Anisotropy of the RSB at 140 MHz

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BAM - Radio Synchrotron Background

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Anisotropy of the RSB

- Measurements so far focus on measuring the large-scale component of the RSB
- Unknown background might have an anisotropic component
- This anisotropy can be measured by interferometers
  - We use the Low-Frequency Array (LOFAR)
- Does not need absolute-calibrated zero level measurements
  - Still a challenging measurement

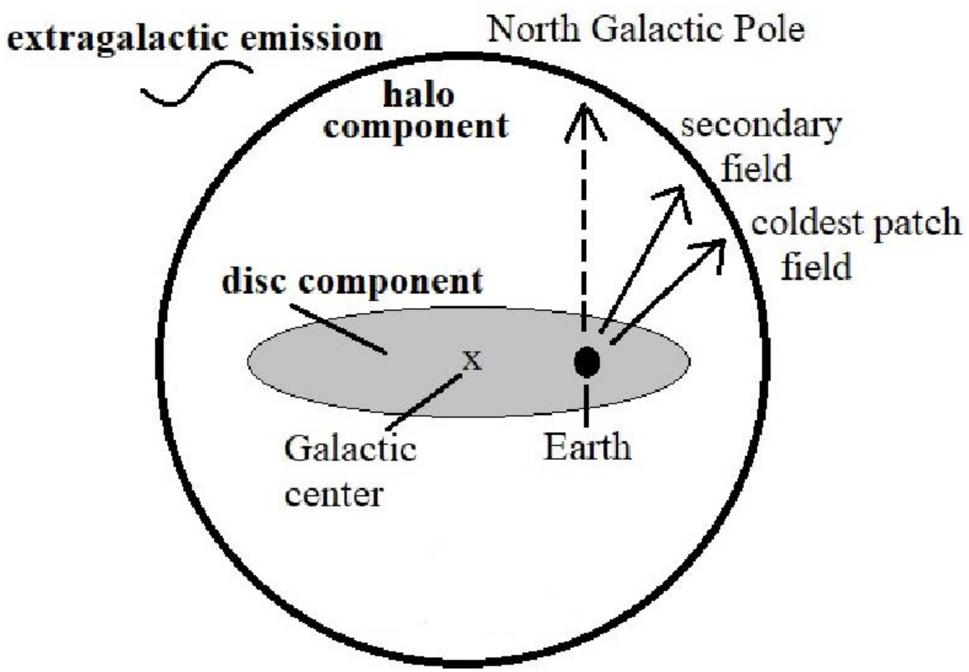
https://www.astron.nl/telescopes/lofar/

What we set out to do

- Targeted measurement of the power spectrum of anisotropies of the RSB
  - Done at 140 MHz where the RSB is the dominant photon background
- Two measurements taken, northern galactic coldest patch (Kogut et al. 2011) and one offset by 15°
- We process the measurements and retrieve angular power spectra
- Create Monte Carlo catalogs of point sources to try and see if they can produce the measured angular power

LOFAR Observations

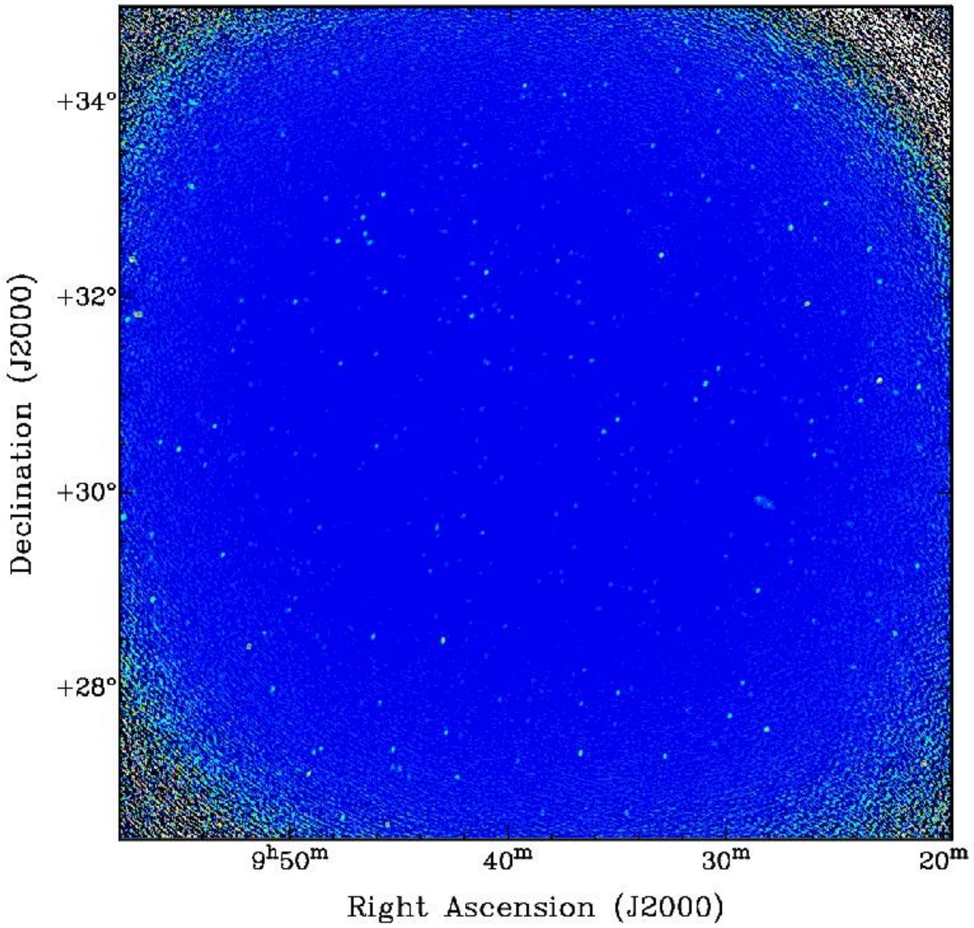
- Two fields measured, 15° apart
- Each field is 18 deg^2
- Both lie along lines of sight with low integrated galactic emission
- Aim: measure anisotropy power spectrum over a range of scales from 2° to 0.2’



Observation schematic

Observations and Data Reduction

- 8 hours of observing in high-band antenna dual mode with Dutch stations only
- Perform direction-independent calibration
  - AOFlagger (Offringa et al. 2012) flags data points with possible RFI contamination
  - WSClean (Offringa et al. 2014) to image the fields with primary beam correction and to get an initial point source model
  - Aegean (Hancock et al. 2018) for source extraction, removing ~3000 sources
- The blue colors in the image is the flux range, brighter blues are higher fluxes



Coldest Patch Field post-processing image

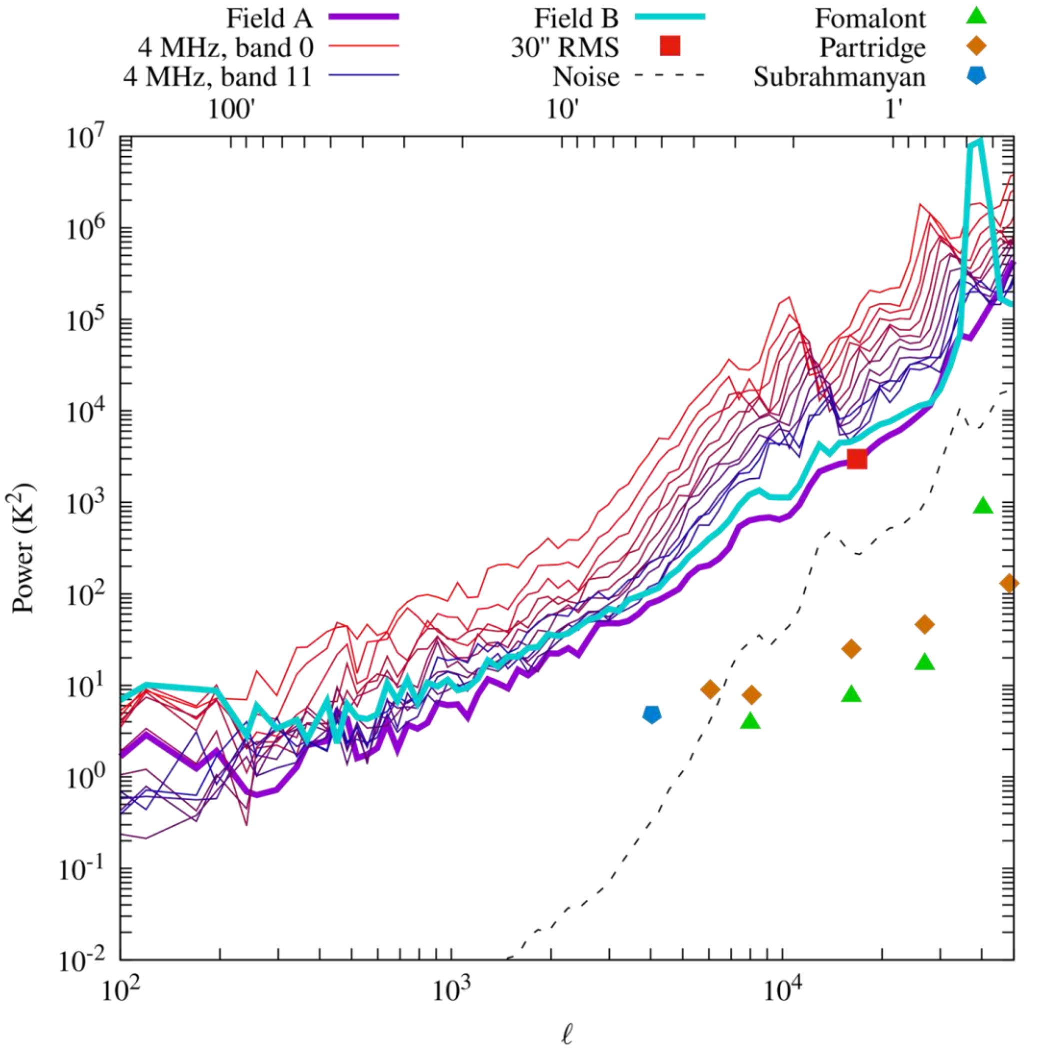
Getting the Angular Power Spectrum

- Pipeline used from Offringa, Mertens, & Koopmans (2019)
- Use central 4.3° square of each target field image with the sources removed
  - We remove point sources as they contribute power on all angular scales

1. Use WSClean to make a naturally weighted image of the source-subtracted data
2. Convert the flux density image to units of temperature (K)
3. Take the spatial Fourier transform of the image and point spread function (PSF) to create a complex (*u,v*) grid for both
4. Elementwise divide the complex *uv* image by the complex value of the *uv* PSF
5. Average the power in annuli and normalize these

Angular Power Spectrum

- Our analysis is done in units K^2, same as 21 cm analyses
  - Power spectra not divided by average value
- As expected, Field A (coldest patch) < Field B
- Noise curve estimates system noise uncertainty
  - Measured power not dominated by system noise
- Includes twelve 4 MHz sub-bands of Field A
  - Higher power due to spectral dependence of synchrotron radiation
  - Full band has less power due to more complete *u-v* coverage



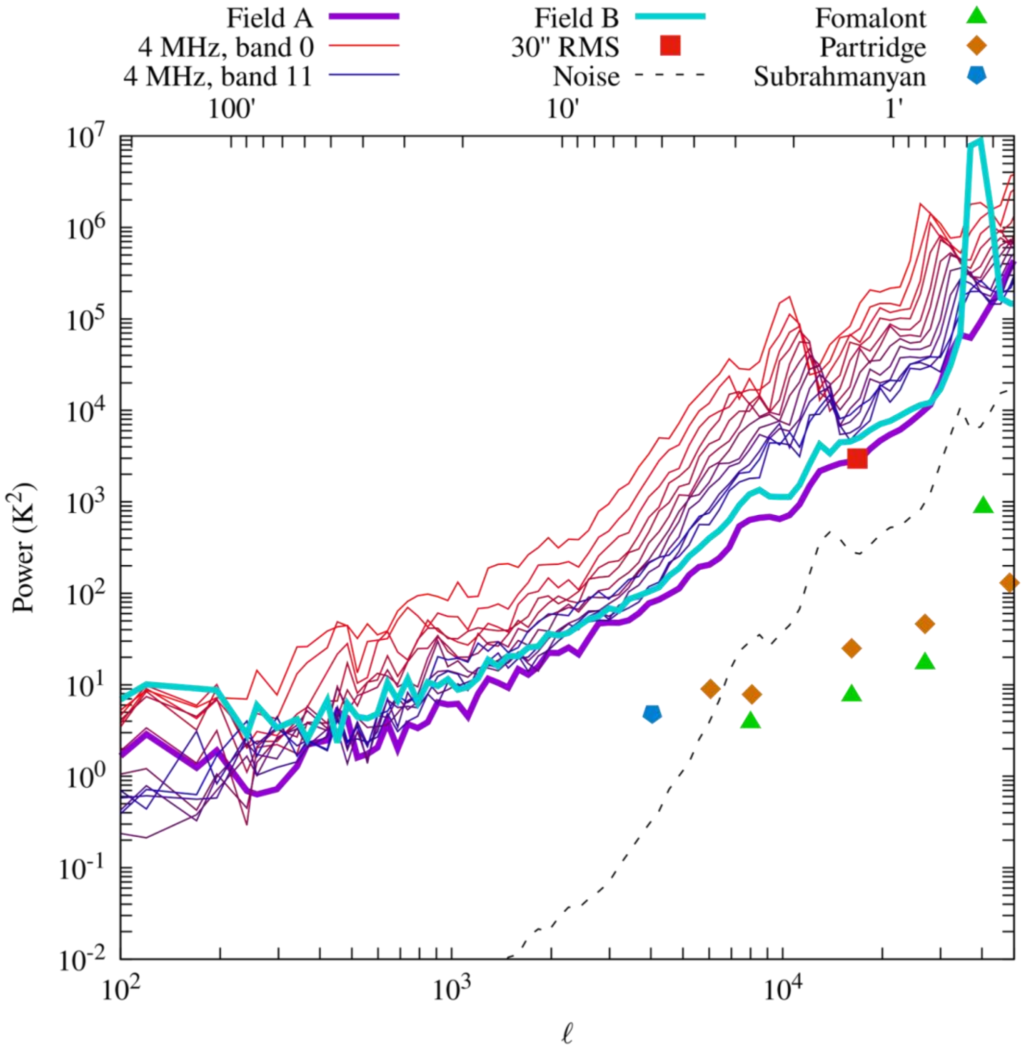
30” RMS Noise Comparison

- Procedure from Holder (2014)
- Average noise per beam in the image with the synthesized beam tapered to 30” FWHM
  - $\Delta S_{\text{Jy,psf}}$
- Beam is fitted to an elliptical Gaussian to find the synthesized beam solid angle

$$\Omega_{\text{psf}} = \pi(w_{\text{maj}} \times w_{\text{min}}) \times \left(\frac{1}{60}\right)^2 \times \left(\frac{\pi}{180}\right) \times \left(\frac{1}{4\log 2}\right)$$

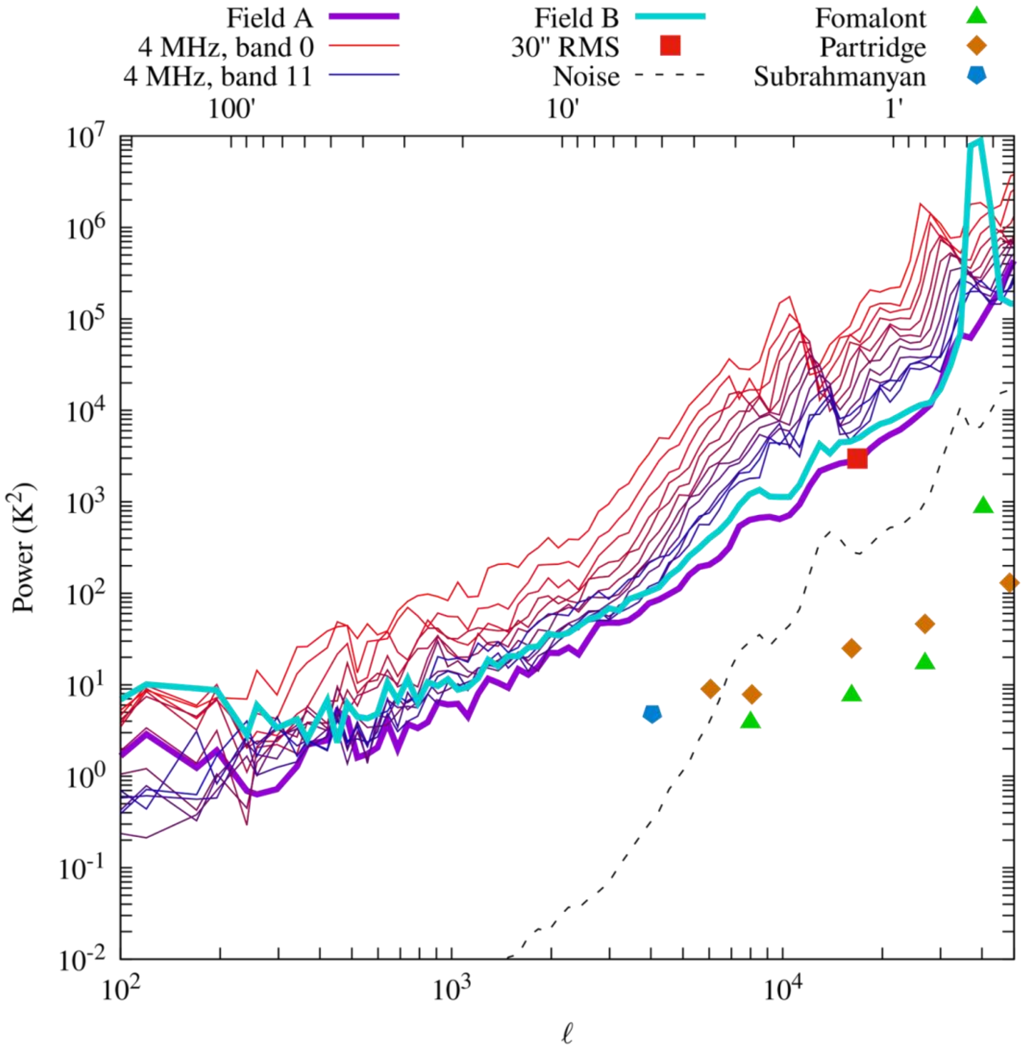
- Resulting temperature fluctuation is found

$$\Delta T = \Delta S_{\text{Jy/psf}} \frac{10^{-26} c^2}{2k_B \nu^2 \Omega_{\text{psf}}} \qquad \ell = \frac{2.35}{\text{FWHM}}$$



Previous GHz Constraints Comparison

- Comparison levels from GHz scale measurements calculated by Holder (2014) scaled to 140 MHz
  - Triangle, diamond, and pentagon markers
- From CMB anisotropy searches
  - VLA at 4.86 GHz (Formalont et al. 1988) and 8.4 GHz (Partridge et al. 1997), and ATCA at 8.7 GHz (Subrahmanyan et al. 2000)
- Scaled using a synchrotron power law of -2.6 in radiometric temperature units
- Our measured angular power is at least an order of magnitude larger than what is inferred from previous GHz scale measurements



Potentially Unremoved Point Sources

- Monte Carlo catalog of simulated sources
- Sources distributed in flux according to the Franzen et al. (2016) models
  - Based on measured and extrapolated deep source counts at 150 MHz
  - Four models with same number of high flux sources, differing number of low flux sources
  - $\mathcal{O}(10^5 \sim 10^6)$ sources in each model
- Distribute randomly in RA in Dec within a 6° square on the surface of a sphere
- Frequency spectral indexes distributed normally around -2.6 in radiometric temperature units with a standard deviation of 0.1

$$n(S) = \frac{dn}{dS} = k_1 \left(\frac{S}{Jy}\right)^{\gamma_1} \mathrm{Jy}^{-1}\,\mathrm{Sr}^{-1} \text{ for } 0.01\,\mathrm{mJy} < S < 6.0\,\mathrm{mJy}$$

$$= k_2 \left(\frac{S}{Jy}\right)^{\gamma_2} \mathrm{Jy}^{-1}\,\mathrm{Sr}^{-1} \text{ for } 6.0\,\mathrm{mJy} < S < 400\,\mathrm{mJy}$$

Making Source Files

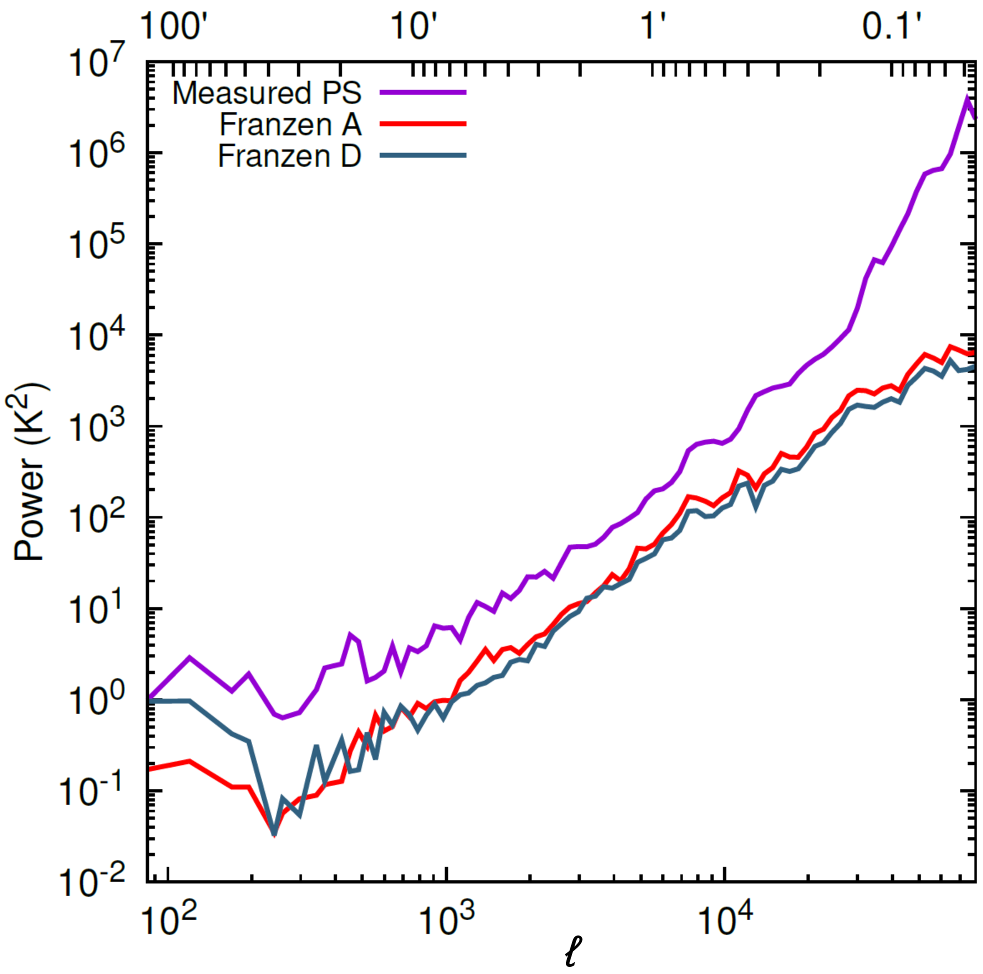
- Use Python to generate source files
- In order to generate sources that follow a certain probabilistic distribution, we use inverse transform sampling (ITS)
  1. Generate a cumulative distribution function (CDF) of the source distribution
  2. Next, we make a spline interpolation of the inverse of the CDF
  3. Passing a number between 0 and 1 into the inverse CDF returns a value that lies within the original distribution (probability density function)
- Also use ITS to place sources randomly on the surface of a sphere
- Random module has built-in random number generation from a normal distribution for the spectral index

Angular Power from Source Files

- Interpolate the simulated sources onto a grid (using sinc-interpolation)
- Simulate visibilities from the resulting sky image in order to apply the instrumental effects that affect the power spectrum (*uv*-sampling and the primary beam)
- Use the Image Domain Gridder (IDG; Van der Tol et al. 2018) inside of WSClean to apply the time and frequency dependent LOFAR beam
- Resulting visibilities are processed with our imaging and power spectrum generation pipeline

Franzen Models

- Randomly distributed Franzen models do not produce enough power
  - $\Longrightarrow$ add clustering on certain scales to increase power
- Try simple sinusoidal spatial clustering on scales of 1’ and 10’
- Even with clustering, not enough power is introduced along all angular scales



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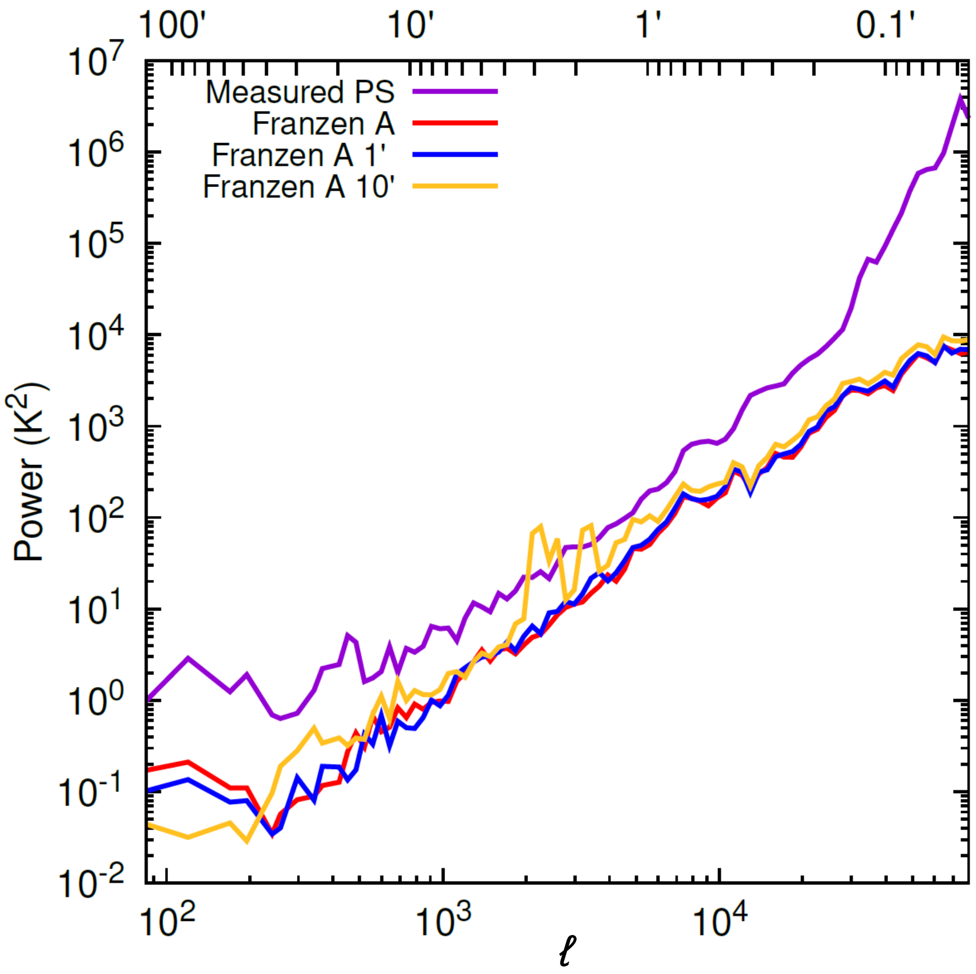
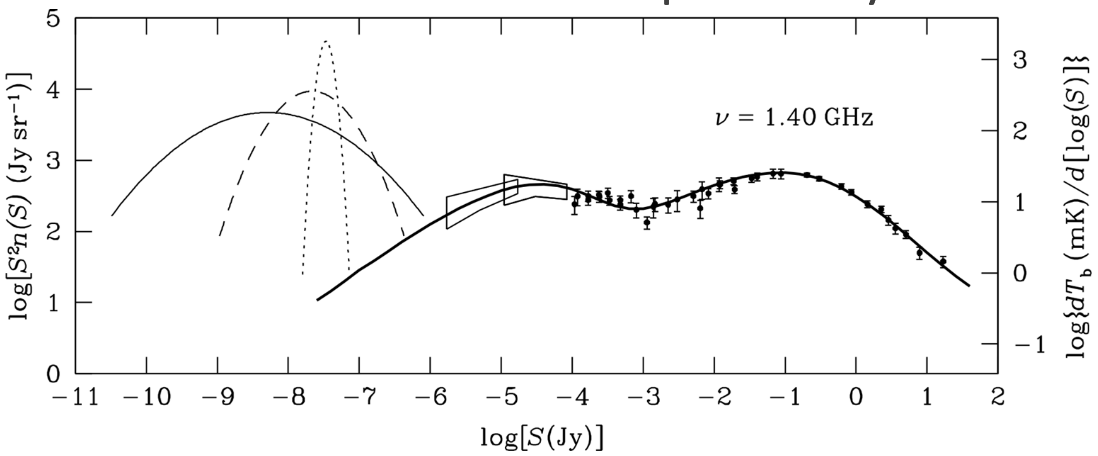


Fainter source distributions

- RSB anisotropy power cannot be totally attributed to point sources above 100 μJy
  - Try even fainter source distributions
- Base source distribution on Condon et al. (2012), which is a faint source distribution that matches the Radio sky brightness
- We use the model with the least number of sources, with S_{pk} = 0.03 μJy
- Source densities exceeds what is measured in the Hubble Ultra Deep Field by at least an order of magnitude

$$n(S) = \frac{A}{S^2} \exp\left(-4\ln(2)\frac{[\log(S) - \log(S_{pk})]^2}{\phi^2}\right) \text{Jy}^{-1}\,\text{Sr}^{-1}$$

From Condon et al. 2012

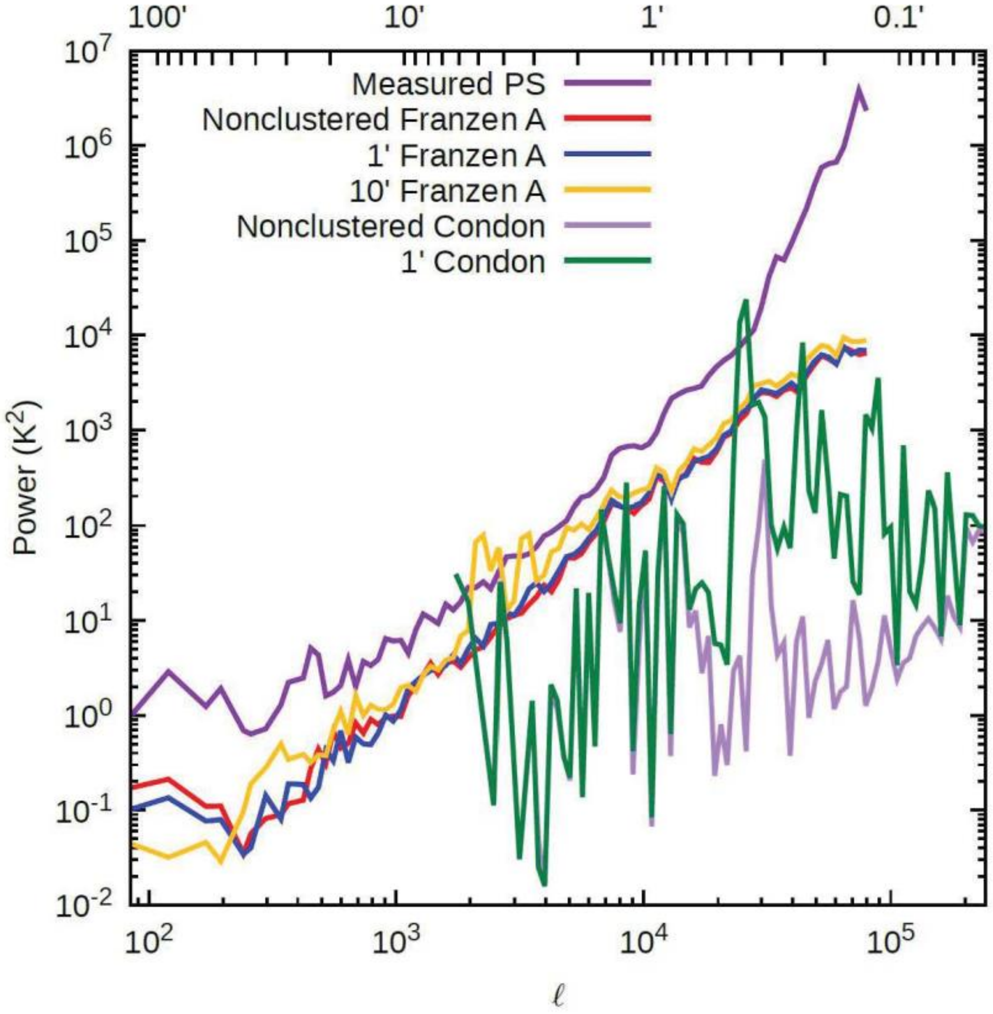


Problems Simulating Condon Model

- Extremely high source density
  - Around 200 million sources in 1° square, or 150 sources per pixel
- Too computationally expensive to simulate a Condon model on the full 6° square as we did with the Franzen models, would produce almost Tb sized source model files
- So, we simulate a smaller 0.5° square instead.
  - Still has many more sources than the Franzen models at 54 million sources
- Again, we do a random spatial distribution on the surface of a sphere and 1' clustering

Comparing Point Source Populations

- Still see that no point source model matches the measured power
- Condon model with clustering sees an increase in power on all angular scales equal to and smaller than the clustering scale
- With appropriate clustering, a model with faint but extremely numerous point sources could reproduce the observed angular power



Analysis: Galactic vs. Extragalactic

- Estimate contribution due to galactic diffuse emission
  - Angular power in Field B systematically larger by a factor of ~ 1.4 in $(\Delta T)^2$ normalization

- The difference between the two fields is the same as the square of ratio of the average absolute brightness in radiometric temperature units for the two regions we calculate using the Haslam et al. (1982) map
  - This difference solely comes from differences in lines of sight through the galaxy
  - Strong indication that proportion in angular power in (ΔT) due to Galactic structure traces the proportion of absolute brightness due to that structure

- Normalized angular power $\left(\frac{\Delta T}{T}\right)$ is the same for both fields
  - Indicates that the contribution from Galactic structure is sub-dominant as that is the component that varies spatially between the fields

Conclusions

- We performed the first targeted measurement of the power spectrum of anisotropies of the RSB
  - Done at 140 MHz where the RSB is the dominant photon background
- We find an excess in anisotropy power that cannot be attributed to point sources above 100 μJy that are distributed either randomly or clustered
  - Angular power is also at least an order of magnitude larger than that inferred from previous measurements at GHz frequencies
  - Analysis shows that the anisotropy is primarily extragalactic
- If the measured excess is due to radio point sources, they must be incredibly numerous and have very low fluxes
- Future plans are to continue modeling using the Condon model, but with more complex spatial clustering on multiple angular scales

BACKUP SLIDES

Equations for the Angular Power Spectrum

First consider that the power spectrum relates to the Fourier transform of the temperature field as

$$P(\mathbf{k}) \equiv A \left|\tilde{T}(\mathbf{k})\right|^2$$

Where the Fourier transform is

$$\tilde{T}(2\pi\mathbf{k}) \equiv \frac{1}{N_x N_y} \sum_{\mathbf{x}} T(\mathbf{x}) e^{-i2\pi\mathbf{k}\cdot\mathbf{x}} \qquad N_x N_y = \frac{\Omega_A}{\Omega_{\mathrm{psf}}} \qquad T(\mathbf{x}) \equiv S_{\mathrm{Jy/psf}}(\mathbf{x}) \frac{10^{-26} c^2}{2 k_B \nu^2 \Omega_{\mathrm{psf}}}$$

Then, bringing everything together we get

$$P(2\pi\mathbf{k}) = A \left| \frac{1}{N_x N_y} \sum_{\mathbf{x}} T(\mathbf{x}) e^{-i2\pi\mathbf{k}\cdot\mathbf{x}} \right|^2$$

Finally, going into "dimensionless units" (e.g. Ali-Haïmoud et al. 2014), ends up with physical units of K^2

$$\Delta^2(2\pi\mathbf{p}) = 2\pi|\mathbf{p}|^2 \left| \frac{1}{N_x N_y} \sum_{\mathbf{x}} T(\mathbf{x}) e^{-i2\pi\mathbf{p}\cdot\mathbf{x}} \right|^2$$