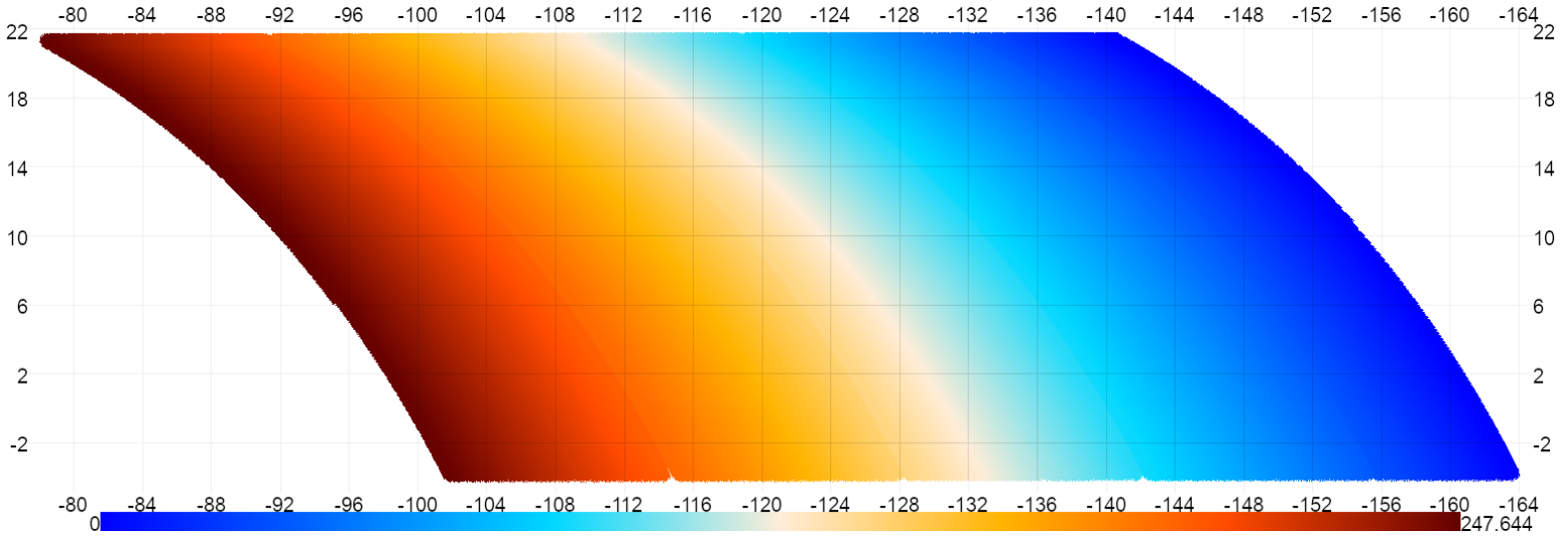
Depth-1 maps

- Will use depth-1 maps as input to the matched filter
- Depth-1 = a single observation deep
- Not the same as a single-observation map
- Can have many observations as long as they don’t overlap

- Useful extra requirement: Homogeneous scanning pattern → scan dir only depends on declination. This makes it easy to understand the noise stripiness

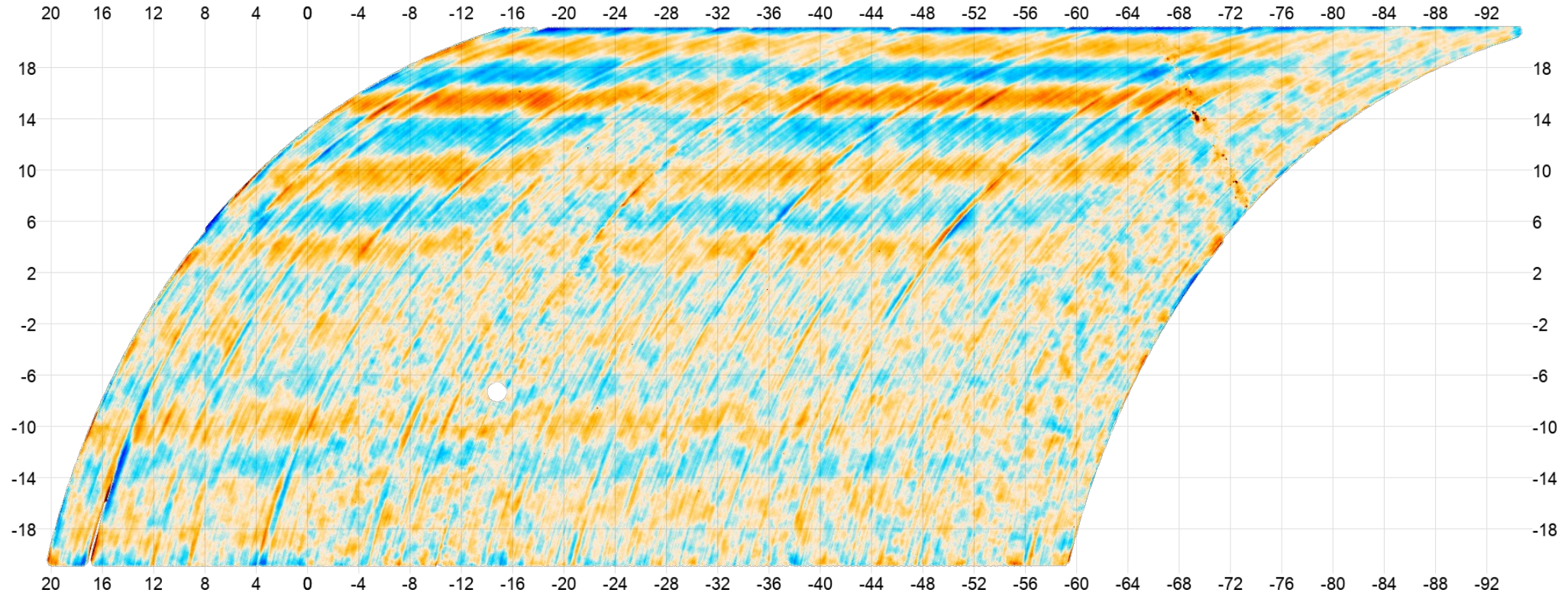
Advantages

- Maximum cadence: Resolves every time telescope covers an area
- Precise event timing: Each pixel timestamped to 4 min precision (worse if more wafers are mapped together)
- More reliable and efficient than single-observation maps

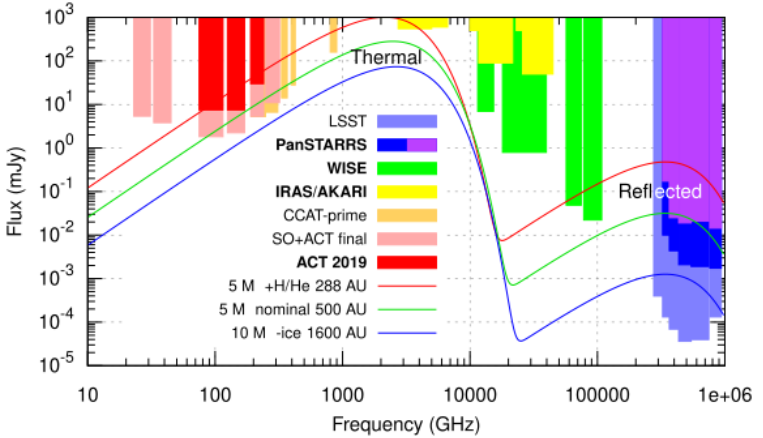


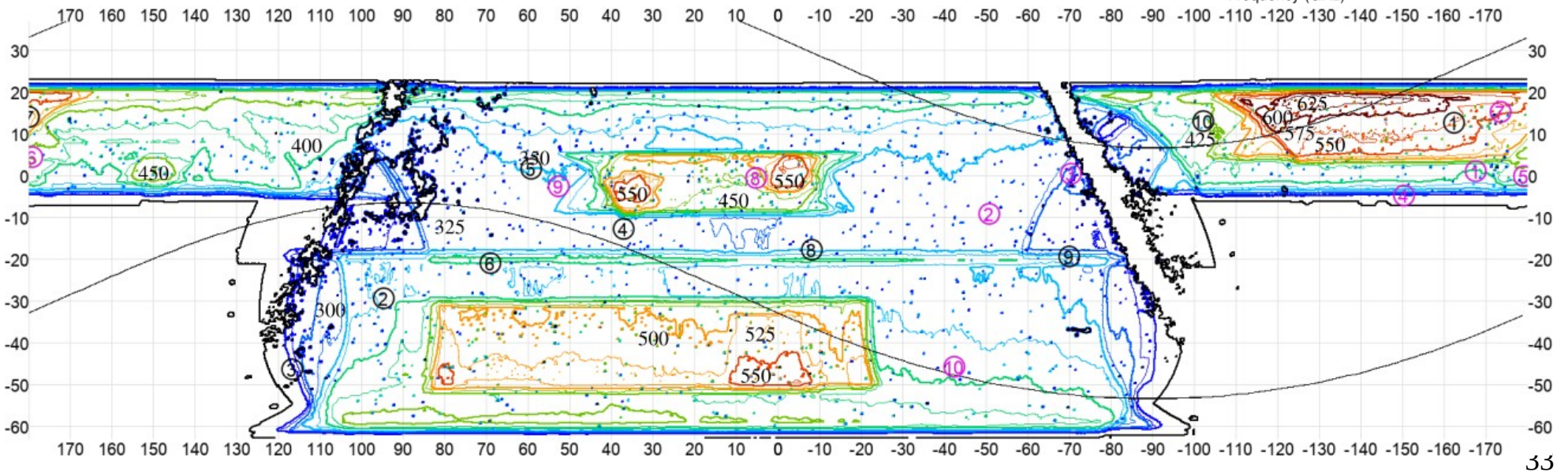
- Matched filtered depth-1 maps primary data product for ACT and SO time domain science

What do they look like?

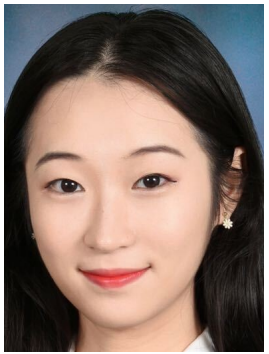


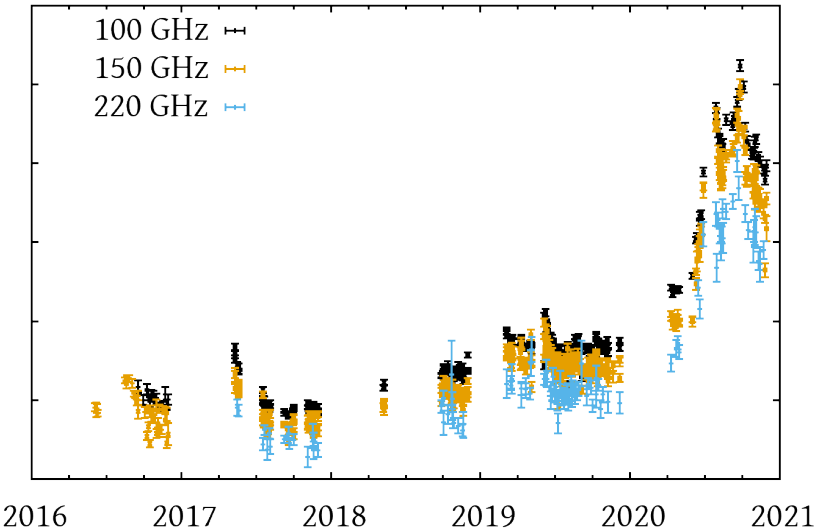
Constrained Planet 9 to be >325-625 AU distant over much of its expected orbit using ACT DR5 data

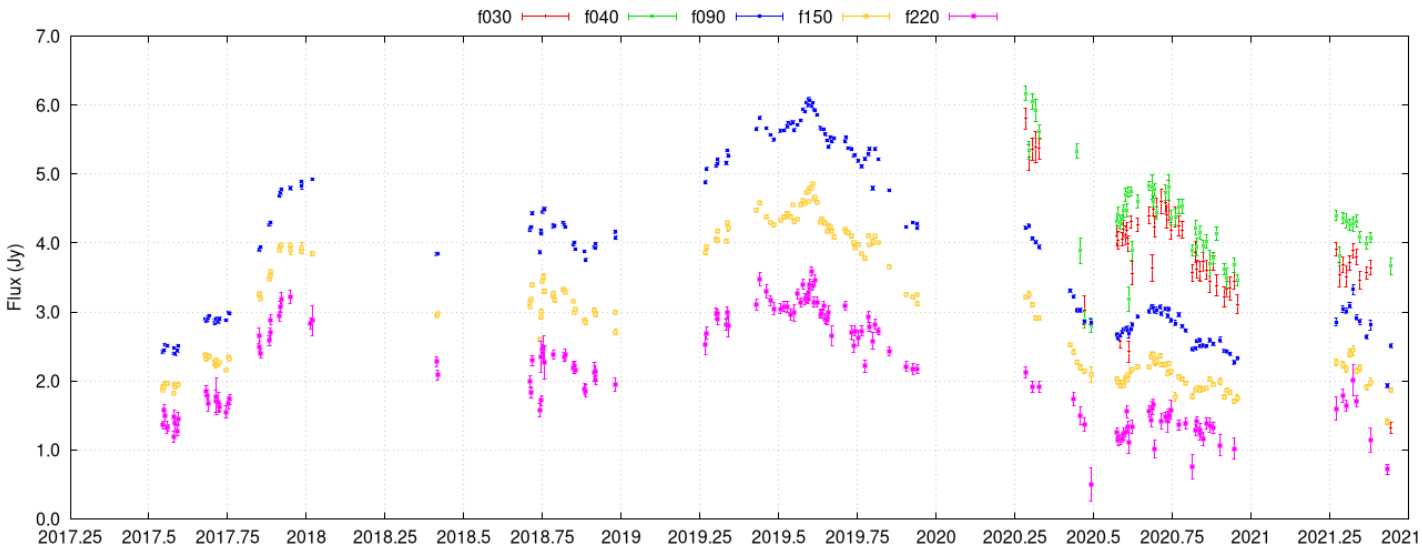




ACT AGN light curves



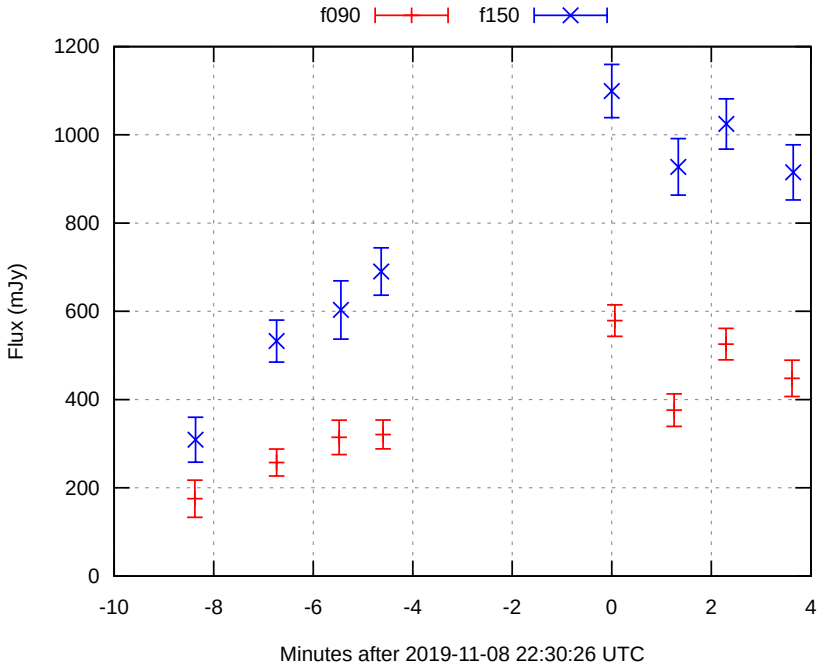




Blind transient search

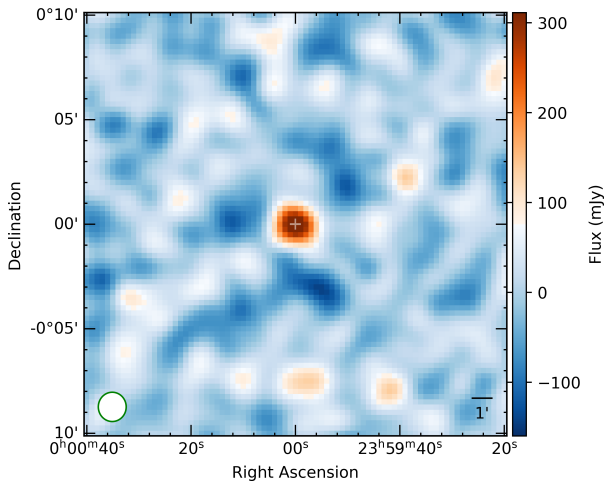


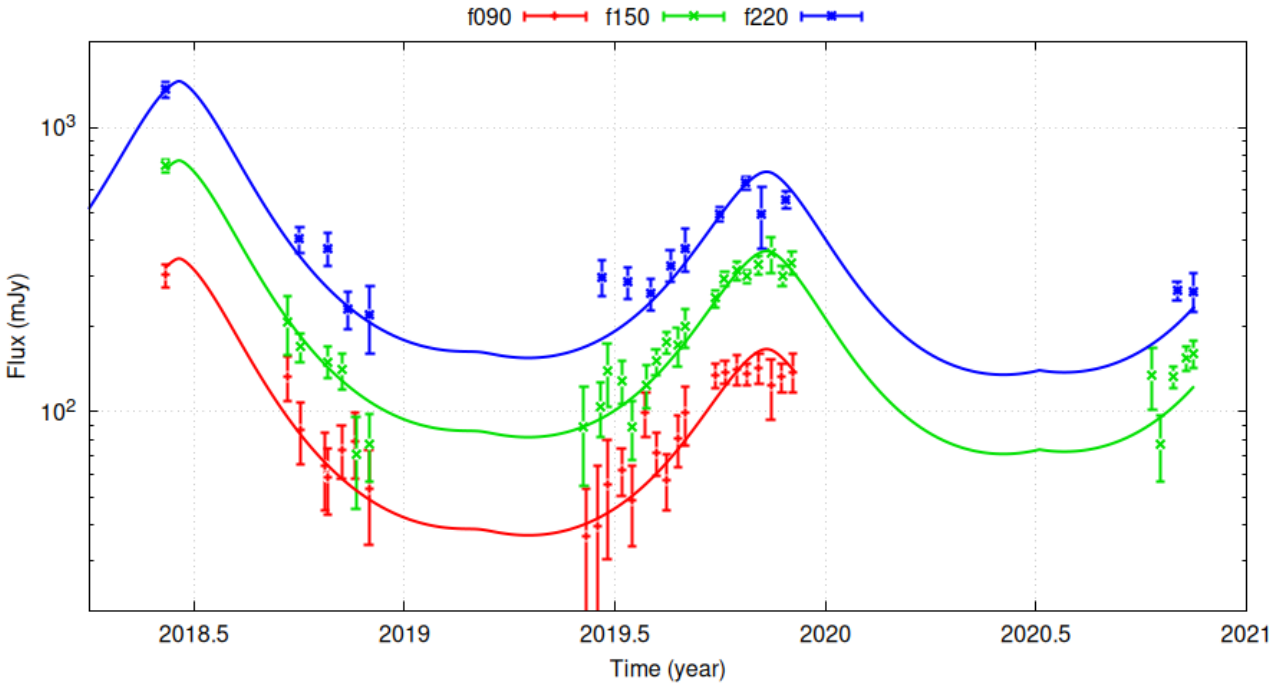
O(10) transients found using old maps meant for Planet 9 search - more expected with new depth-1 maps



Rapid stellar flare from the star 2MASS J18151564-4927472, 62 pc away. Corresponds to an X5000000 flare!

Asteroid light curves and modelling



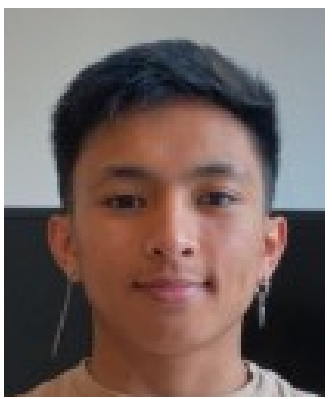


Vesta from ACT DR6 depth-1 maps. mm observations probe subsurface properties of asteroid regolith

And more...

- Targeted search for gamma-ray bursts, supernovas and tidal disruption events
- Measurements of pulsars, e.g. the galactic center magnetar, possibly pulse-folded



Guided tour of ACT maps