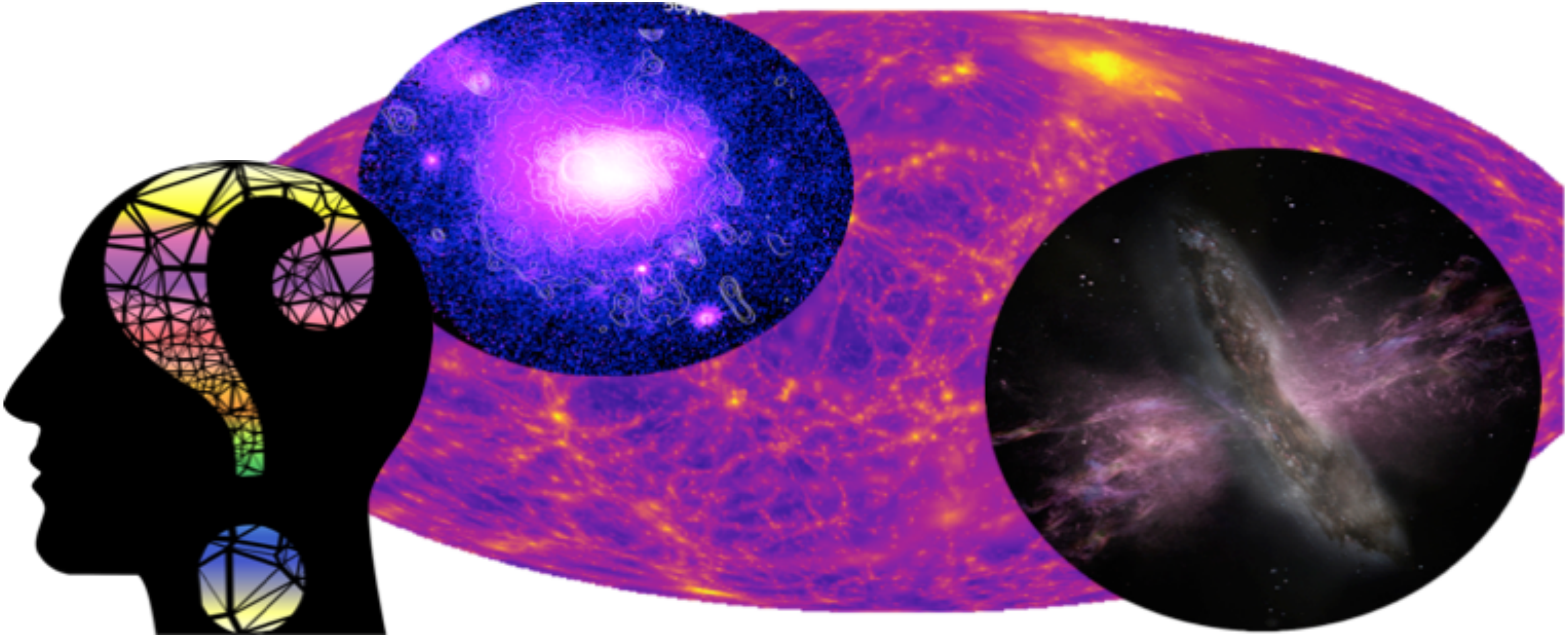

Confusion, Correlations, and the Faint Extragalactic Radio Background

Tessa Vernstrom| CSIRO Bolton Fellow
May 2019
SPARCS IX – LISBON

CSIRO ASTRONOMY & SPACE SCIENCES, CASS
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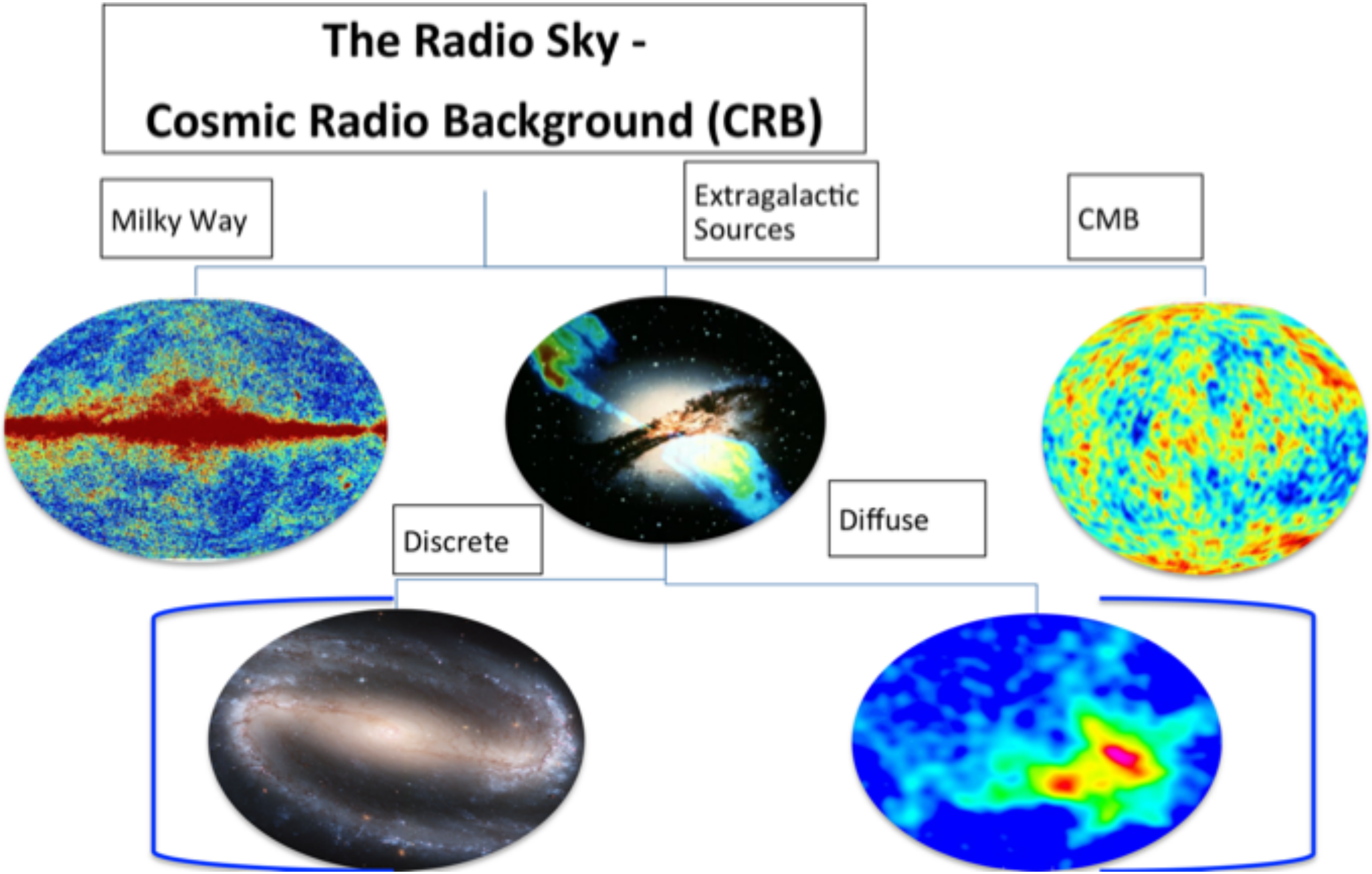
The Cosmic Radio Background



The Radio Sky -

Cosmic Radio Background (CRB)

Milky Way

Extragalactic Sources

CMB

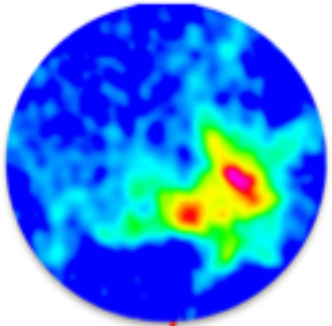
Discrete

Diffuse

The Cosmic Radio Background

Discrete

Point source emission:
- Starburst/star-forming galaxies
- Active Galactic Nuclei (AGN)
- Other: e.g. Dwarfs

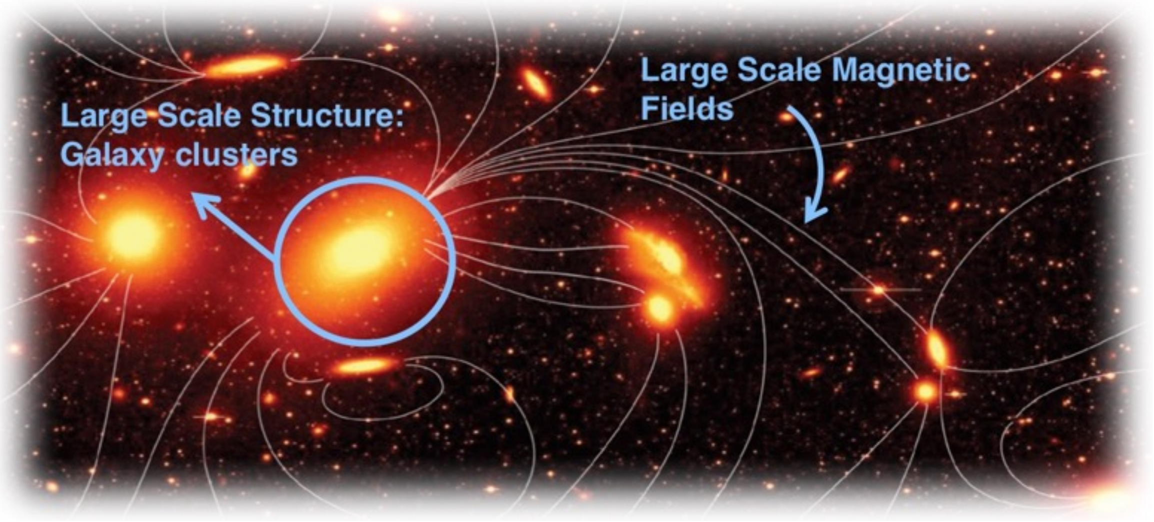


Diffuse

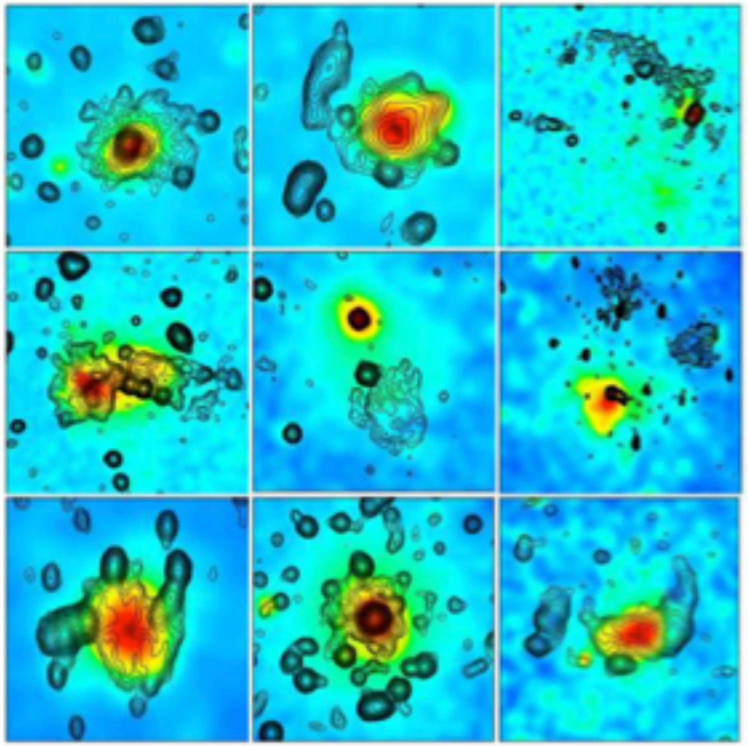
Low surface brightness emission:
- Galactic Halos
  - Starburst
  - AGN
- Cluster Emission
  - Giant/mini radio halos
  - Radio relics
  - Intra-cluster medium
- Cosmic web/Large Scale Structure

How Can We Detect It?

- **Direct imaging**
- **Statistical methods:**
  - Confusion
  - Cross Correlation
  - Stacking
- **Polarization:**
  - Faraday rotation from background AGN
  - Dispersion from fast radio bursts

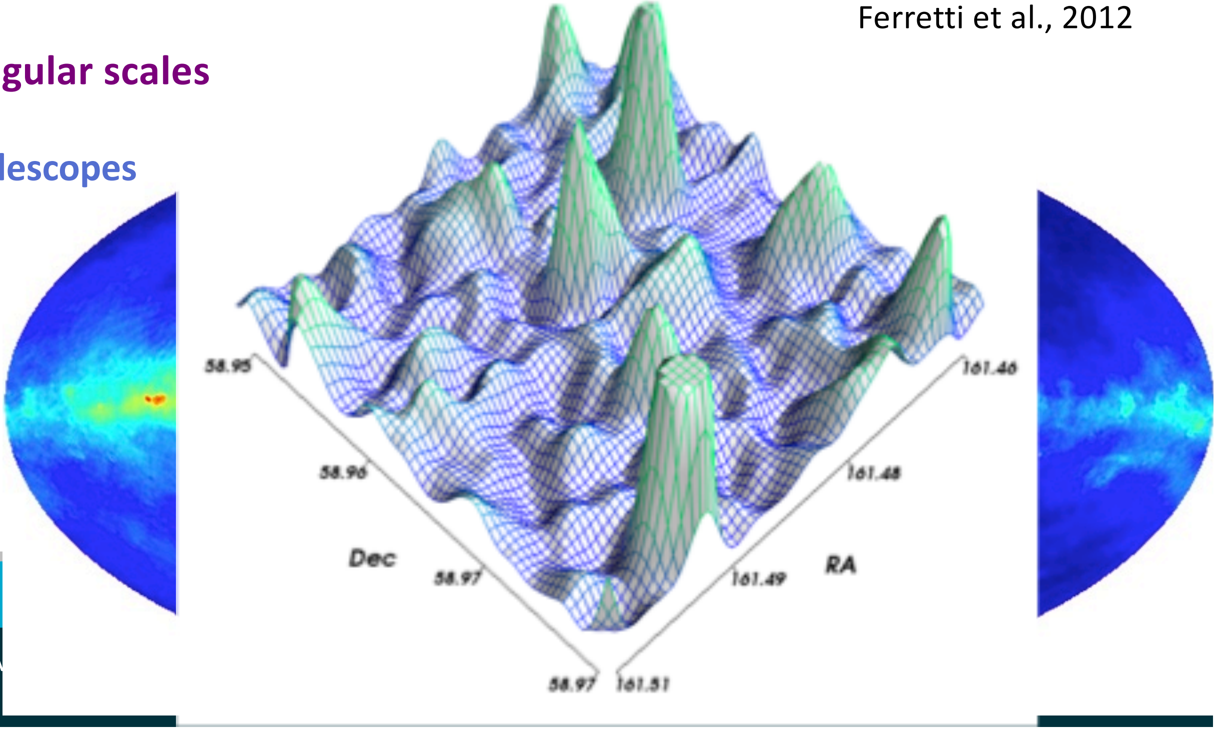


Diffuse Emission – Direct Imaging



Ferretti et al., 2012

- Diffuse emission in clusters
  - Halos
  - Mini-halos
  - Relics
  - But only few hundred detected (more coming now from low frequency surveys)
- Only bright sources (>1mJy) in high(er) mass clusters detected.
- Difficult to directly detect due to:
  - low surface brightness
  - Requires high sensitivity to large angular scales
    - Sizes up to Mpc scales
    - Difficult for radio interferometer telescopes
  - Bright Galactic foregrounds
  - Bright point sources
  - Faint point source confusion



How Can We Detect It?

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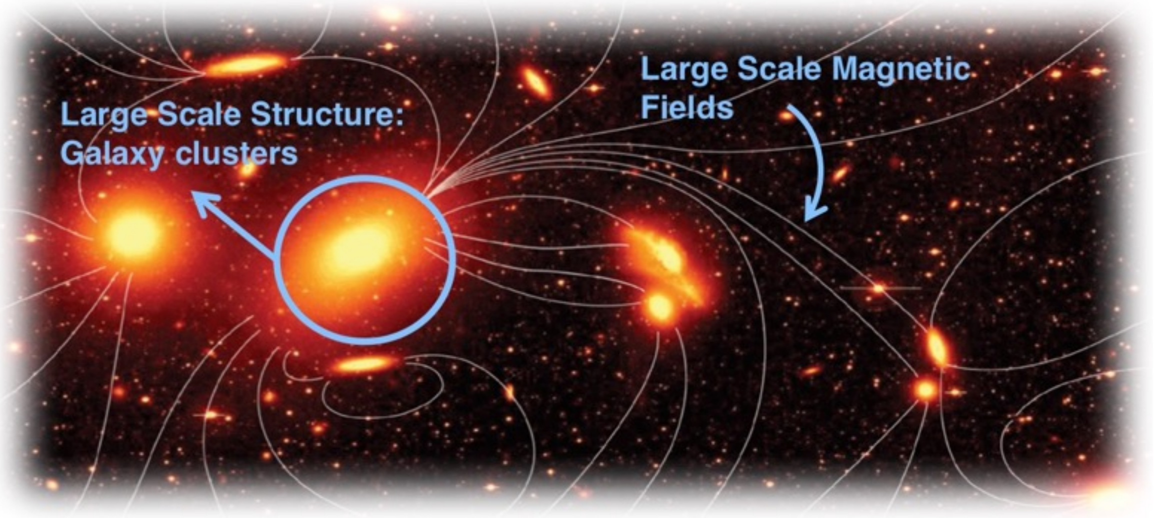
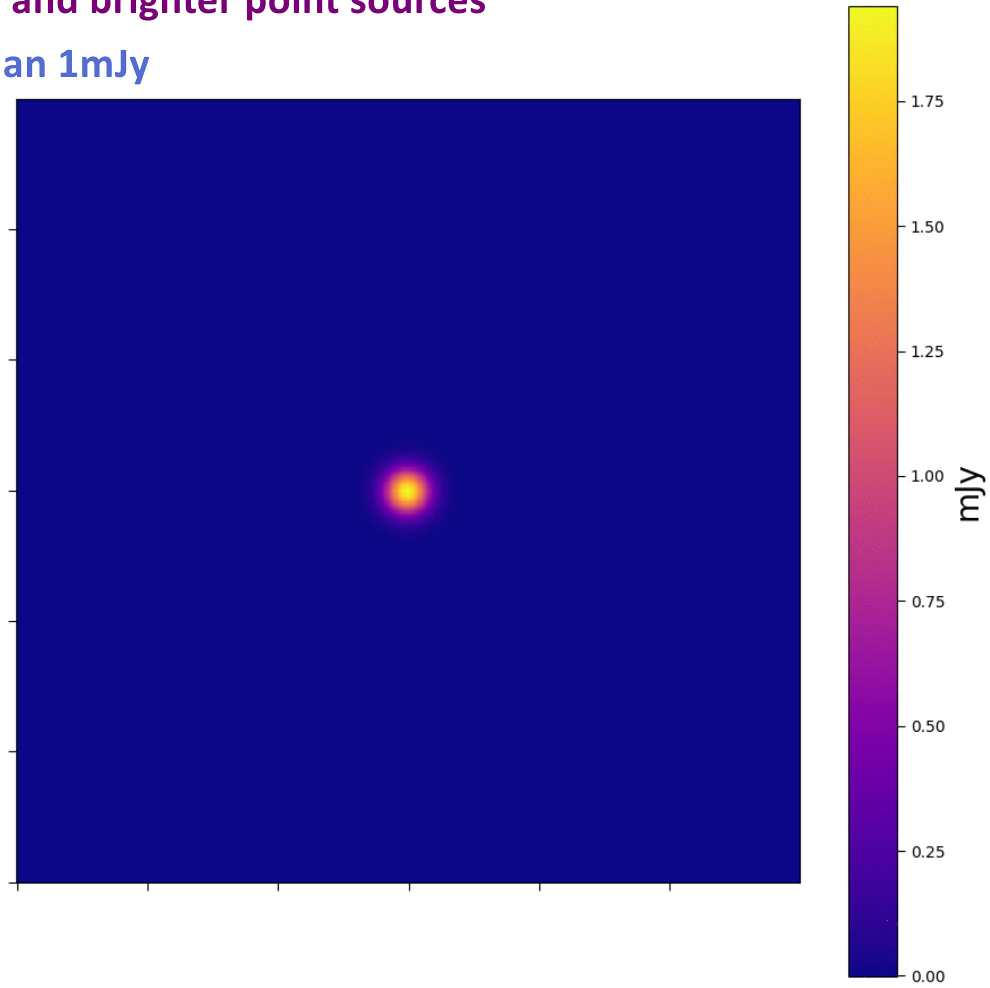


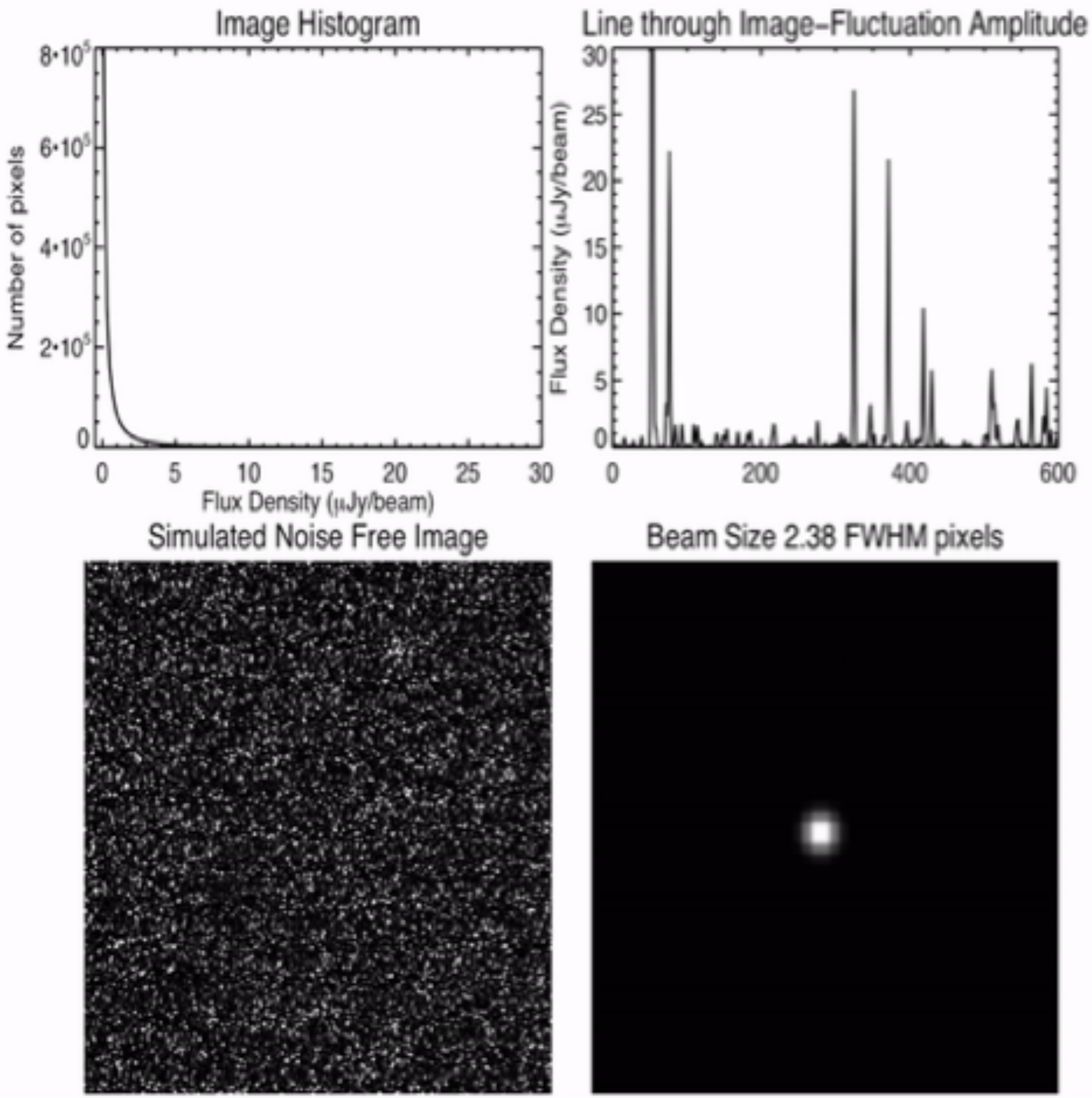
Confusion: Friend or Foe?

- **Simulated Gaussian "Halo"**
  - 60" size
  - 5 mJy total brightness
  - 45" beam
  - Addition of brighter and brighter point sources
    - None brighter than 1mJy



Using Confusion

- **Confusion is the blending of faint sources within a telescope beam**
- **PDF of image pixel histogram from confusion known as P(D)**
- **Confusion noise, σ_c (width of P(D))**
  - → **governed by beam and source count**



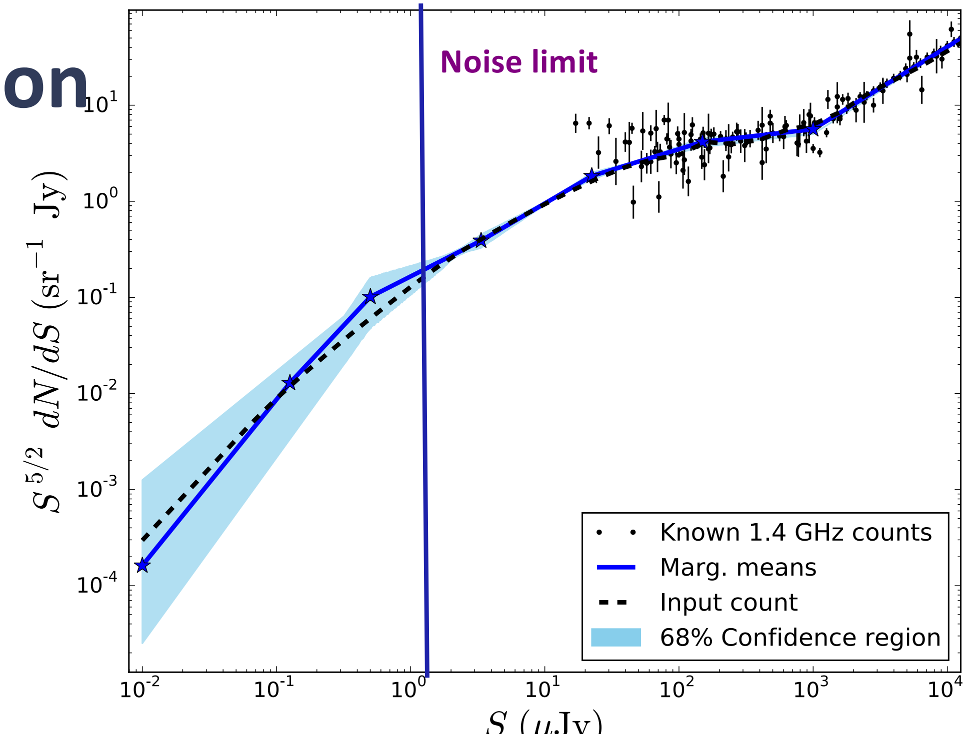
How? Probability of Deflection

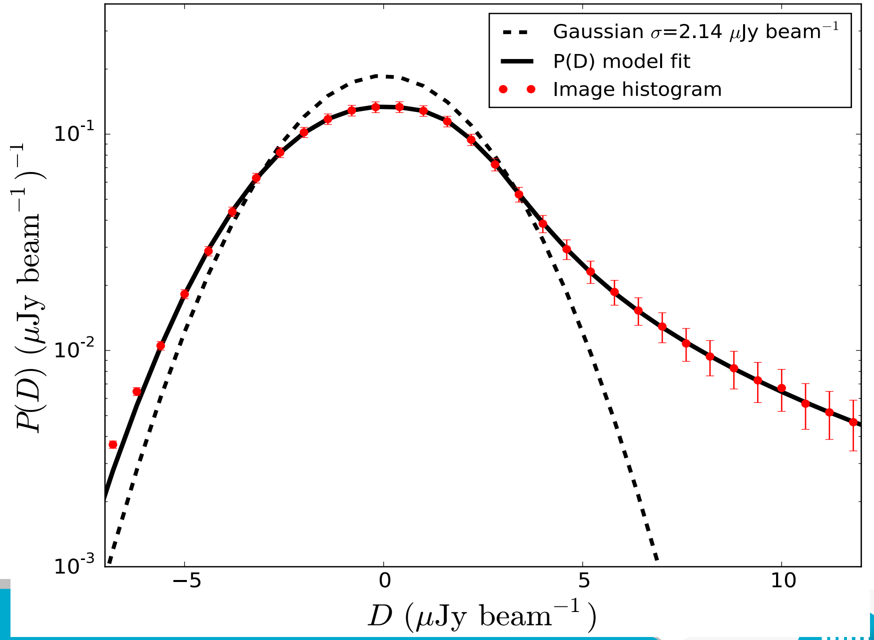
- Fitting of Image histogram → statistical estimate of source counts as faint as ~ σ_c
- Input
  - Source count model
  - Pixel size, beam shape(s)
  - Instrumental noise
- Mean density of observed flux

$$R(x)\,dx = \int_{\Omega} \frac{dN}{dS}\left(\frac{x}{b}\right) b^{-1}\, d\Omega\, dx$$

$$P(D) = \mathcal{F}^{-1}\left[\exp\left(\int_0^{\infty} R(x)\, e^{iwx}\, dx - \int_0^{\infty} R(x)\, dx - i\mu w - \frac{\sigma_n^2}{2} w^2\right)\right]$$

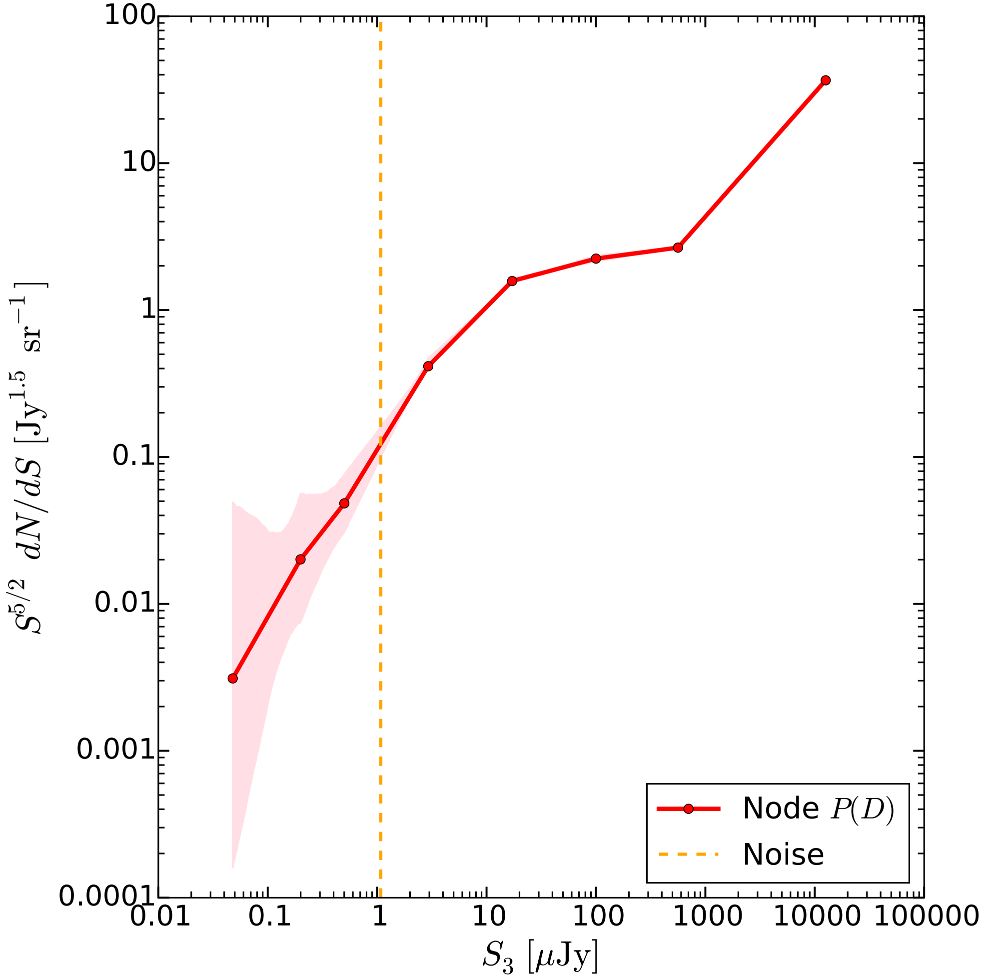
- Can use any continuous source count model
- Node model
  - Fixed position in Log(S)
  - Fit amplitude of node in Log(dN/dS)
  - Interpolate between nodes
  - Set of connected power-laws

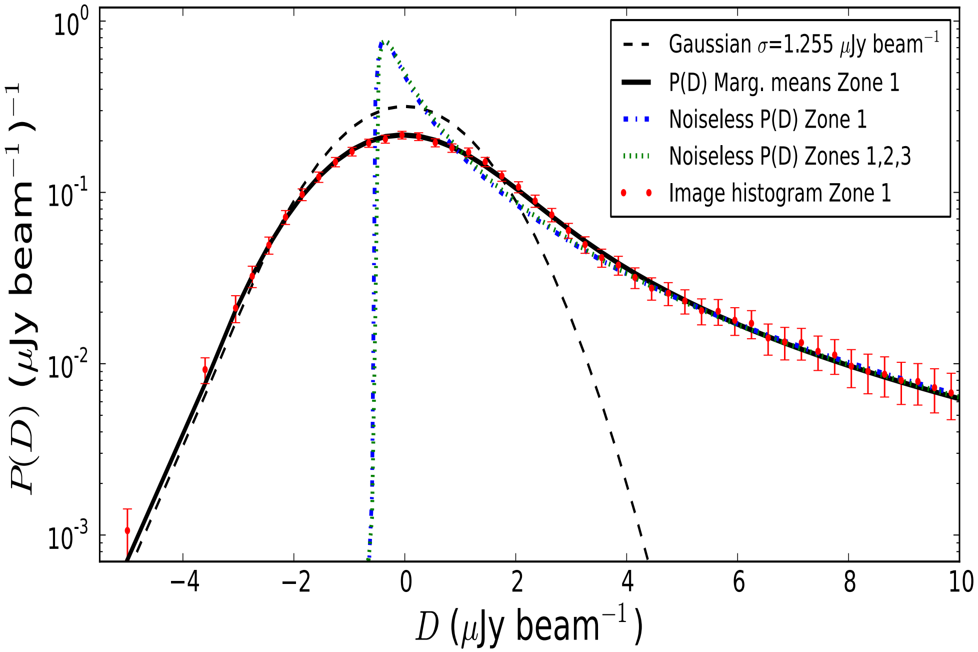


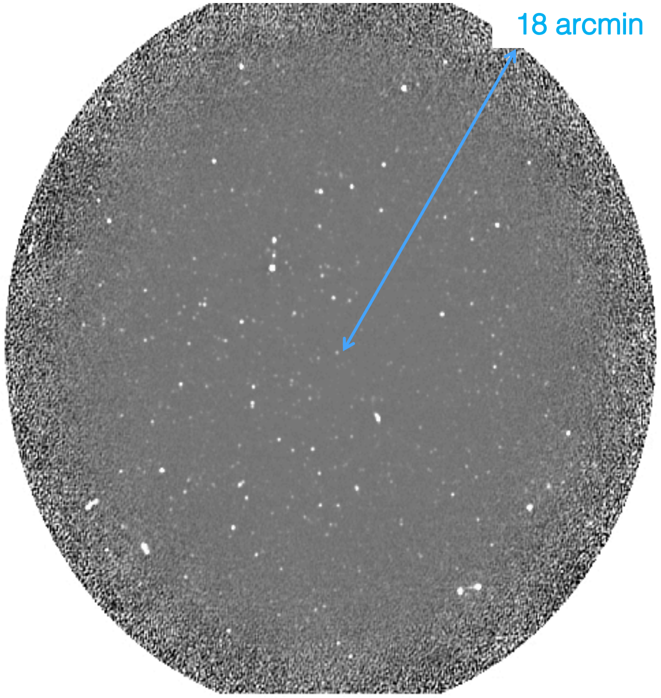


P(D) Source Count - Discrete

JVLA 3GHz Lockman Hole North







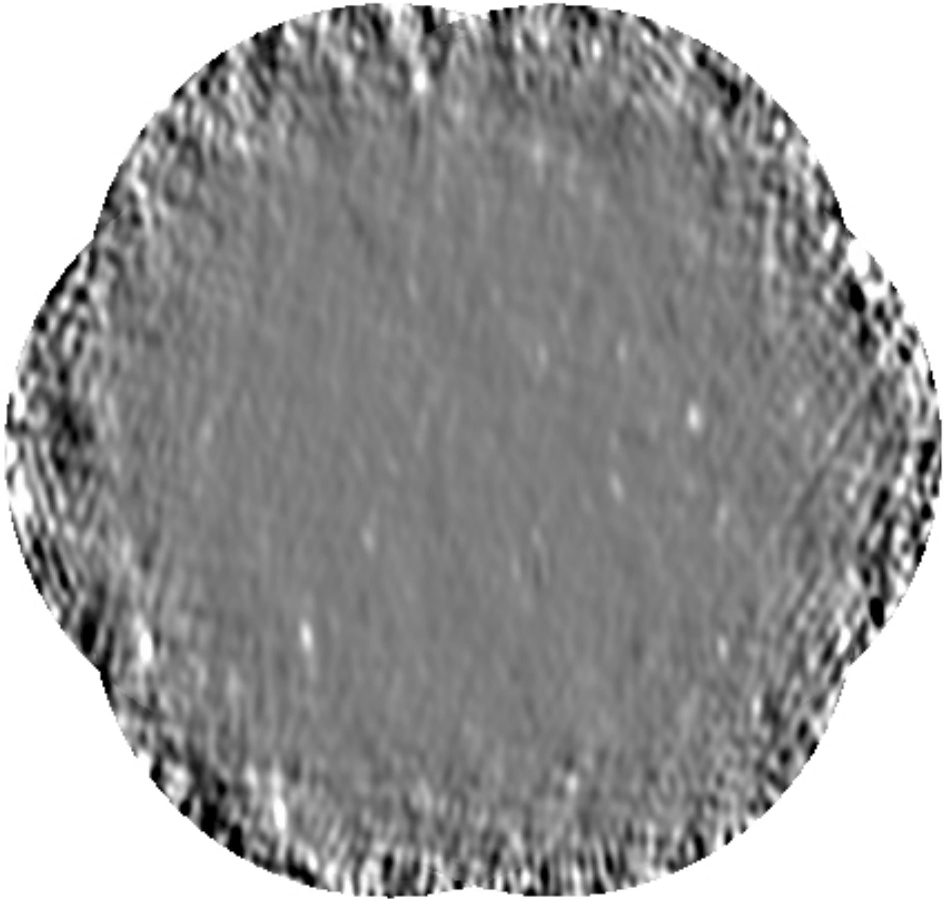
Confusion Diffuse Emission - Data

- Can try to statistically detect presence of sources too faint or diffuse to be detected normally

- Subtract point sources or use discrete source count model

- Example: ATCA
    - ELAIS S1
    - 7 pointing mosaic
    - 1.7 GHz
    - 2.5’ x 1’ beam
    - RMS ~ 50 μJy
    - Subtraction limit ~150 μJy

- Use ATLAS point source models to subtract bright sources and JVLA discrete count for un-subtracted sources



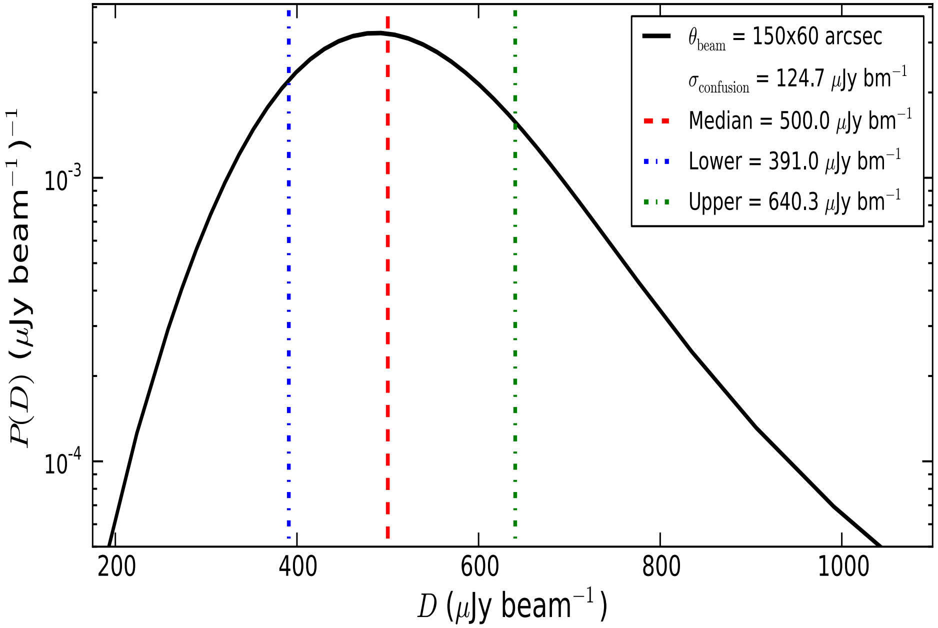
Confusion Diffuse Emission - Results

- **Can try to statistically detect presence of sources too faint or diffuse to be detected normally**

- **Subtract point sources or use discrete source count model**

- **Example: ATCA**
  - **ELAIS S1**
  - **7 pointing mosaic**
  - **1.7 GHz**
  - **2.5’ x 1’ beam**
  - **RMS ~ 50 μJy**
  - **Subtraction limit ~150 μJy**

- **Use ATLAS point source models to subtract bright sources and JVLA discrete count for un-subtracted sources**



Model P(D) of faint sources

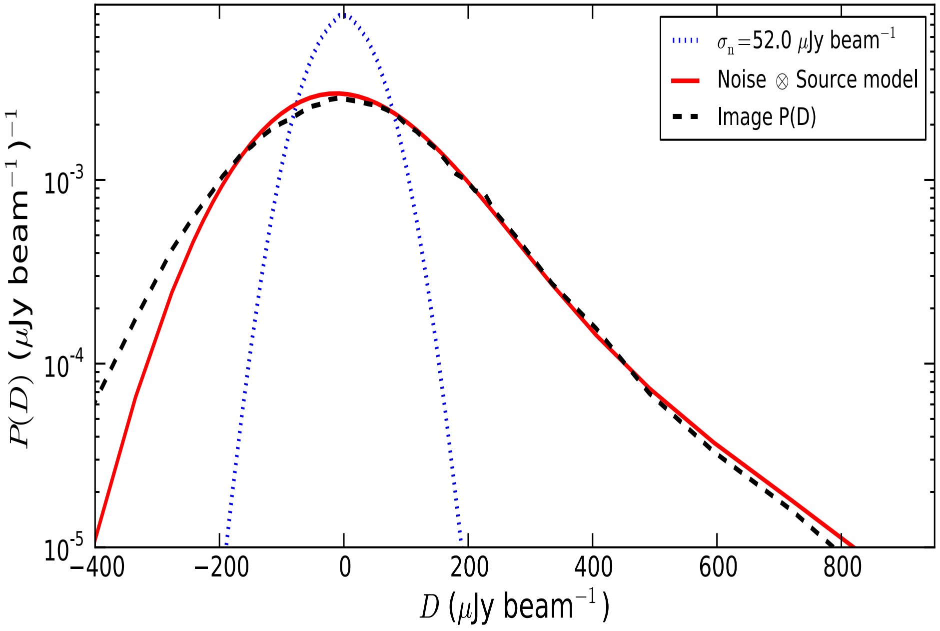


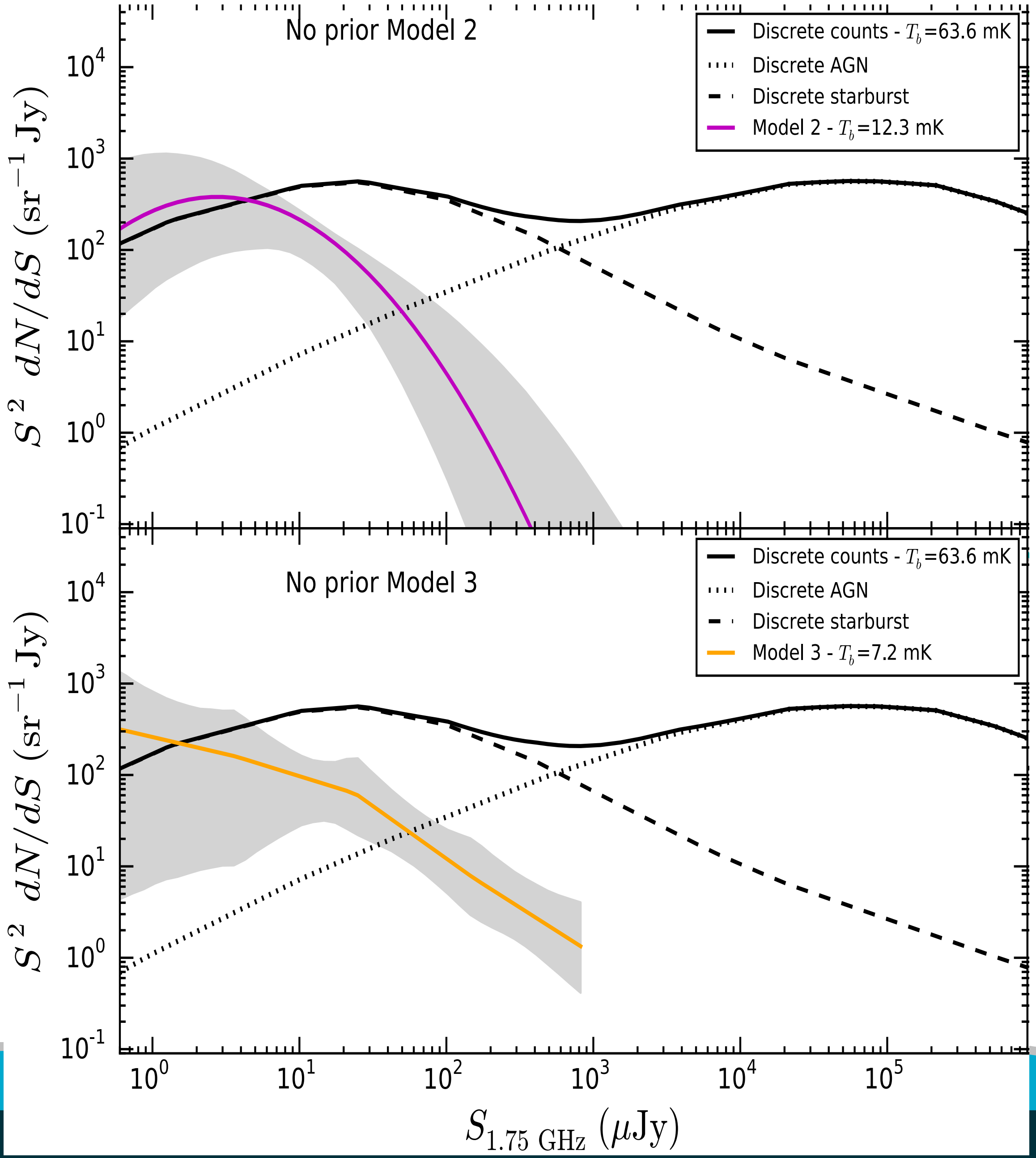
Image P(D) compared to model

← 3σ difference

Confusion Diffuse Emission - Results

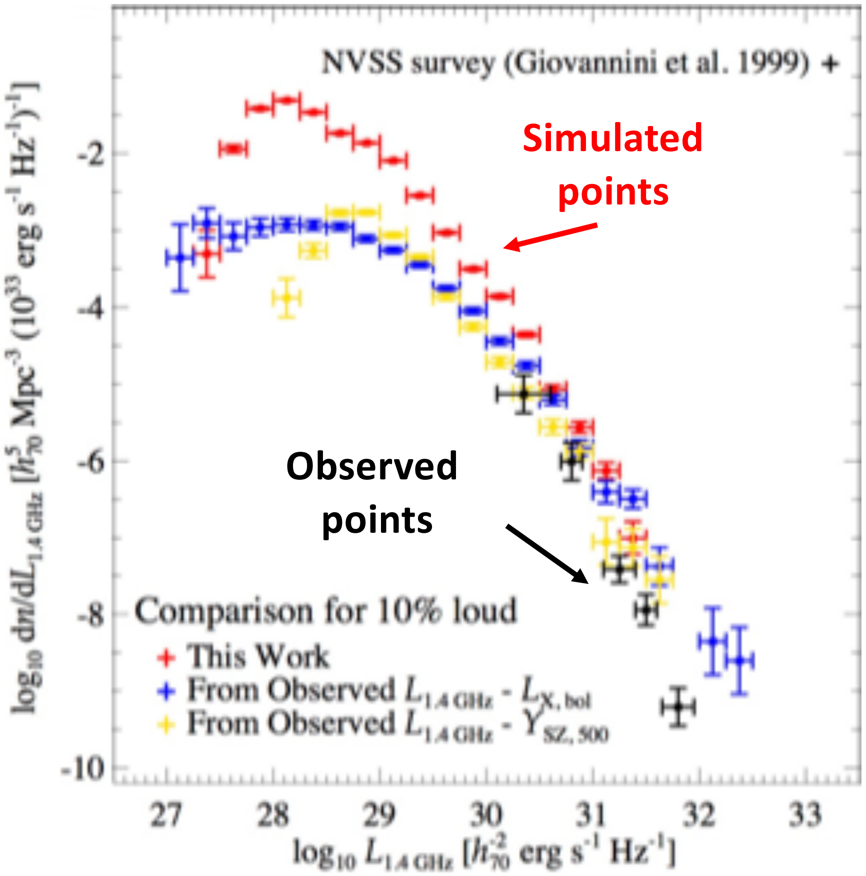
Model:
Parabola

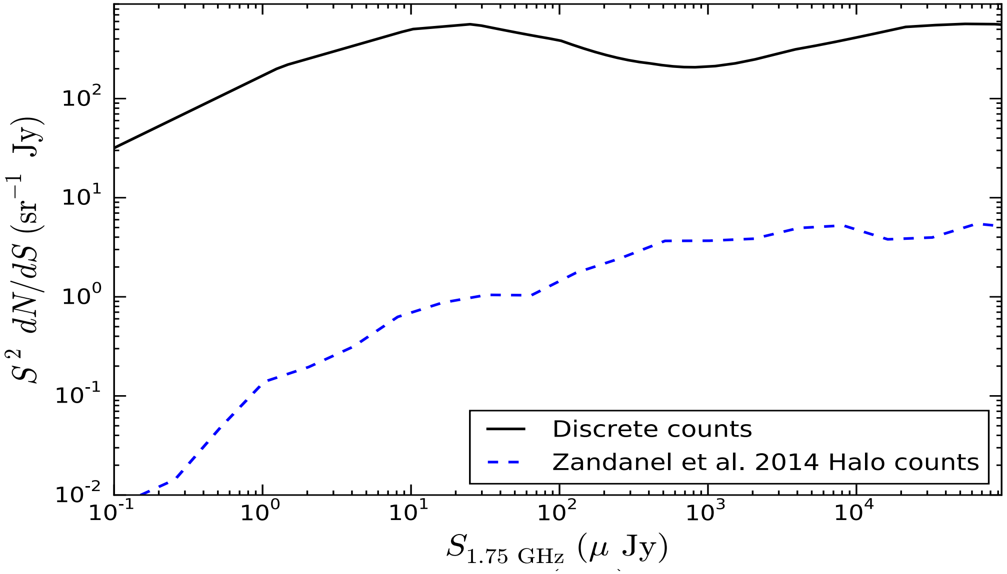
Model:
Nodes



Confusion Diffuse Emission - Models

- **Simulated model from Zandanel et al 2014 of cluster haloes**





Confusion Diffuse Emission - Models

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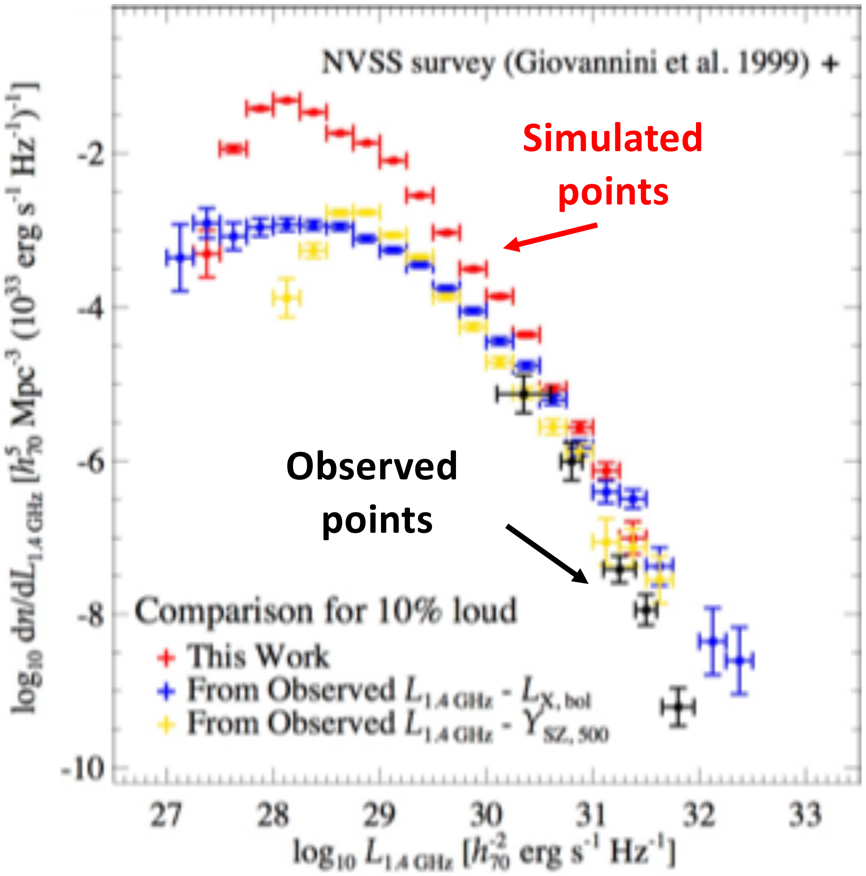
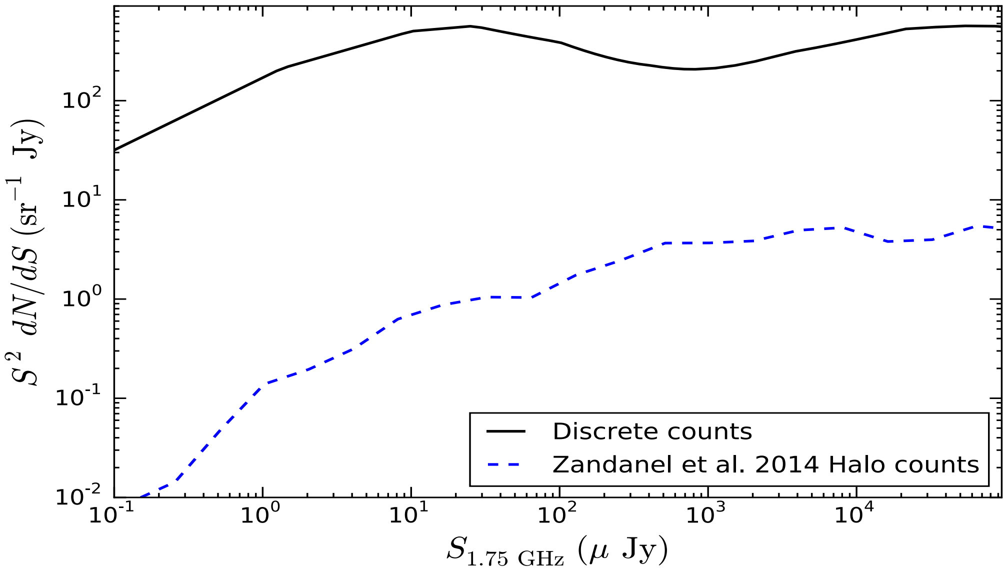
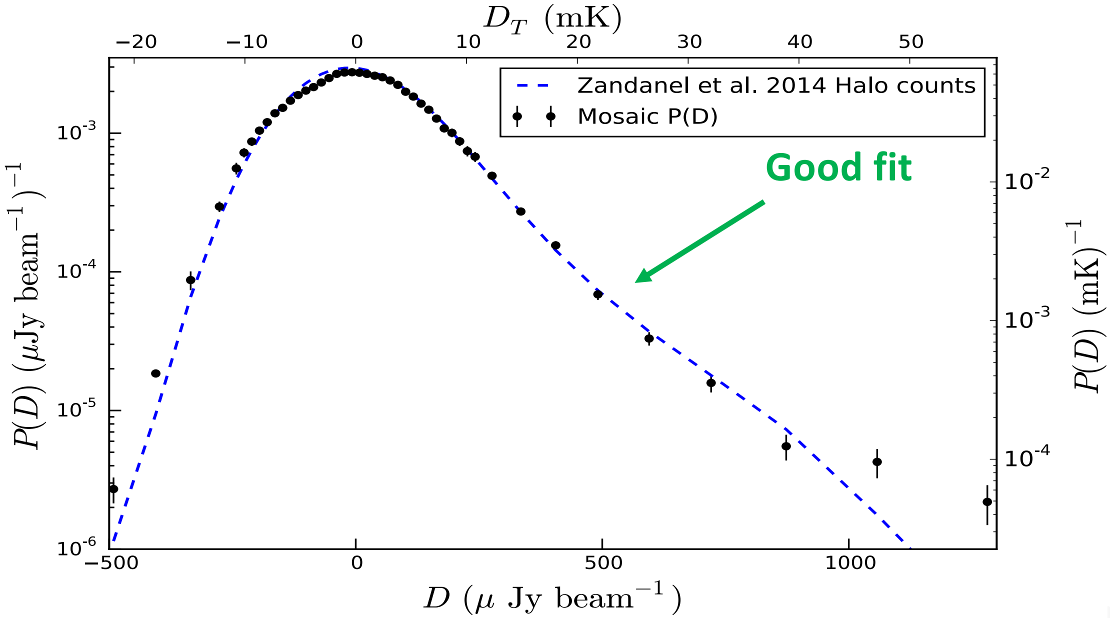


Simulated points

Observed points





Good fit

Confusion Diffuse Emission

Advantages:

- Detection of emission below confusion level
- Possible to constrain models of cluster emission

Disadvantages / Caveats:

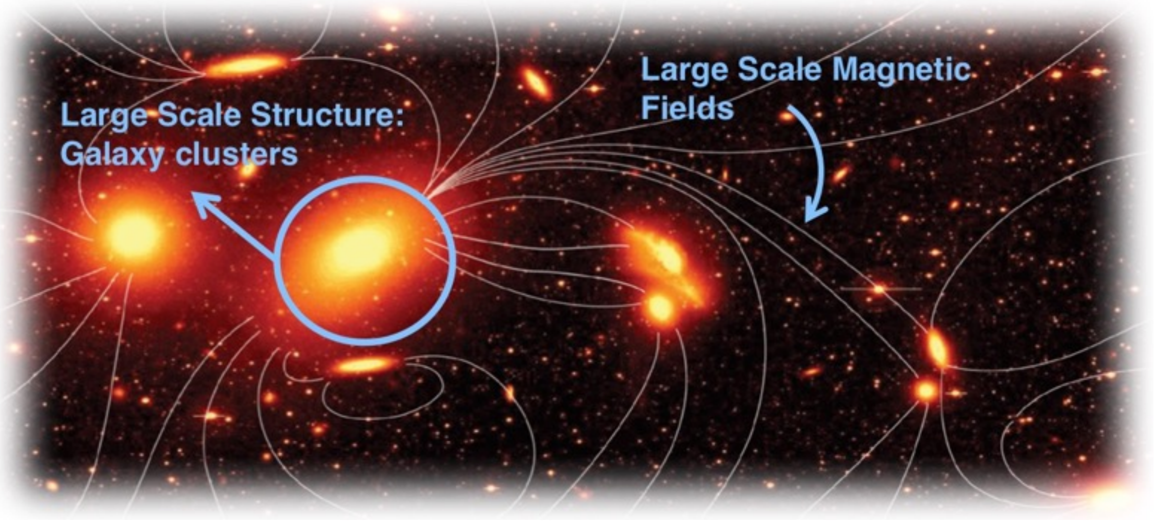
- Assumes emission smaller than (or roughly equal to) the beam size
- Requires point source subtraction and/or model for point sources
- Need to know beam shape(s) and noise properties well

Future work / Continuations:

- Repeat with different / larger area
- Compare results for regions with and without known diffuse emission
- Different (lower) frequency

How can we detect it?

- Direct imaging
- Statistical methods:
  - Confusion
  - Cross Correlation
  - Stacking
- Polarization:
  - Faraday rotation from background AGN
  - Dispersion from fast radio bursts



Cosmic Web - Cross Correlation

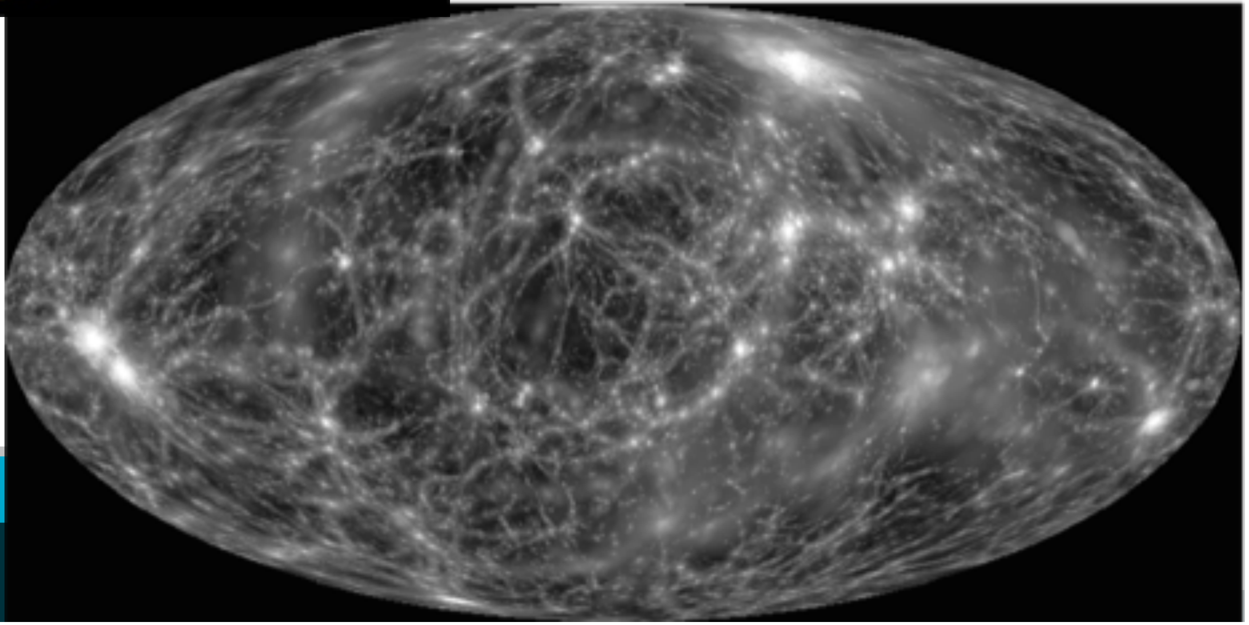
- **Galaxy number density → traces thermal baryon distribution → should correlate with diffuse synchrotron**

Cosmic Web - Cross Correlation

- Galaxy number density → traces thermal baryon distribution → should correlate with diffuse synchrotron

2MASS Galaxy Distribution coded by redshift

(photo credit :Thomas Jarrett (IPAC/Caltech))



Simulated radio synchrotron

(credit: Klaus Dolag)

Cosmic Web - Cross Correlation

- Galaxy number density → traces thermal baryon distribution → should correlate with diffuse synchrotron

- How correlated as a function of distance or angular scale?
  - Unknown

- How correlated?
  - Unknown

- Reasons for a positive correlation:
  - AGN (core)
  - Starbursts and disk emission
  - AGN (WAT and NAT associated with clusters)
  - Cluster halos
  - Cluster relics
  - Synchrotron cosmic web

- Reasons for a negative correlation:
  - Galactic extinction (galaxy number counts down, synchrotron up)

Increasing angular
scale

Cross Correlation with MWA

The MWA:

- **Frequency range: 80 – 300 MHZ**
- **2048 dual polarization dipoles**
- **Number of antenna tiles: 128**
- **Number of baselines: 8128**
- **Collecting area: 2000 sq. meters**
- **FOV: 15 - 50 deg. (200 - 2500 sq. deg.)**
- **Polarization: I, Q, U, V**

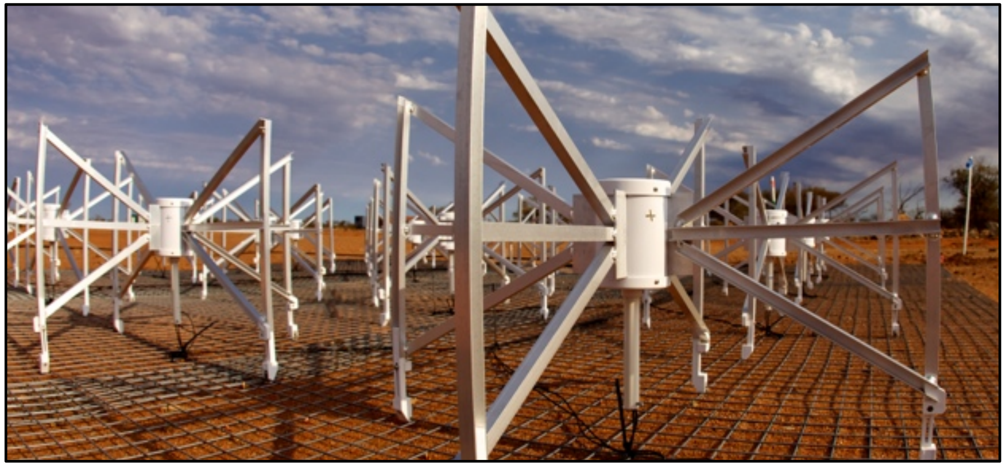


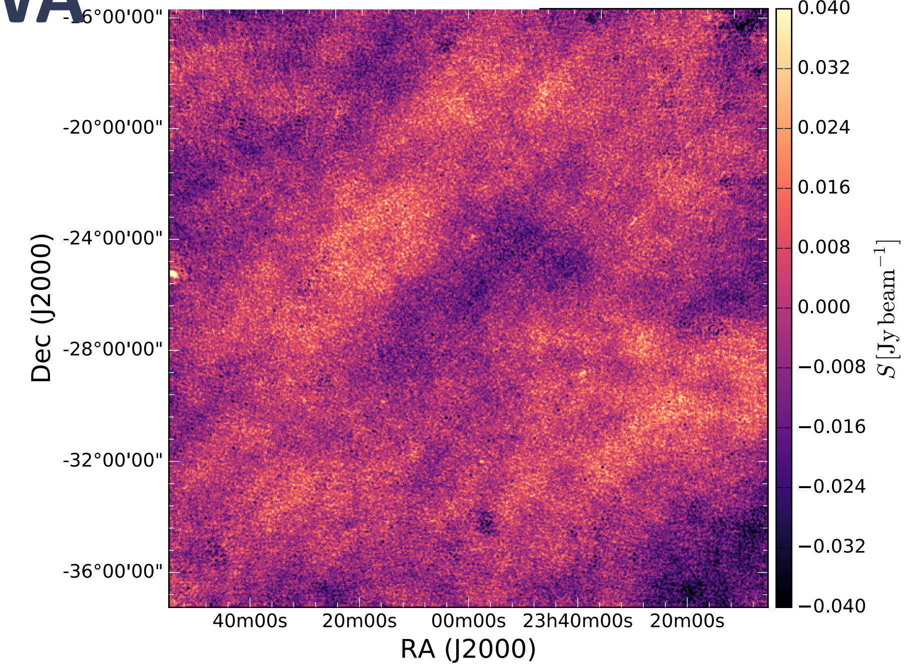
Photo credit: Natasha Hurley-Walker

★ **Good sensitivity to large angular scales, low frequency, large field of view**

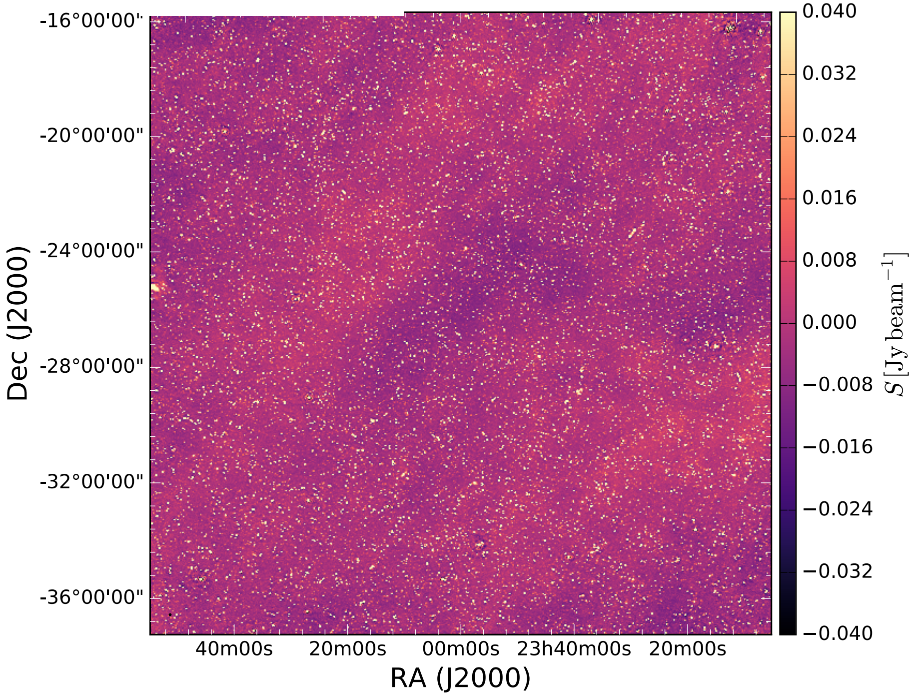
Cross Correlation with MWA

- Field: EoR0 RA=0 Dec= -27
- υ = 180 MHz
- Beam 2.3’ – 2.9’
- σ_n= 0.6 – 0.96 mJy beam^{-1}
- σ_c = 4.4 - 9.5 mJy beam^{-1}
- Subtraction limit ~ 50 mJy

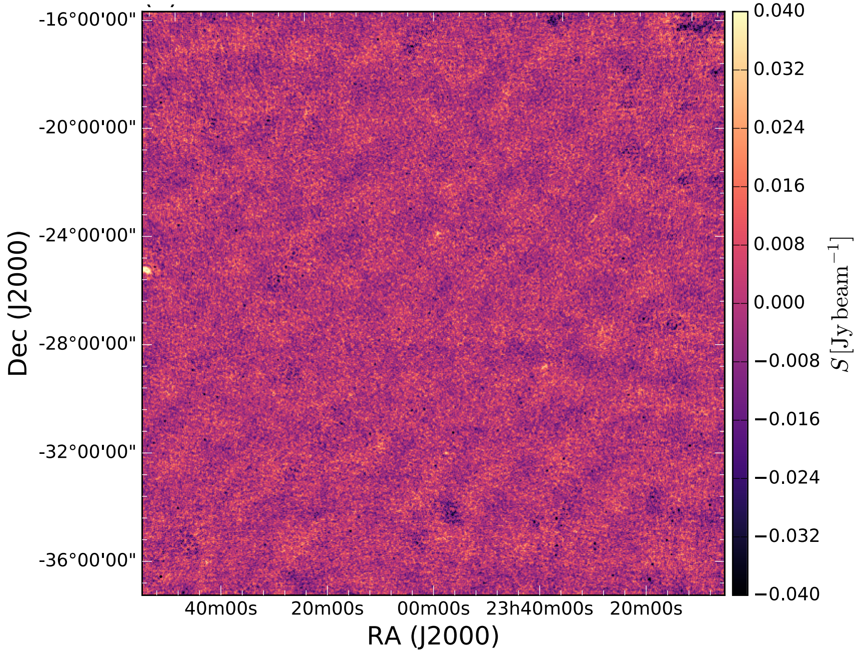
Point source sub



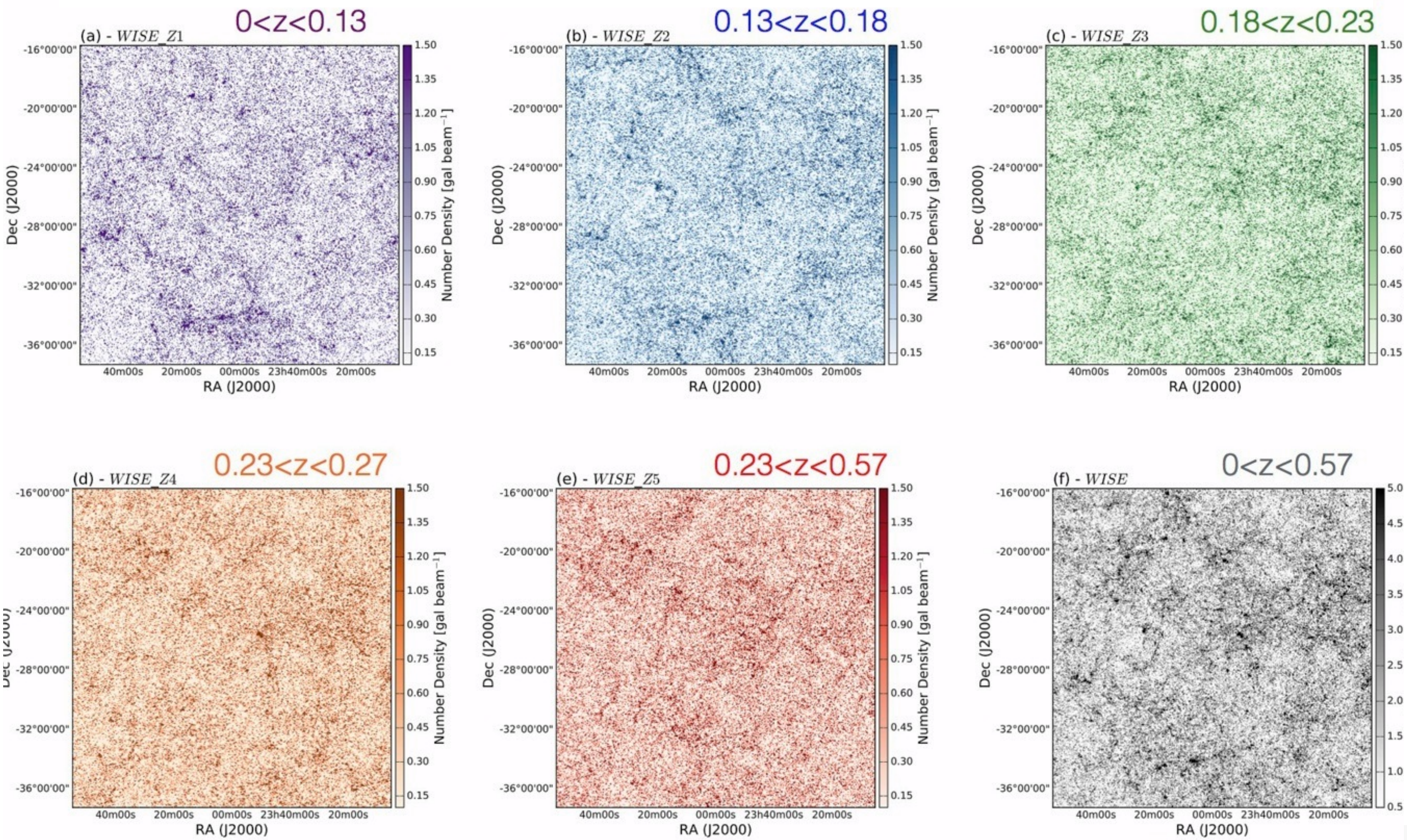
Full



Point source & Galaxy sub

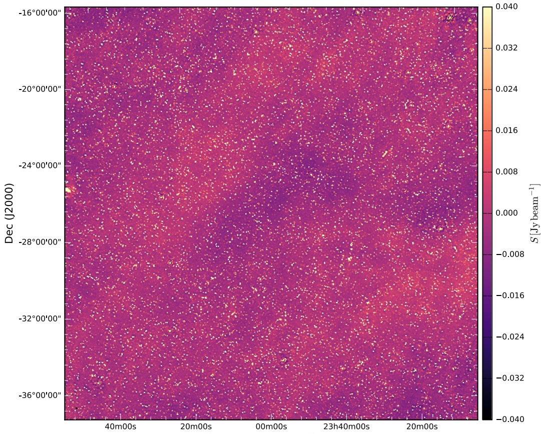


Cross Correlation with MWA - WISE Number Density

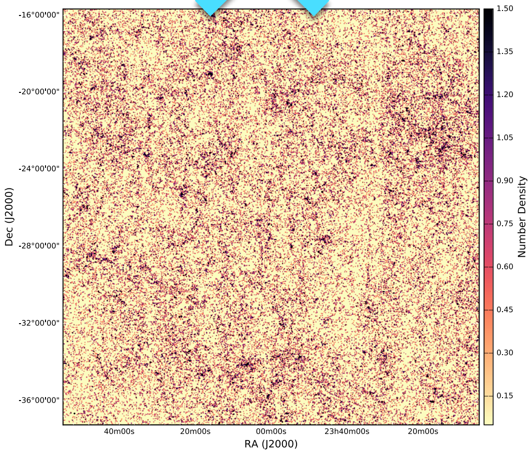


Cross Correlation with MWA

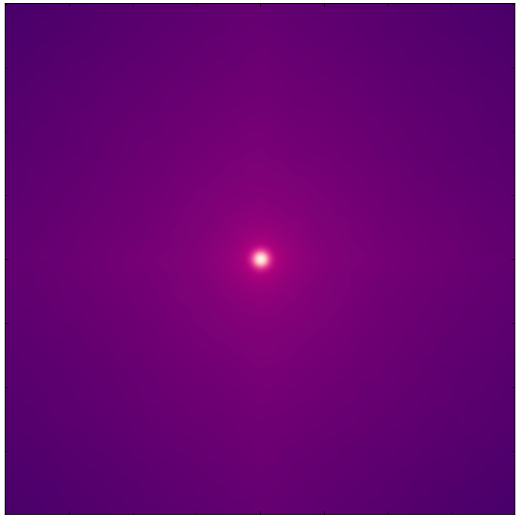
$$CCF\,(xshift, yshift) = \frac{1}{n}\sum(R_{i,j} - \bar{R})(G_{i,j} - \bar{G})$$



×



Δθ



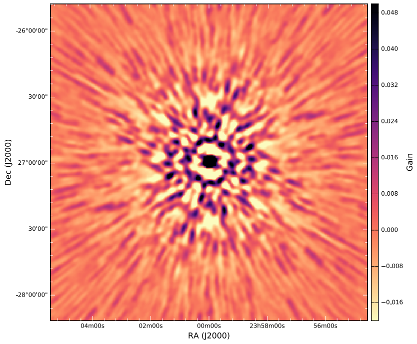
Δθ

Take radial average

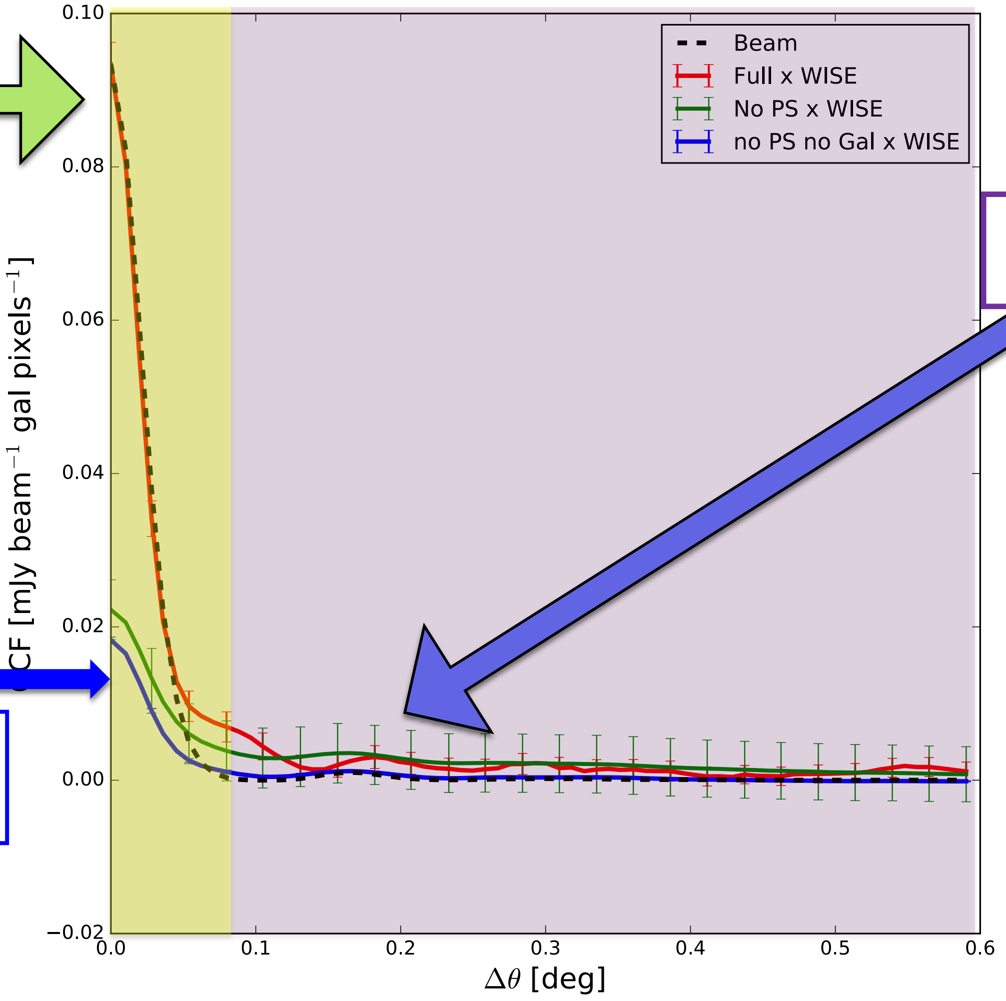
Cross Correlation with MWA

$$CCF\,(xshift, yshift) = \frac{1}{n}\sum(R_{i,j} - \bar{R})(G_{i,j} - \bar{G})$$

Point Sources→ smaller than beam



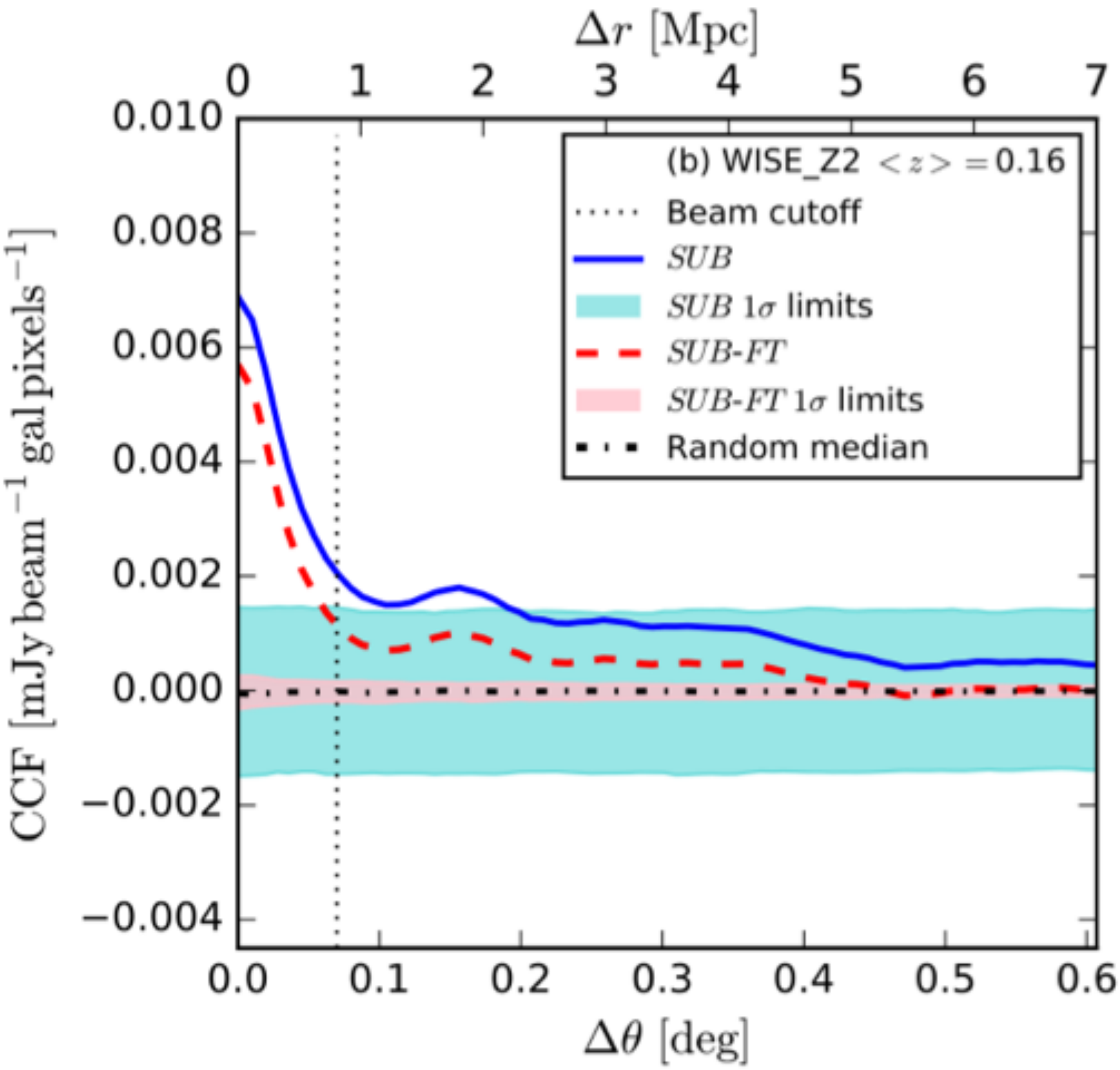
Still some point source contribution



Diffuse emission → larger than beam

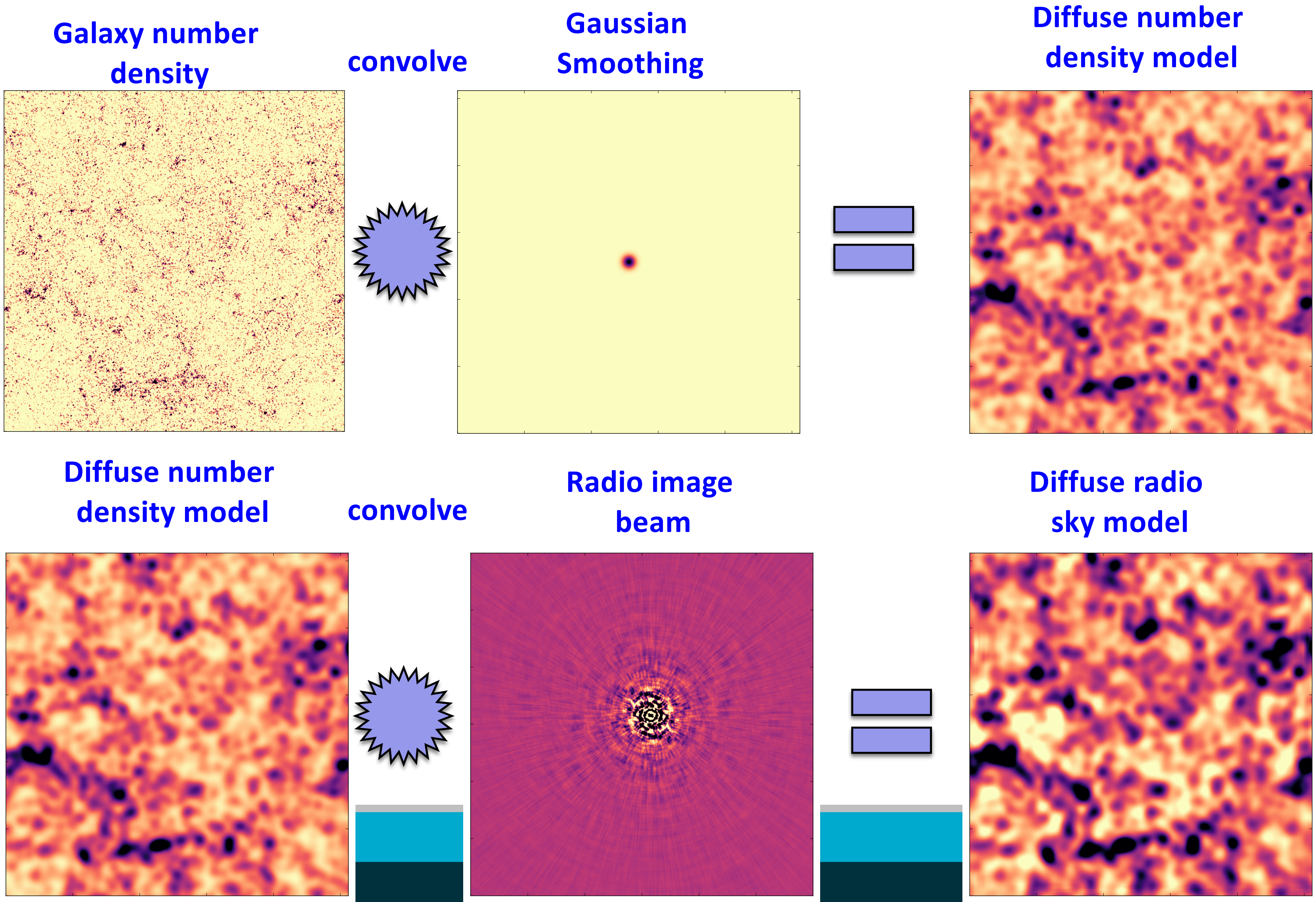
So how much diffuse is there ???

Cross Correlation with MWA



20 total CCFs
(2 radio images x
10 number density maps)

Cross Correlation with MWA – Emission Upper Limits



Galaxy number density

convolve

Gaussian Smoothing

Diffuse number density model

Diffuse number density model

convolve

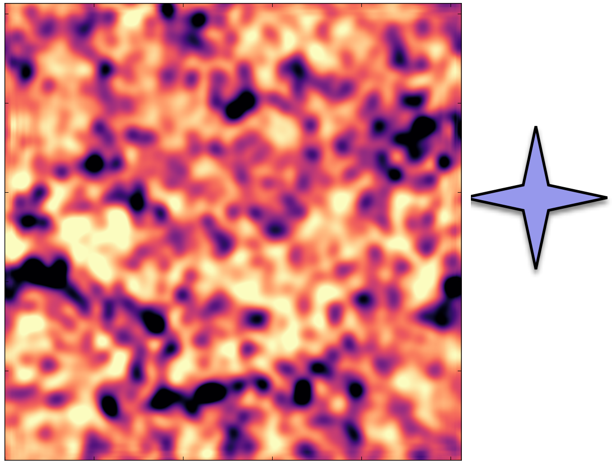
Radio image beam

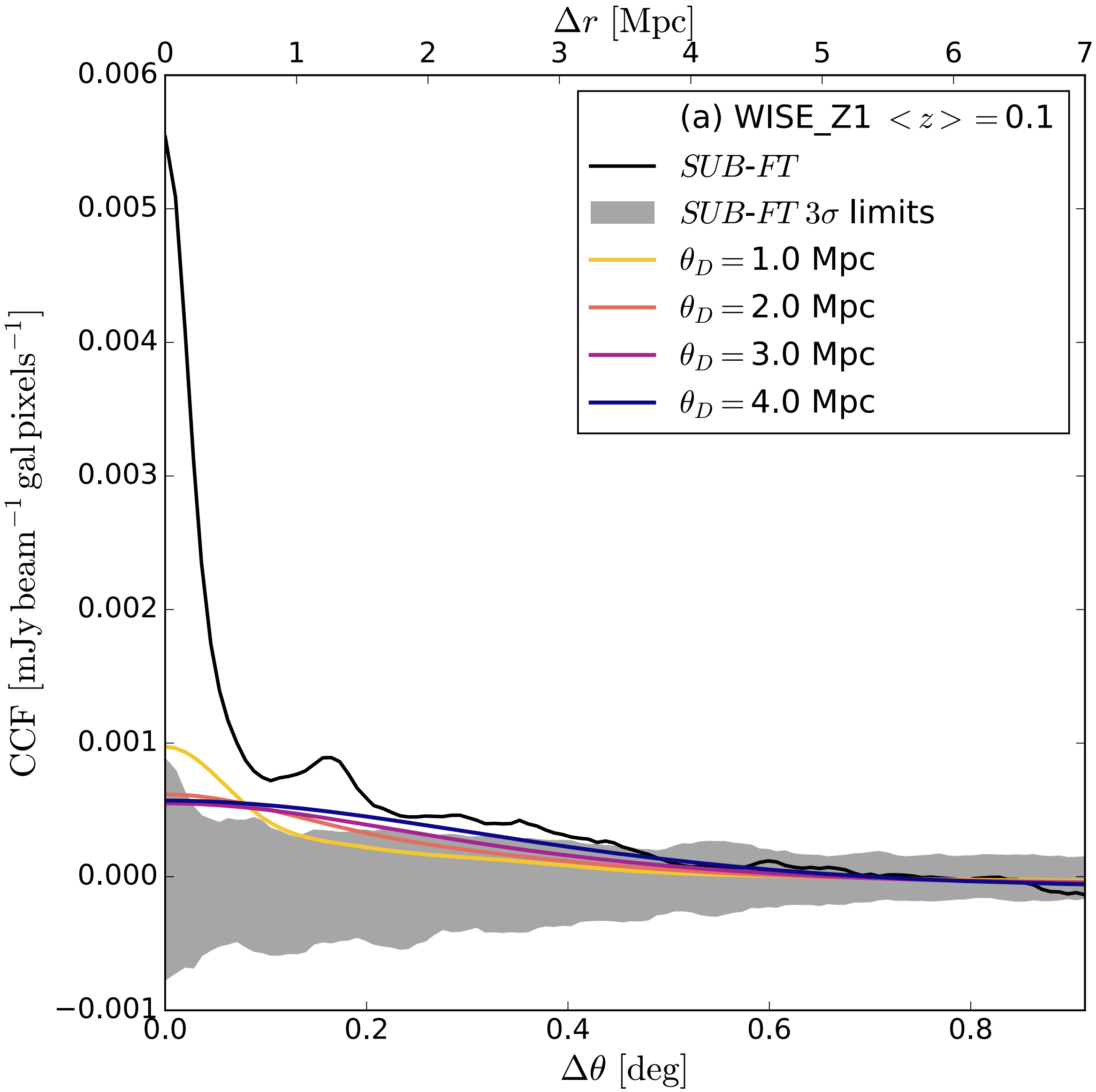
Diffuse radio sky model

Cross Correlation with MWA – Emission Upper Limits

Diffuse radio sky model

Cross correla





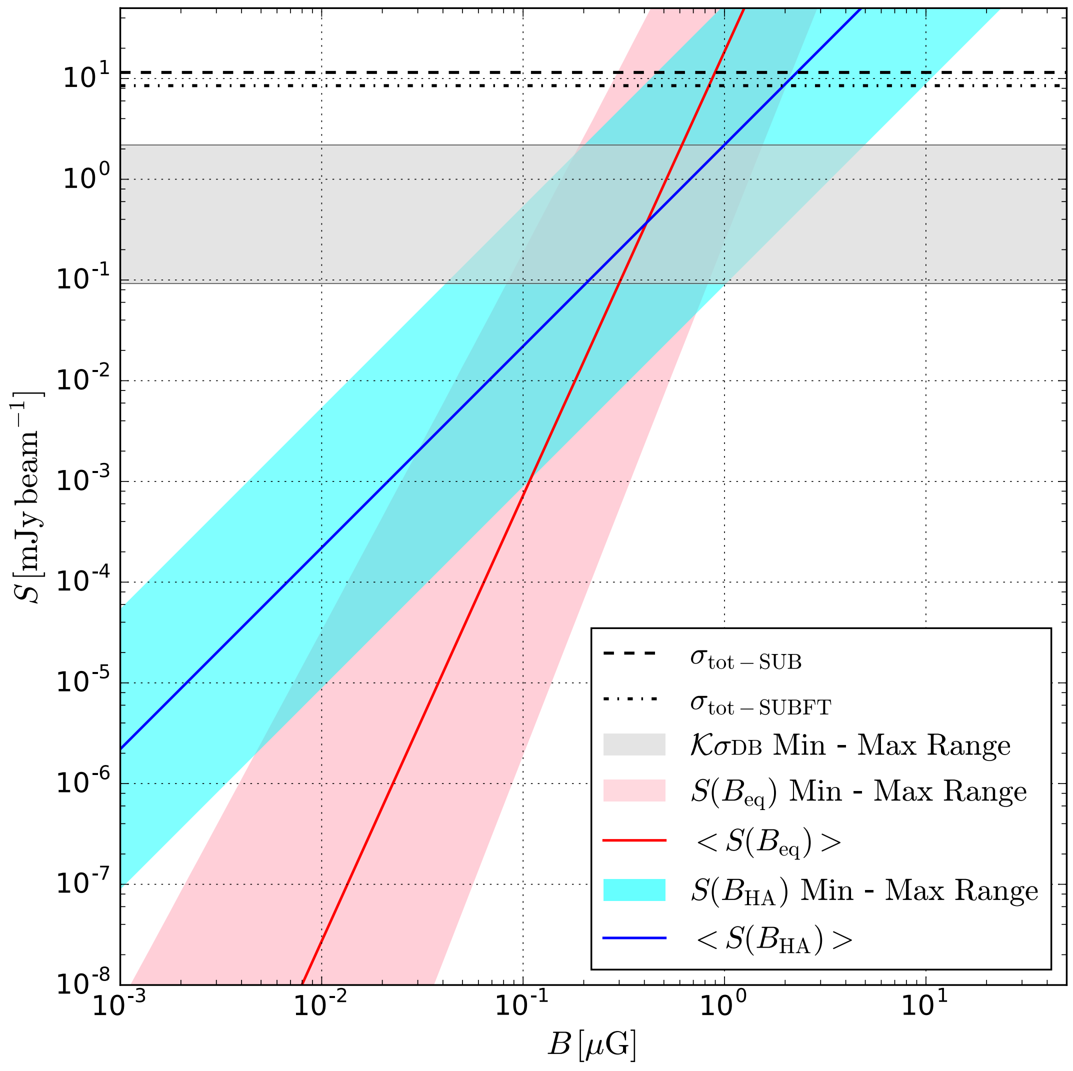
Scale CCF until > 3σ

0.09 < S [mJy beam^{-1}] < 2.2

0.01< S [mJy arcmin^{-2}] < 0.3

Cross Correlation with MWA – Magnetic Field Limits

$$B_{\rm eq} = \left[\frac{4\pi(1-2\alpha)(K_0+1)E_{\rm p}^{1+2\alpha}(\nu/2c_1)^{-\alpha}I_\nu(1+z)^{3-\alpha}}{(-2\alpha-1)\,c_2(\alpha)\,l\,\eta\,c_4(i)}\right]^{1/(3-\alpha)}$$



$1 < K_0 < 300$ $0.01 < \eta < 1$ $-0.6 < \alpha < -2.25$

- **$0.03 < B_{eq}$ [μG] < 1.98**

$K_0=100$ $\eta=1.0$ $\alpha = -1.25$

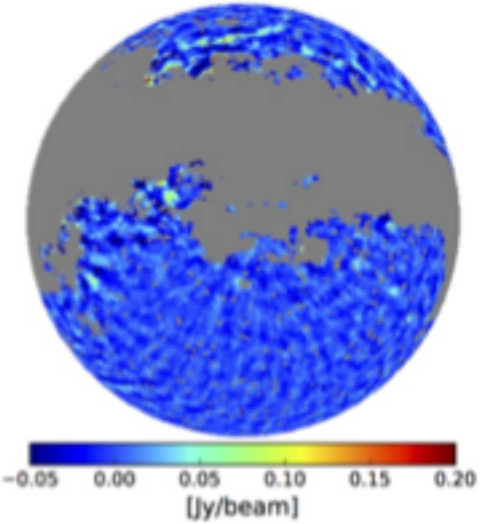
- **$0.22 < B_{eq0}$ [μG] < 0.62**

$$B_{\rm HA} \simeq 0.05\,\mu{\rm G}\sqrt{\frac{\rm I_{WHIM}}{5\times10^{-3}\,{\rm Jy\,deg^{-2}}\,\left(\frac{100\,\rm MHz}{\nu}\right)^{\alpha}\left(\frac{\xi}{10^{-3}}\right)}}$$

Vazza et al., 2015

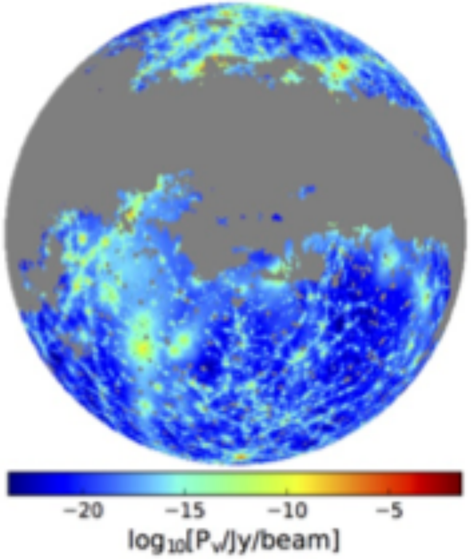
Cross Correlation S-PASS

- Single Dish 2.3 GHz All Sky
- Cross correlate with MHD simulation (Dolag)
  - Brown et al., 2017



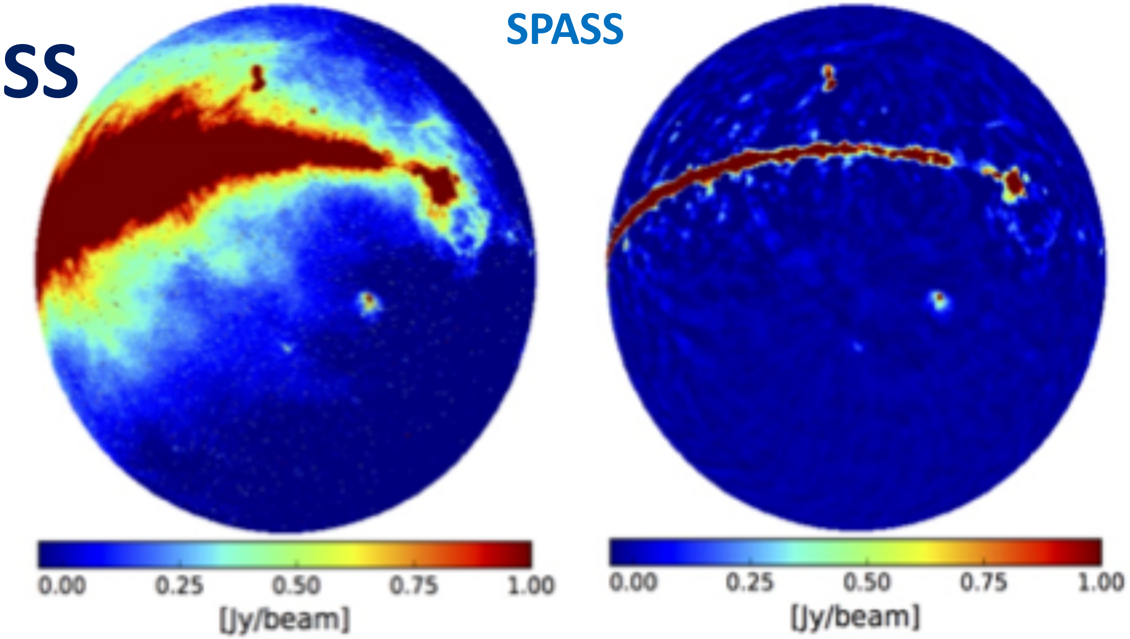
SPASS

Masked

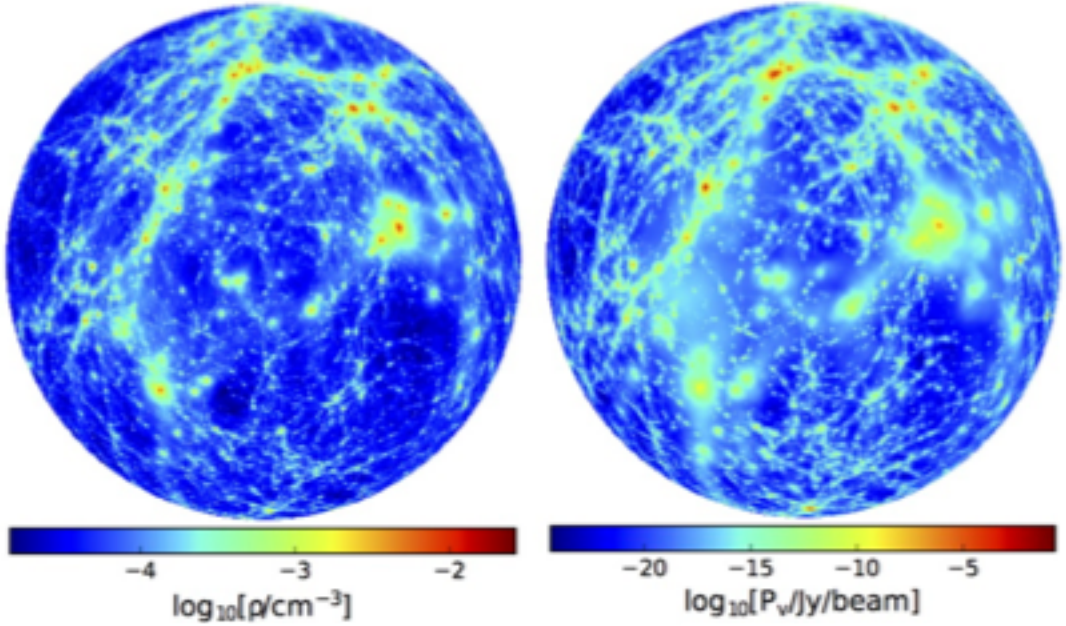


Sim

SPASS



Simulations



Electron density

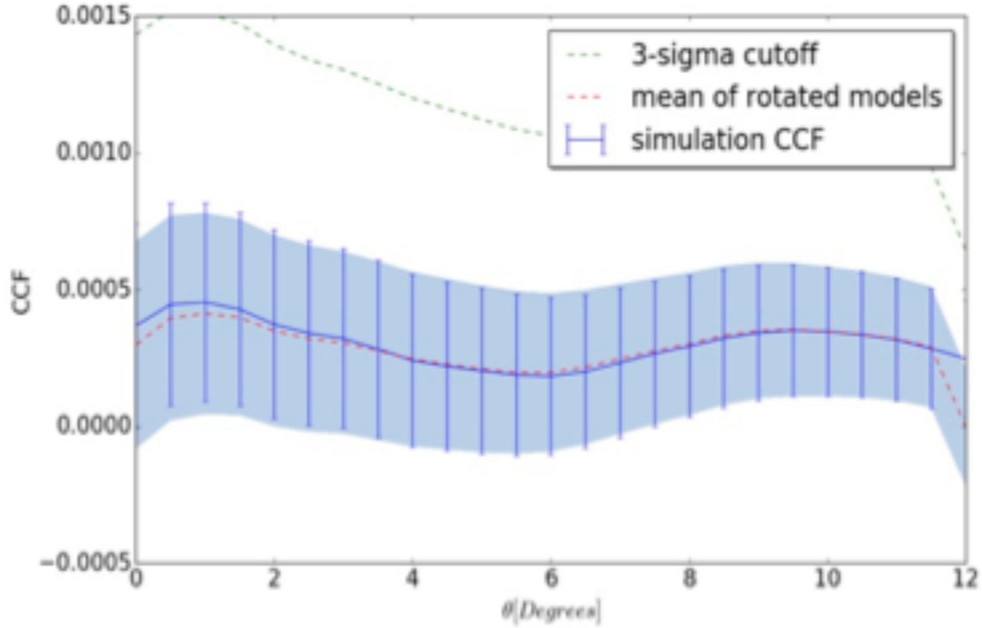
Synchrotron

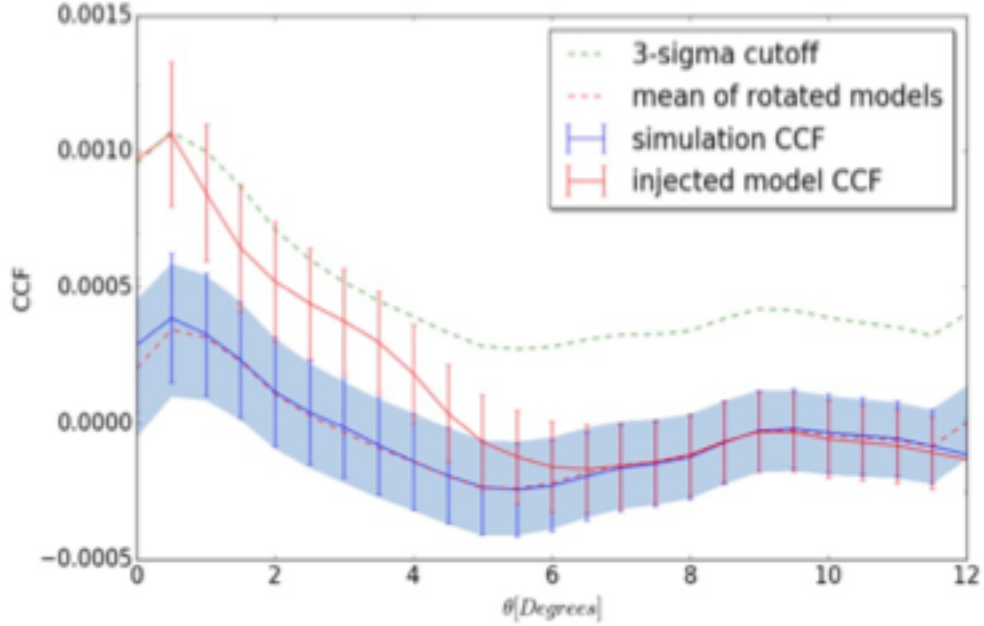
Cross Correlation S-PASS

- **Single Dish 2.3 GHz All Sky**
- **Cross correlate with MHD simulation (Dolag)**
  - **Brown et al., 2017**

Flux upper limit:
0.16 mJy arcmin^{-2}

Magnetic field upper limit:
0.13 μG





Cross Correlation

Advantages:

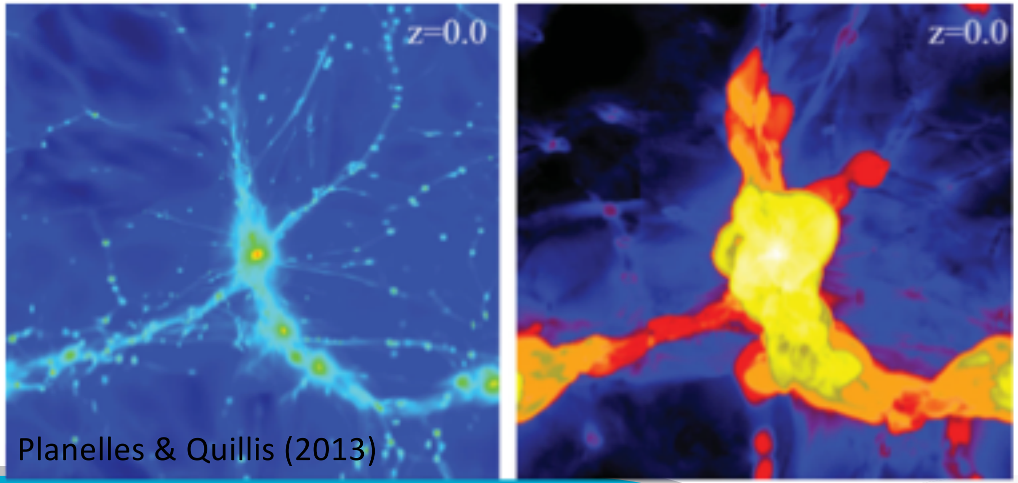
- Enhance signals hidden in the noise

Caveats:

- Need models to interpret results physically
- Need to know (dirty) beam shape well
- Requires point source subtraction and/or model for point sources
- Galactic emission can interfere over large areas

Future Work

- Repeat with different data
- New MHD simulations
- Model for point sources



Planelles & Quillis (2013)

Other Methods

- **2D P(D) analysis**

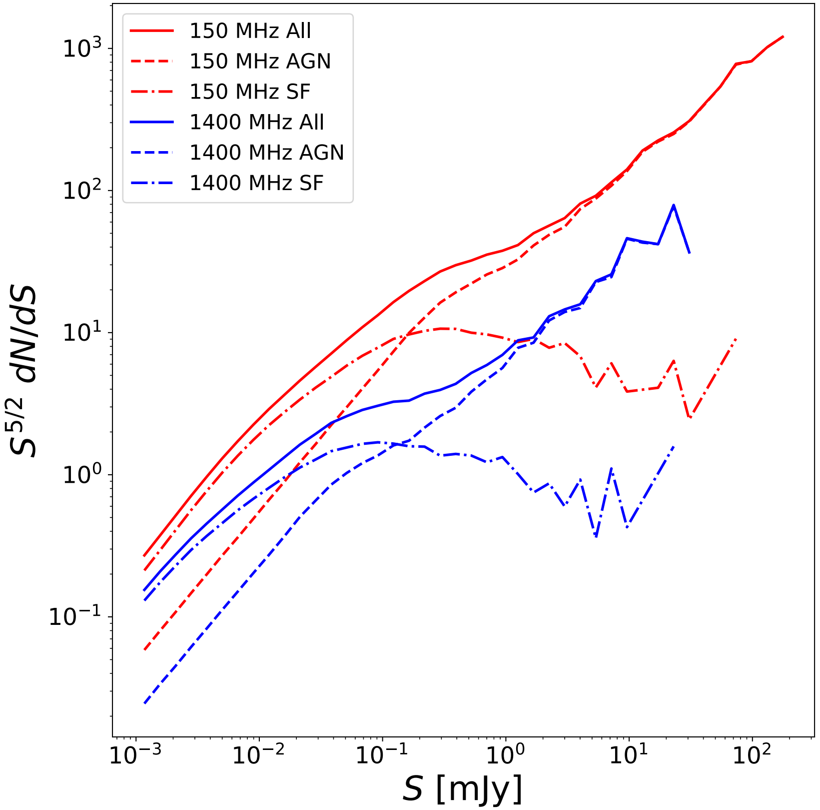
- **Fit 2D source count to 2D histogram**
- **Can be two frequencies, two resolutions, Stokes I and polarised intensity**
- **Provides tighter constraints, uses more data, breaks degeneracies**

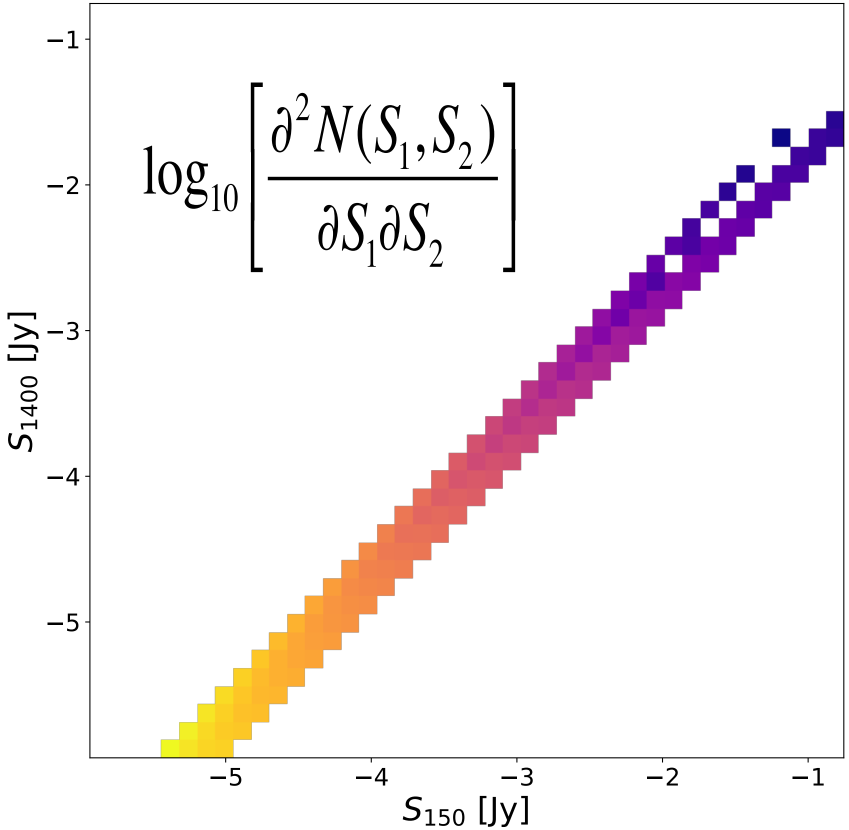
Two populations:

- AGN **α = -0.85**
- Star-forming **α = -0.55**

Two Frequencies:

- 150 MHz (MWA)
- 1400 MHz (ASKAP)

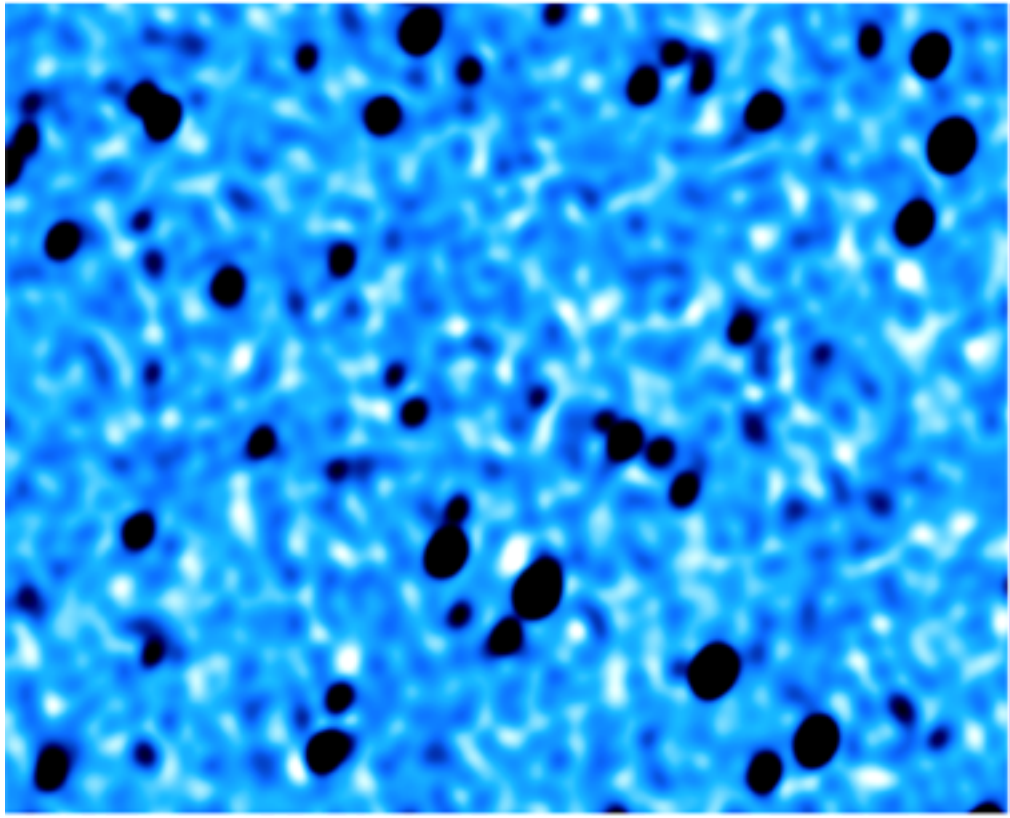




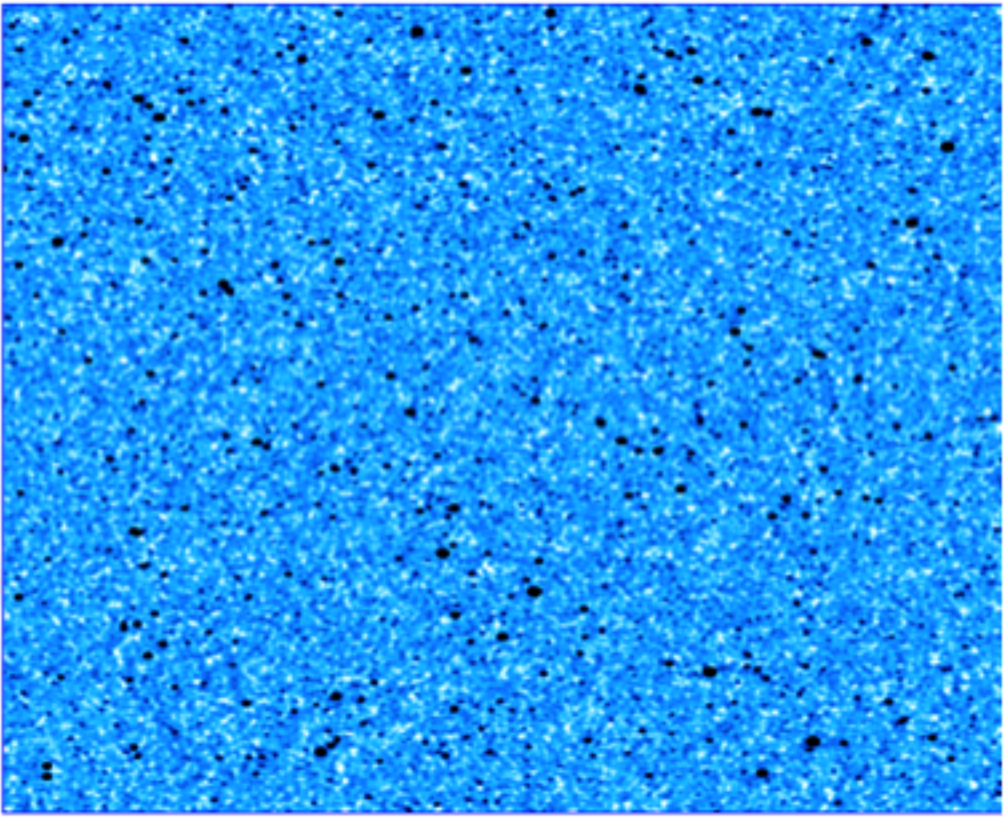
Other Methods

- **2D P(D) analysis**

- Fit 2D source count to 2D histogram
- Can be two frequencies, two resolutions, Stokes I and polarised intensity
- Provides tighter constraints, uses more data, breaks degeneracies



MWA PH 2 – 150 MHz – 55” beam –
400 microJy instrumental noise



ASKAP – 1.4 GHz – 10” beam –
10 microJy instrumental noise

Other Methods

- **2D P(D) analysis**

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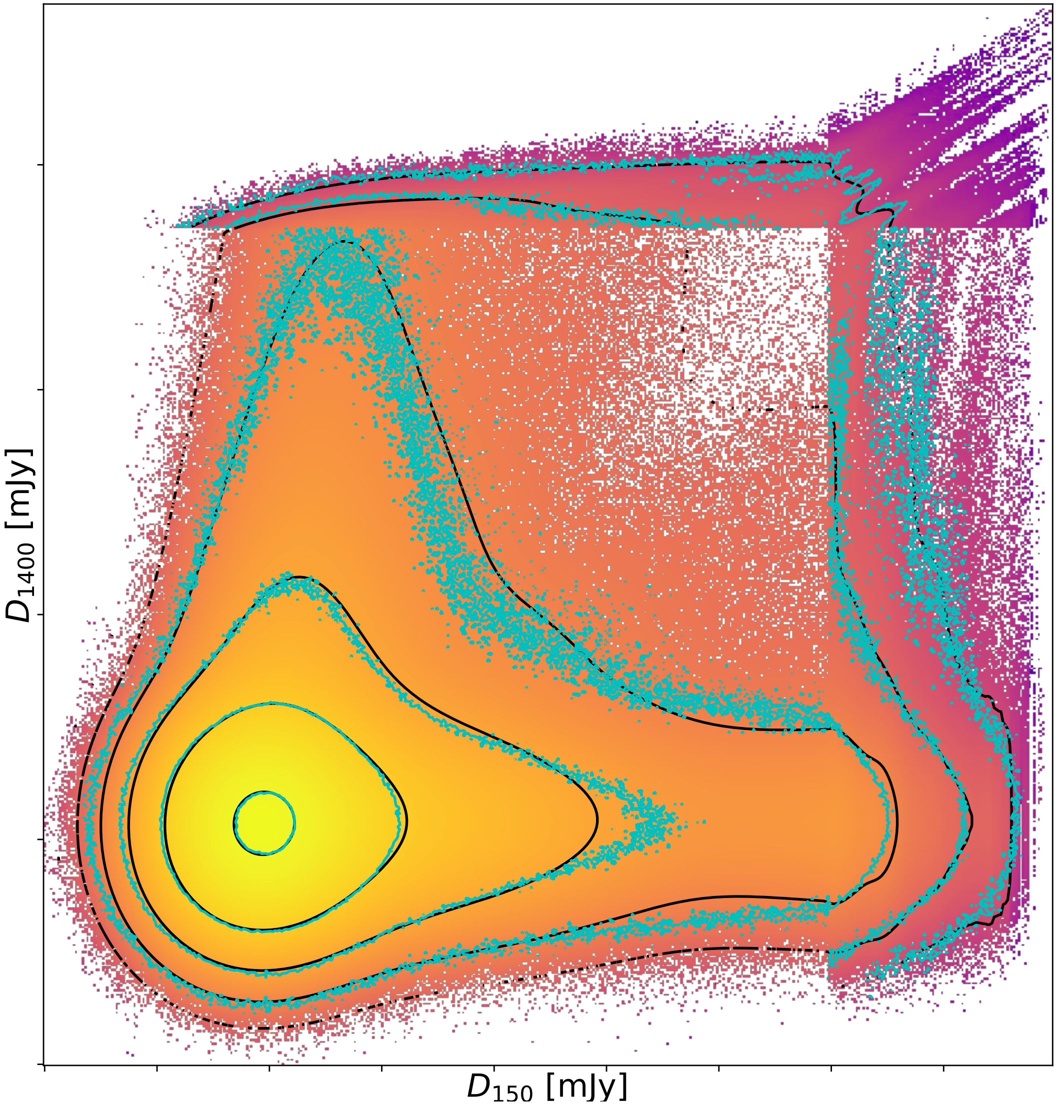
Two populations:

- AGN **α = -0.85**
- Star-forming **α = -0.55**

Two Frequencies:

- 150 MHz (MWA)
- 1400 MHz (ASKAP)



Cyan – Image P(D) Contours

Black Lines – Model P(D) Contours

Other Methods

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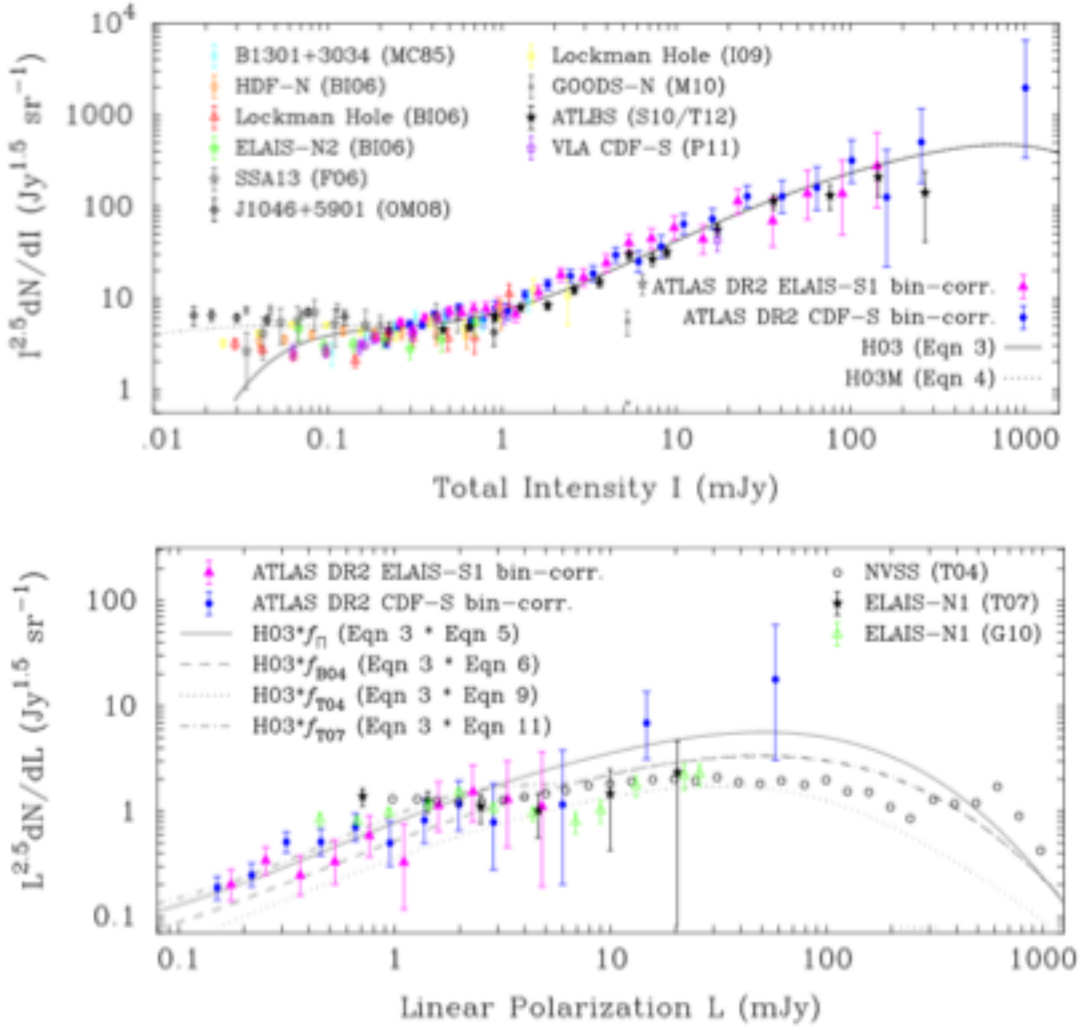

Not as deep or as constrained

Hales et al., 2014

Other Methods

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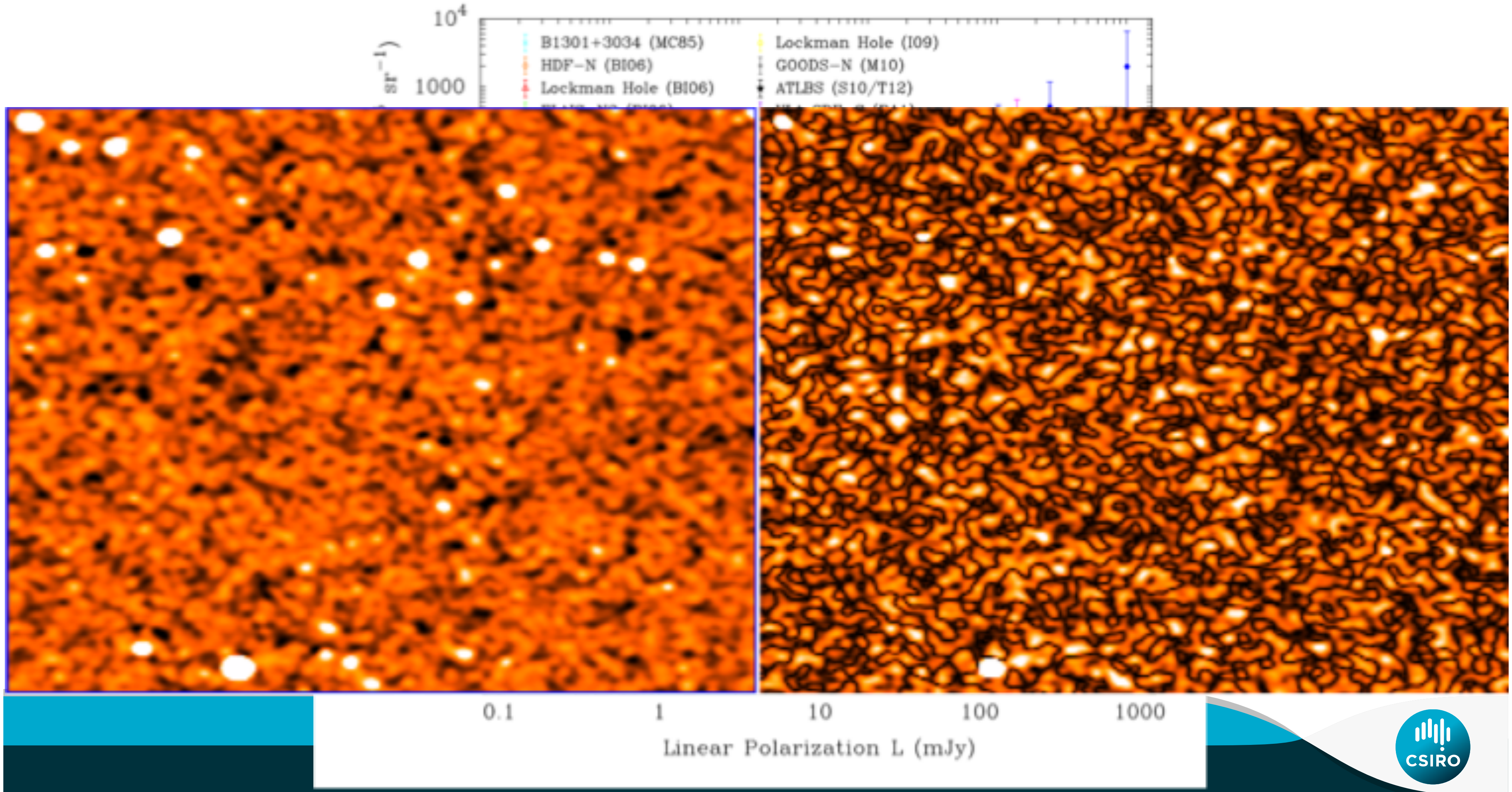

Other Methods

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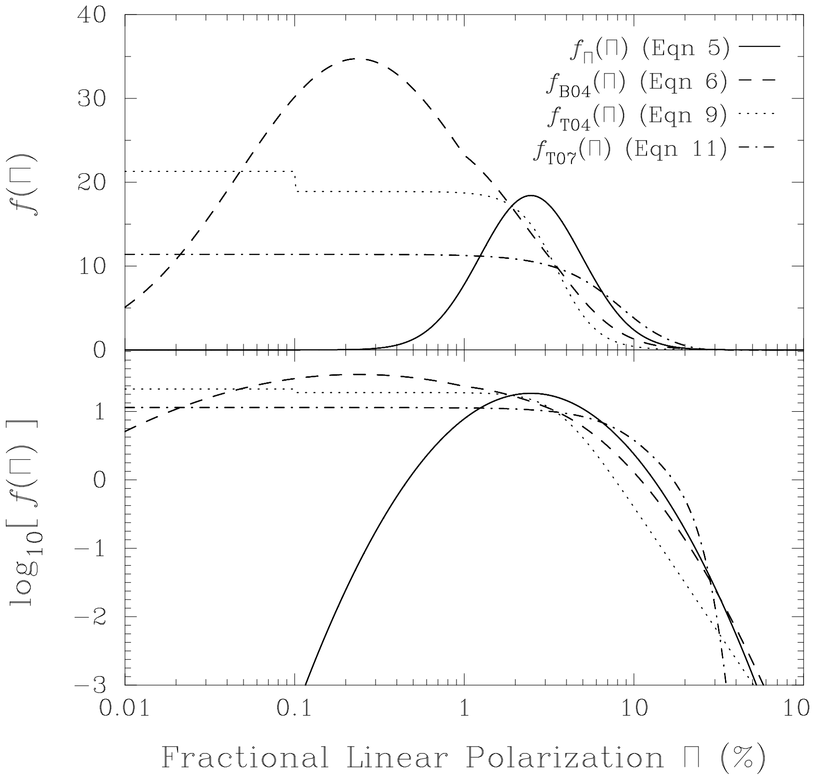
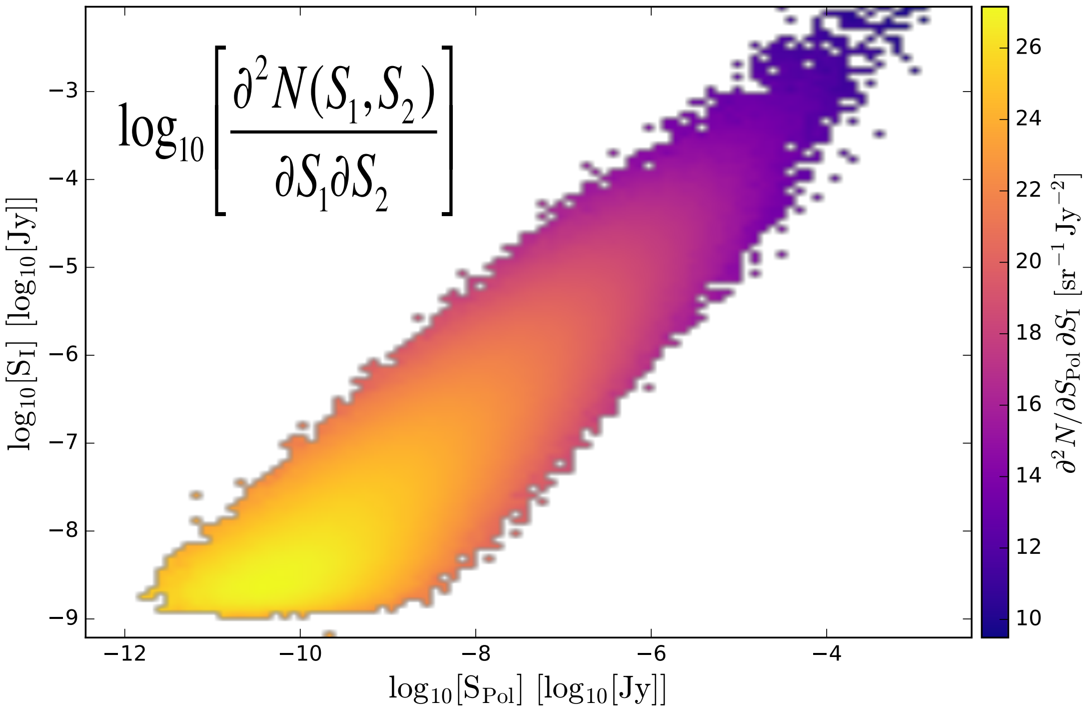
$$f_\Pi(\Pi) = \frac{1}{\Pi\sigma_{10}\ln(10)\sqrt{2\pi}}\exp\left\{\frac{-[\log_{10}(\Pi/\Pi_0)]^2}{2\sigma_{10}^2}\right\}$$





Other Methods

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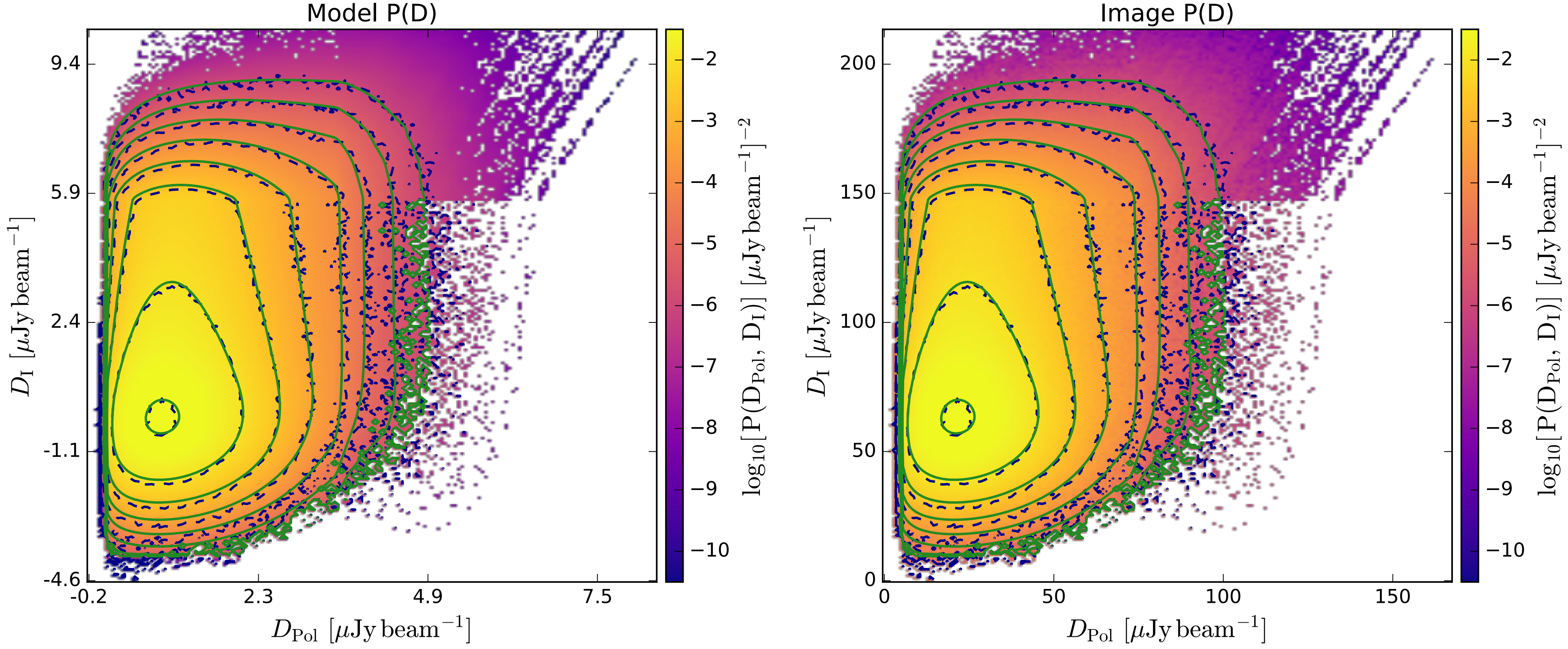

Other Methods

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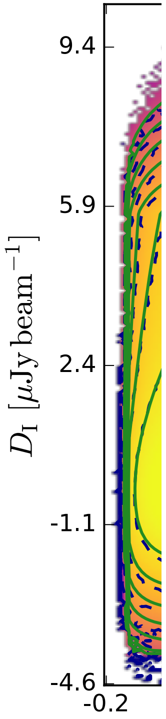
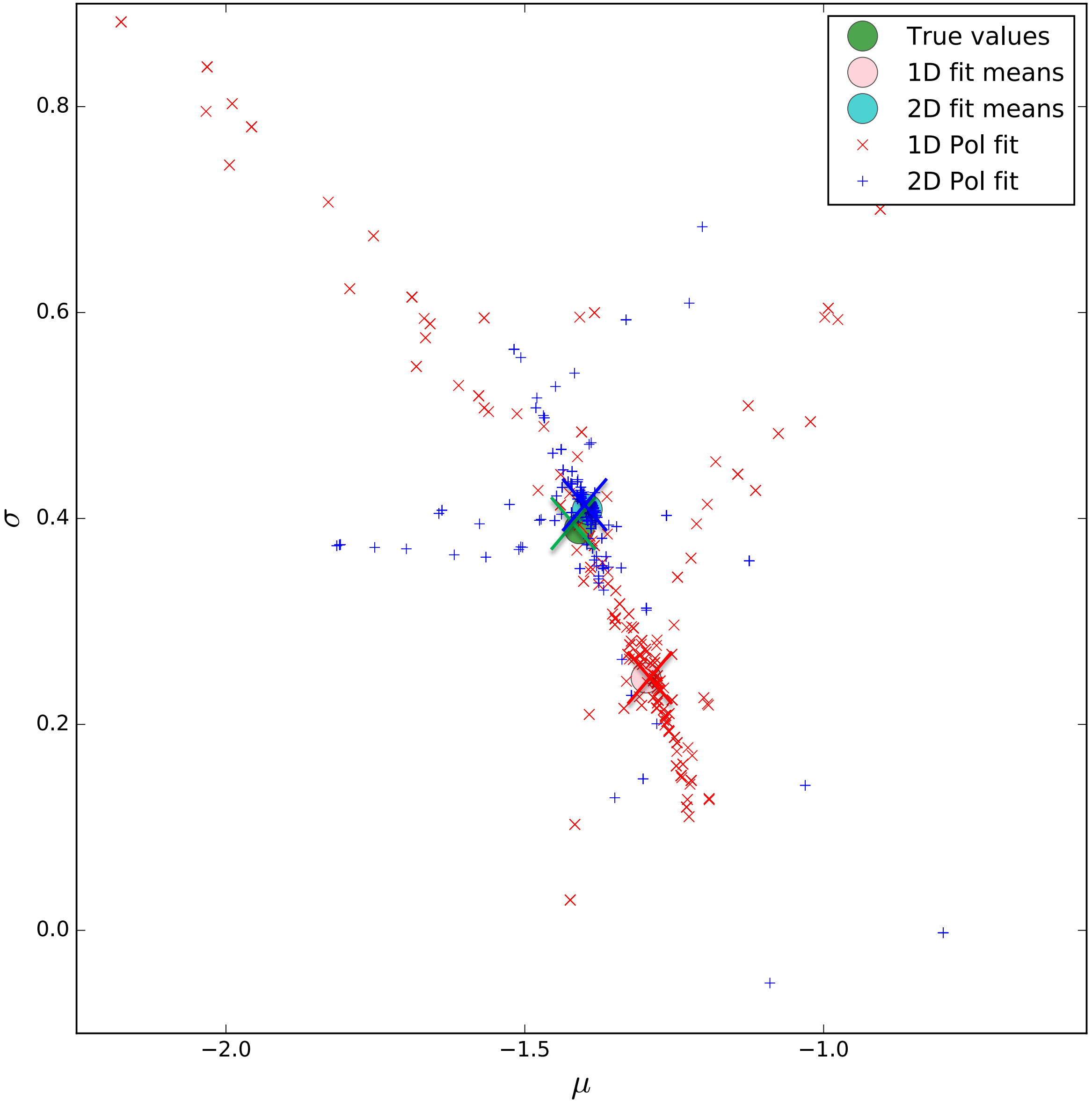
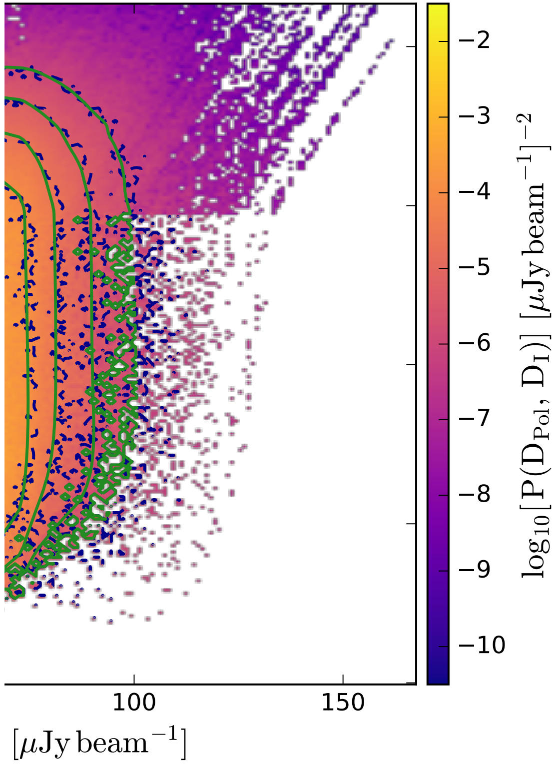
ata, breaks degeneracies

$$\exp\left\{\frac{-\left[\log_{10}(\Pi/\Pi_0)\right]^2}{2\sigma_{10}^2}\right\}$$

nage P(D)







Other Methods

- 2D P(D) analysis
- Stacking (point sources and diffuse/filaments)
- Radio to X-ray correlation
- Cross power spectrum
- Wavelet covariance
- 2D Angular power spectrum
- Combinations, e.g. confusion analysis + cross correlation

Summary & Conclusions

- Confusion can be a hindrance or a tool
  - Can use it to get constraints on counts below confusion and instrumental noise limits
  - Excess diffuse emission can be detected via confusion analysis
  - Can be extended to multiple dimensions

- Cross correlation technique can enhance signals below the noise
  - Need more / better models to interpret results

- Need to understand noise and beams well

- Statistical techniques can be powerful tools for reaching below the noise

- Understanding current and developing new techniques crucial for fully utilizing new large surveys

Thank you

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