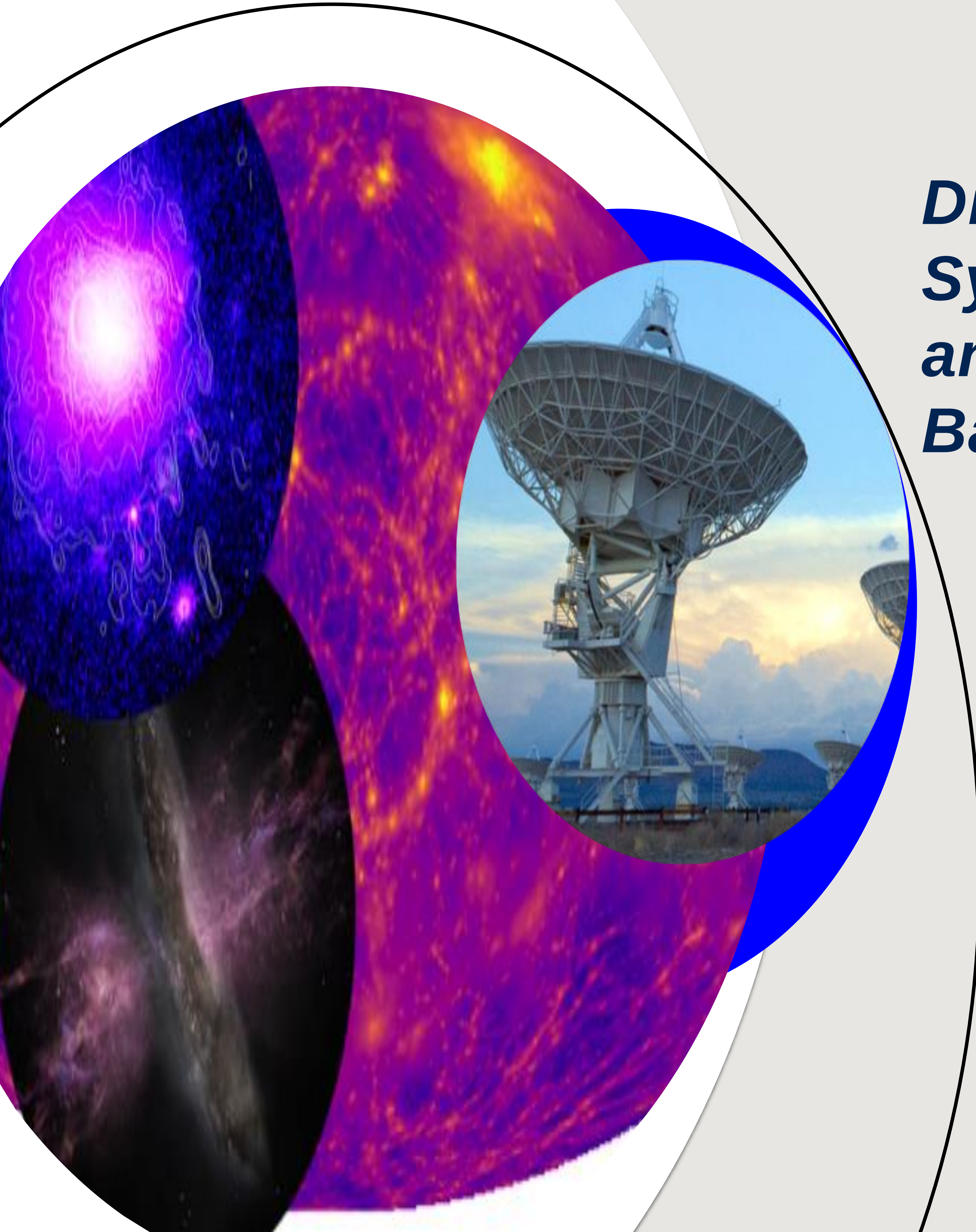

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Diffuse Extragalactic Synchrotron Emission and the Radio Background

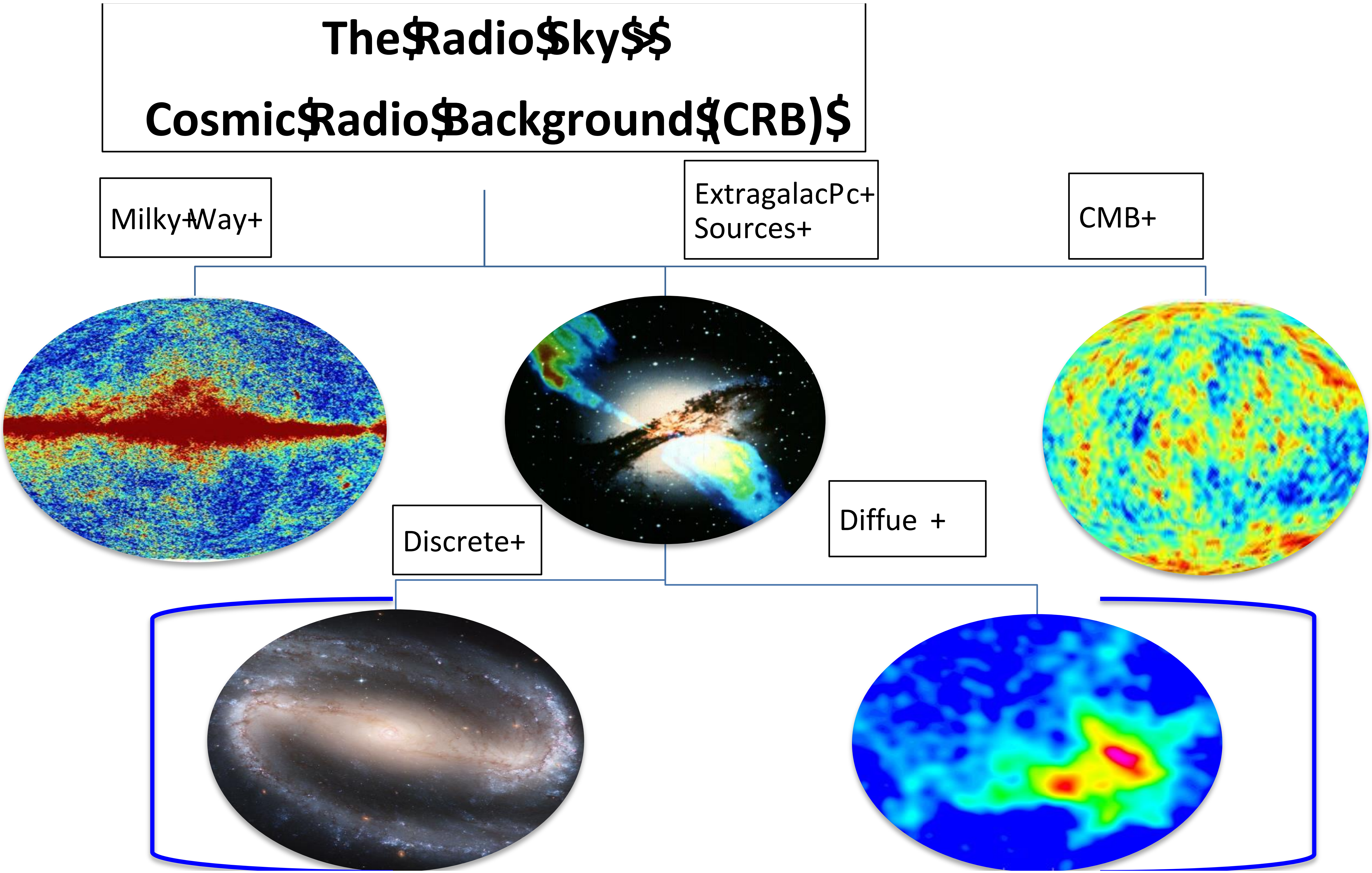
Tessa Vernstrom

Richmond, VA 2017

Collaborators: Bryan Gaensler, Ray Norris, Douglas Scott, Jasper Wall

Dunlap Institute for
Astronomy & Astrophysics
UNIVERSITY OF TORONTO

The Cosmic Radio Background

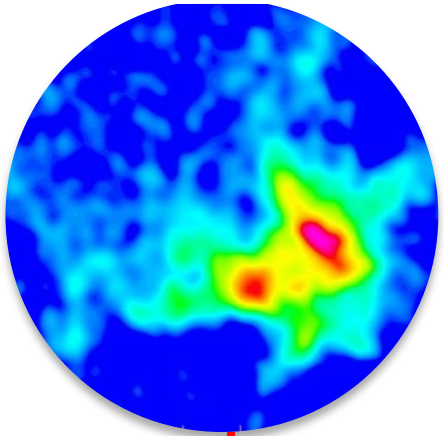


The Cosmic Radio Background

Discrete+

Point source emission:

- Starburst/star-forming galaxies
- Active Galactic Nuclei (AGN)
- Other: spirals, ellipticals, etc.



Diffue +

Low surface brightness emission:

- Galactic Halos
  - Starbursts
  - AGN
- Cluster Emission
  - Giant/mini radio halos
  - Radio relics
  - Intra-cluster medium
- Cosmic web/Large Scale Structure

The Cosmic Radio Background – Why Study It?

The basics:

- **How much radio emission is there?**
- **Where is it coming from?**
    - **Individual galaxies, clusters, filaments …?**
- **How many of these types of sources are there? How bright are they?**
- **How clustered is the emission? In total and at different times?**

These answers can then be used to investigate:

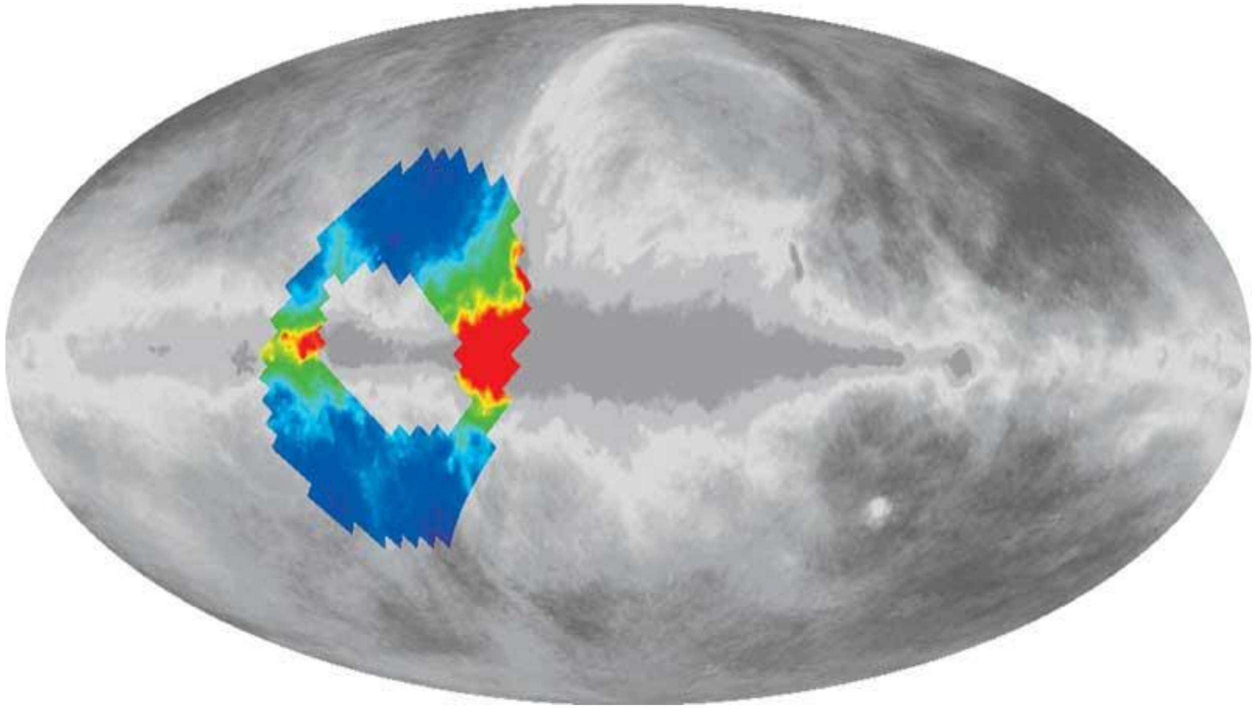
- **Cosmic magnetism**
- **Galaxy evolution**
- **Large scale structure formation and evolution**
- **Other (e.g. dark matter)**

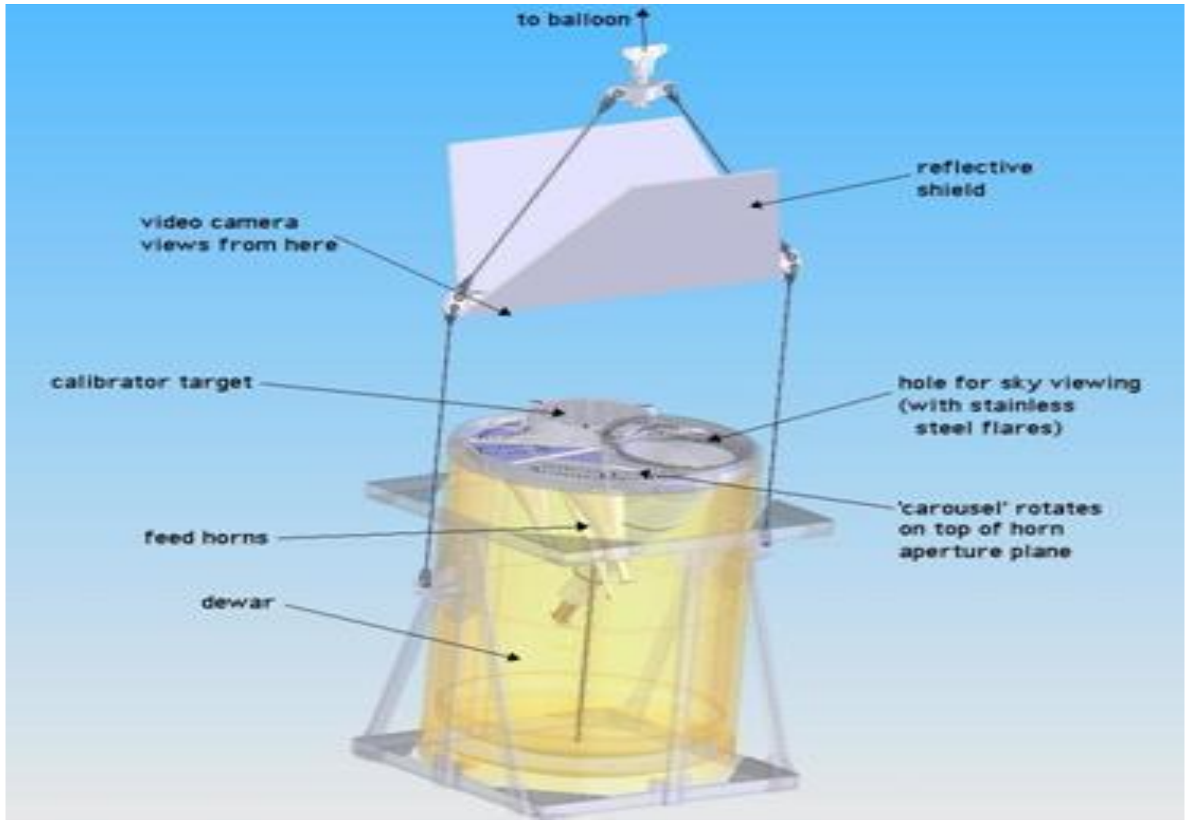
ARCADE 2

- **Balloon experiment measuring absolute temperature at multiple frequencies (Fixsen et. al, 2009)**
- **Reported value of T_b = 55 mk at 3.3 GHz**

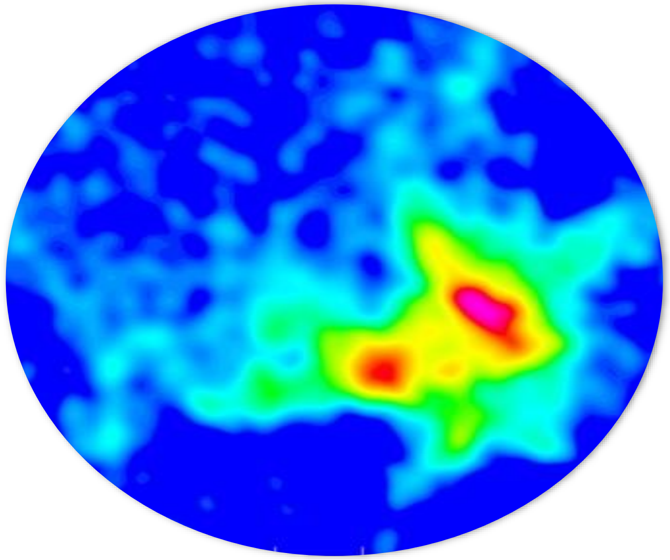
→much higher than estimates for extragalactic component

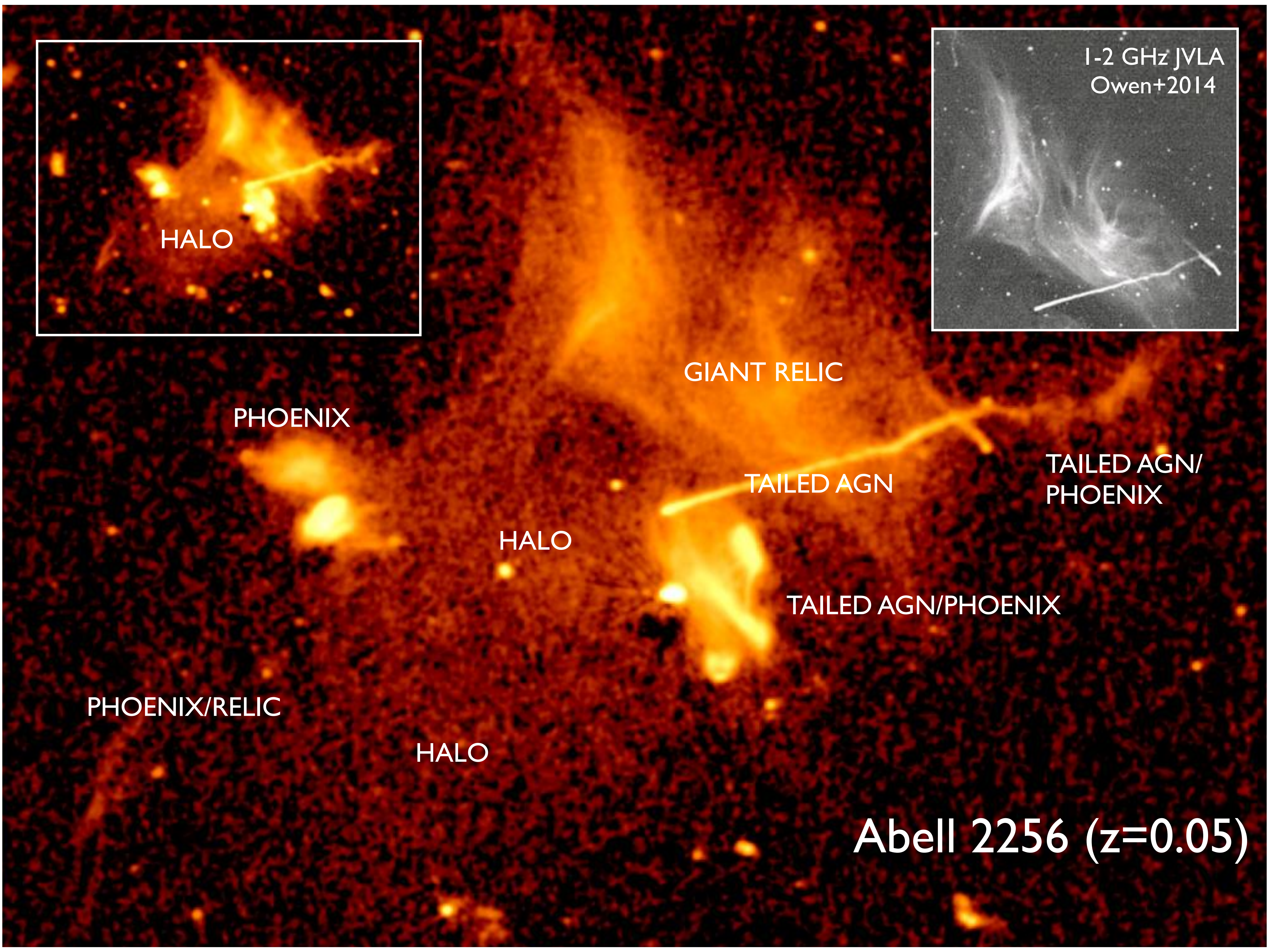
- **What could be causing the discrepancy?**
  - **New faint source population in sub-microJy region**
  - **Diffuse emission in clusters or the cosmic web**
  - **Dark matter annihilation in galactic haloes**
  - **FRBs**
  - **??**





Diffuse Emission
Clusters

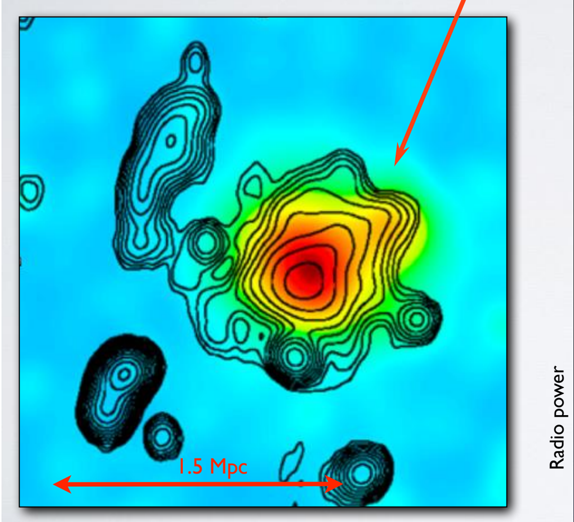



HALO
1-2 GHz JVLA
Owen+2014
GIANT RELIC
PHOENIX
TAILED AGN
TAILED AGN/
PHOENIX
HALO
TAILED AGN/PHOENIX
PHOENIX/RELIC
HALO
Abell 2256 (z=0.05)

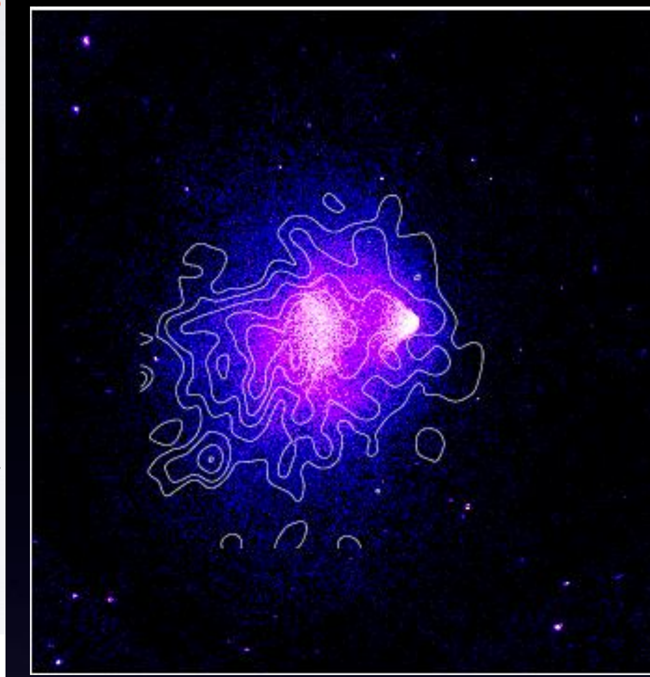
Radio Halos

- Giant and mini halos
- Mpc sizes, centrally located
- Unpolarized
- $L_{1.4\ GHz} \sim 10^{24} - 10^{25}$ W/Hz
  - Radio luminosity scales with cluster mass
- Found in disturbed clusters
- Diffuse, low surface brightness
- Steep spectrum $\alpha \sim -1.2$
  - Can have curved spectra
  - Steepening with radial distance
- Morphology similar to X-ray or SZ emission
  - No severe projection bias

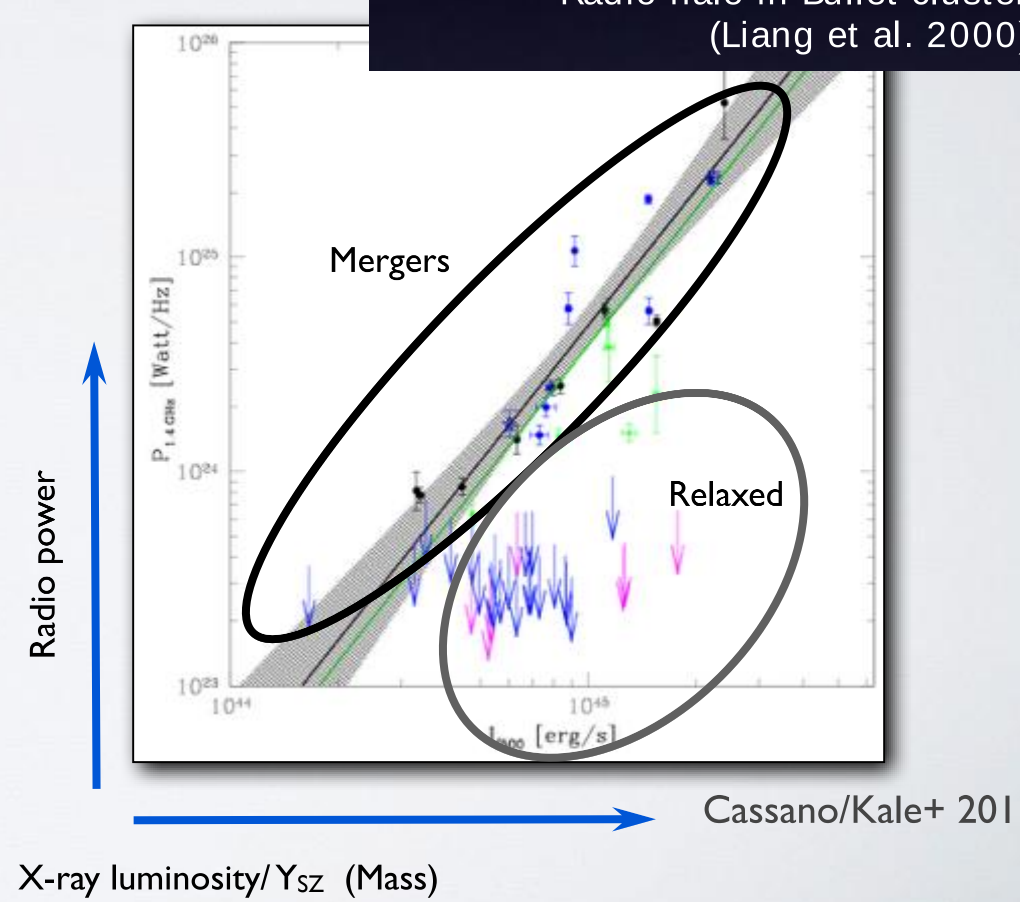
- Particle acceleration mechanisms:
  - Turbulent reacceleration
  - Secondary electrons: products of hadronic collisions



Abell 2744: Feretti+ 2012; Govoni+ 2001



Radio halo in Bullet cluster (Liang et al. 2000)



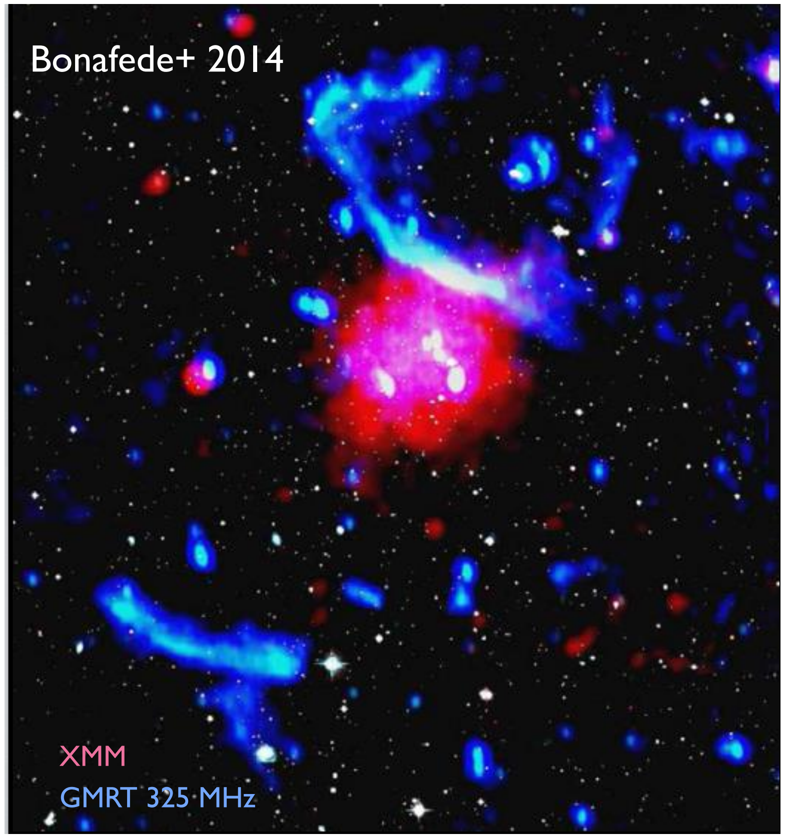
Cassano/Kale+ 2013

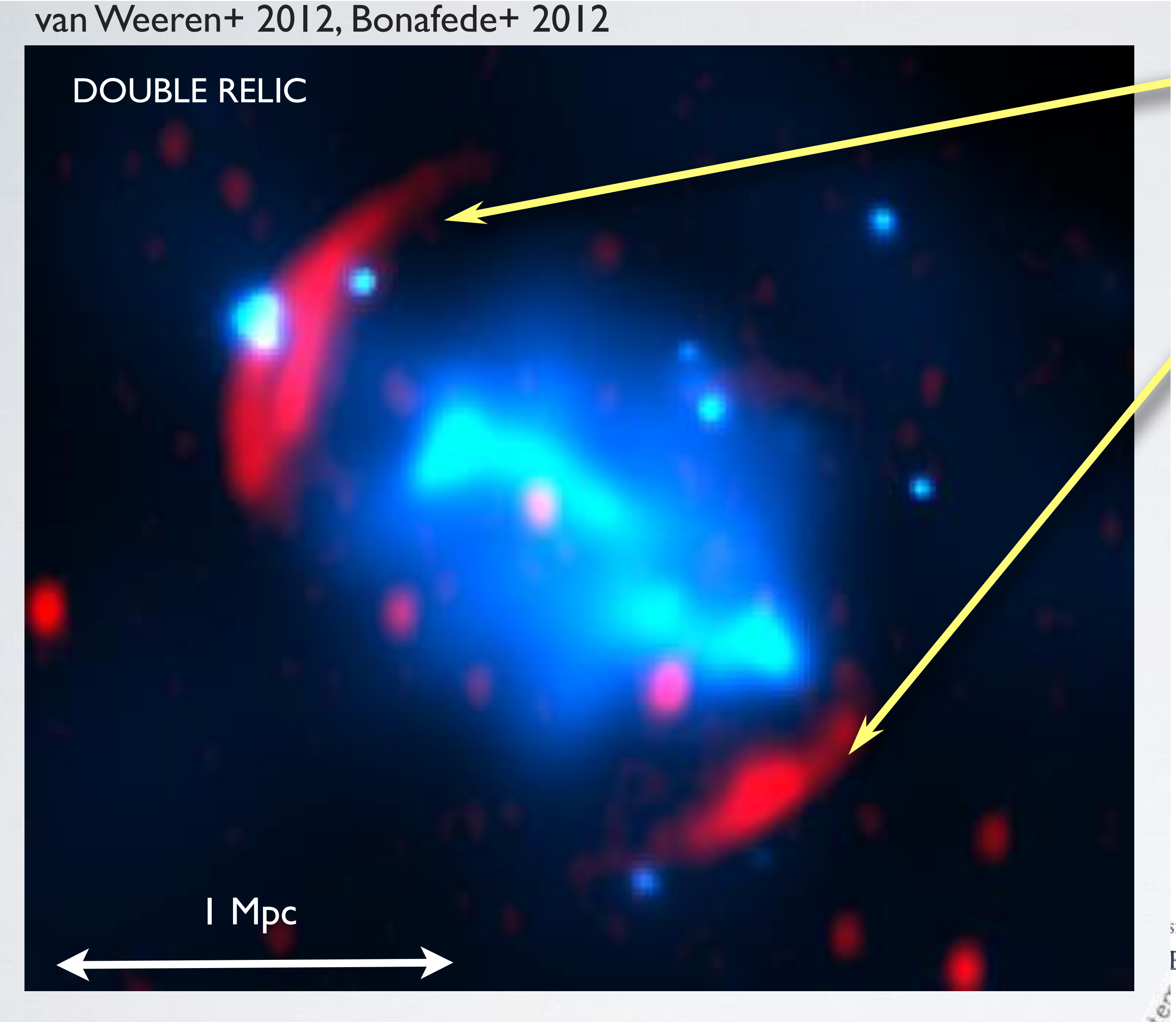
A521; Brunetti+ 2008; Dallacasa+2009

Radio Relics

- **Elongated or filamentary morphology**
- **Near cluster periphery**
- **Higher surface brightness**
- **Polarized**
- **$L_{1.4\ GHz} \sim 10^{23} - 10^{25}$ W/Hz**
- **Also steep spectrum $\alpha \sim -1.2$**
- **Traces shocks**
  - **Subject to projection bias**

- **Particle acceleration mechanisms:**
  - **Diffusive shock acceleration**
  - **Shock re-acceleration**
  - **Adiabatic compression**

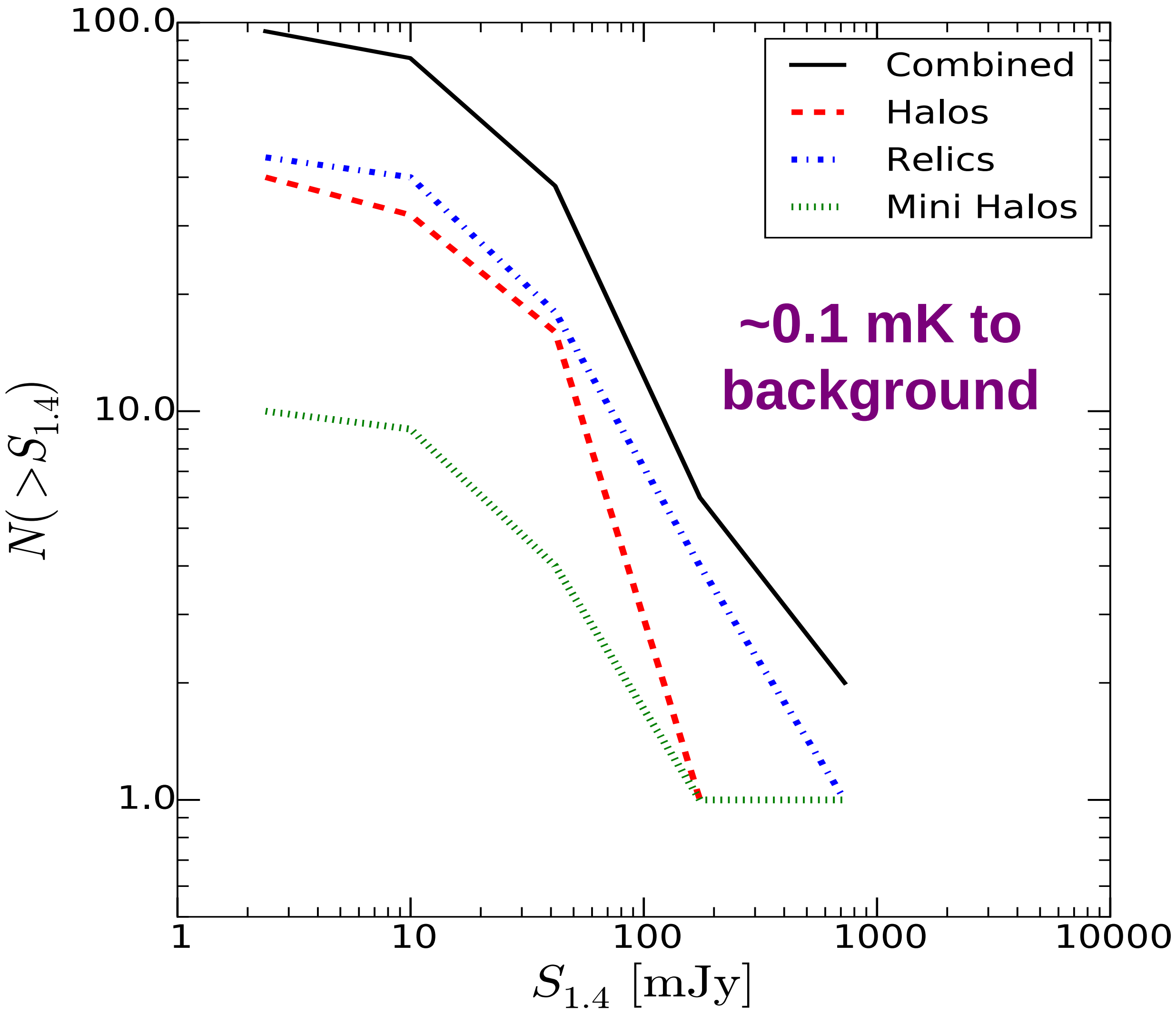


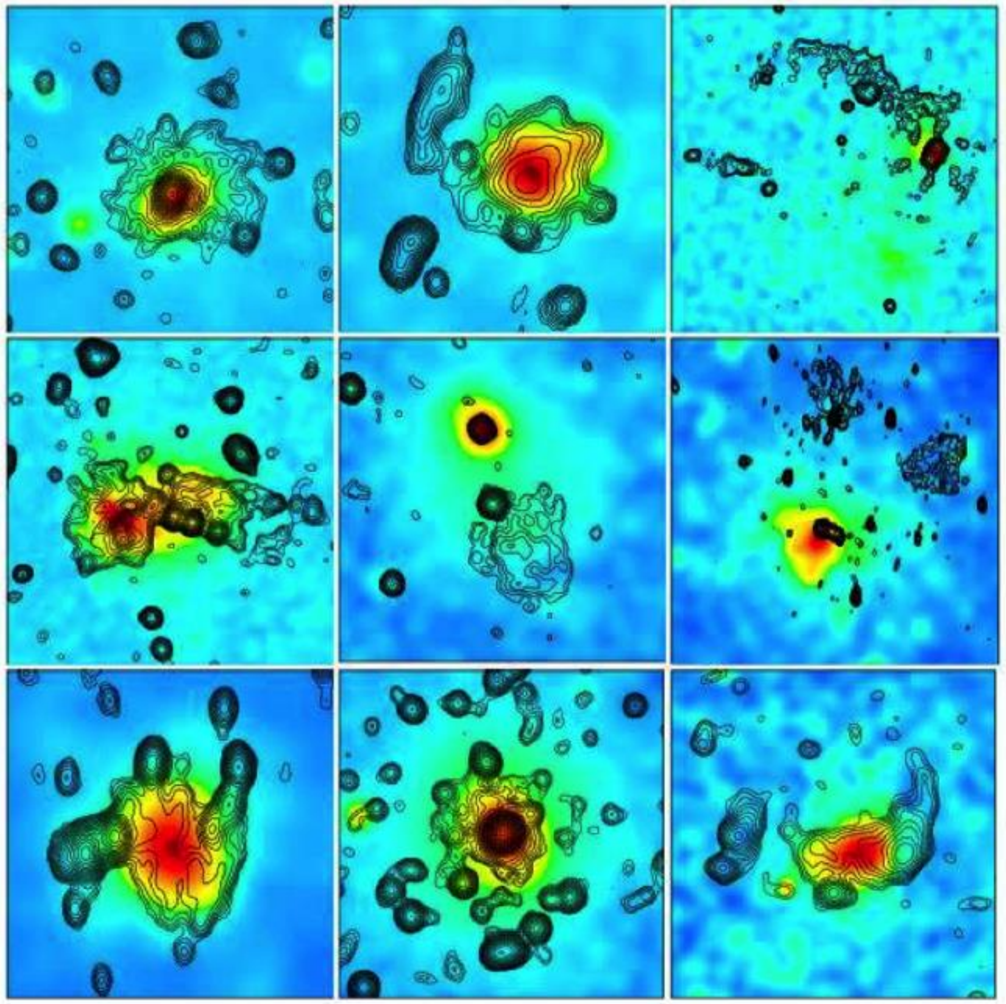


Double Relics

Diffuse Emission

- **Diffuse emission in clusters**
  - **Halos**
  - **Mini-halos**
  - **Relics**
  - **But only ~100-150 detected (more coming now from low frequency surveys)**
- **Only bright sources (>1mJy) in high(er) mass clusters detected.**





Ferretti et al., 2012

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Diffuse Emission

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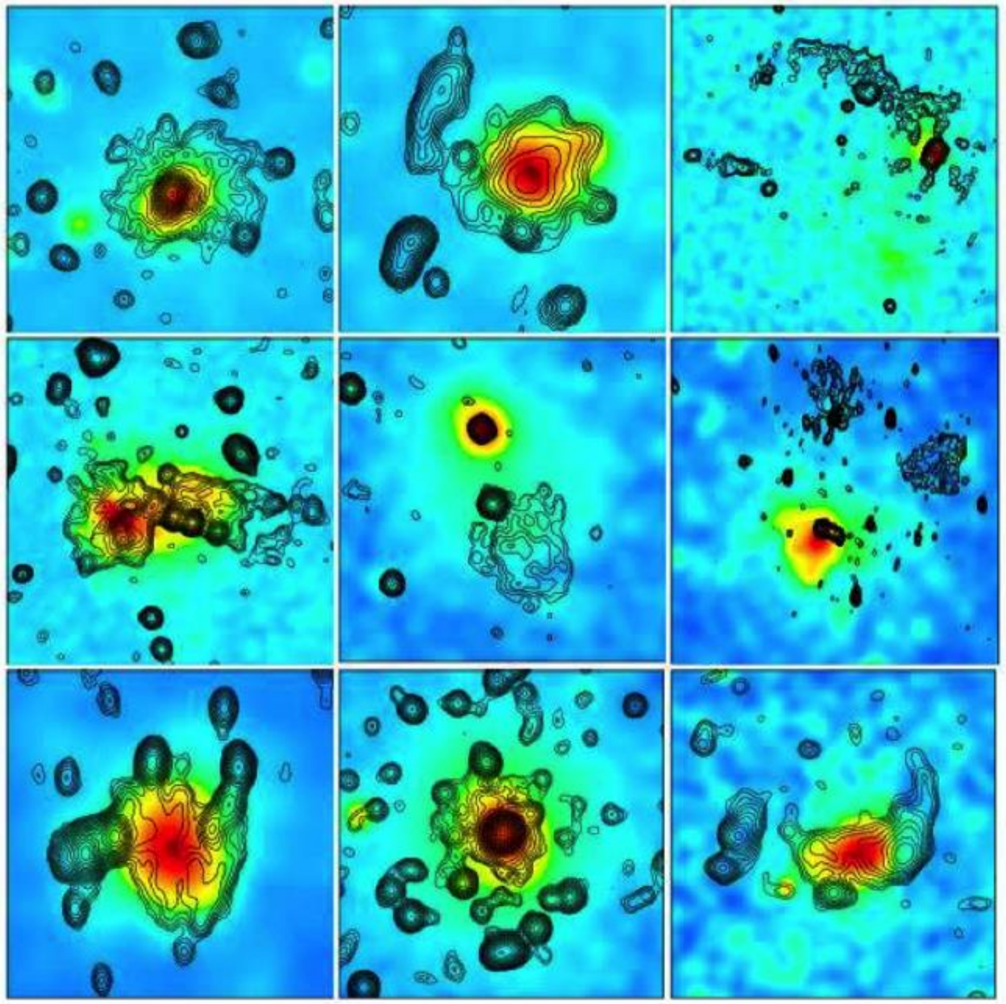
  - **Mini-halos**
  - **Relics**
  - **But only ~100-150 detected (more coming now from low frequency surveys)**

- **Only bright sources (>1mJy) in high(er) mass clusters detected.**

- **Difficult to directly detect due to:**
  - **low surface brightness**
  - **Requires high sensitivity to large angul scales**
    - **Sizes up to Mpc scales**
    - **Difficult for radio interferomet**
  - **Bright Galactic foregrounds**
  - **Bright point sources**
  - **Faint point source confusion**



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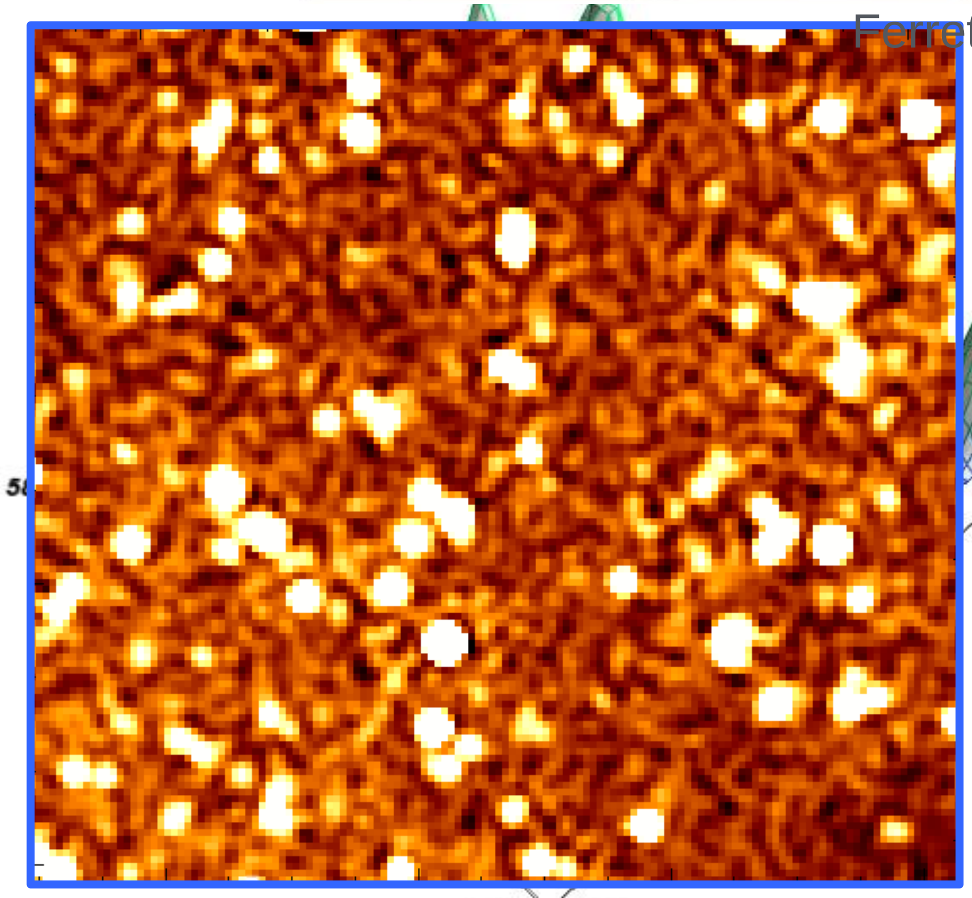
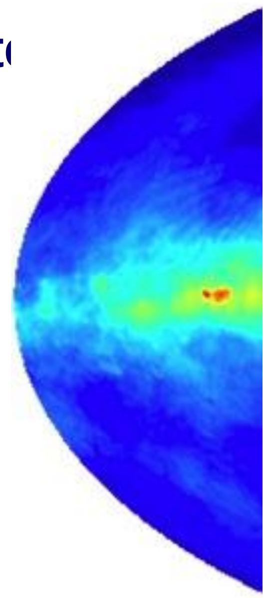
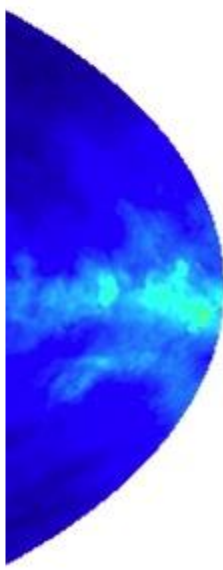
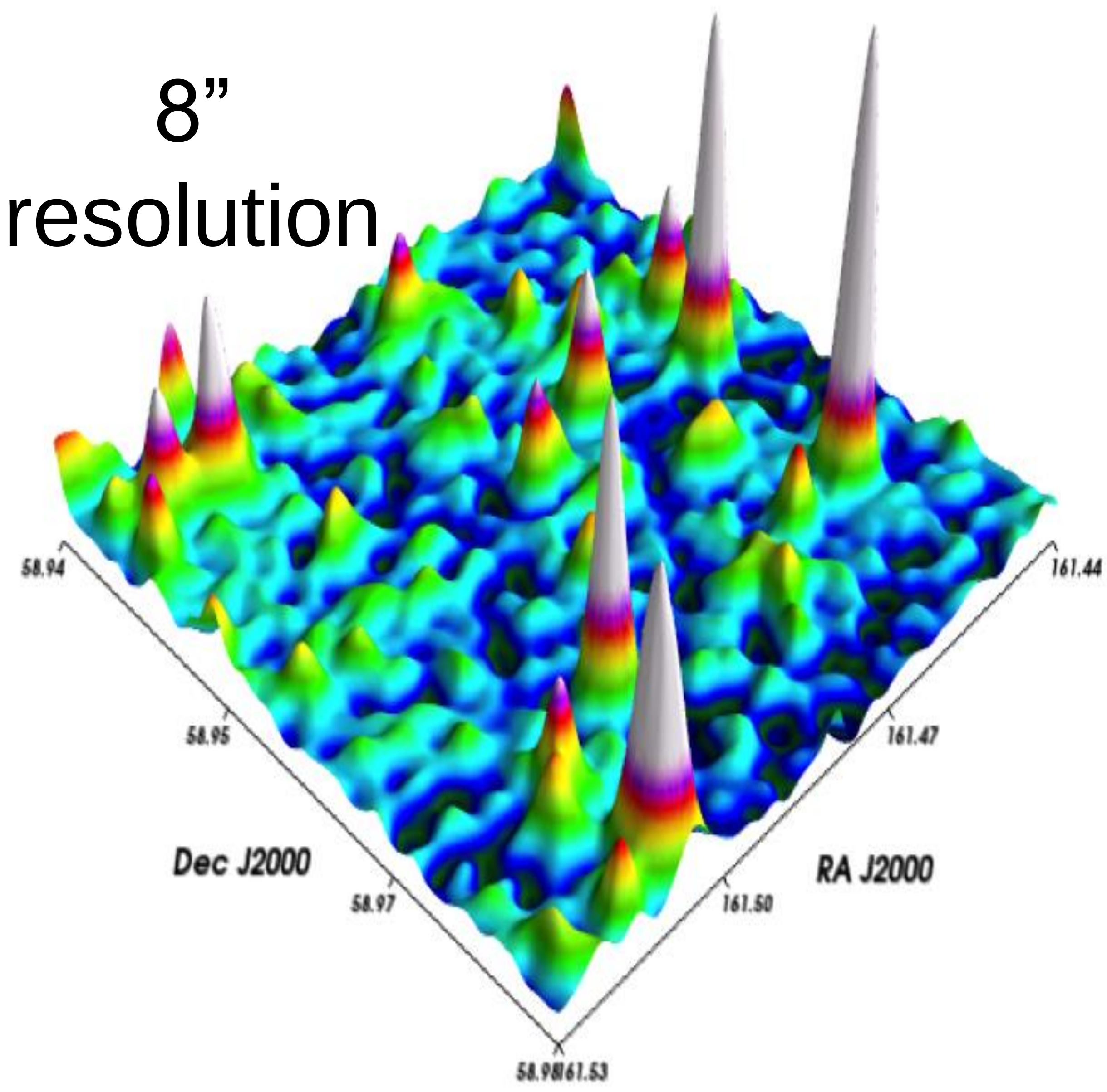


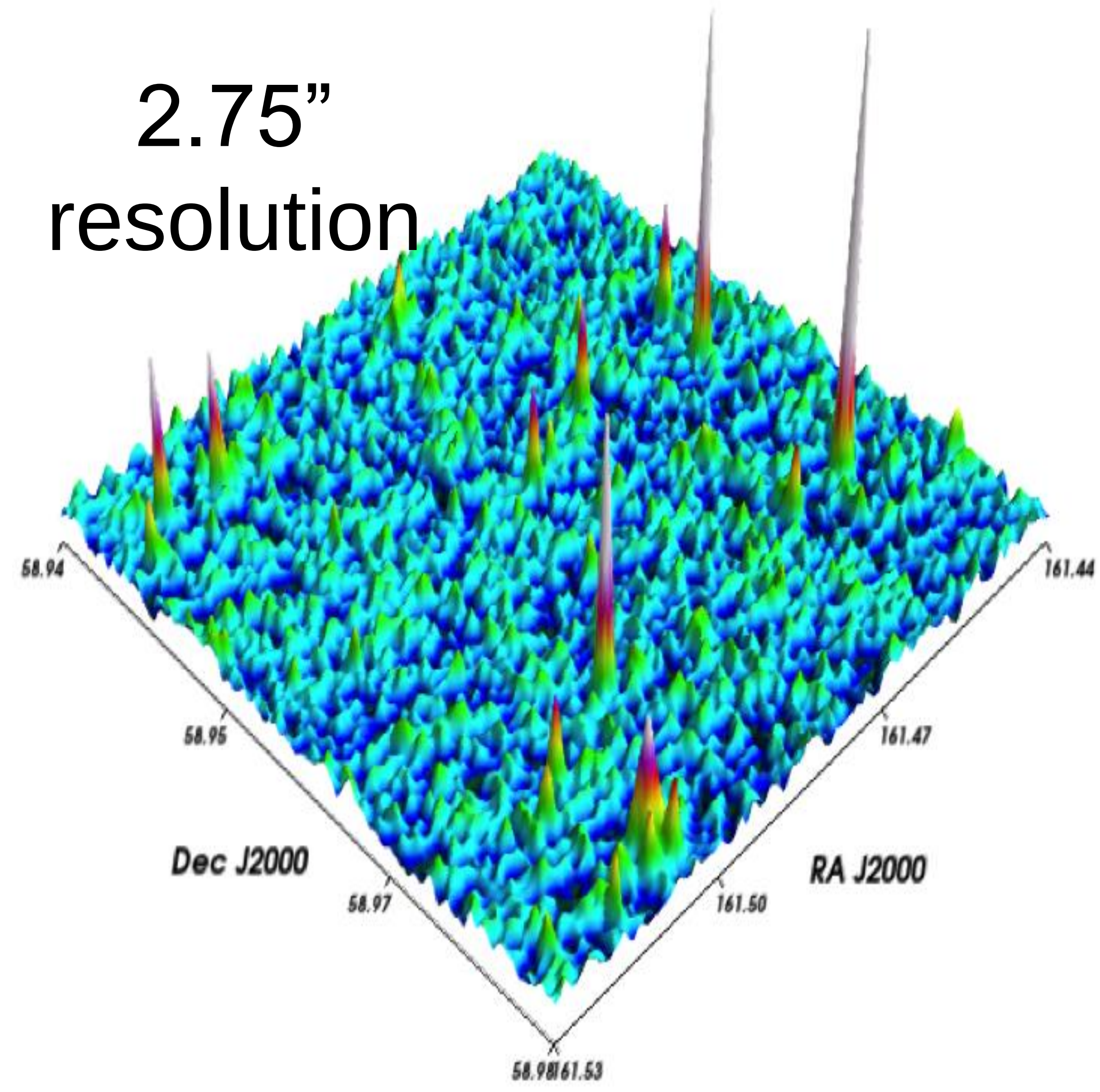




What is Confusion?

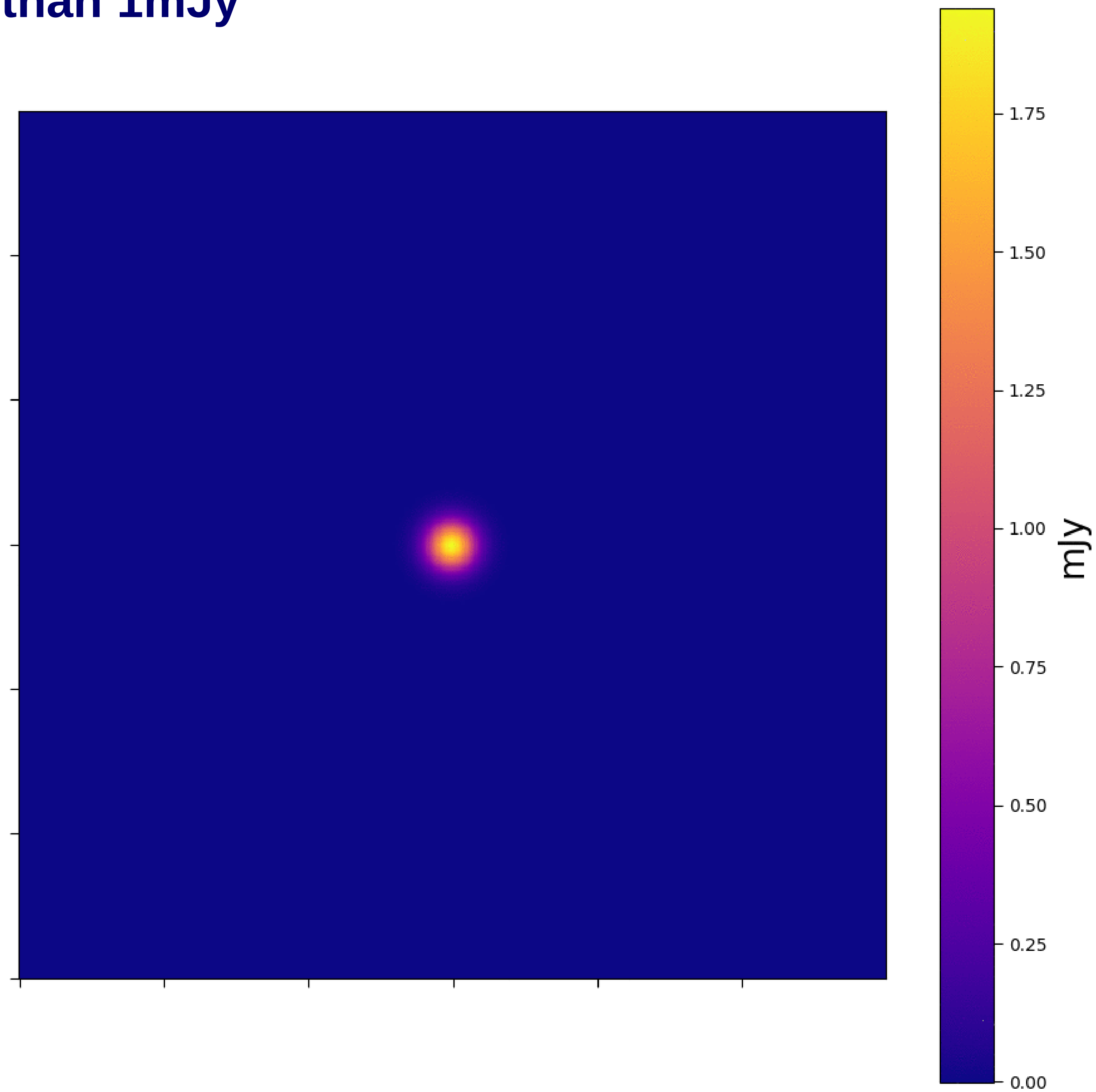
- **Confusion is the blending of faint sources within a telescope beam**





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**

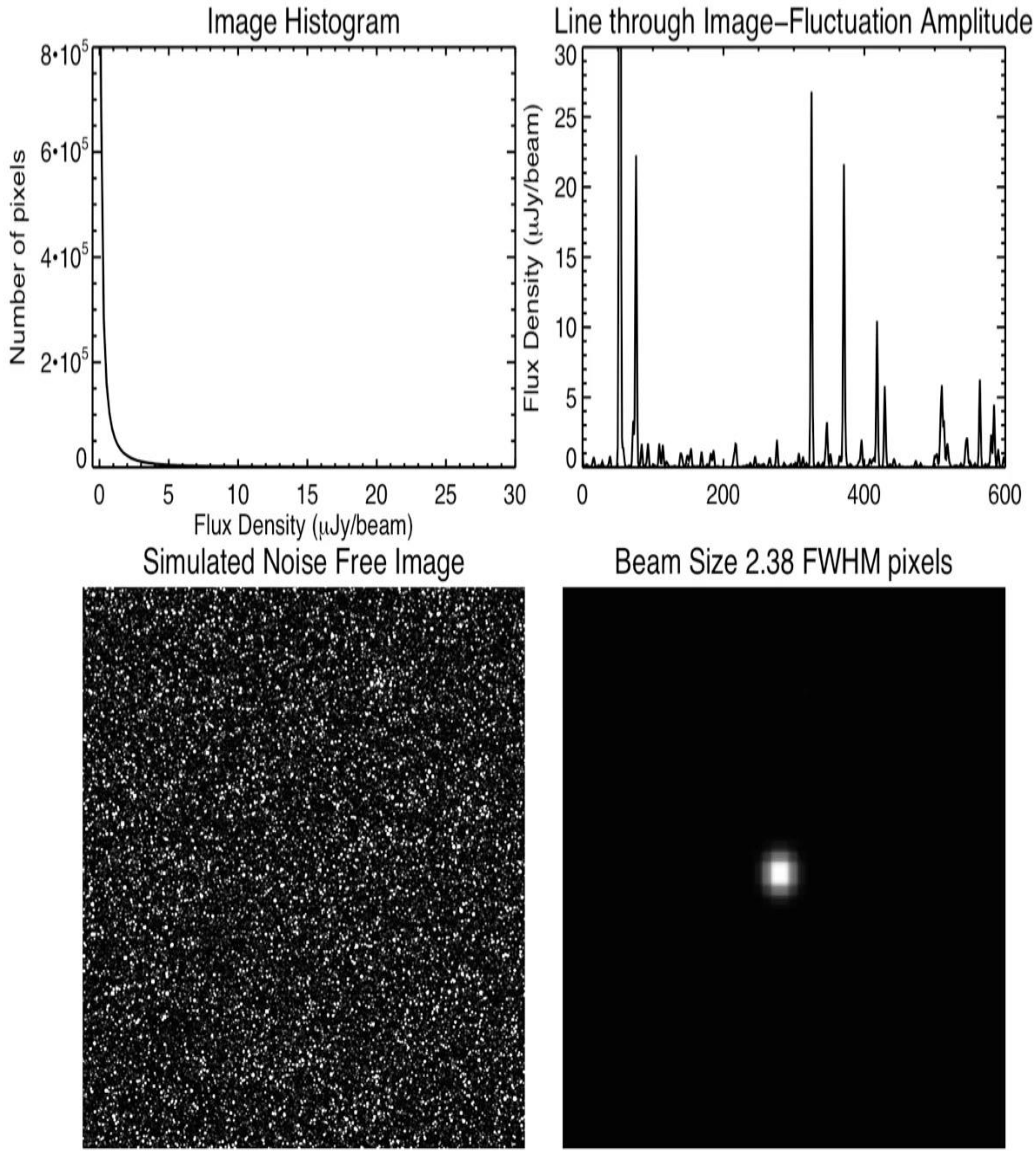


Confusion Analysis

- **Confusion is the blending of faint sources within a telescope beam**

- **PDF of image pixel histogram from confusion known as P(D)**

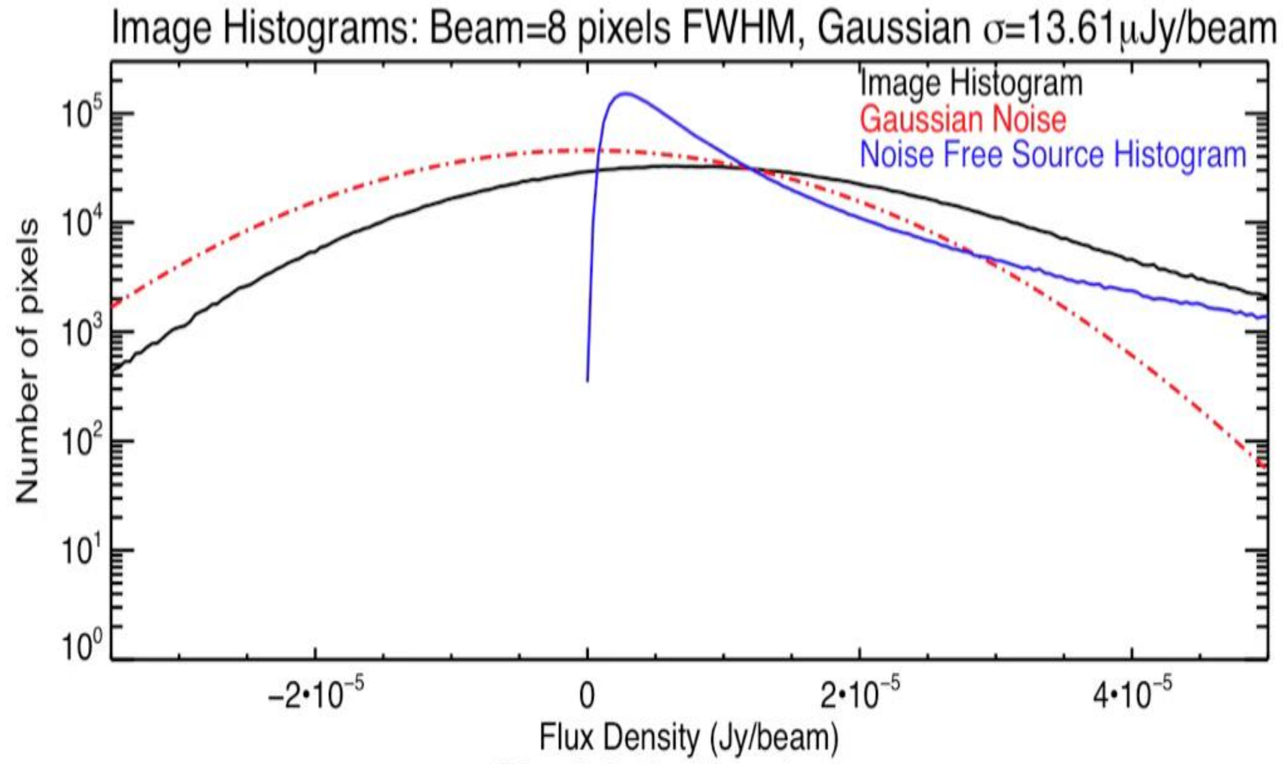
- **Confusion noise, σ_c (width of P(D))**
  → governed by beam and source count

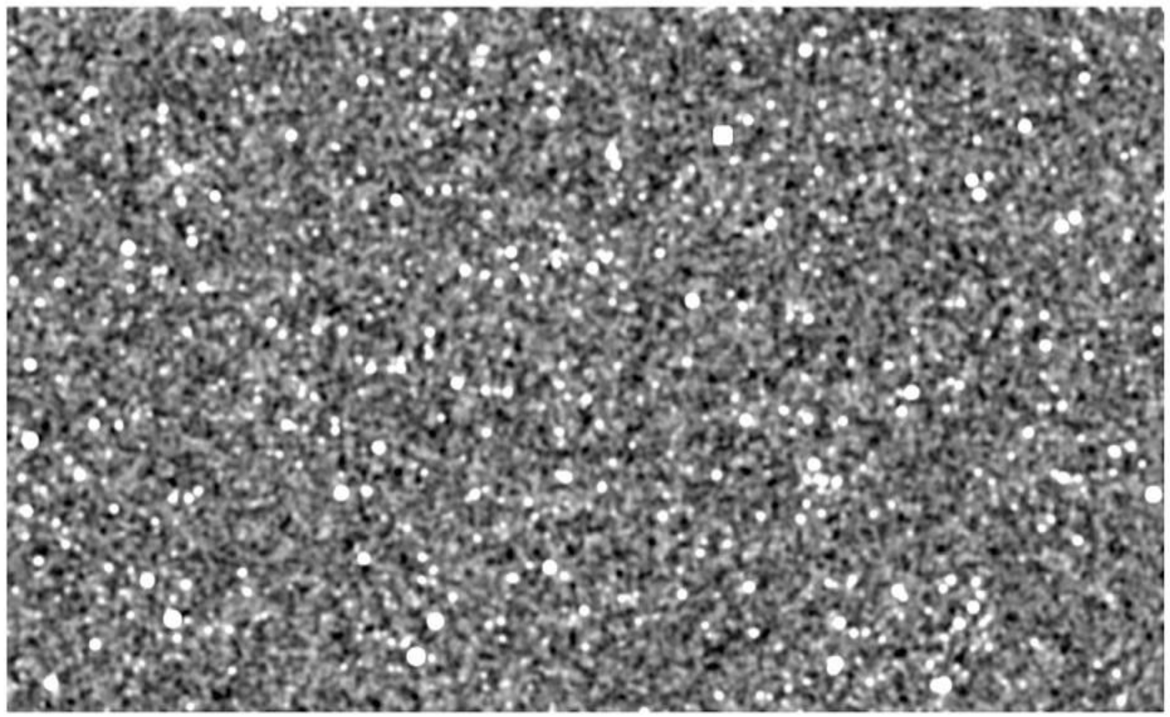


Why Confusion Limited?

$\sigma_t^2 = \sigma_n^2 + \sigma_c^2$

For faint counts want $\sigma_c > \sigma_n$





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**
  - **Instrumental noise**

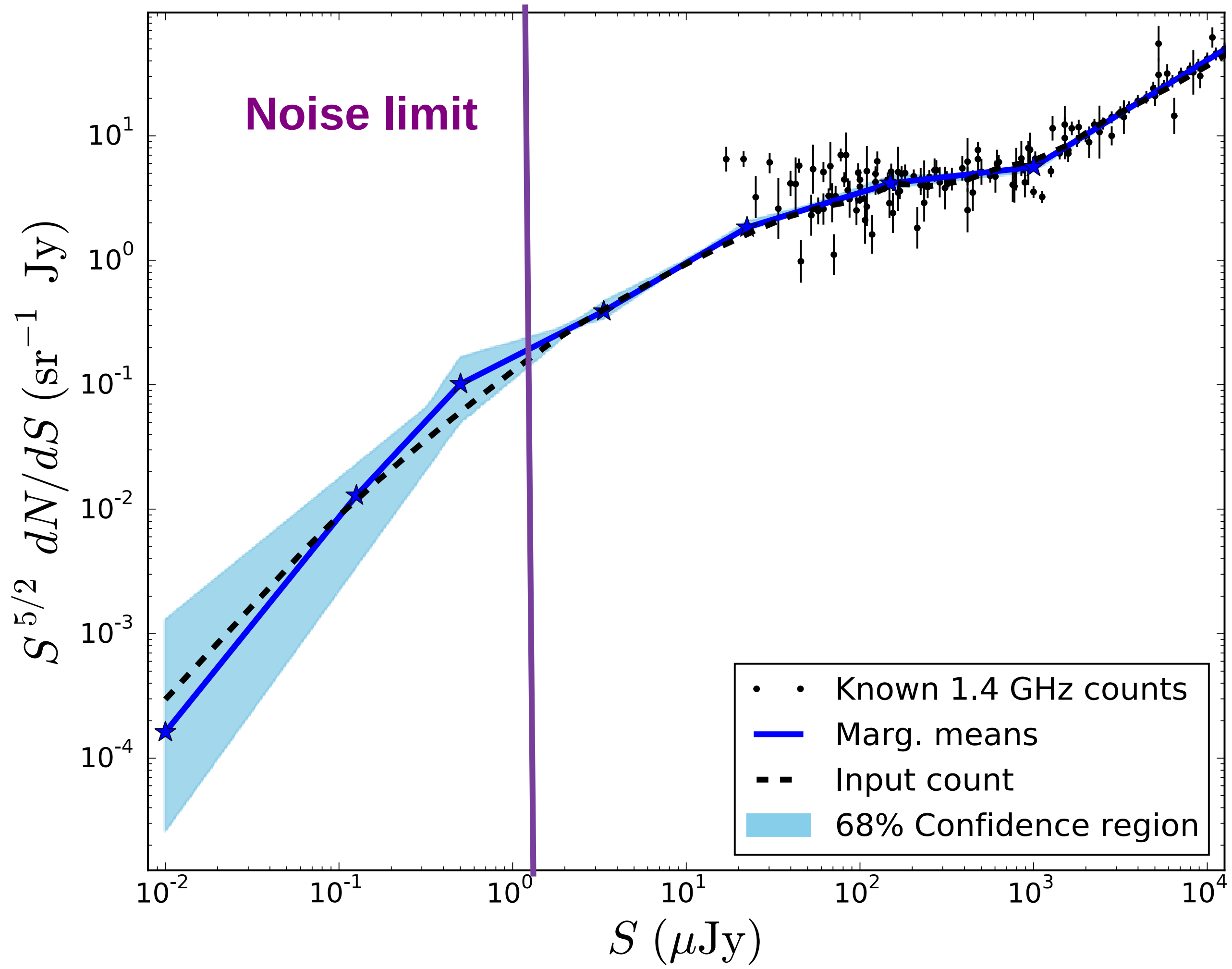
- **Mean density of observed flux**

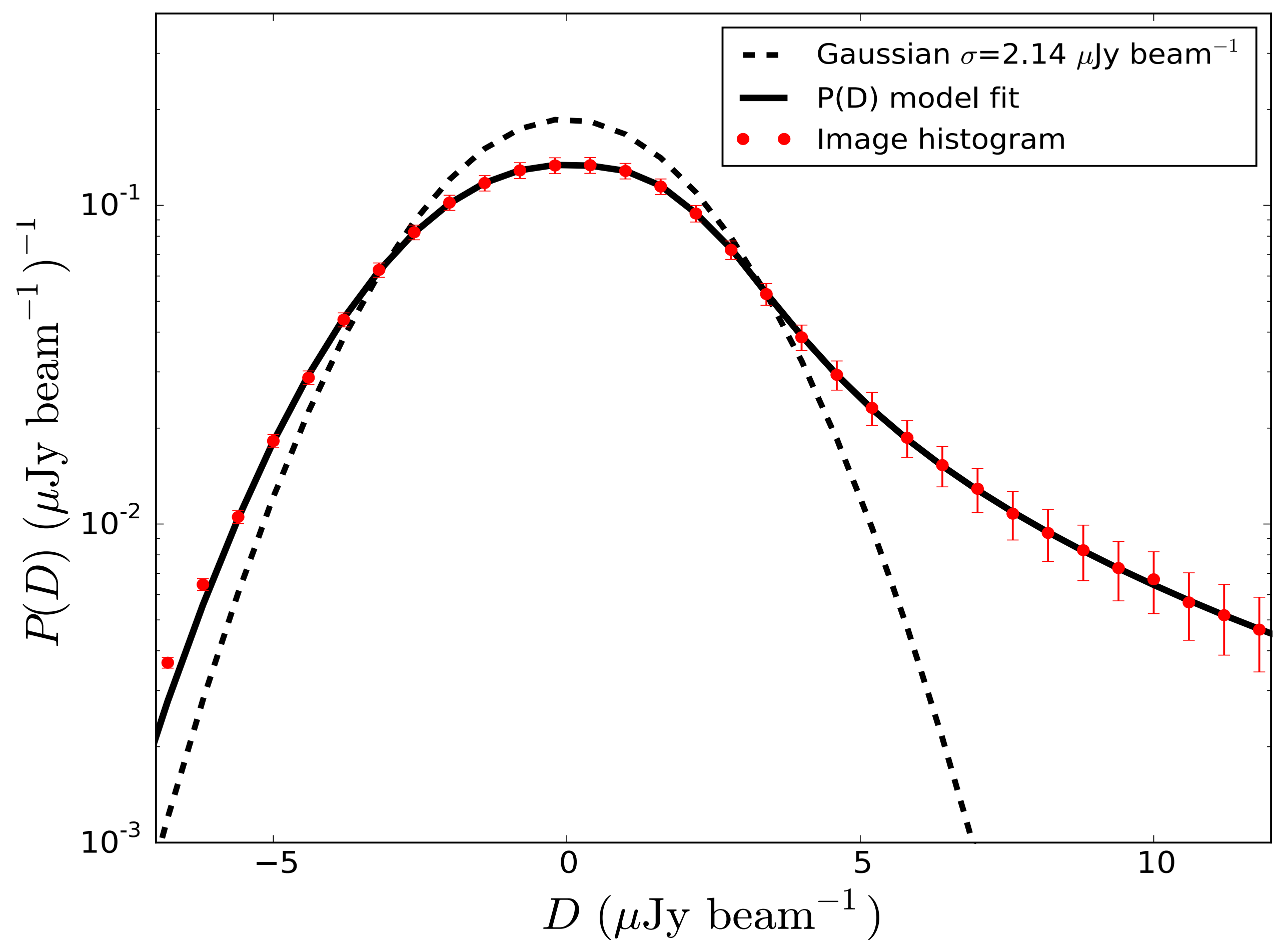
$$R(x)\,dx = \int_\Omega \frac{dN}{dS}\left(\frac{x}{b}\right) b^{-1}\, d\Omega\, dx$$

$$P(D) = \mathcal{F}^{-1}\left[\exp\left(\int_0^\infty R(x)\,e^{i\omega x}\,\mathrm{d}x - \int_0^\infty R(x)\,\mathrm{d}x - i\mu\omega - \frac{\sigma_\mathrm{n}^2}{2}\omega^2\right)\right]$$

- **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**





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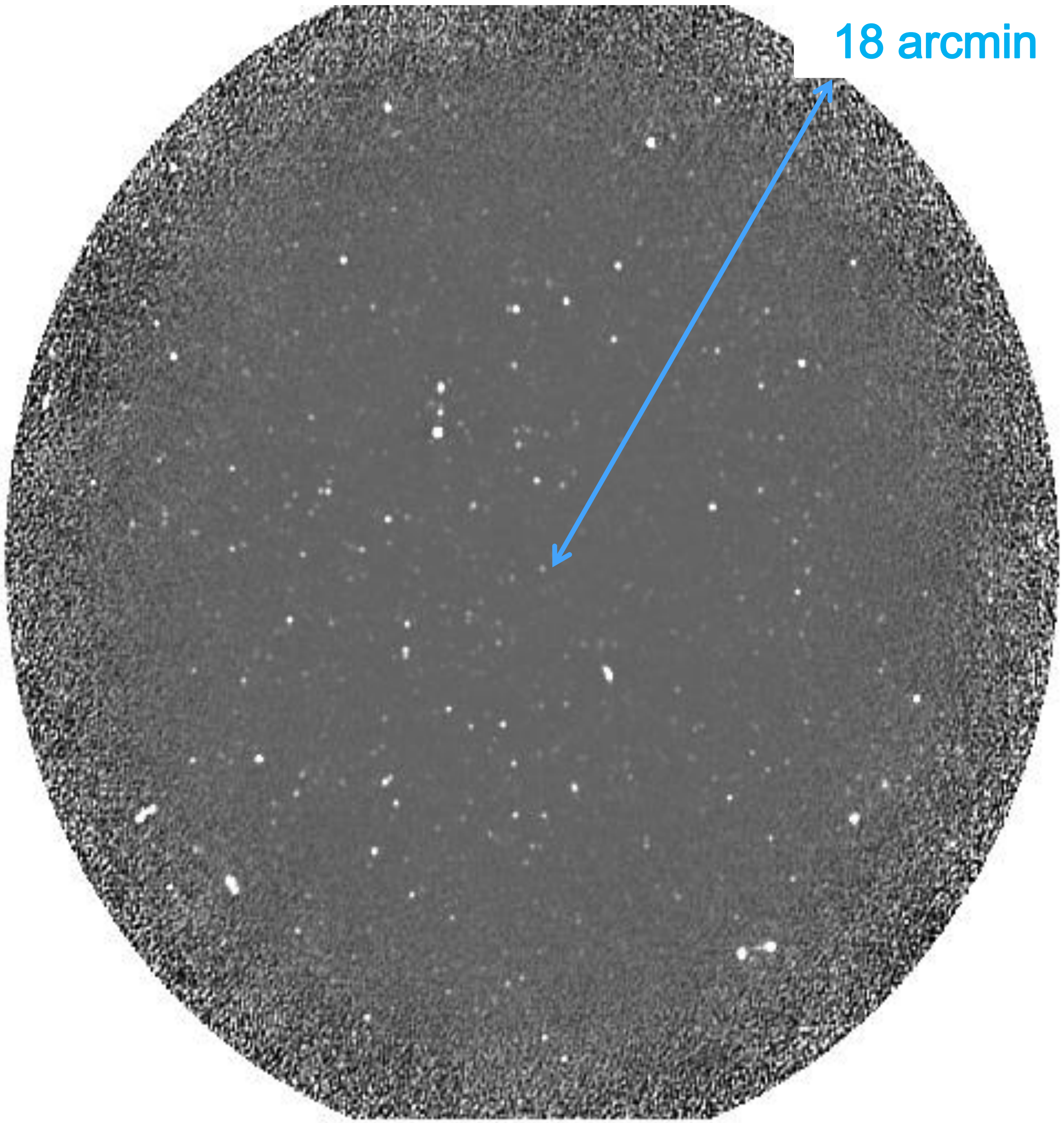
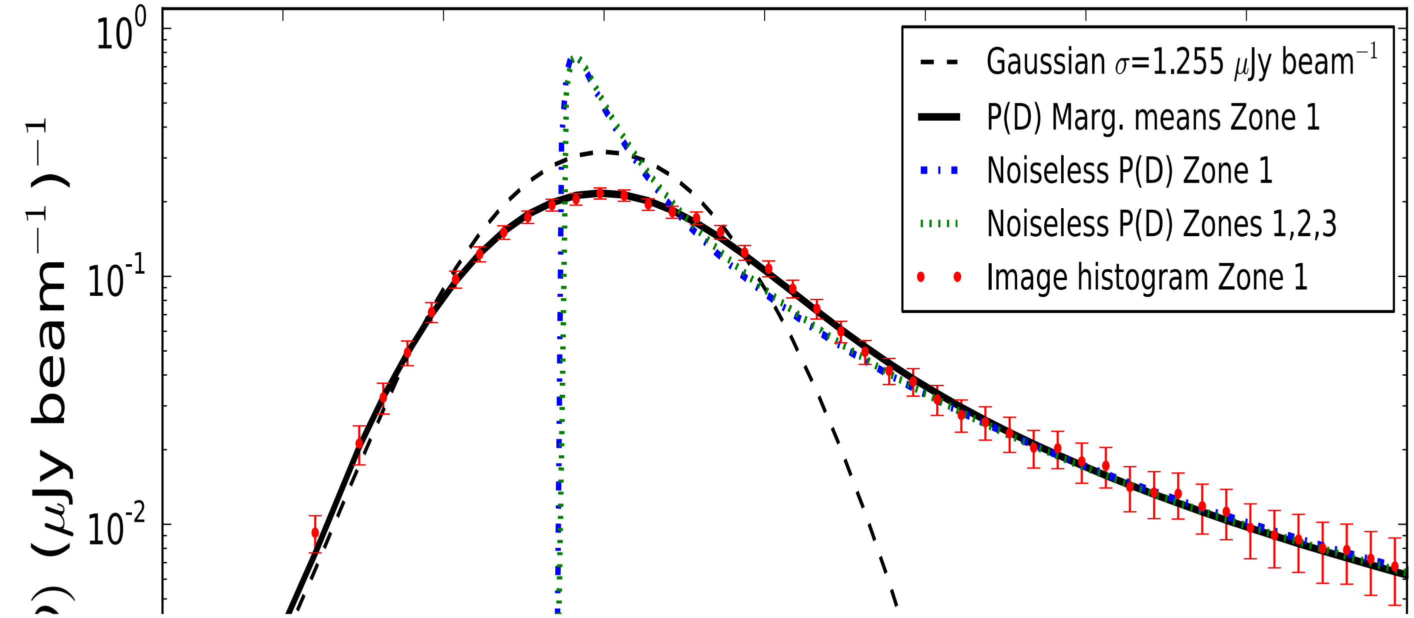
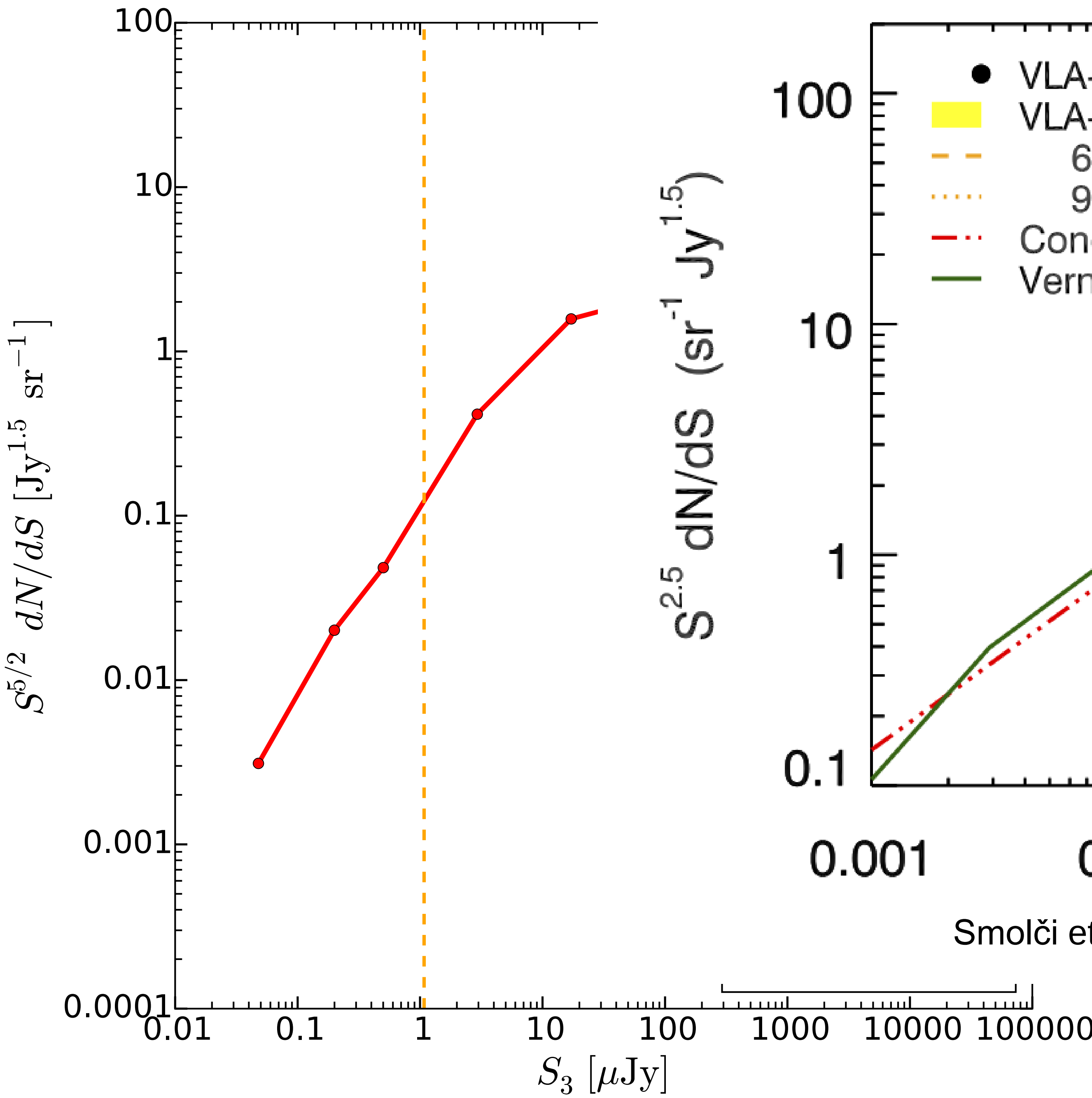
P(D) Source Count -Data

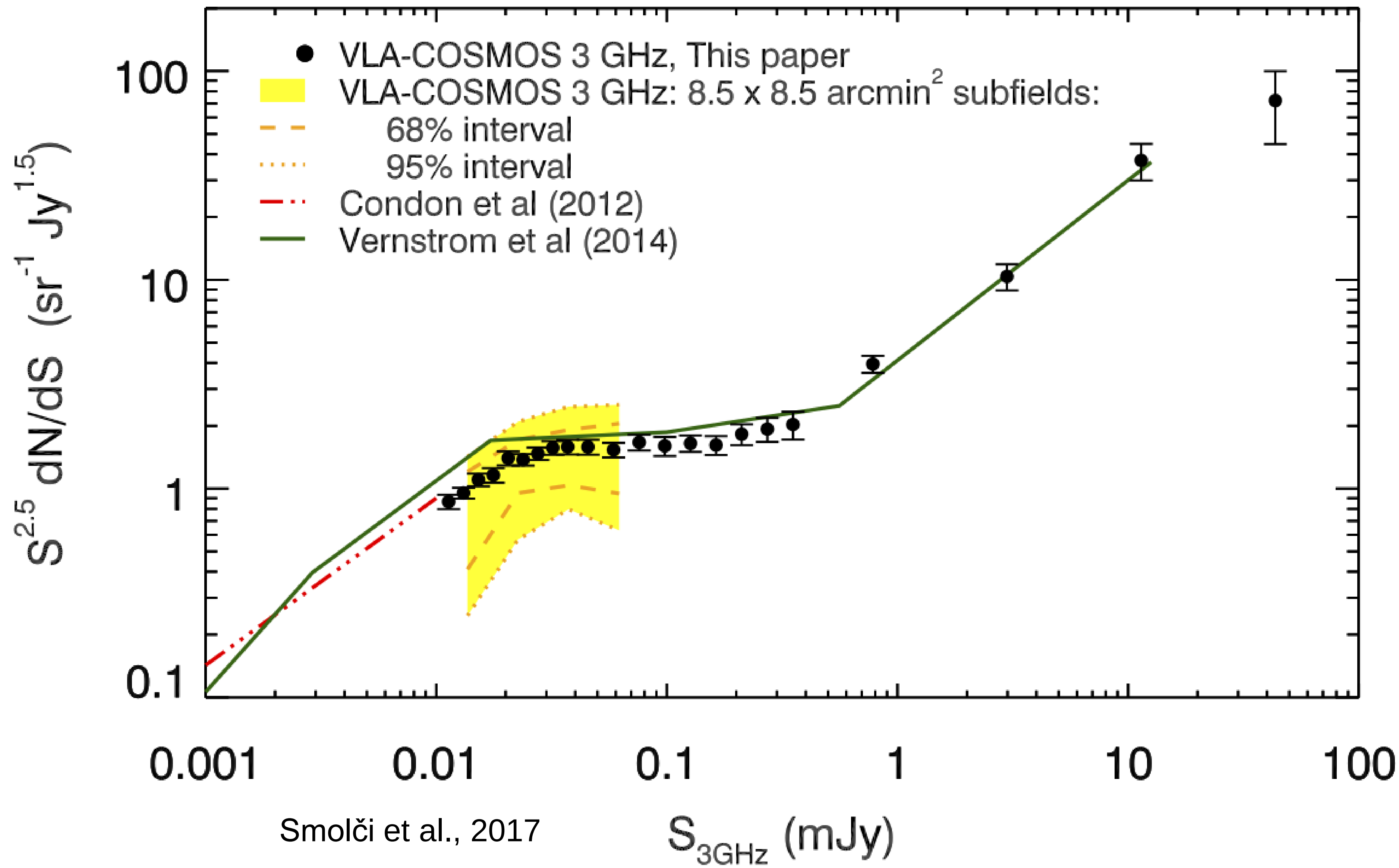
- **JVLA**
  - **Lockman "Owen" Hole North**
  - **3 GHz single pointing**
  - **C configuration**
  - **Rms: 1.02 μJy/beam**
  - **Beam: 8 arcsec**
  - **Time: 50 hours**



P(D) Source Count - Results







Smolči et al., 2017

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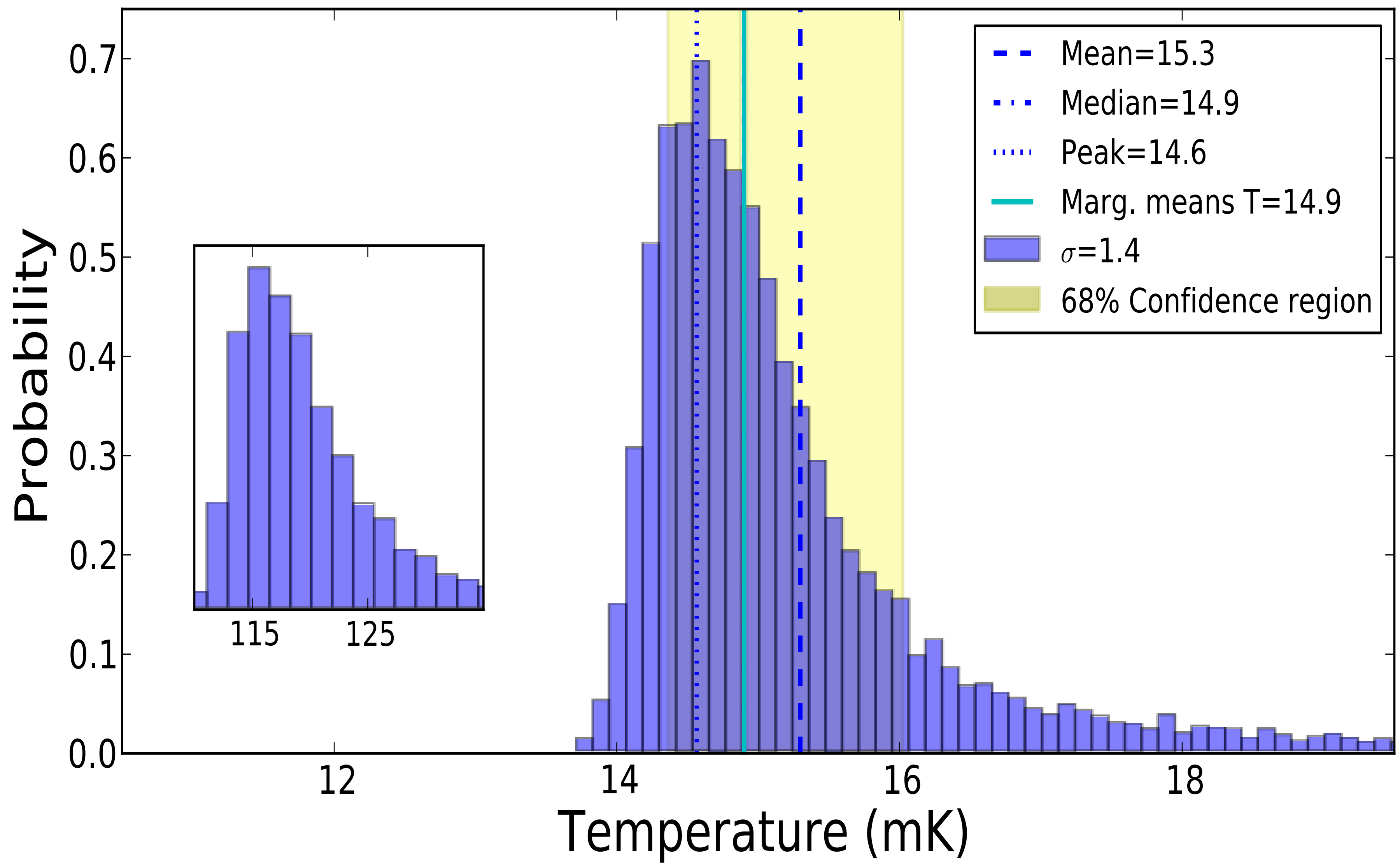
P(D) Source Count - Temperatures

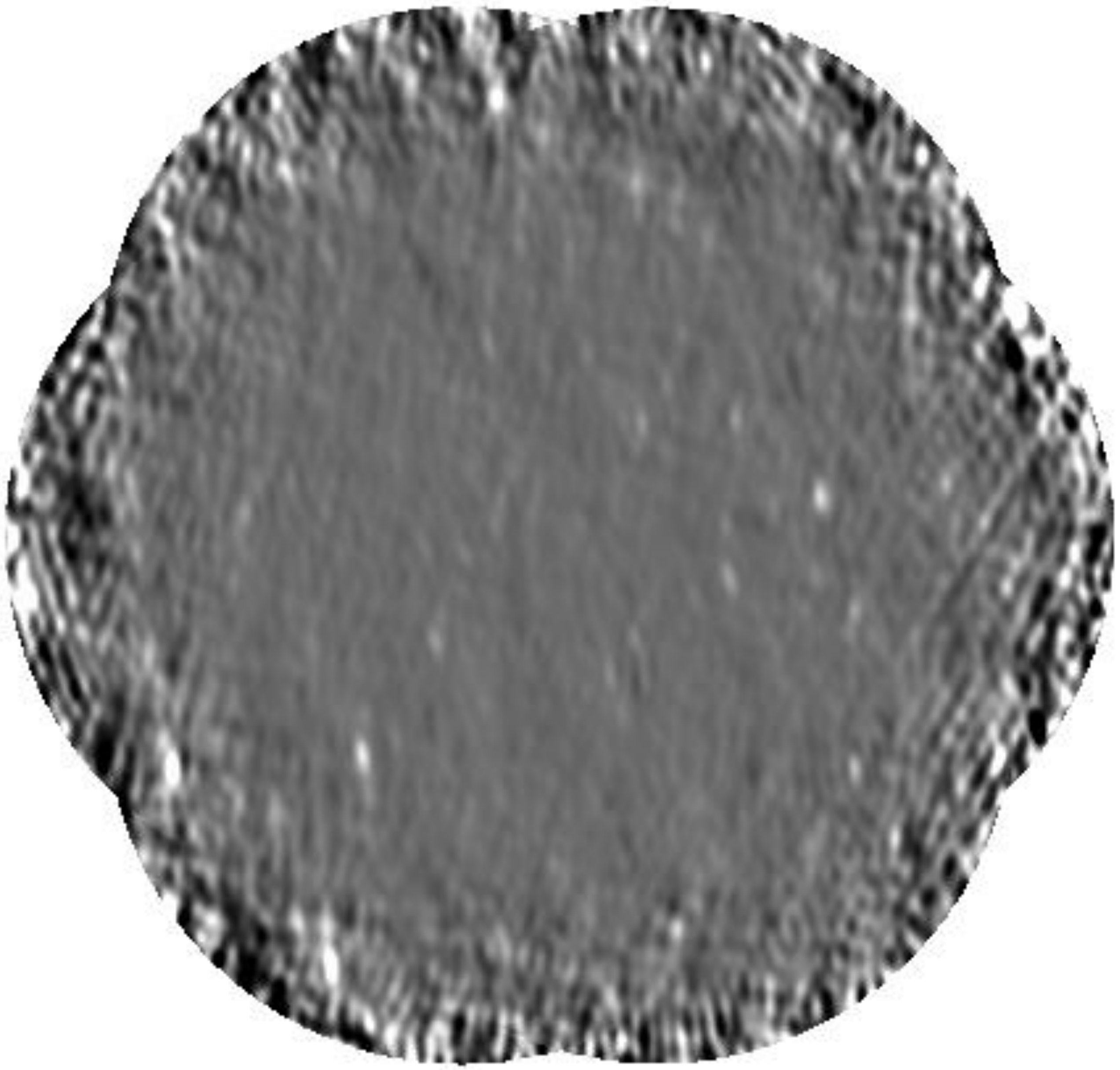
$$\int_{S_{\min}}^{\infty} S \frac{dN}{dS} dS = \frac{T_b 2 k_B \nu^2}{c^2}$$

- T_b = 13 - 16 mK at 3 GHz
- T_b = 105 - 120 mK at 1.4 GHz



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**



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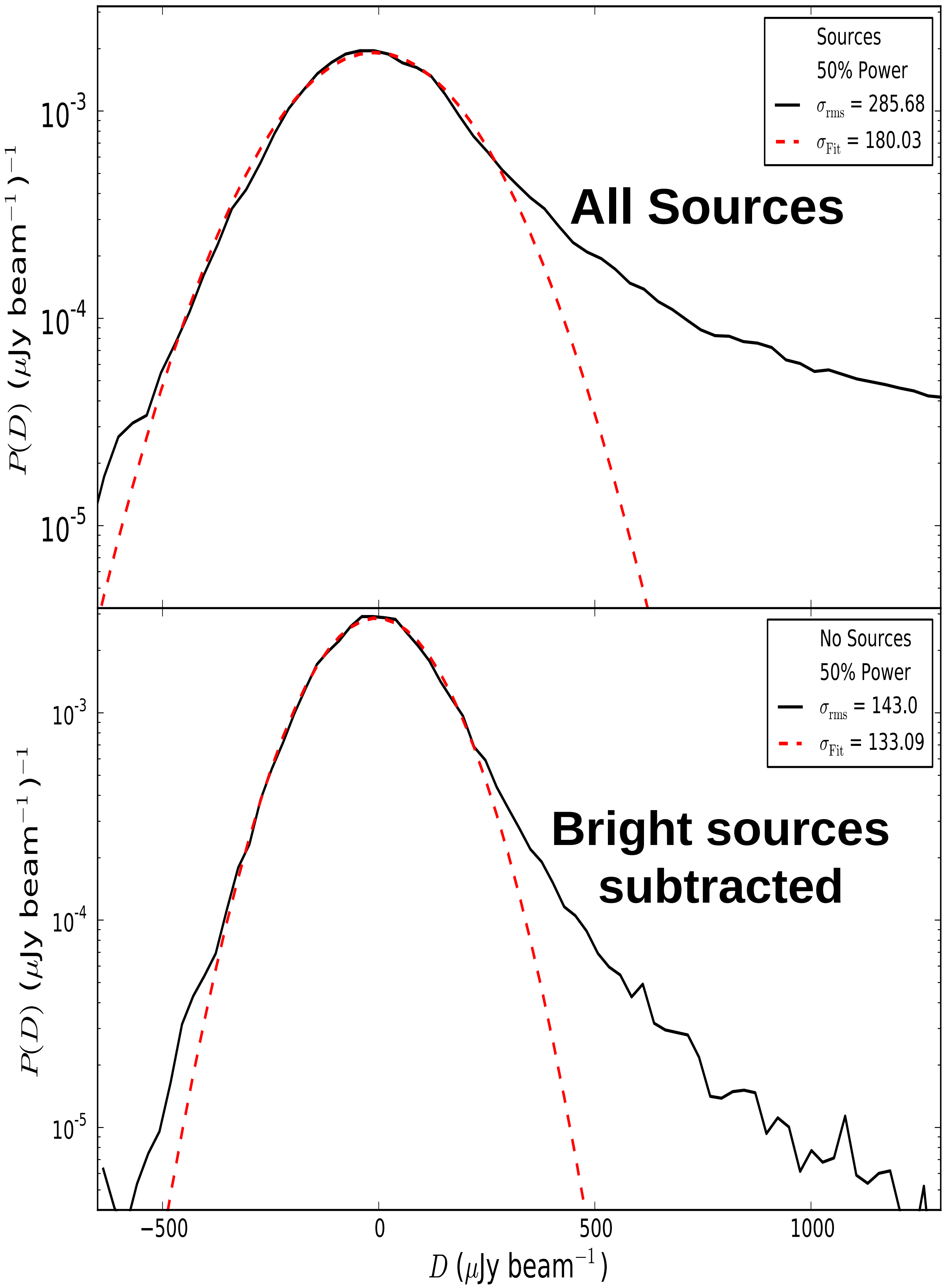

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Confusion Diffuse Emission - Results

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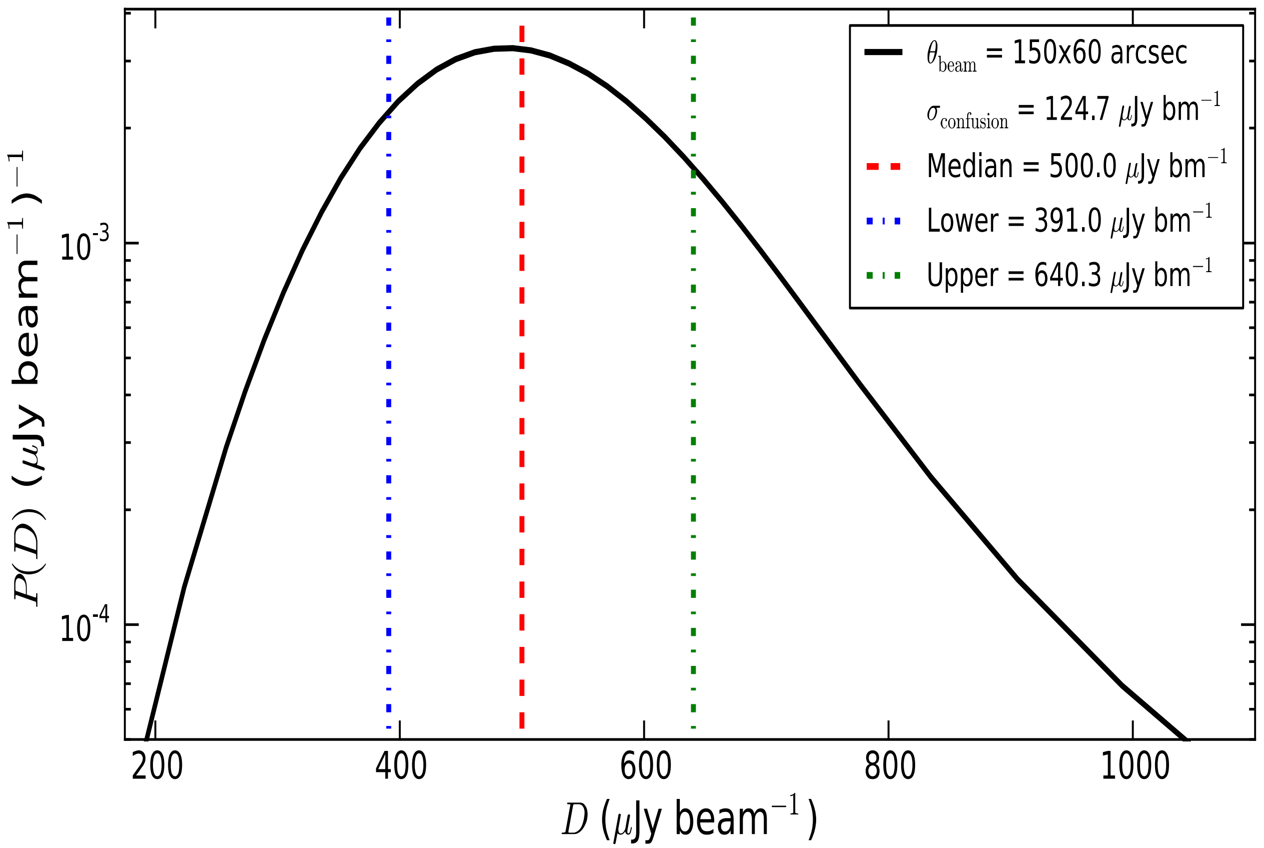


Model P(D) of faint sources

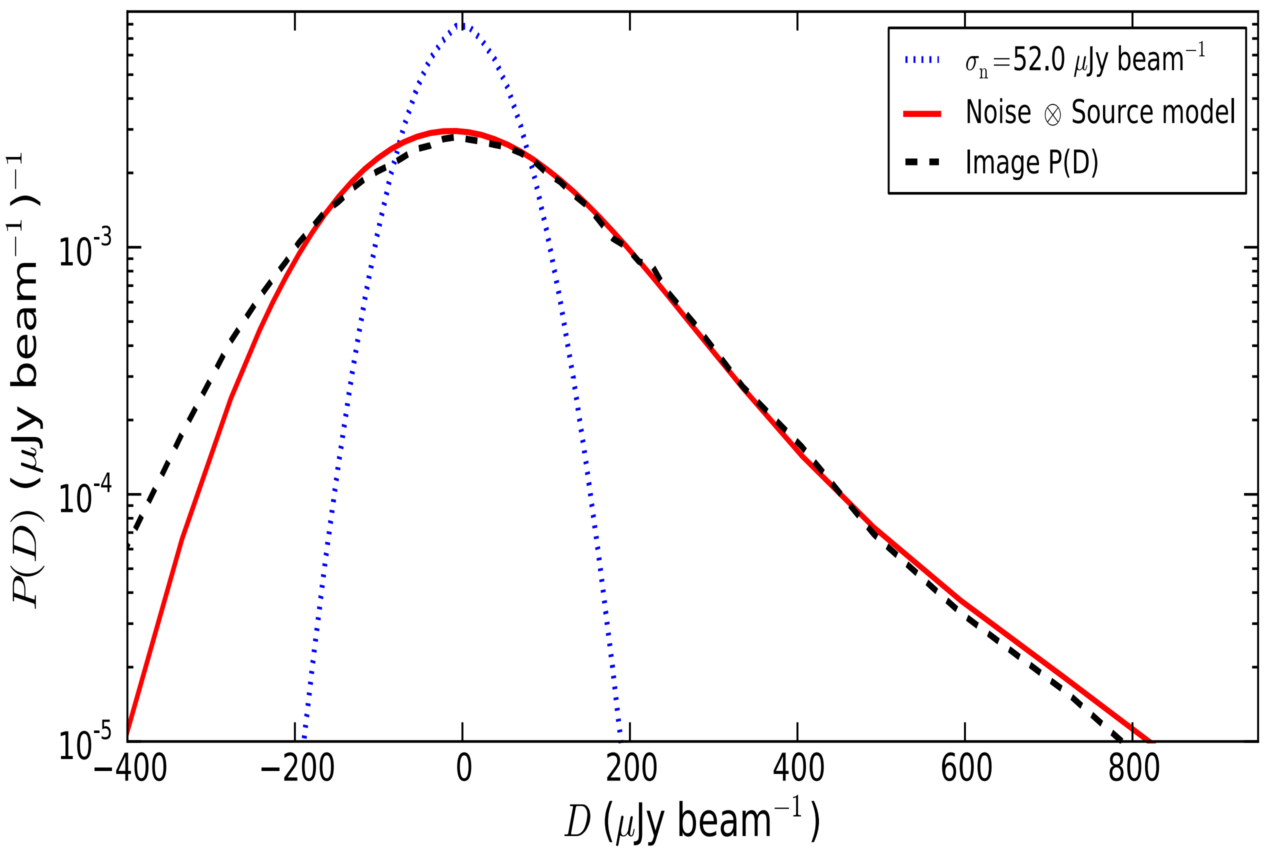


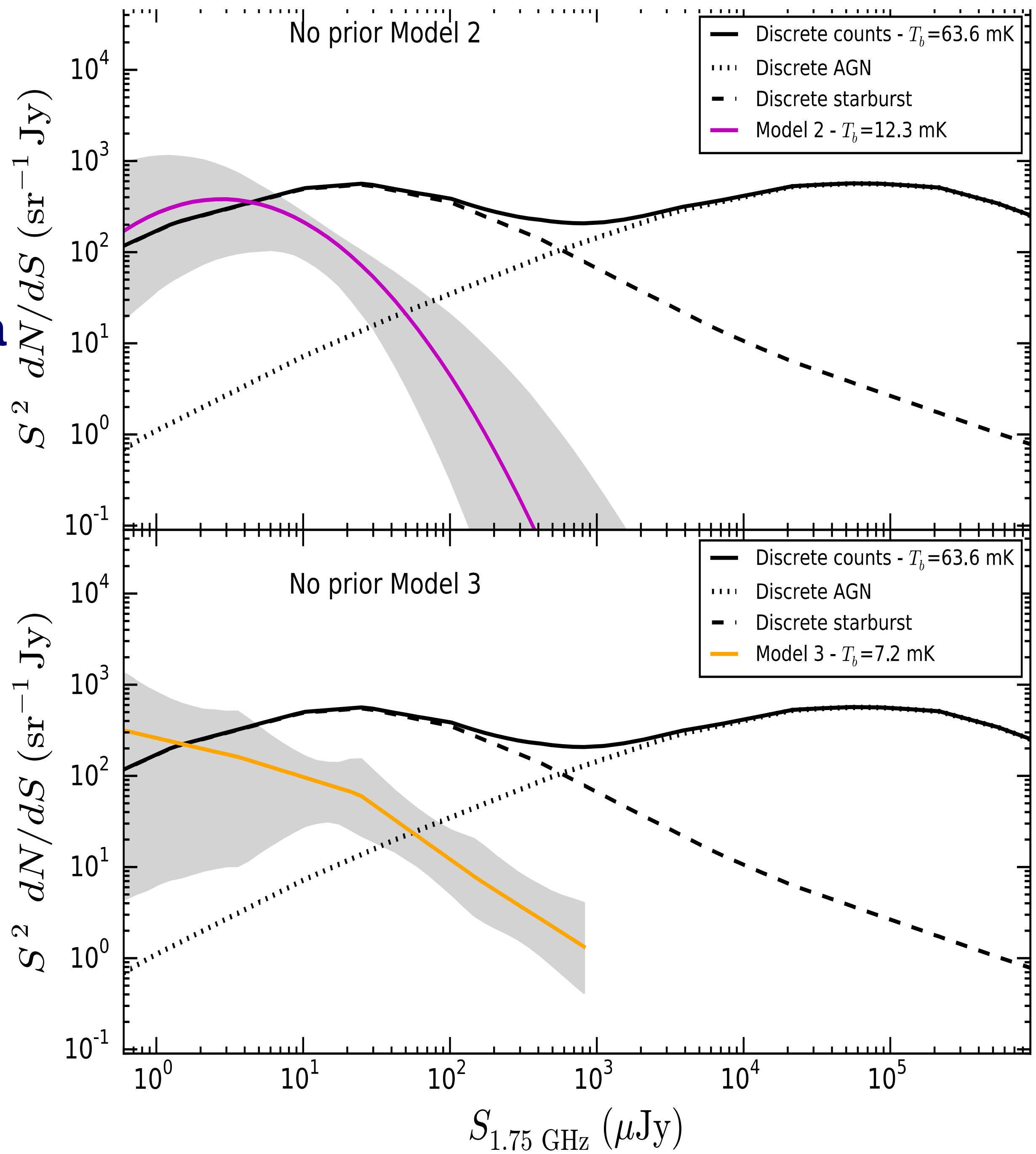
Image P(D) compared to model

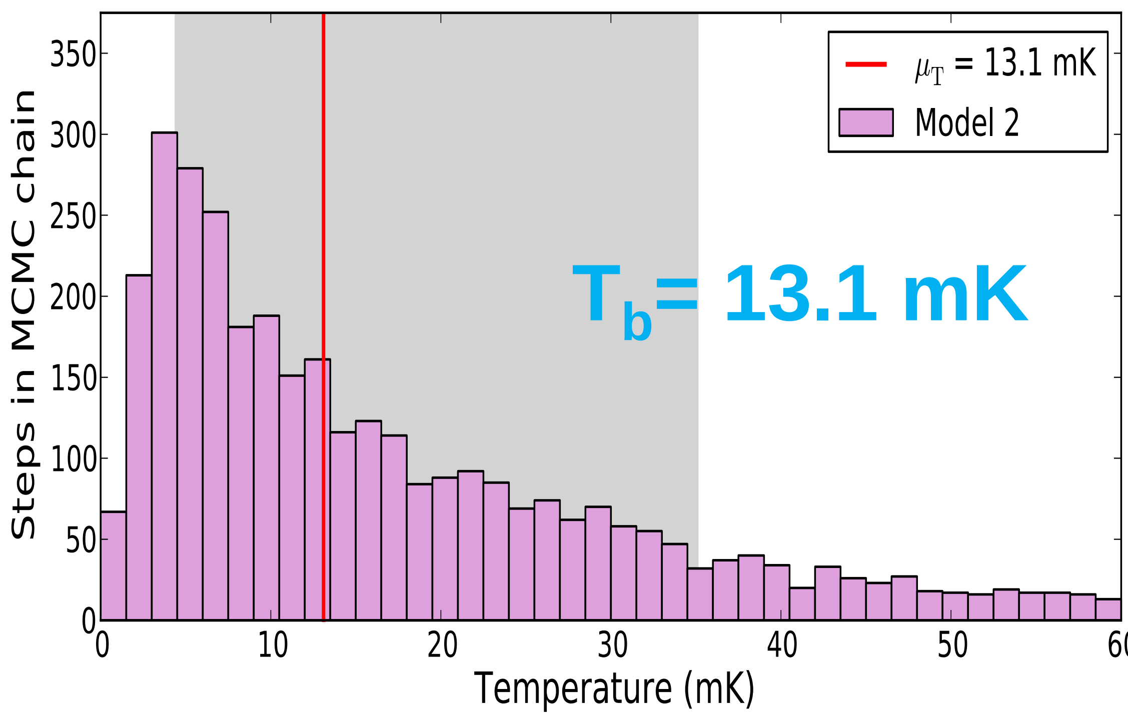
← 3σ difference

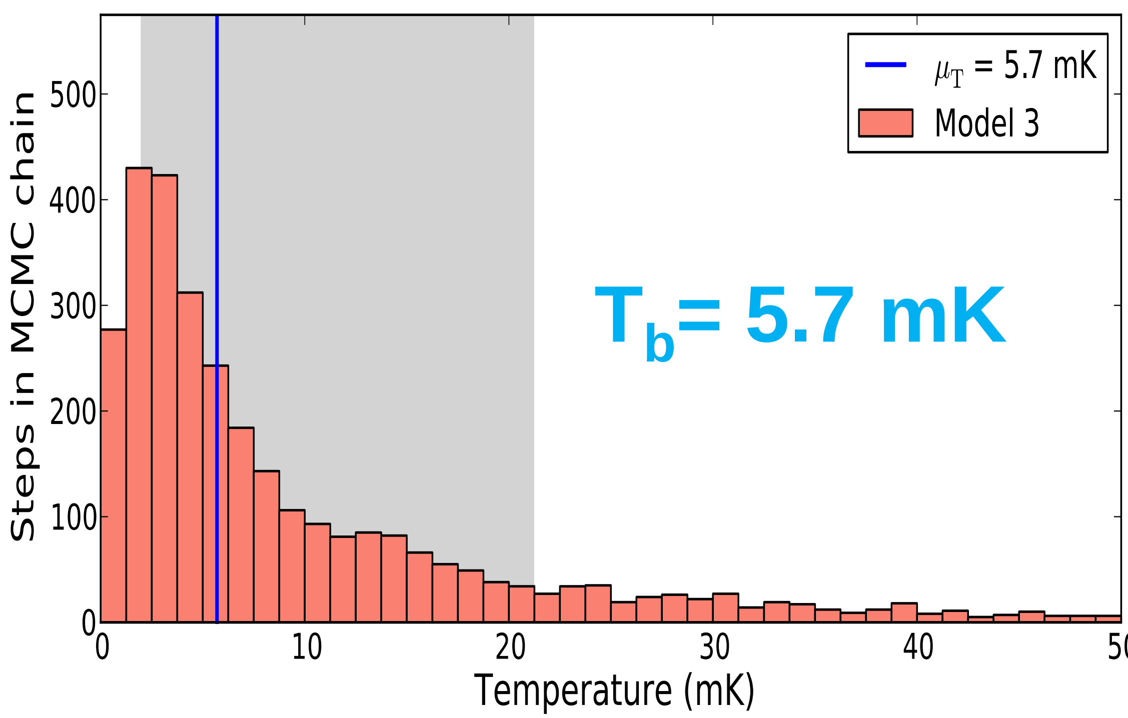
Confusion Diffuse Emission - Results

Model: Parabola

Model: Nodes



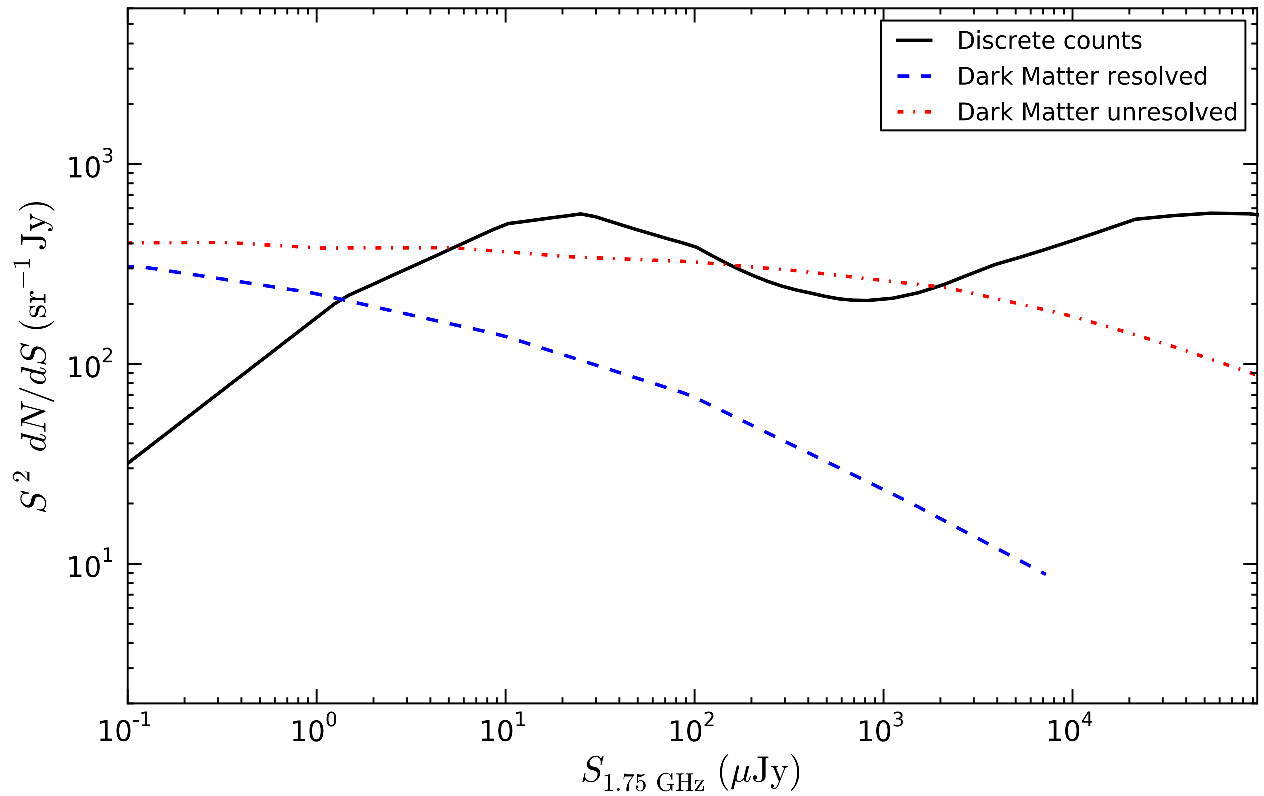


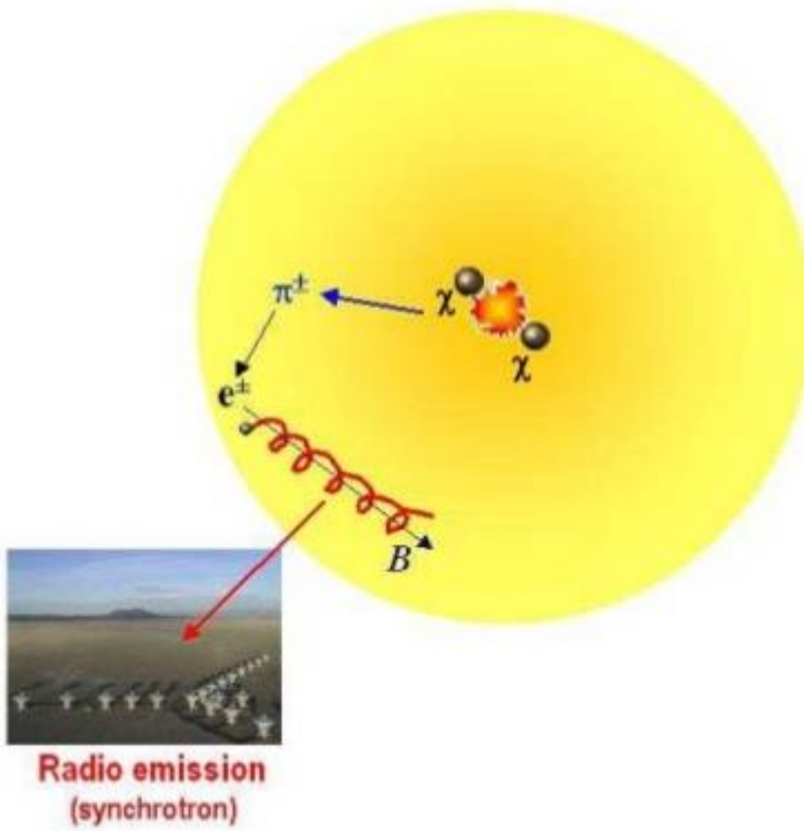


Confusion Diffuse Emission - Models

- **Dark matter particles in halos synchrotron emission from annihilation/decay**

- **Fornengo et. al 2011 model:**
  - **particle mass of 10 GeV assuming decay into leptons**
  - **Gives predicted source count**





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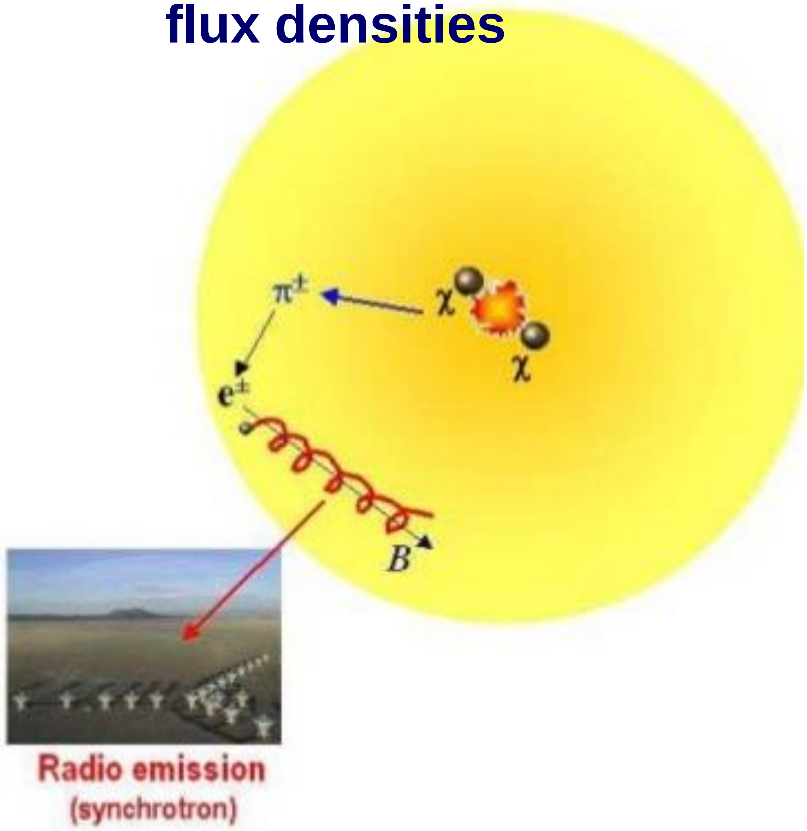
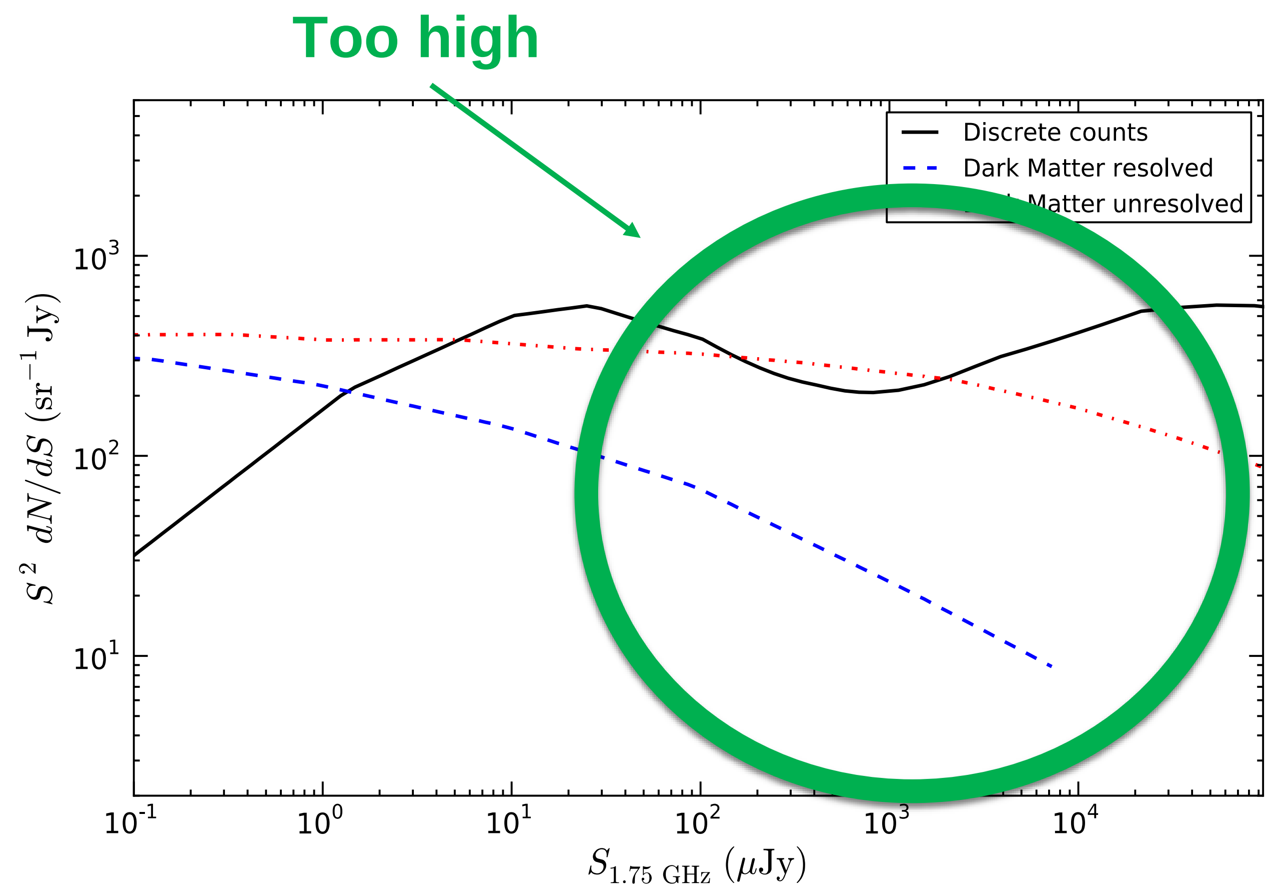
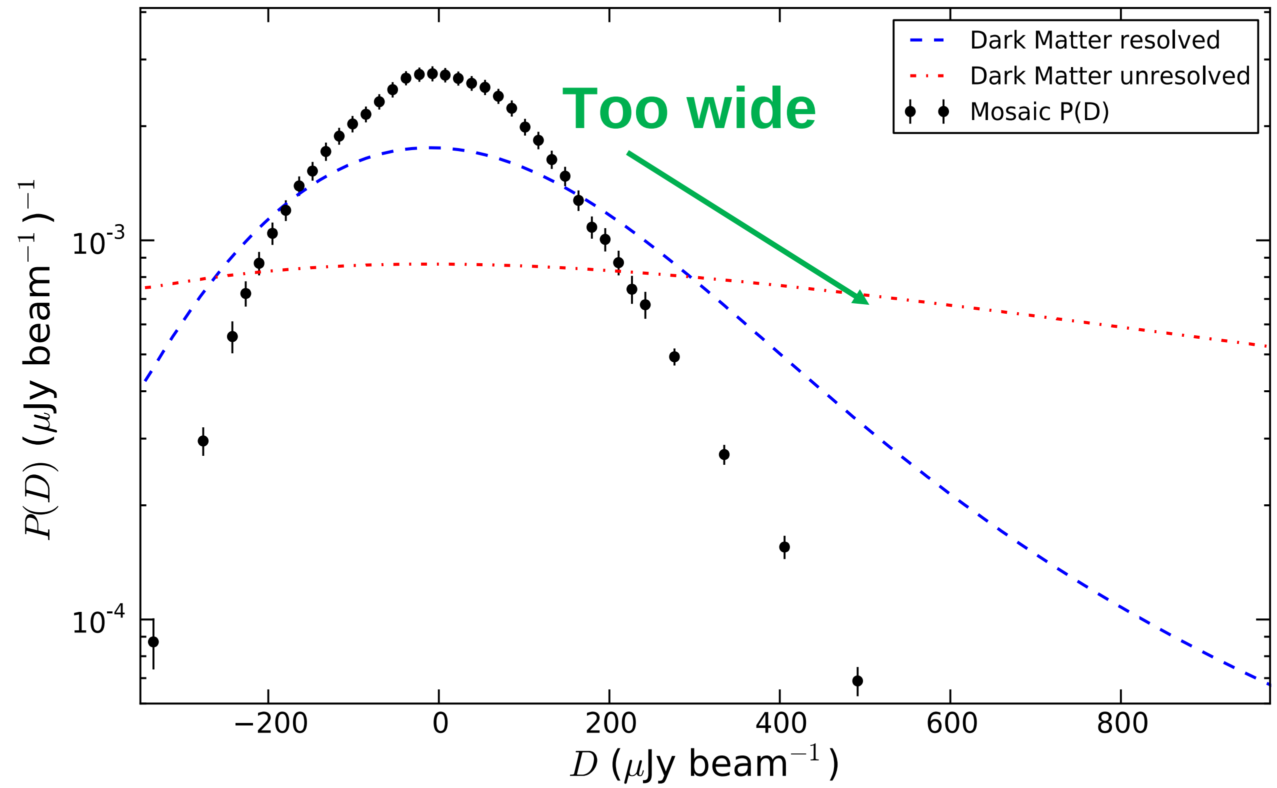
- **Both produce inconsistent fits to the data**
  - **Counts much too high at bright flux densities**

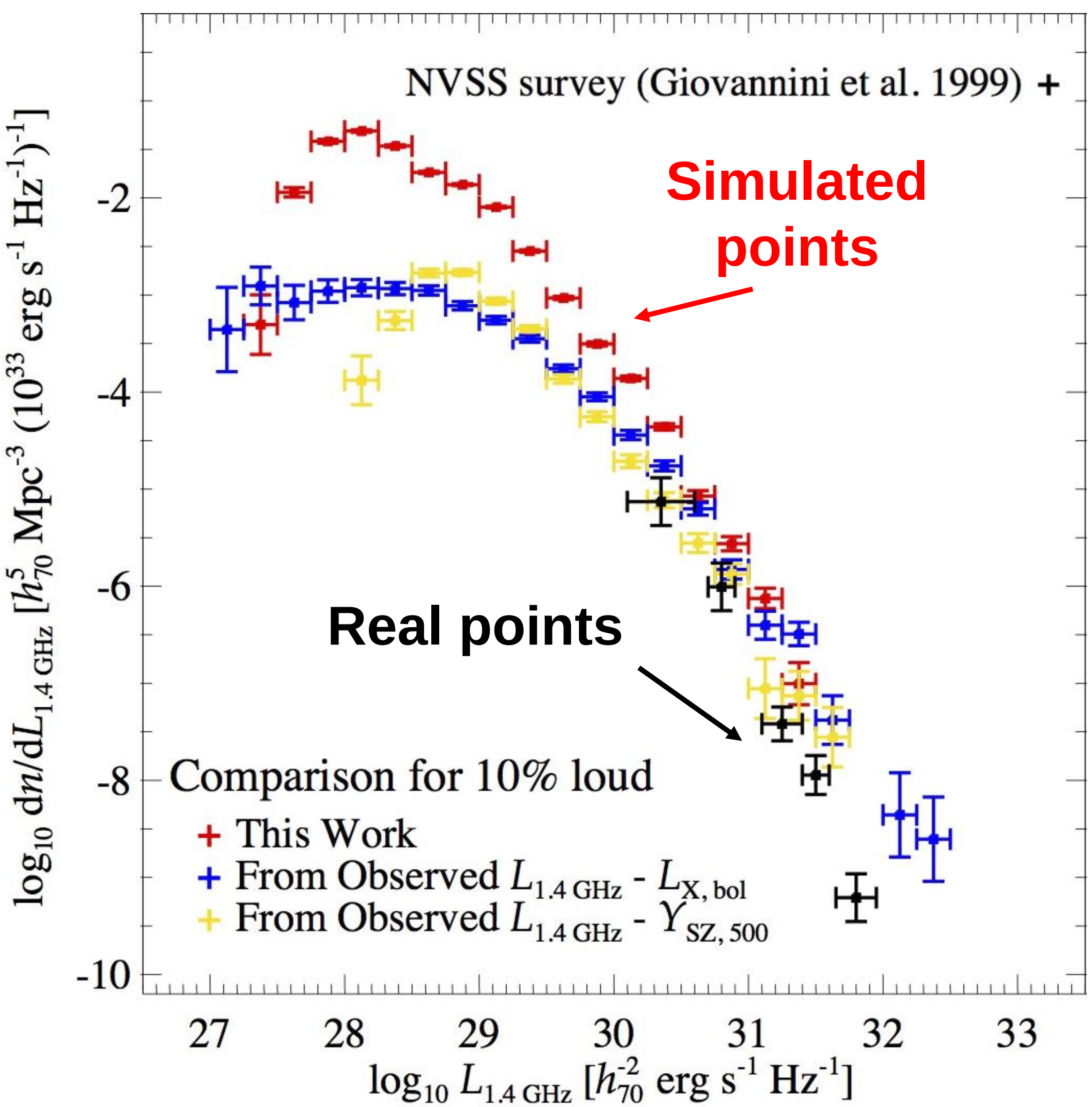


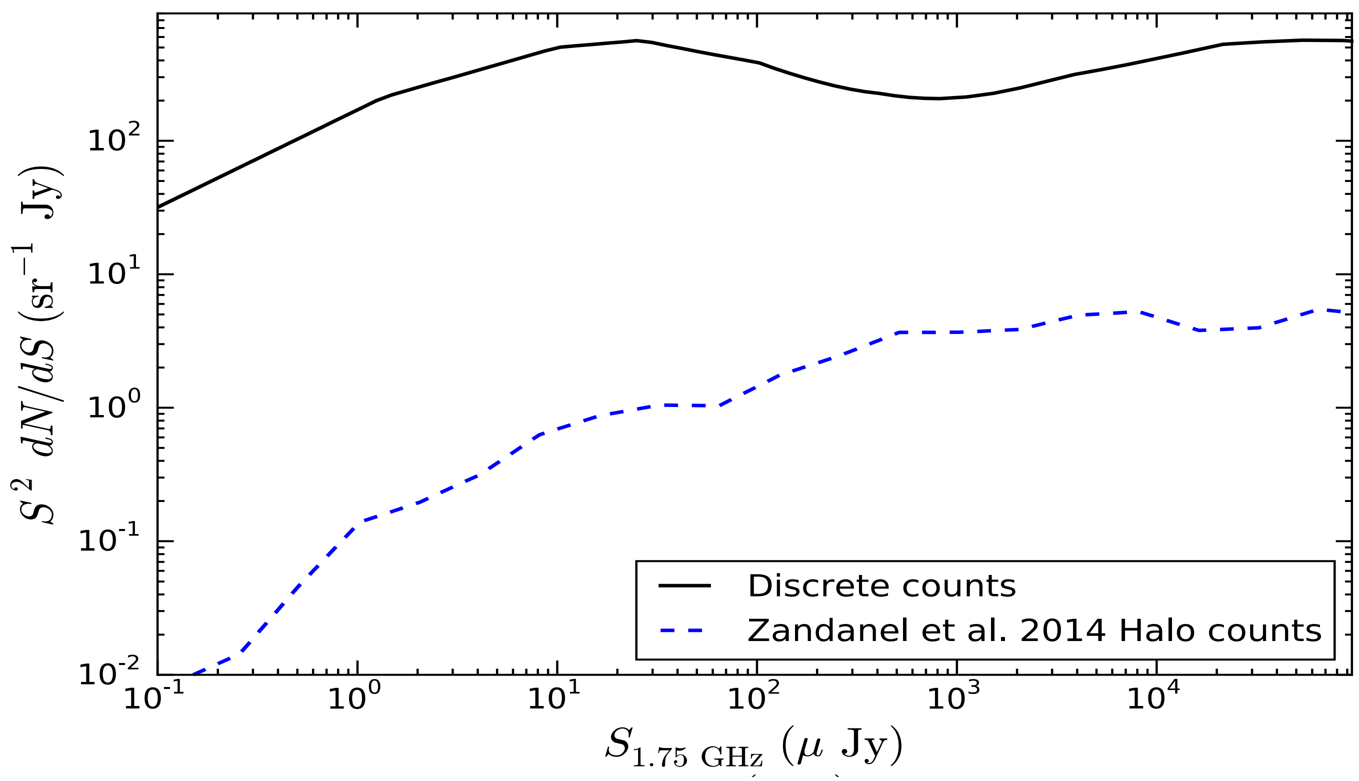




Confusion Diffuse Emission - Models

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





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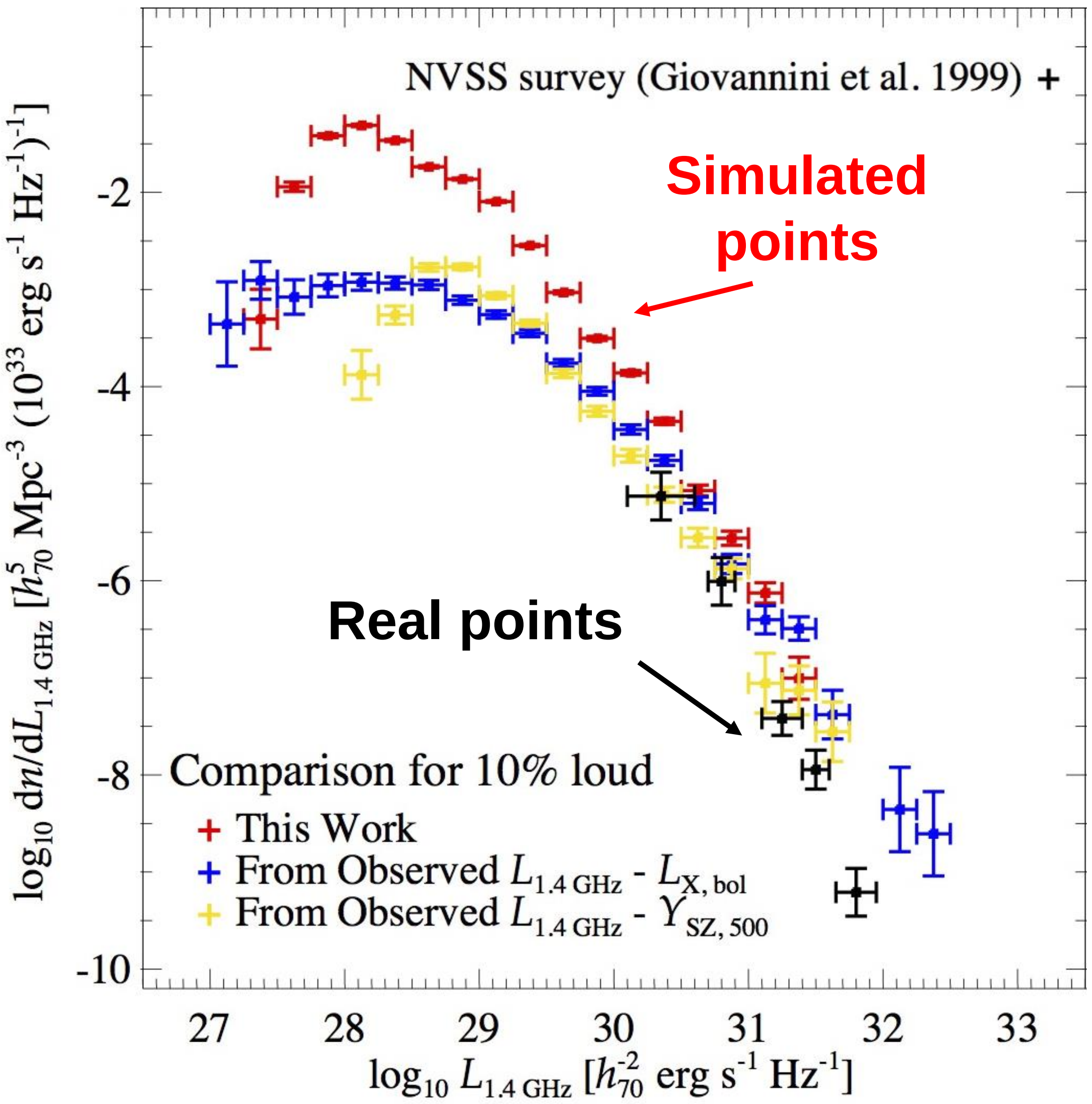
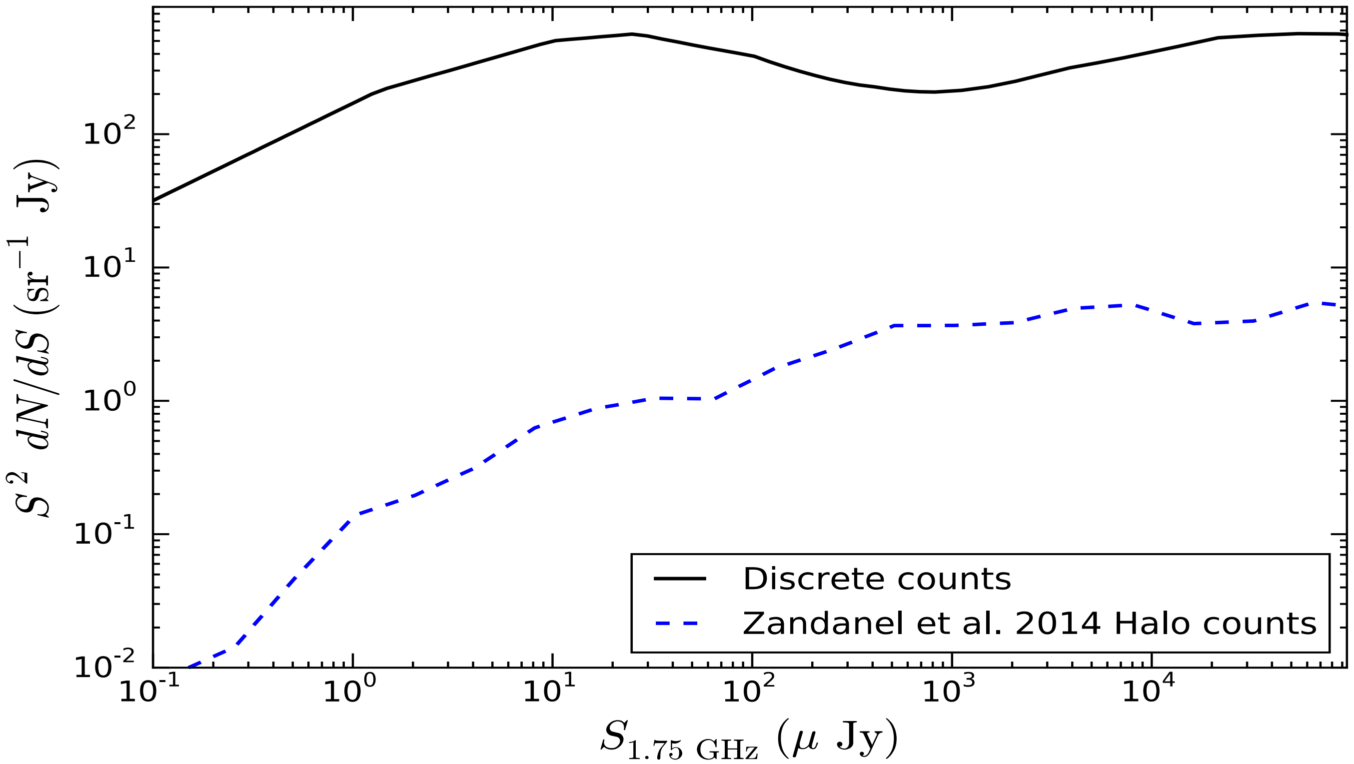
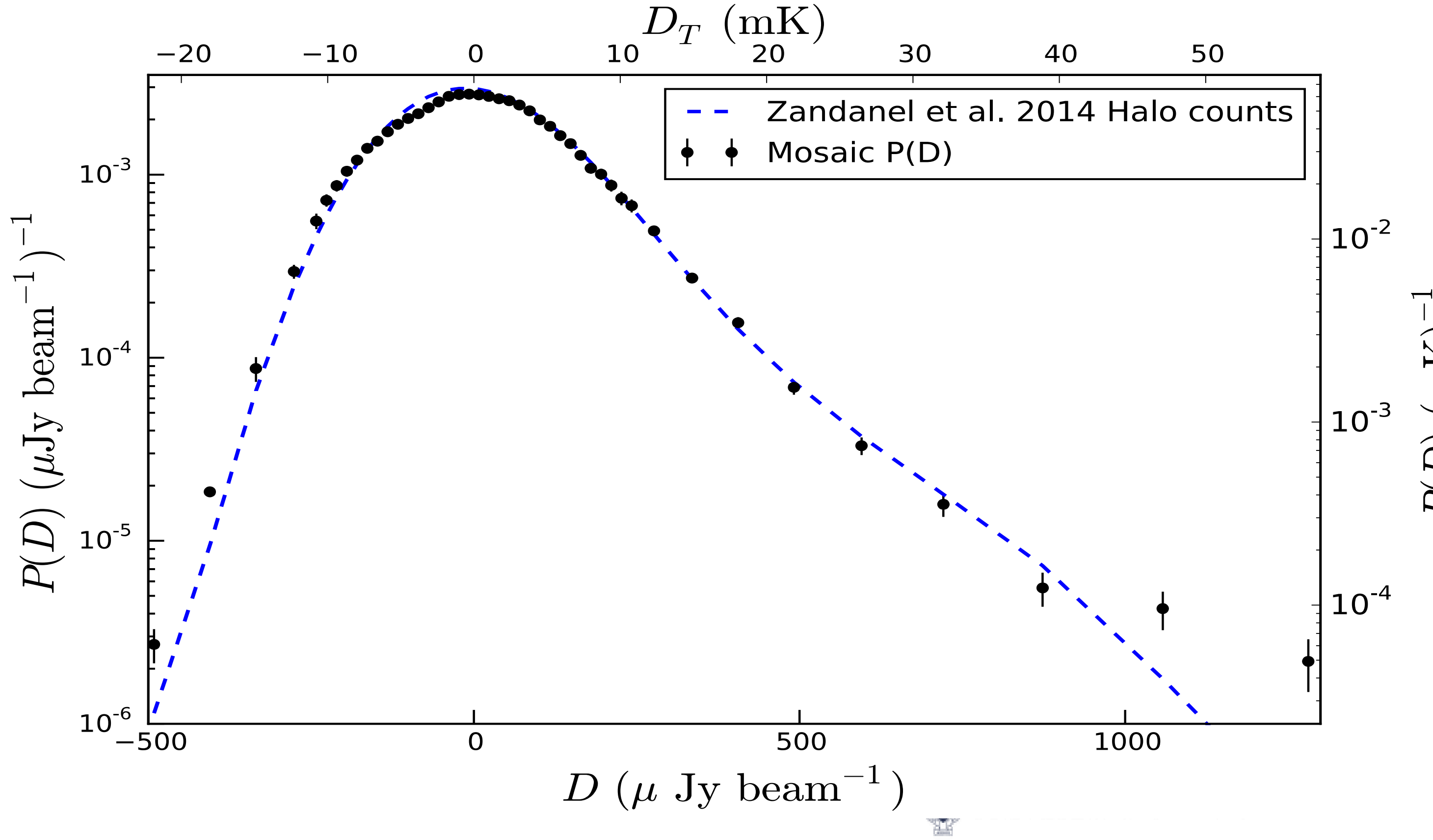






Confusion Diffuse Emission

Advantages:

- **Detection of emission below confusion level**
- **Possible to constrain models of halos or dark matter**

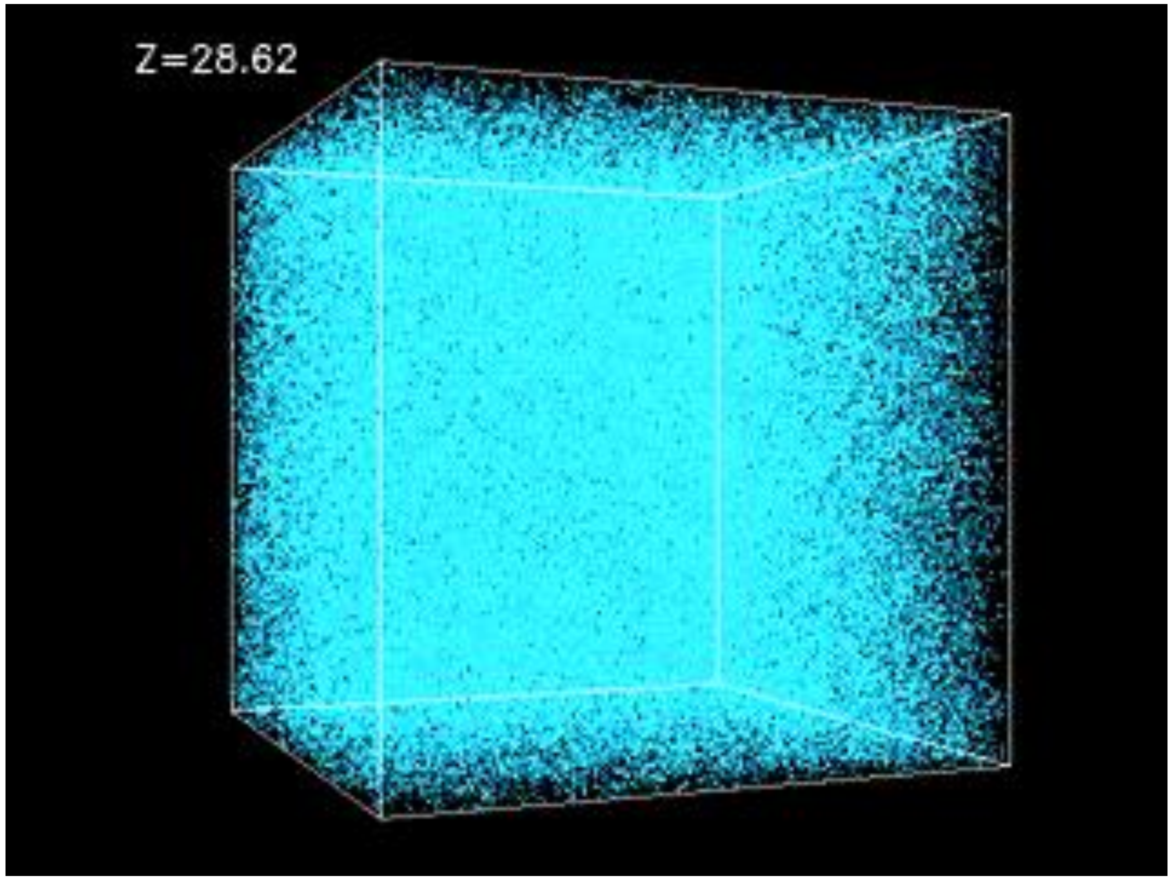
Disadvantages / Caveats:

- **Assumes emission smaller than (or roughly equal to) the beam size**
- **Requires point source subtraction and/or model for un-subtracted 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 or multi-frequency test**

Diffuse Emission
Filaments/Cosmic Web



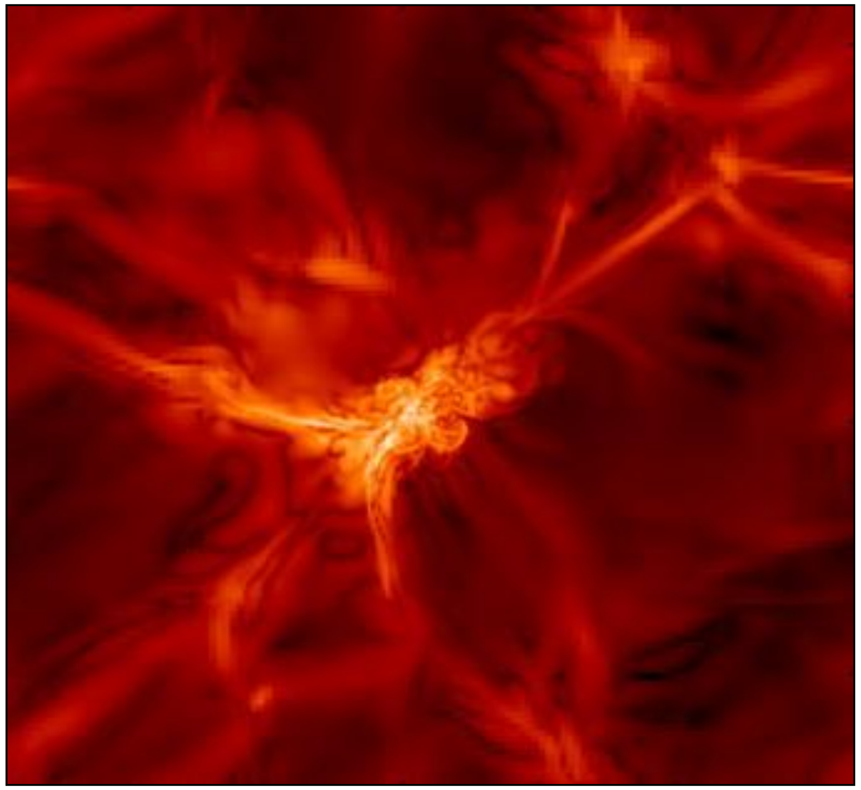
The Synchrotron Cosmic Web

- **Intergalactic shocks from infall into and along filaments accelerate electrons and amplify magnetic fields → producing synchrotron emission**

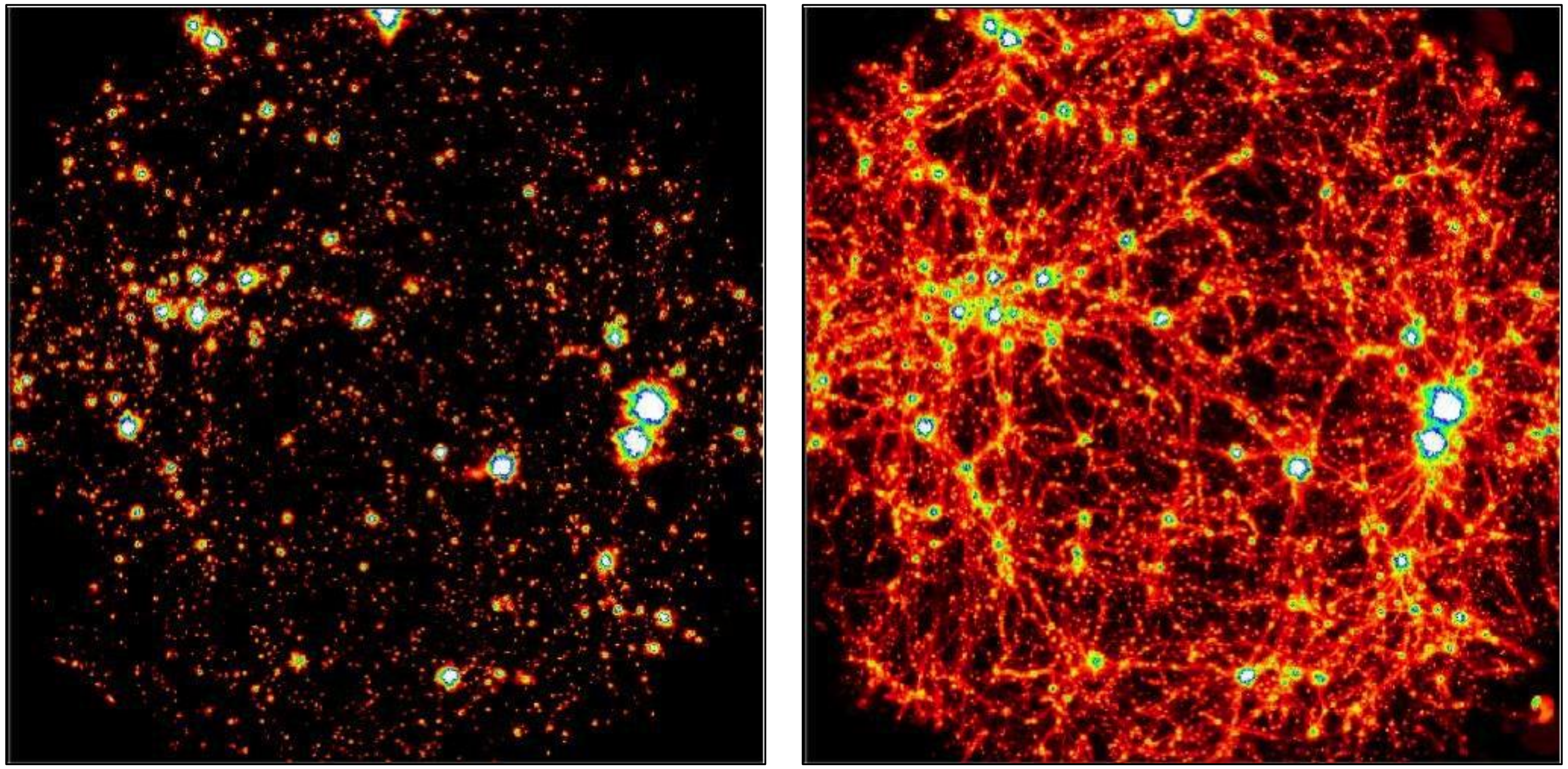
(Keshet et al. 2004; Hoeft & Brüggen 2007; Battaglia et al. 2009; Araya-Melo et al. 2012, Vazza et al., 2015)

- **Faint synchrotron radiation should trace large-scale structure and cosmic filaments**

- **Signal should be strongest on scales ~ 10′ to 1^o at frequencies ~100 MHz**



MHD simulation of magnetised large-scale structure (Brüggen et al. 2005)



Injected fields vs primordial fields (Donnert, Dolag et al. 2008)

How can we detect it?

- **Direct imaging**
(Bagchi et al. 2002; Wilcots 2004; Vazza et al. 2014)

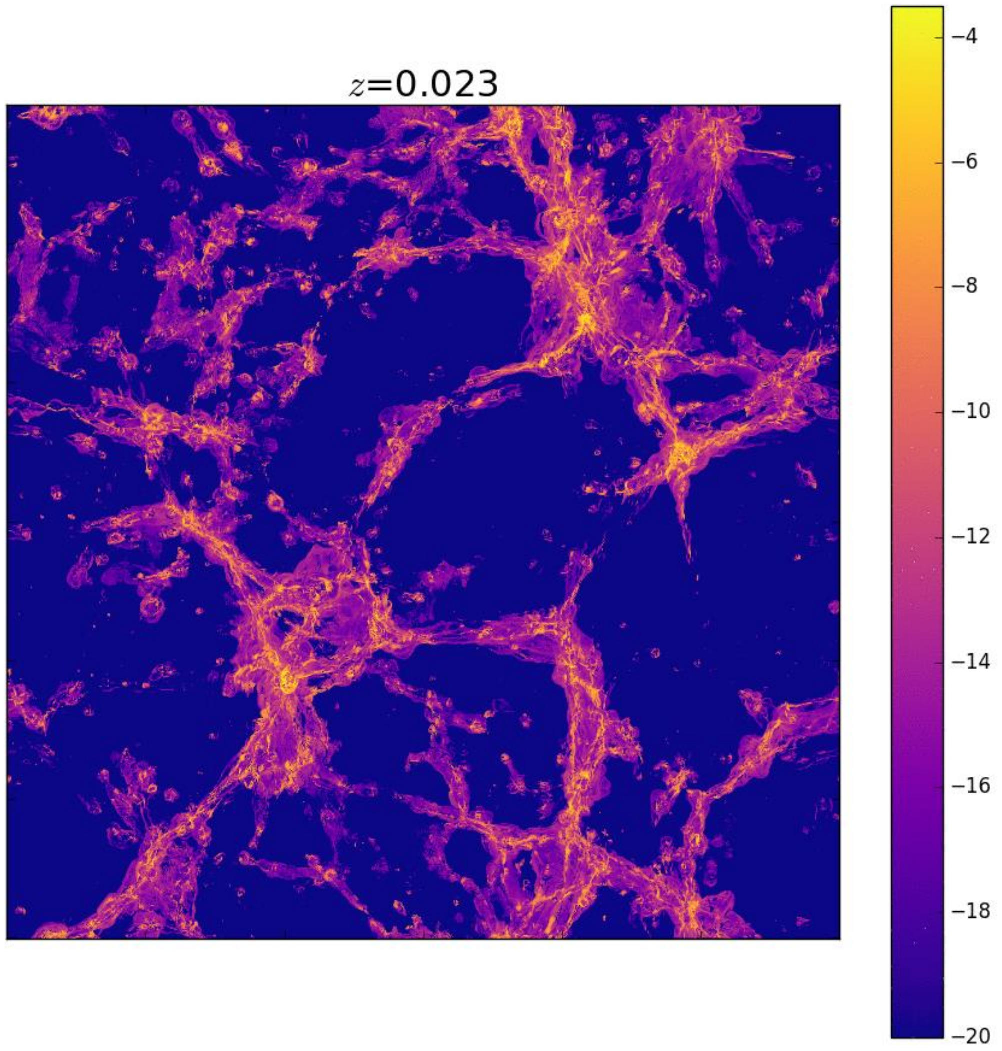
- **Statistical methods:**
    - **Cross Correlation (Brown et al. 2010, 2011)**
    - **Stacking**

- **Polarisation:**
    - **Faraday rotation from background AGN**
    - **Dispersion from fast radio bursts**
    - **Also stacking and cross correlation**

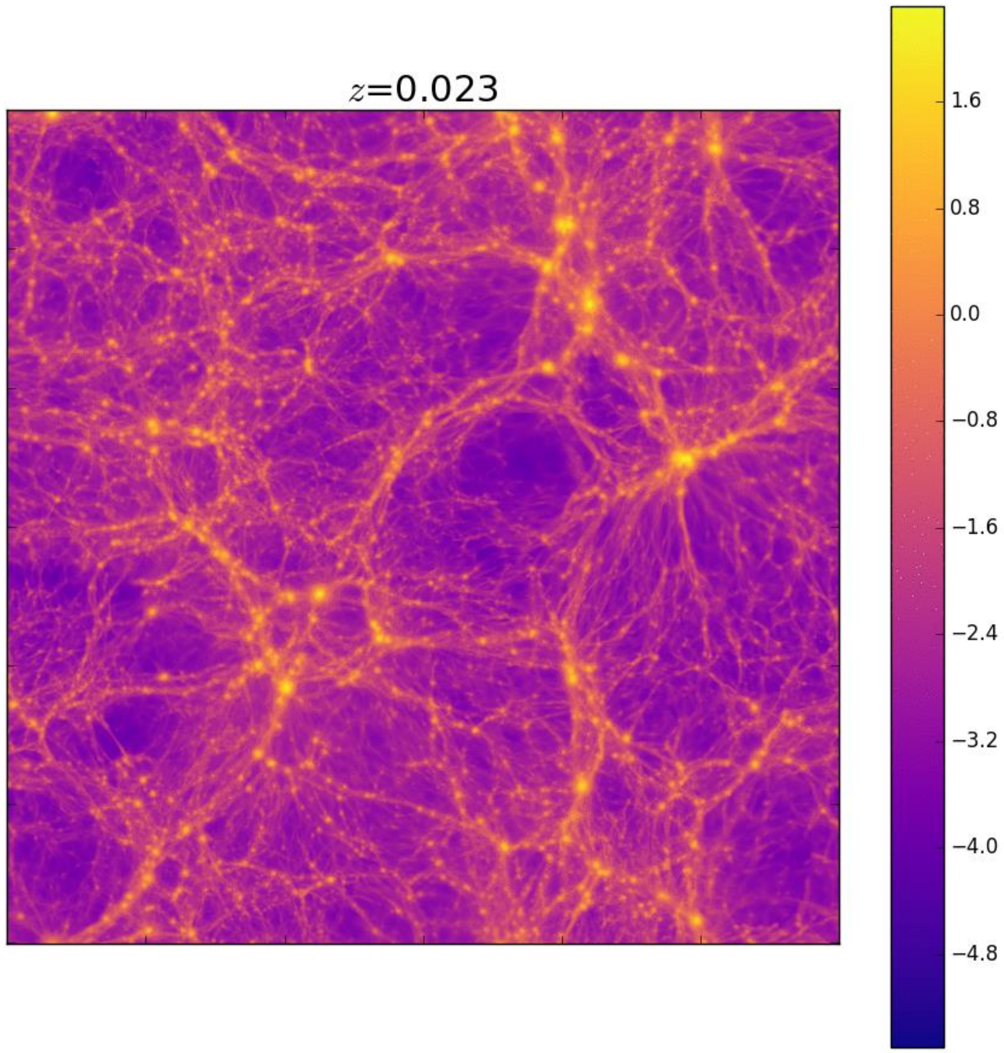
Cosmic Web - Cross Correlation

Vazza et al., 2015, 2016 MHD simulations – 14 sq deg

Diffuse Synchrotron



Thermal gas



Cosmic Web - Cross Correlation

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

Cosmic Web - Cross Correlation

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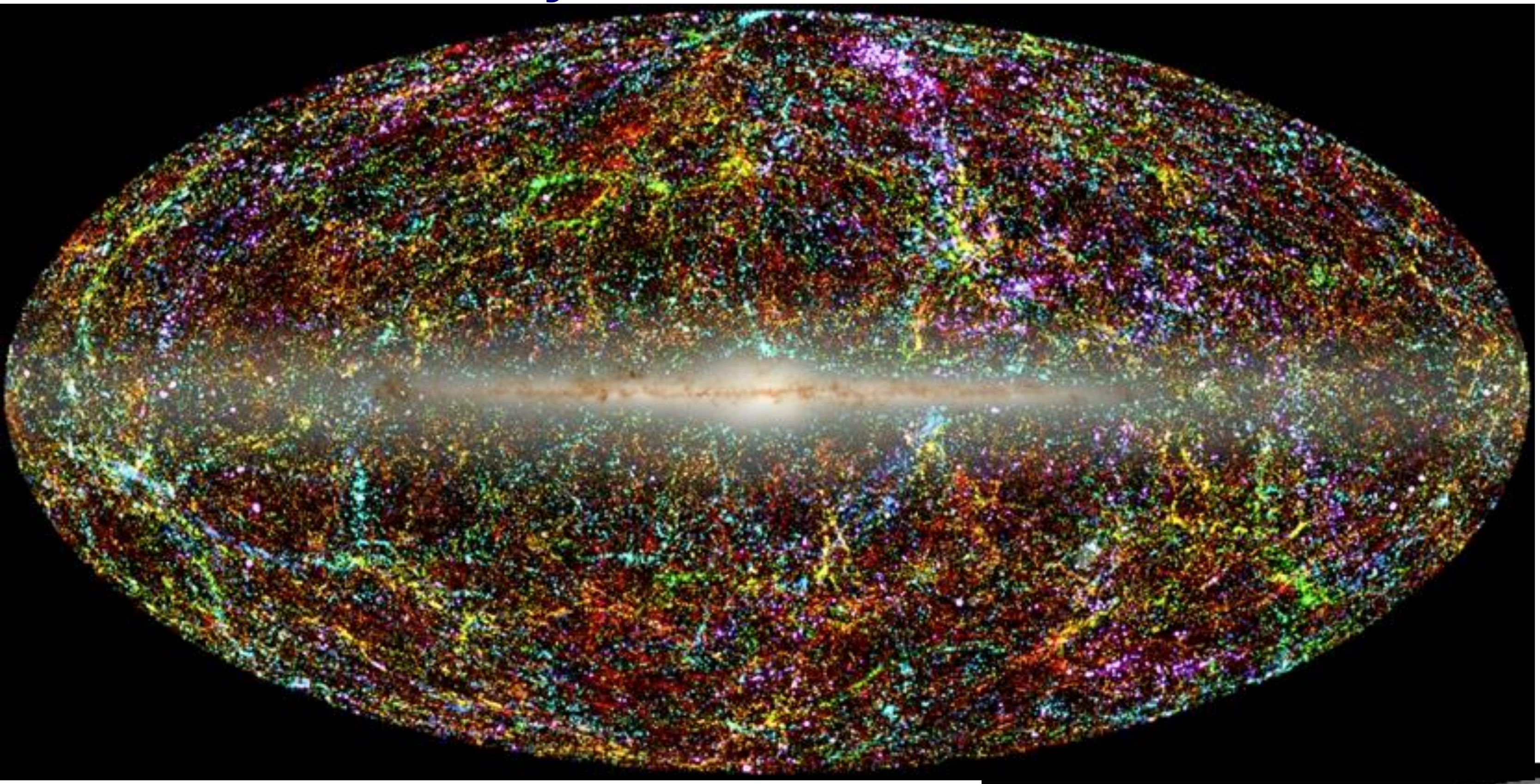
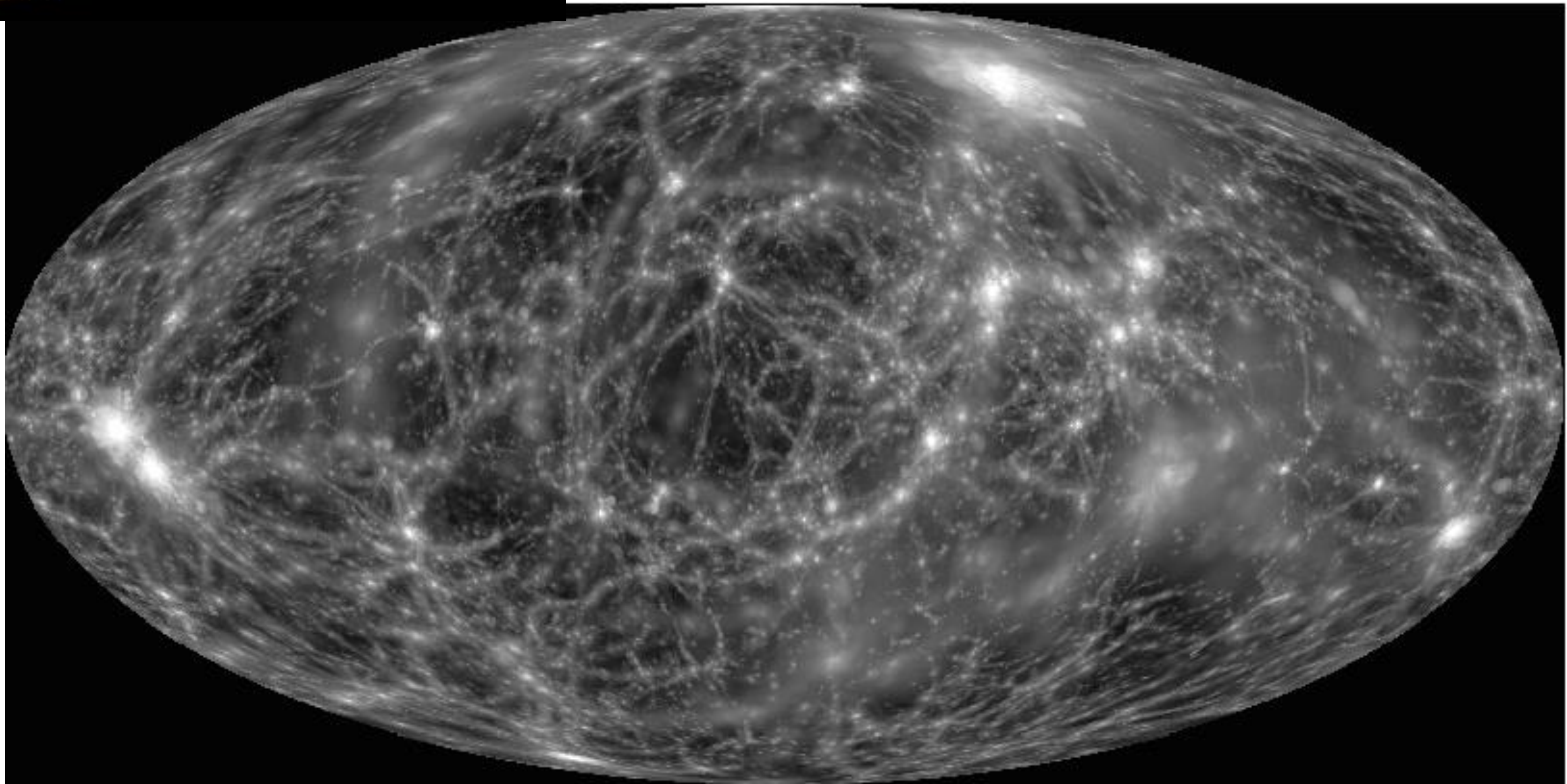


2MASS Galaxy Distribution coded by redshift
(photo credit :Thomas Jarrett (IPAC/Caltech))

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**

- **Cross correlation function: how correlated as a function of angular distance – image plane**

- **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**
- **Approximate collecting area: 2000 sq. meters**
- **Field of view: 15 - 50 deg. (200 - 2500 sq. deg.)**
- **Instantaneous bandwidth: 30.72 MHz**
- **Spectral resolution: 40 kHz**
- **Temporal resolution: 0.5 seconds**
- **Polarization: I, Q, U, V**

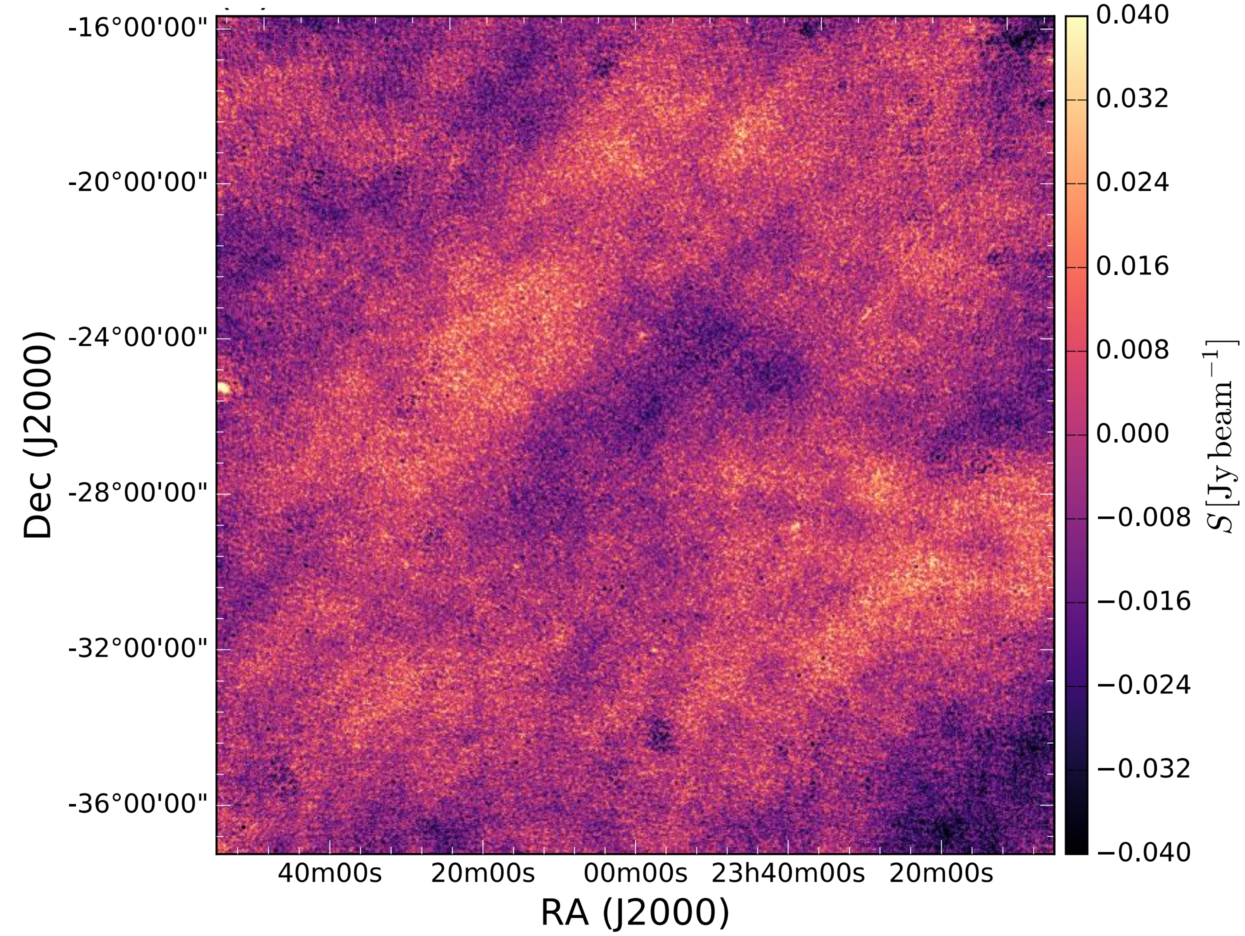
Photo credit: Natasha Hurley-Walker

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

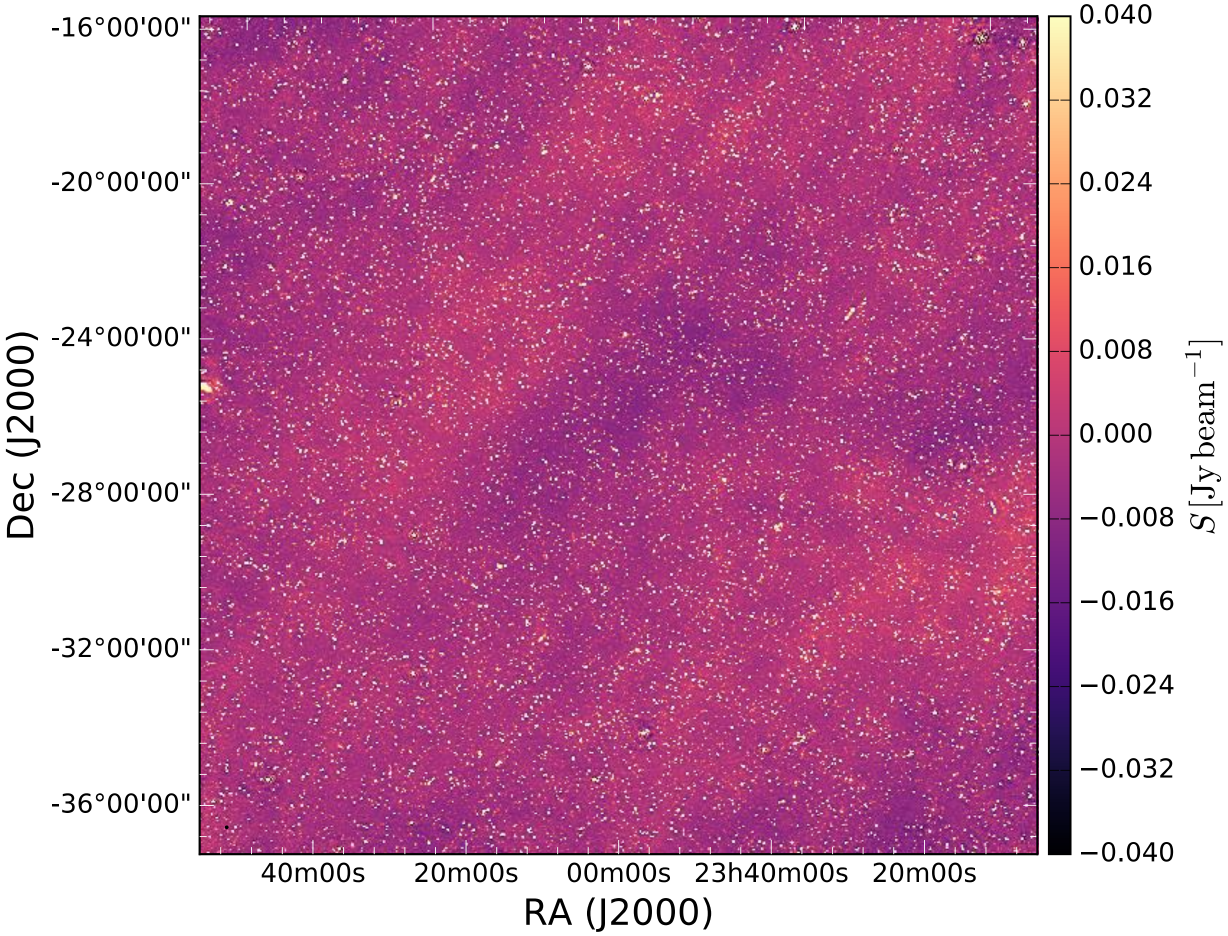
Cross Correlation with MWA - Radio

- **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**

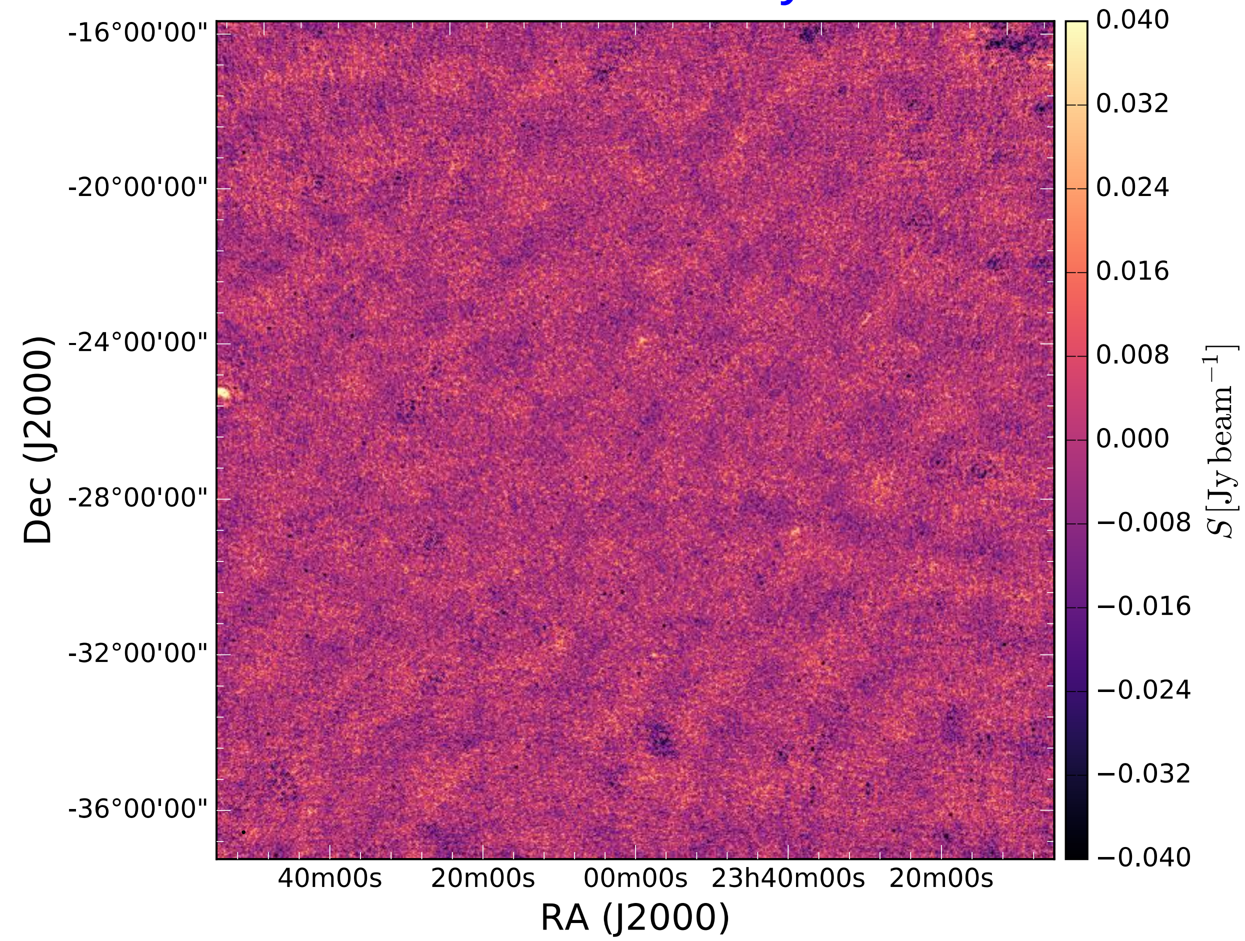
Point source sub



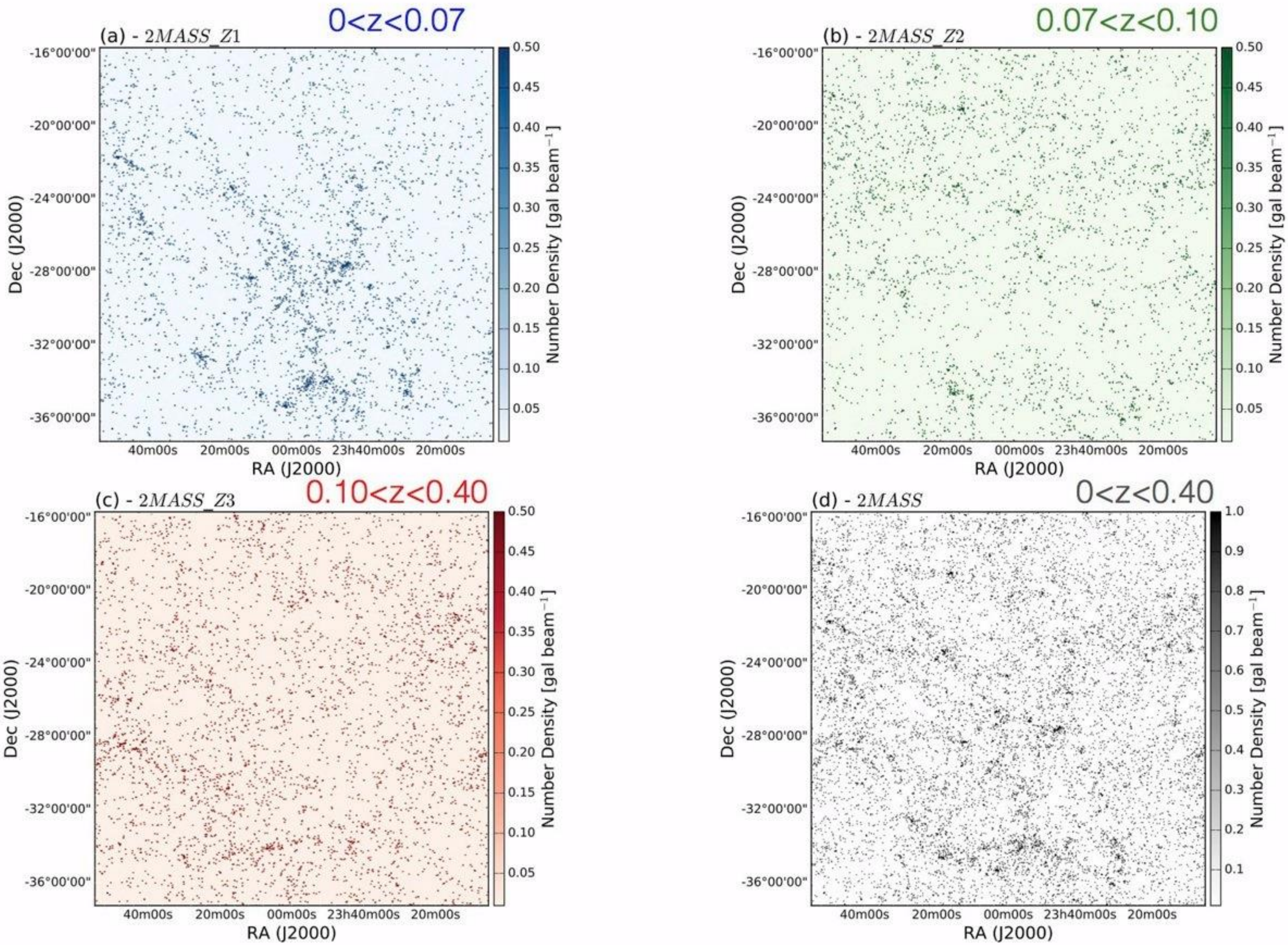
Full



Point source & Galaxy sub

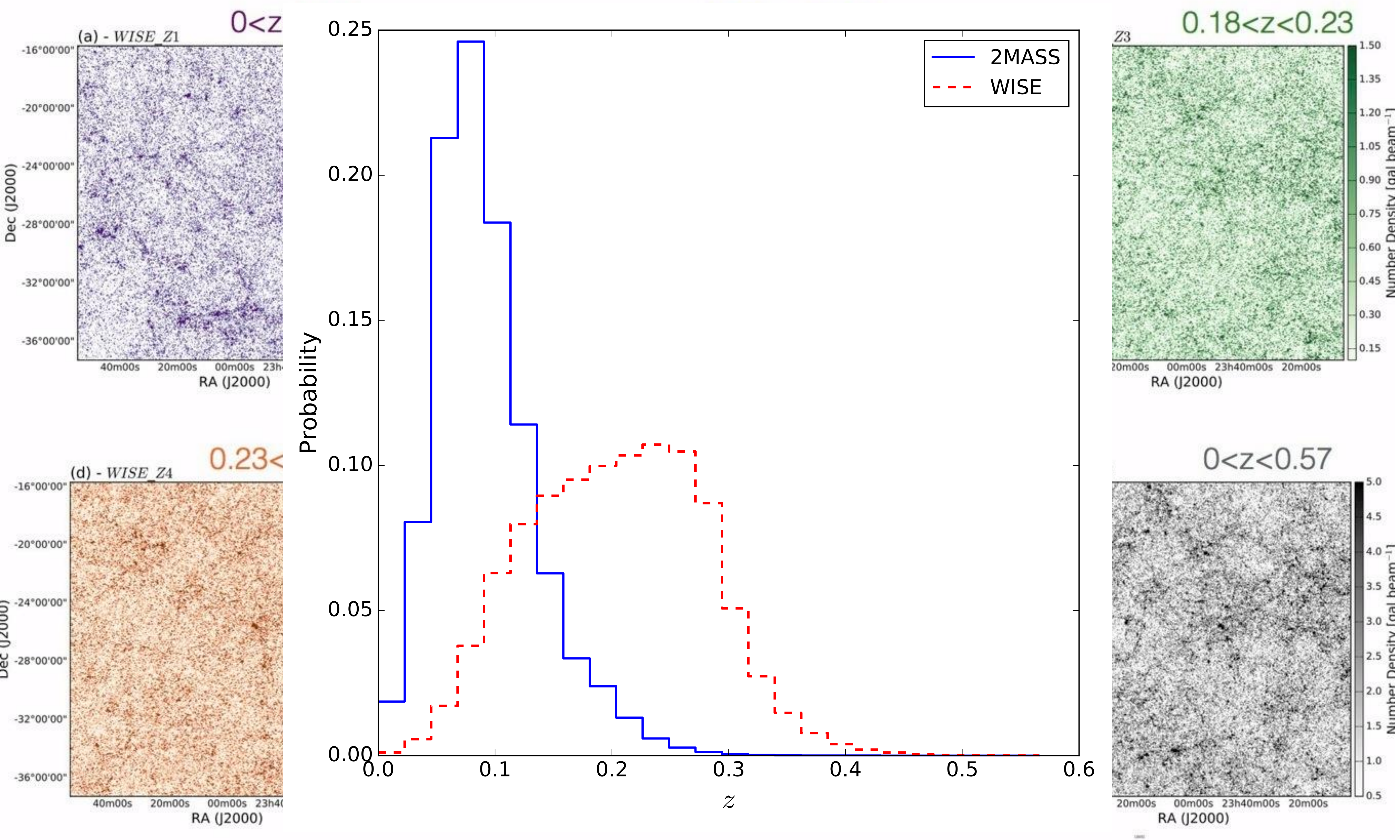


Cross Correlation with MWA - 2MASS Galaxy Density



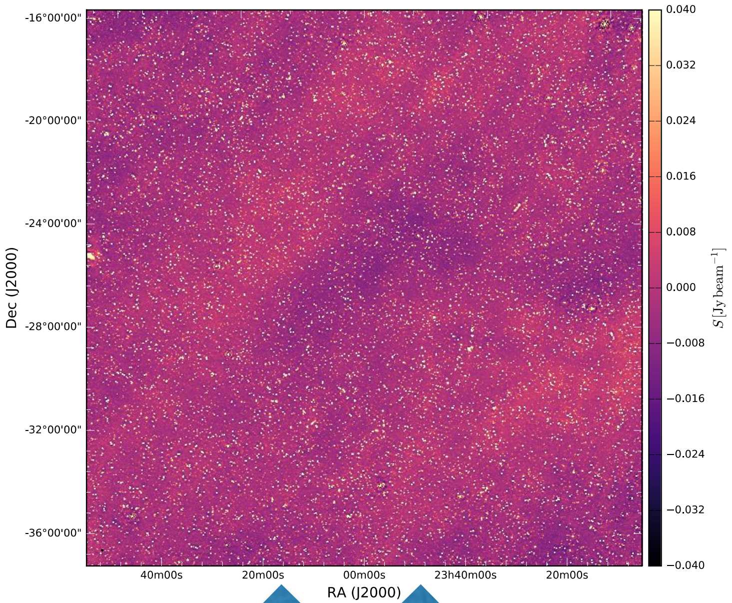
)NTO

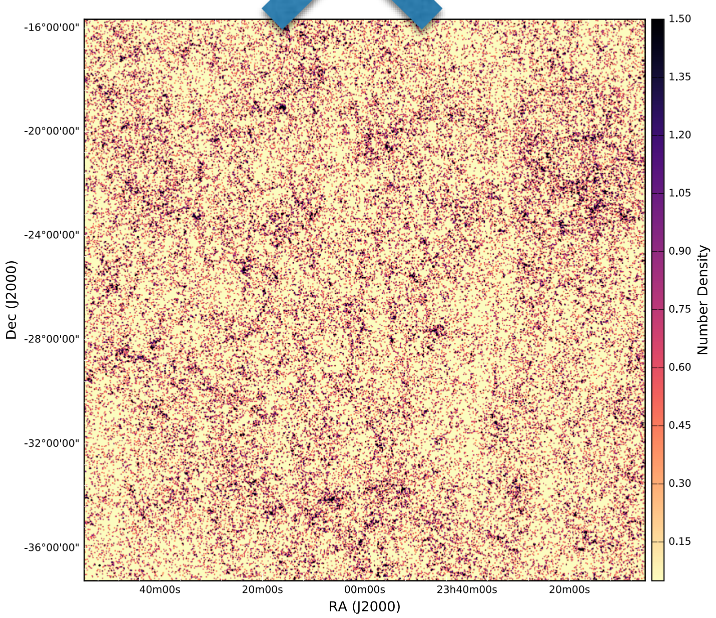
Cross Correlation with MWA - WISE Number Density



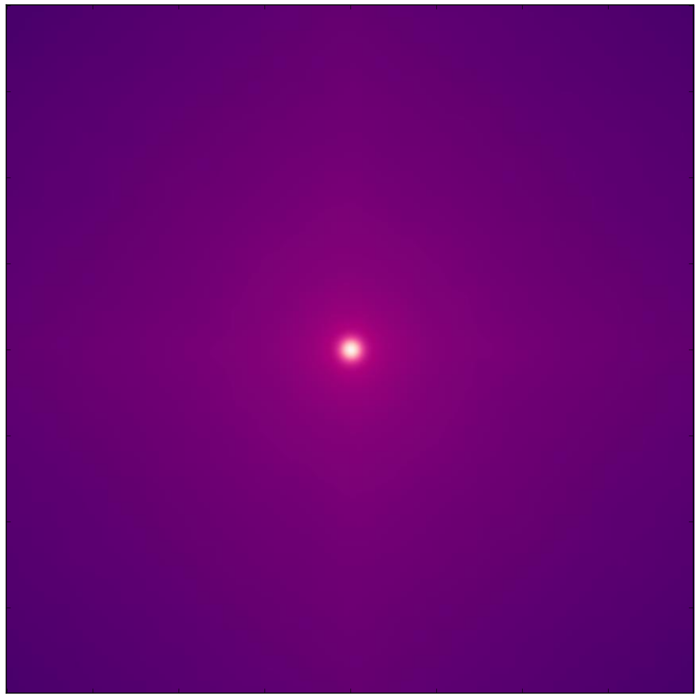
Cross Correlation with MWA

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





Δθ



Δθ

Take radial average

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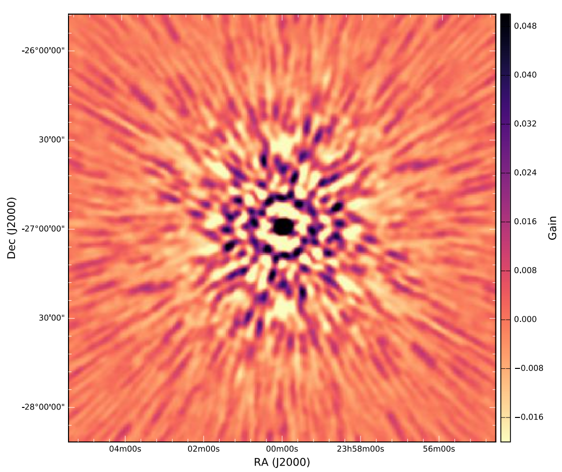
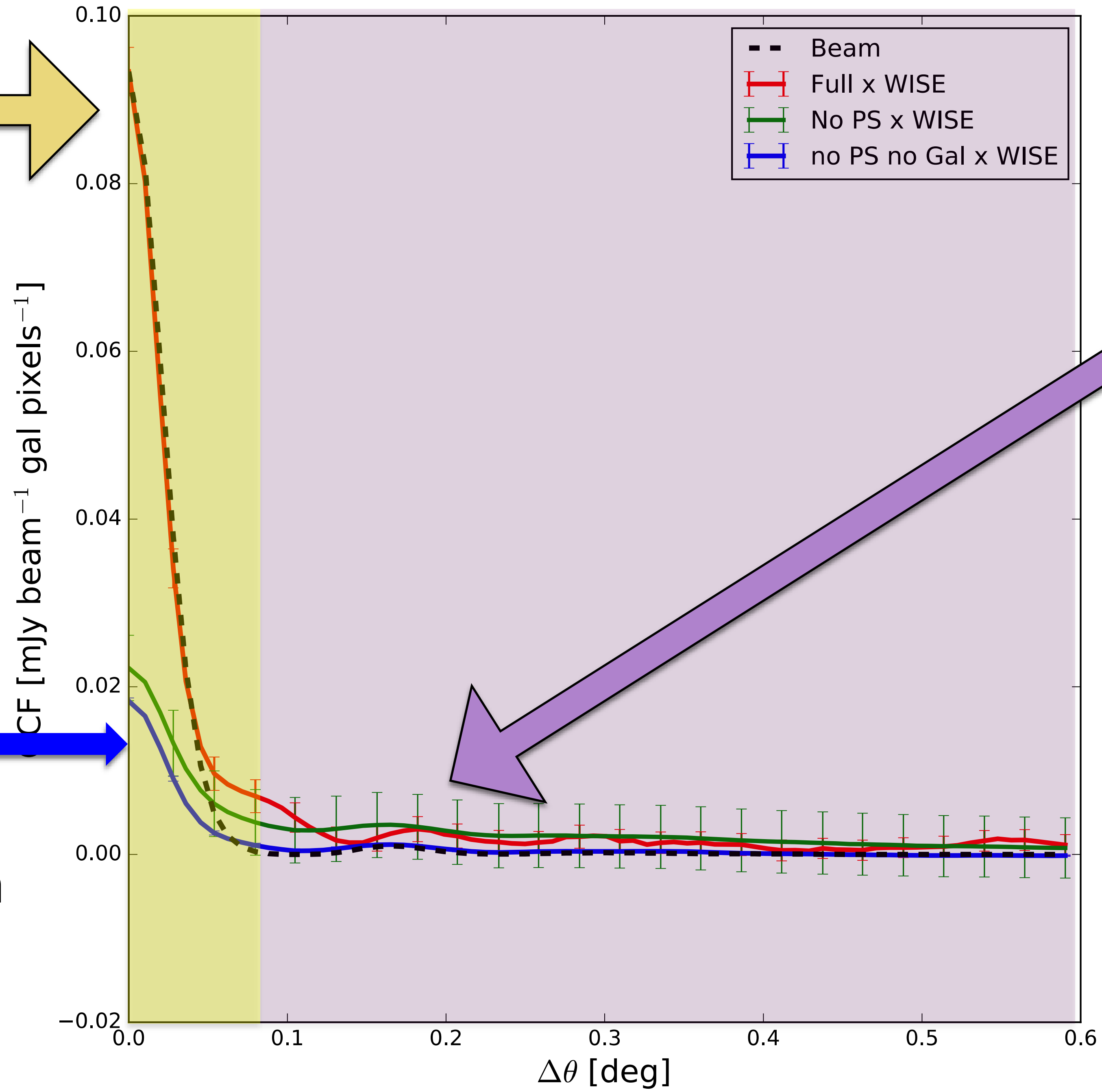
Dunlap Institute for Astronomy & Astrophysics UNIVERSITY OF TORONTO

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



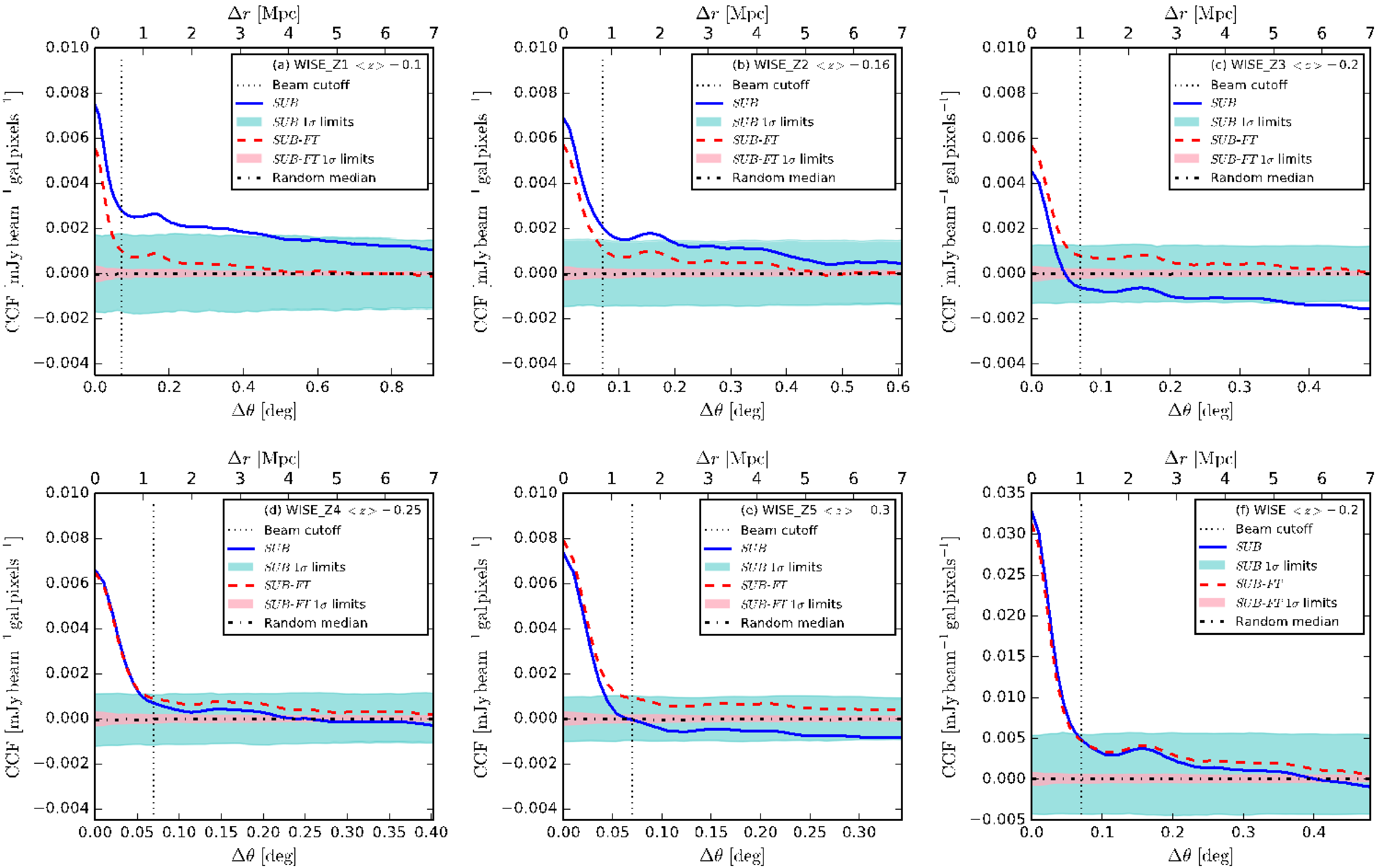


Diffuse emission → larger than beam

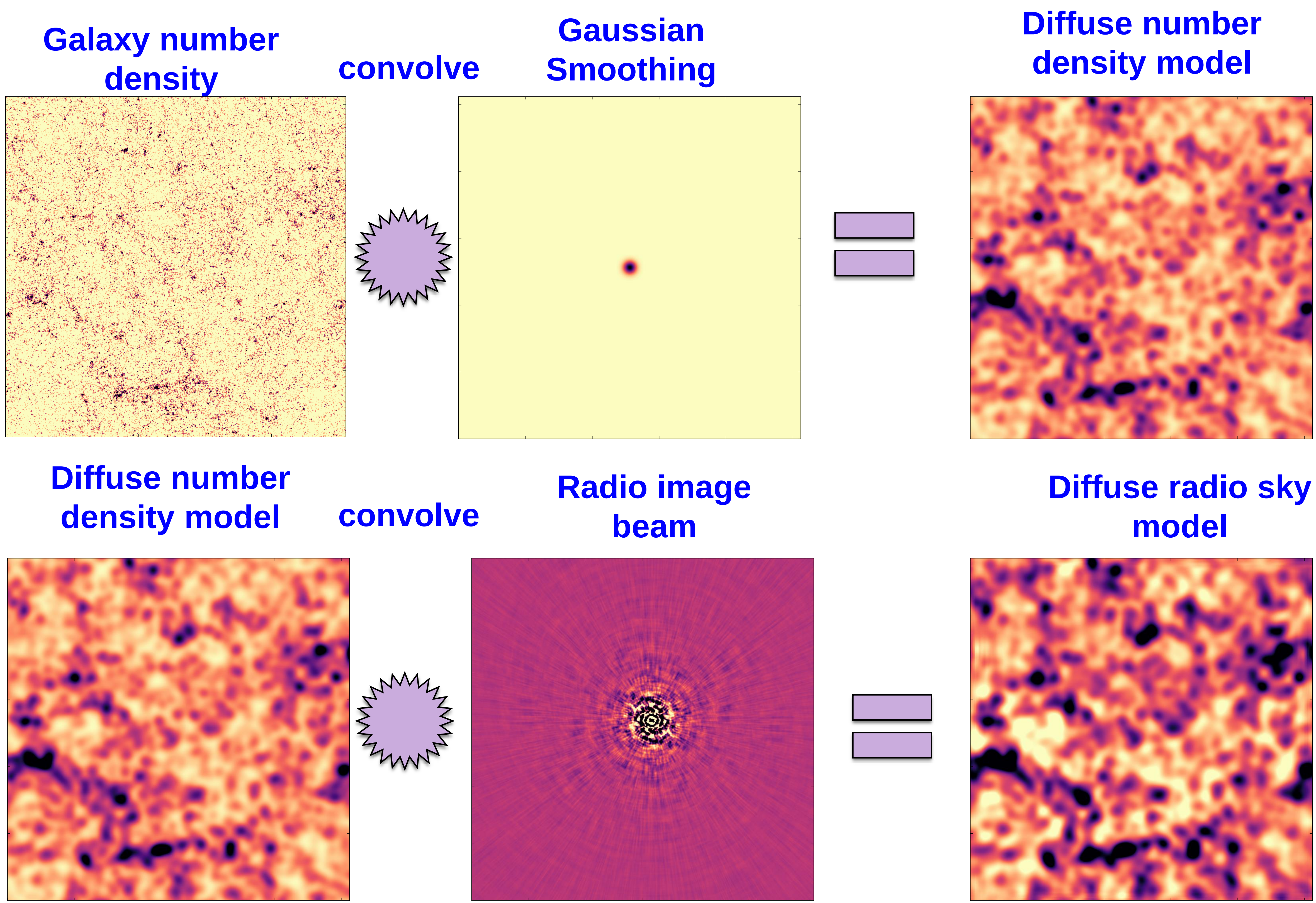
Still some point source contribution

So how much diffuse is there ???

Cross Correlation with MWA

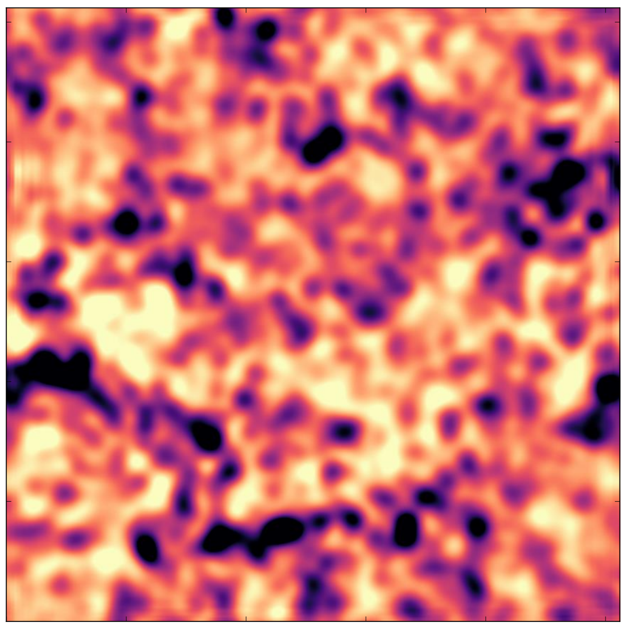


Cross Correlation with MWA – Emission Upper Limits

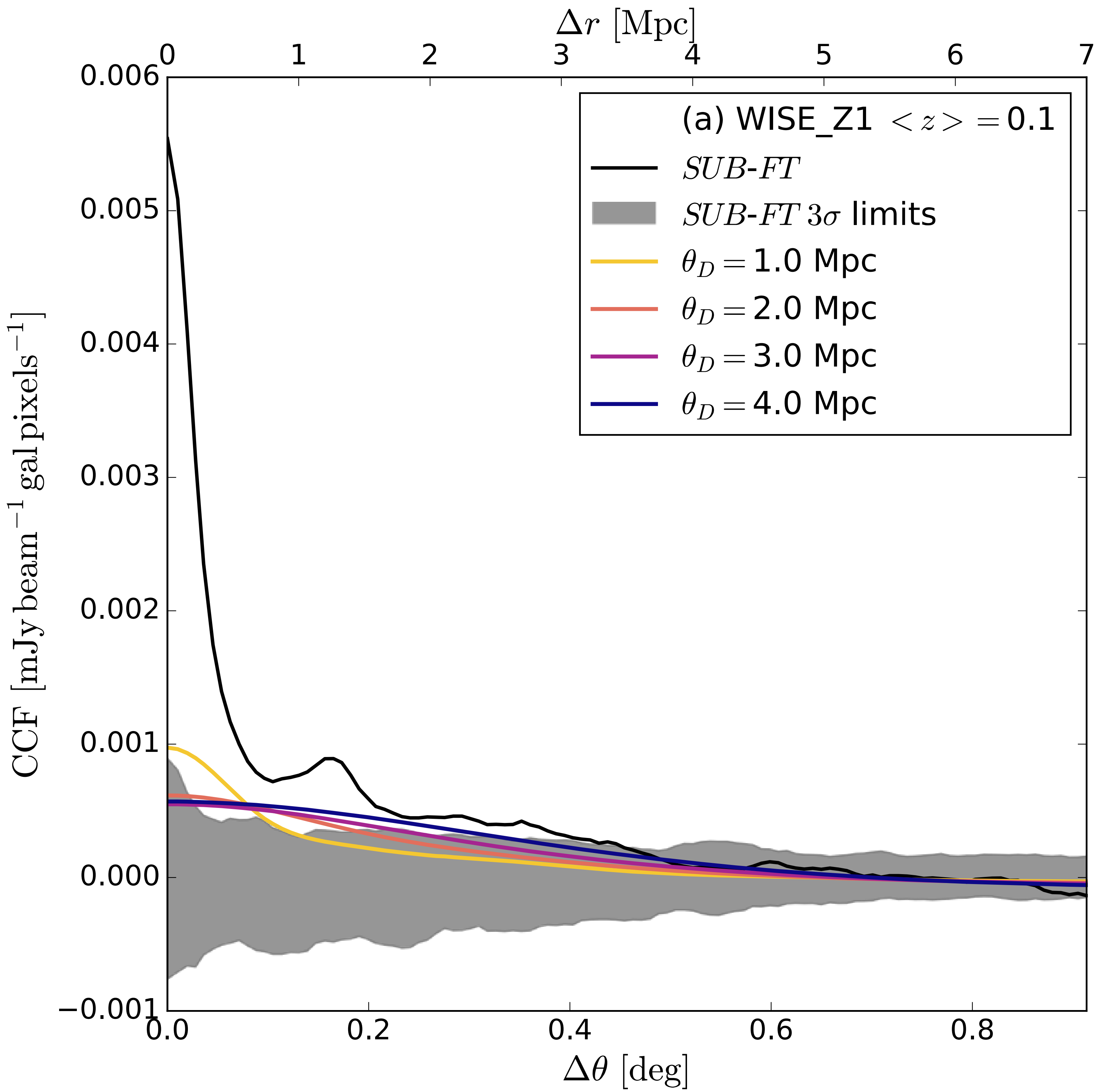


Cross Correlation with MWA – Emission Upper Limits

Diffuse radio sky model



Cross correl



Scale CCF until > 3σ

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

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

At 180 MHz

$130 < T_b$ [mK] < 1300

At 1.4 GHz ($\alpha = -1$)

$0.27 < T_b$ [mK] < 2.7

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Cross Correlation with MWA – Magnetic Field Limits

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

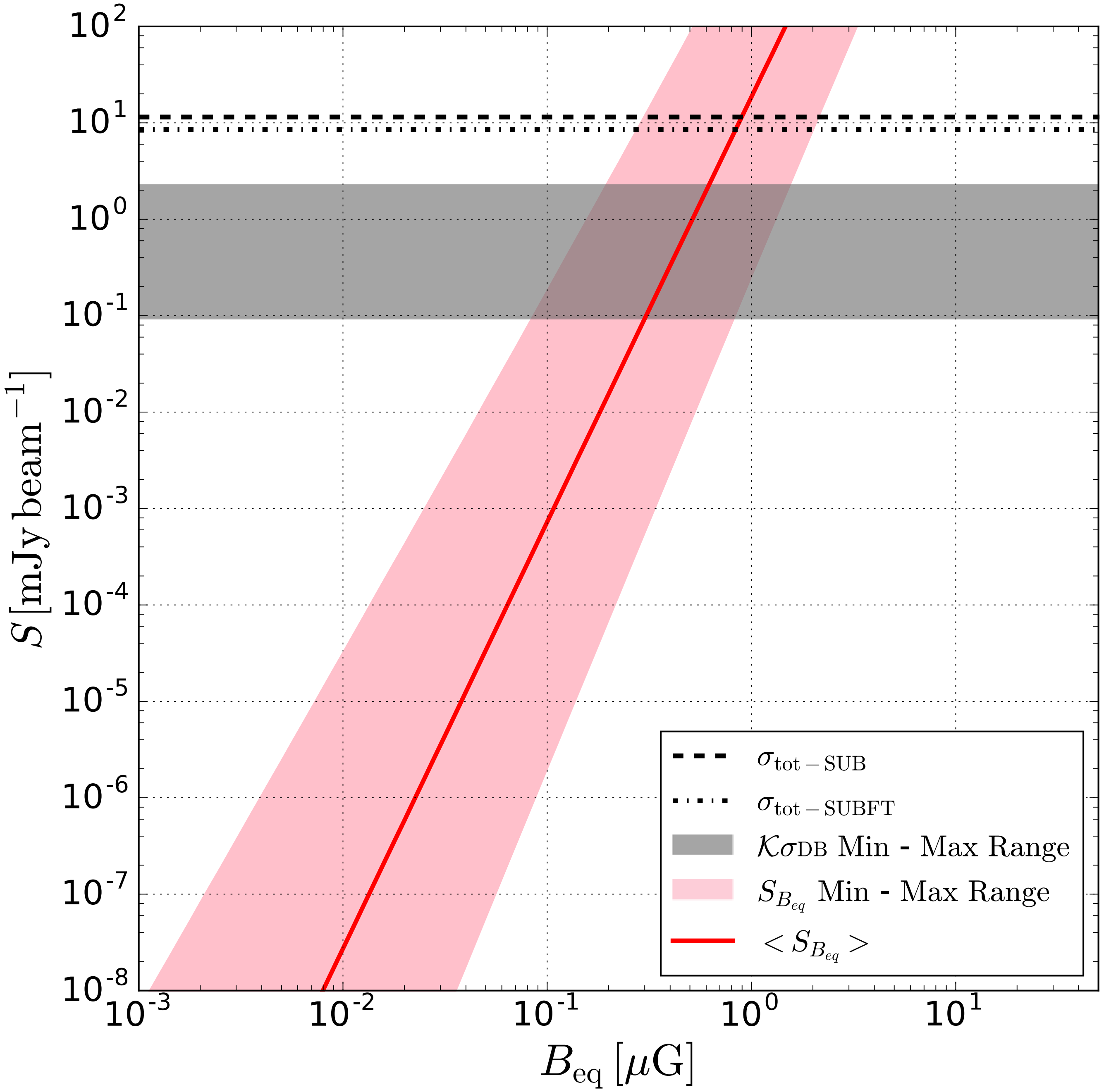
K_0 - ratio of number densities of cosmic ray protons and electrons per particle energy interval

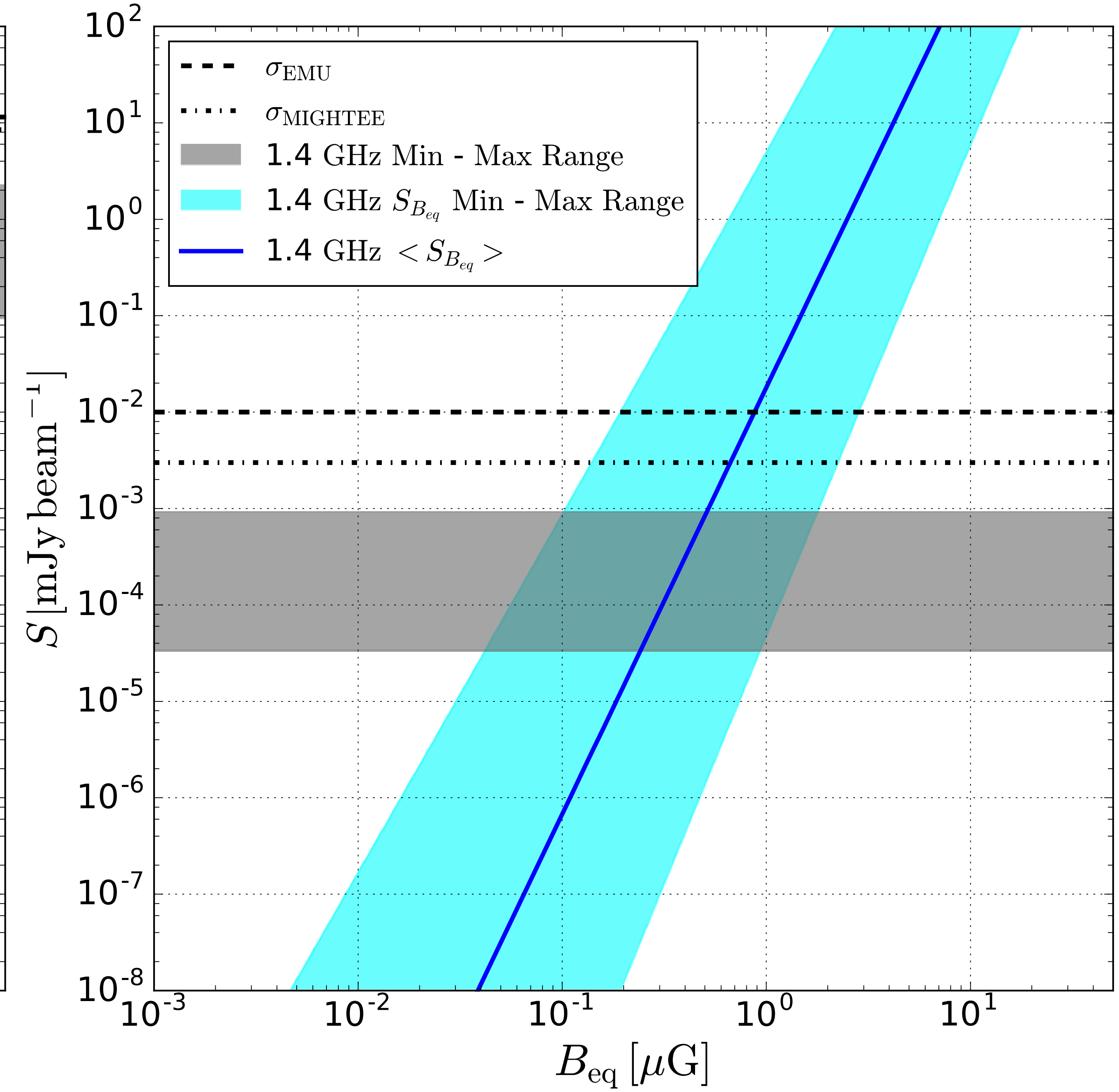
η – Volume filling factor

α – spectral index

Cross Correlation with MWA – Magnetic Field Limits

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





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Astronomy & Astrophysics UNIVERSITY OF TORONTO

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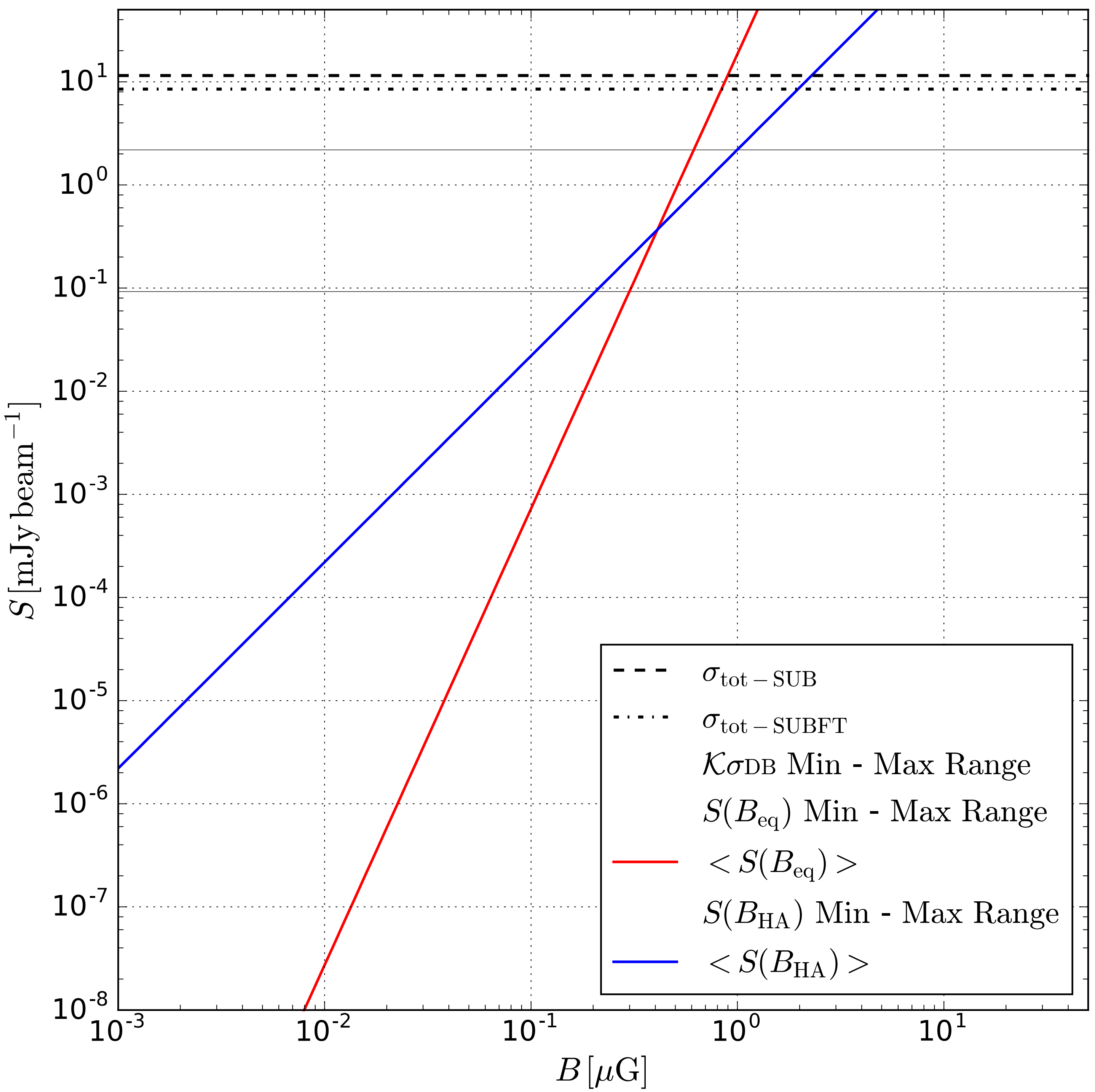


< K_0 < 300   0.01 < η < 1   -0.6 < α < -2.25

- **0.03 < B_{eq} [μG] < 1.98**

K_0=100   η=1.0   α = -1.25

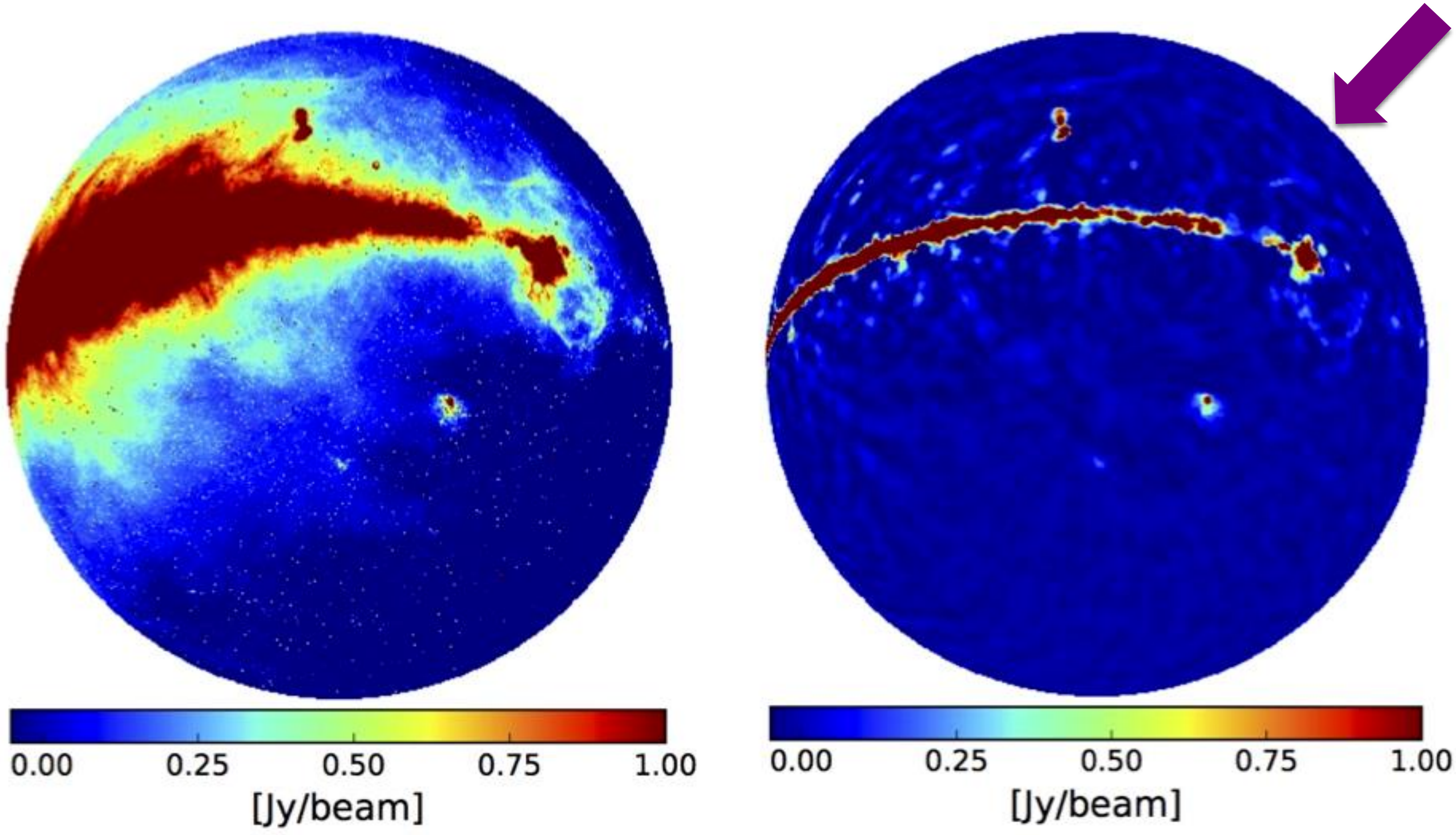
- **0.22 < B_{eq0} [μG] < 0.62**

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

Cross Correlation S-PASS

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

Galactic and point source filtering



Cross Correlation S-PASS

- **Single Dish 2.3 GHz All Sky**
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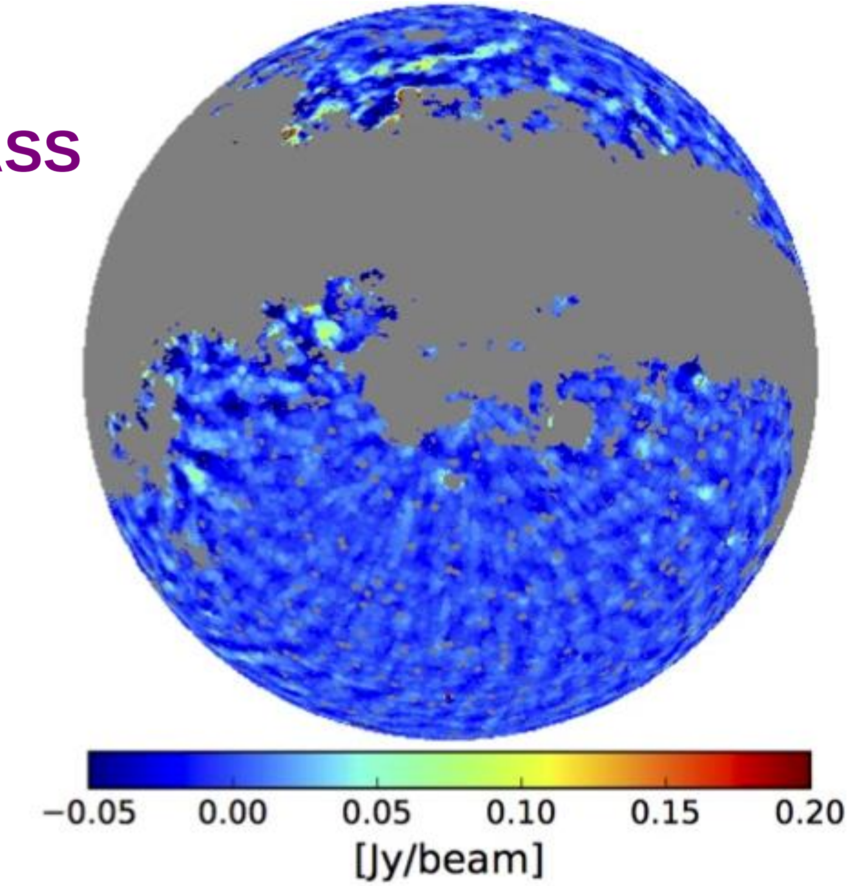
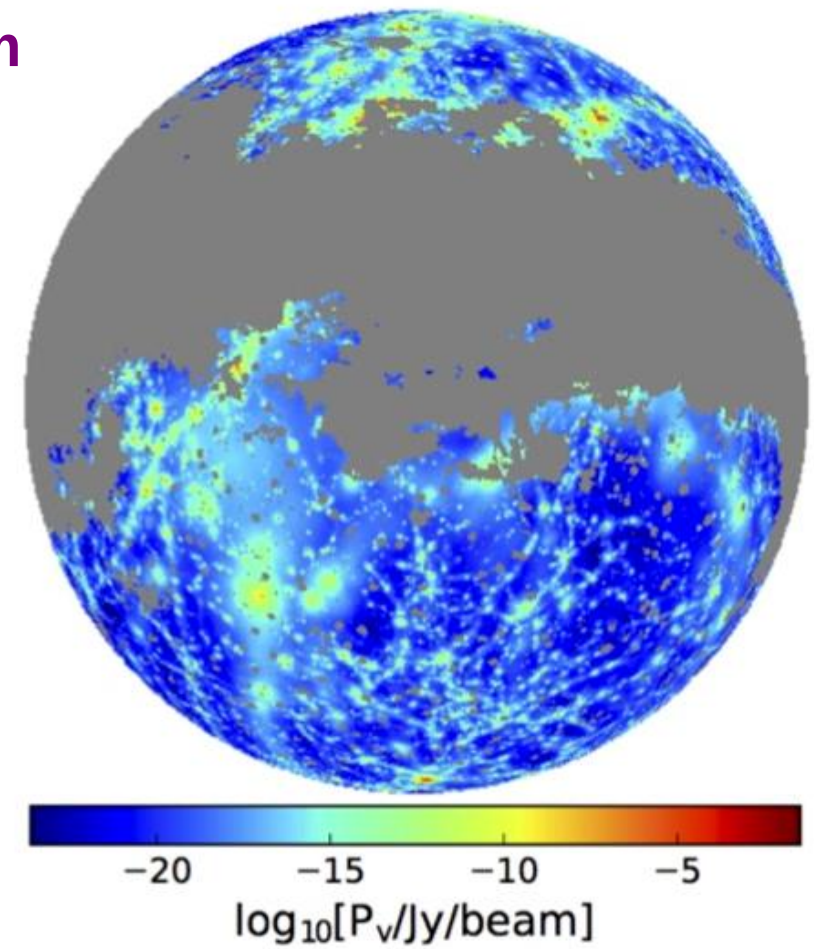
  - **Brown et al., 2017**

Masked

SPASS

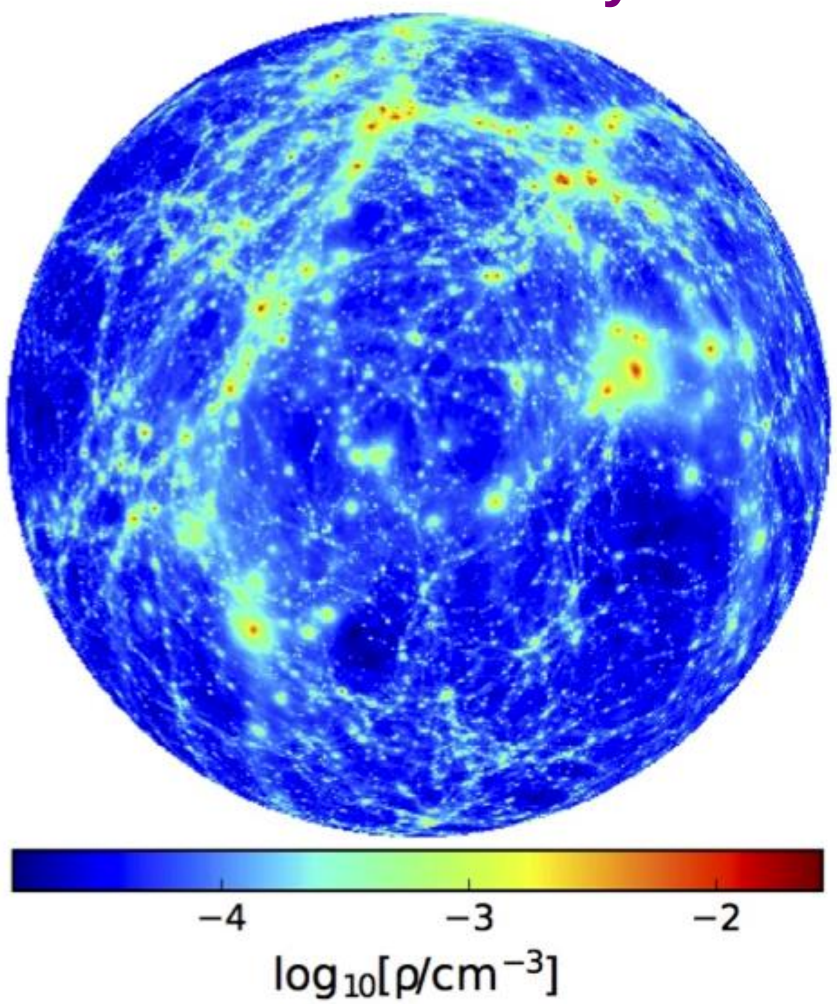


Sim

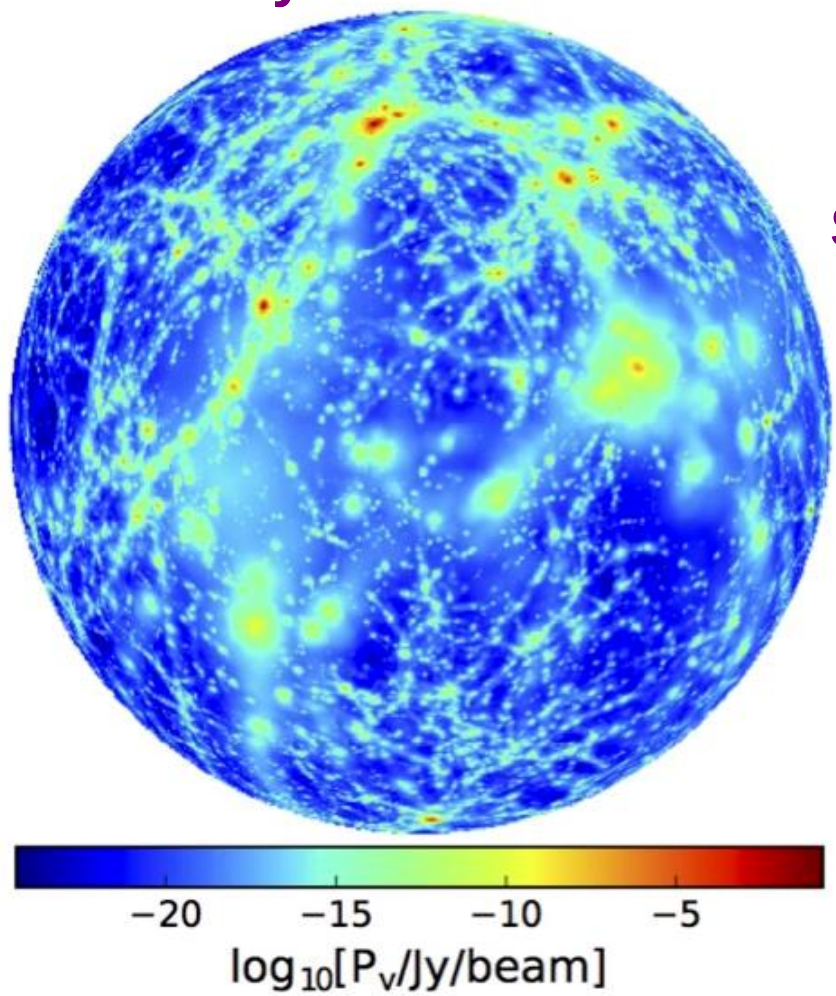


Simulations

Electron density



Synchrotron



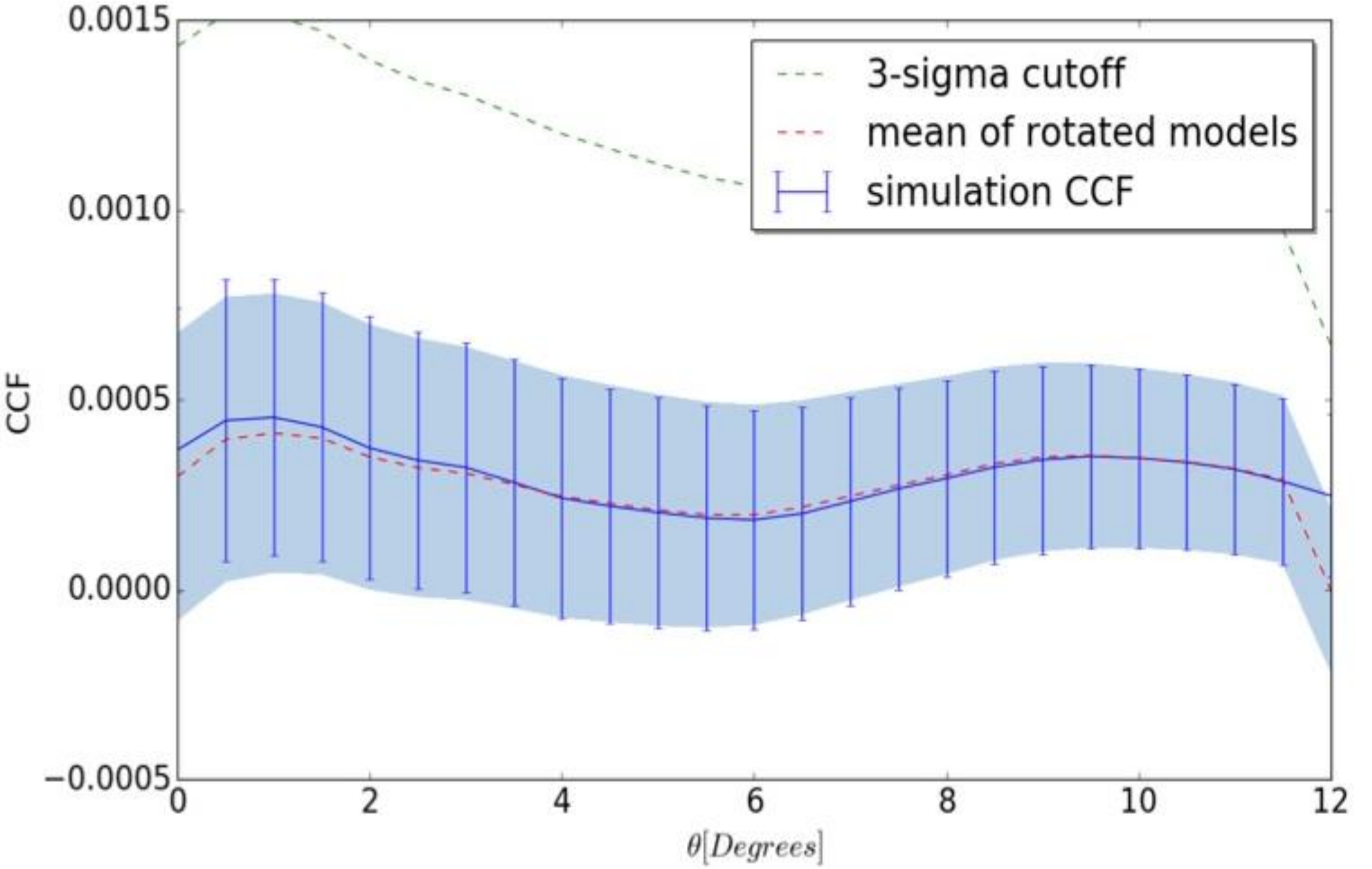
Cross Correlation S-PASS

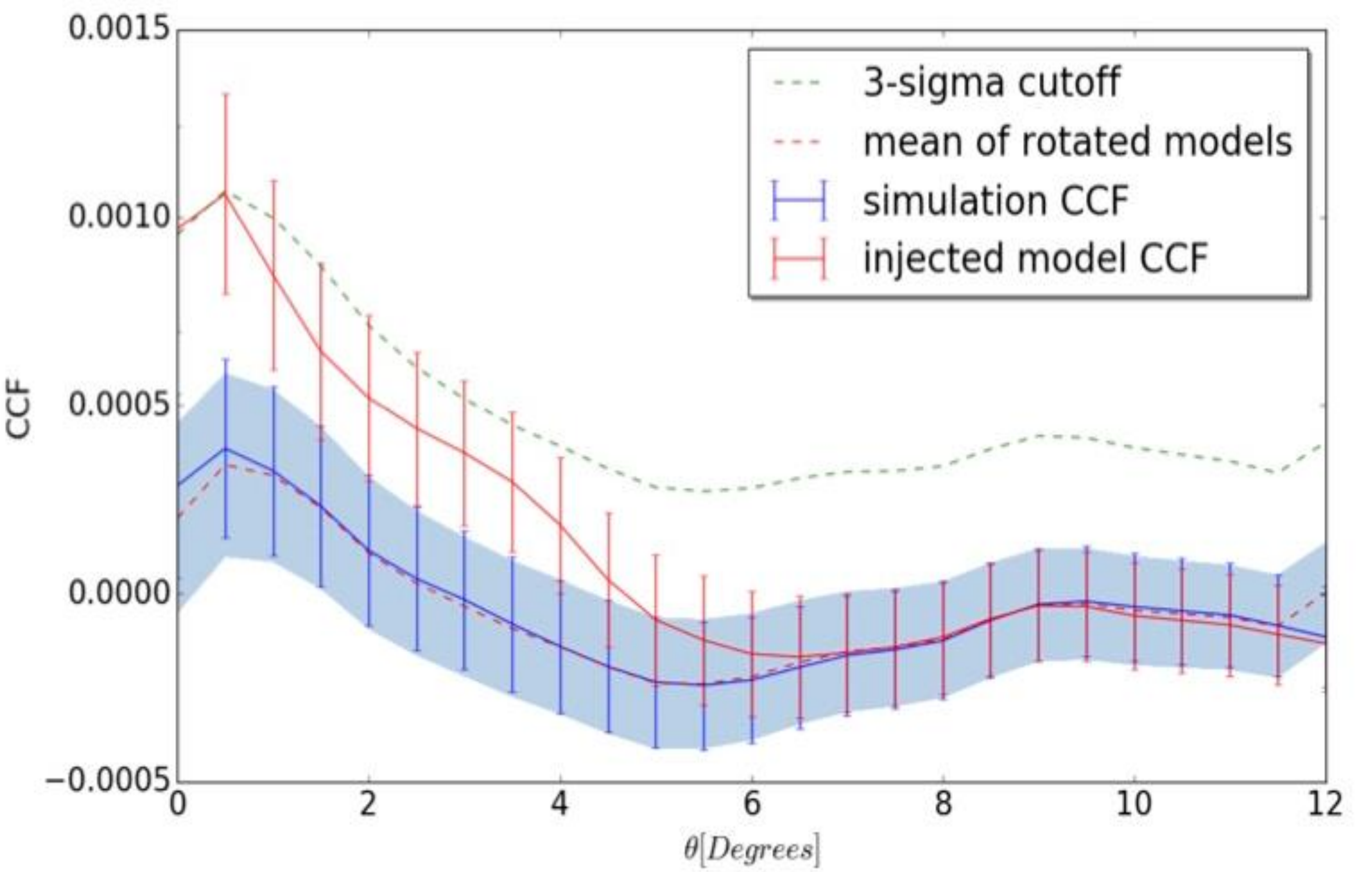
- **Single Dish 2.3 GHz All Sky**
- **Cross correlate with MHD simulation**
  - **Brown et al., 2017**

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

Magnetic field upper limit:
0.13 μG

Primordial Magnetic Field Limit:
1.0 nG





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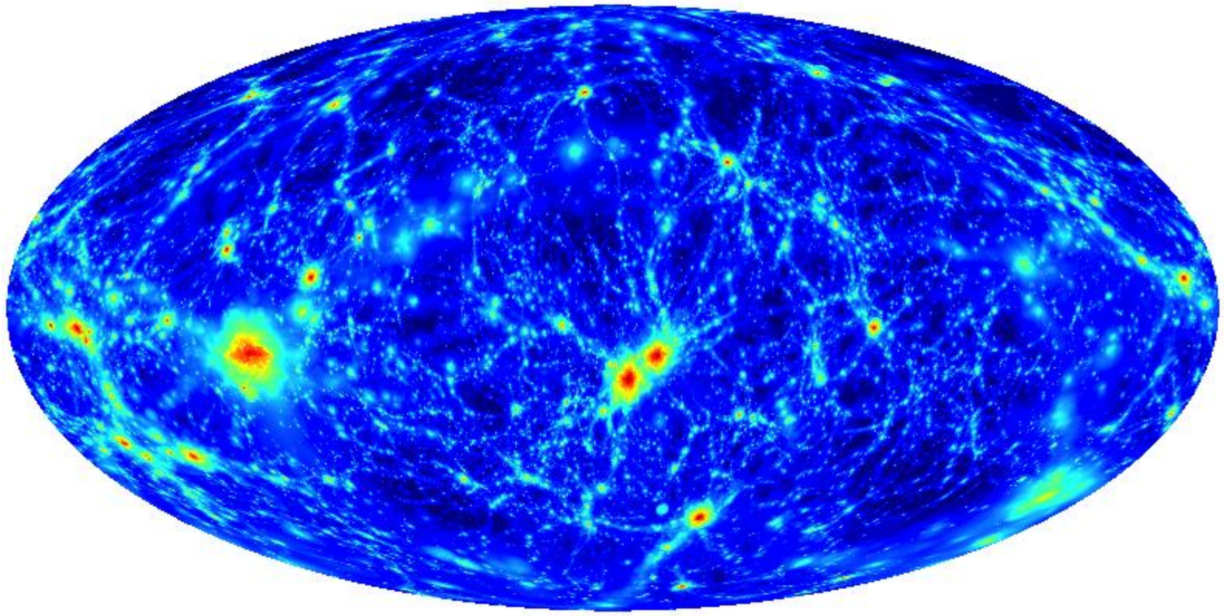
Cross Correlation



Advantages:

- Can enhance signals hidden in the noise

Disadvantages / Caveats:

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

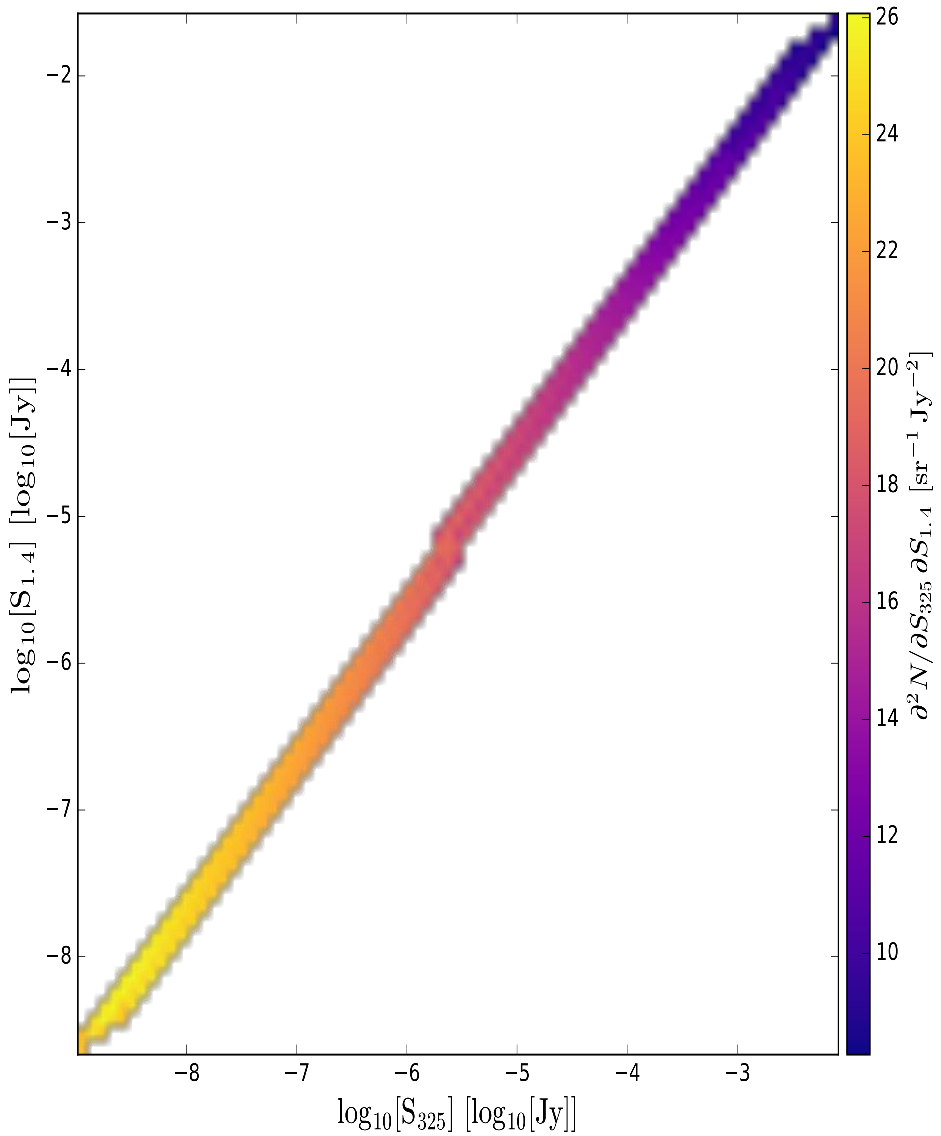
Future work / Continuations:

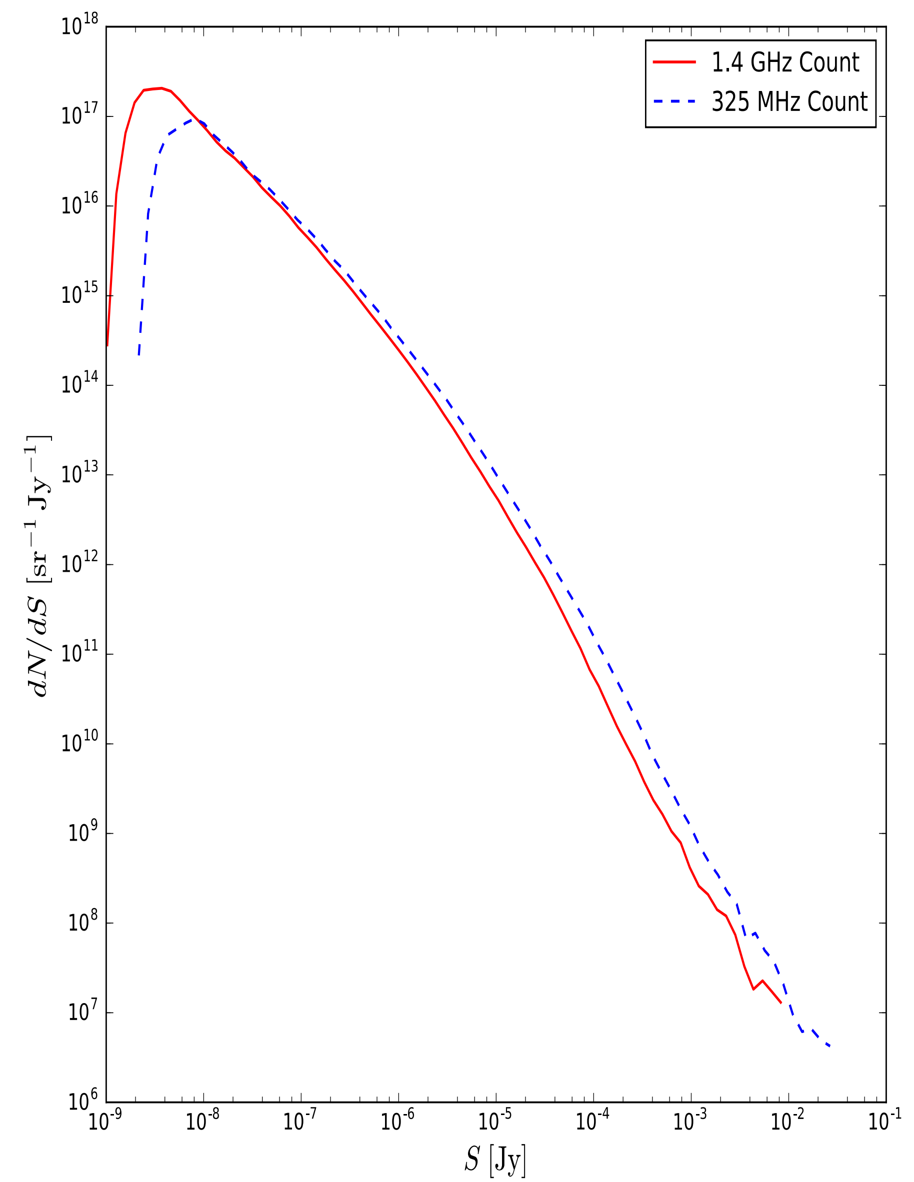
- Repeat with different area / frequency / resolution / sky coverage
- Multi-frequency approach
- Other similar tests: Cross power correlation, wavelet covariance

Other Methods

- **2D P(D) analysis**
  - **Fit 2D source count to 2D histogram**
  - **Can be two frequencies, two resolutions, total and polarised intensity**
  - **Provides tighter constraints, uses more data, breaks degeneracies**

$$\log_{10}\left[\frac{\partial^2 N(S_1, S_2)}{\partial S_1 \partial S_2}\right]$$





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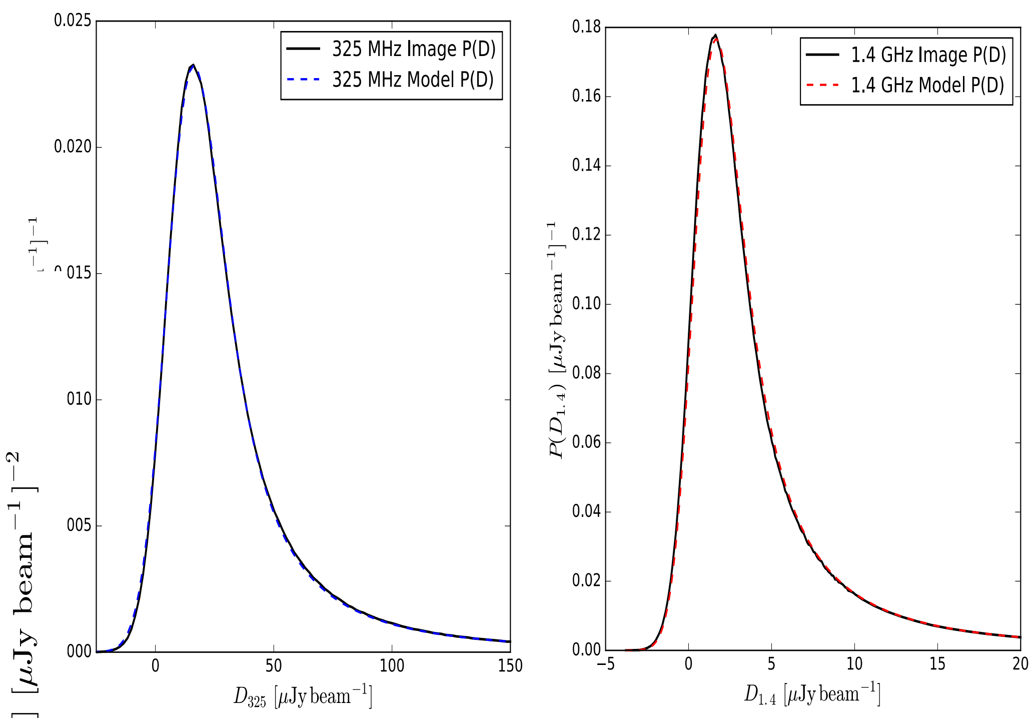
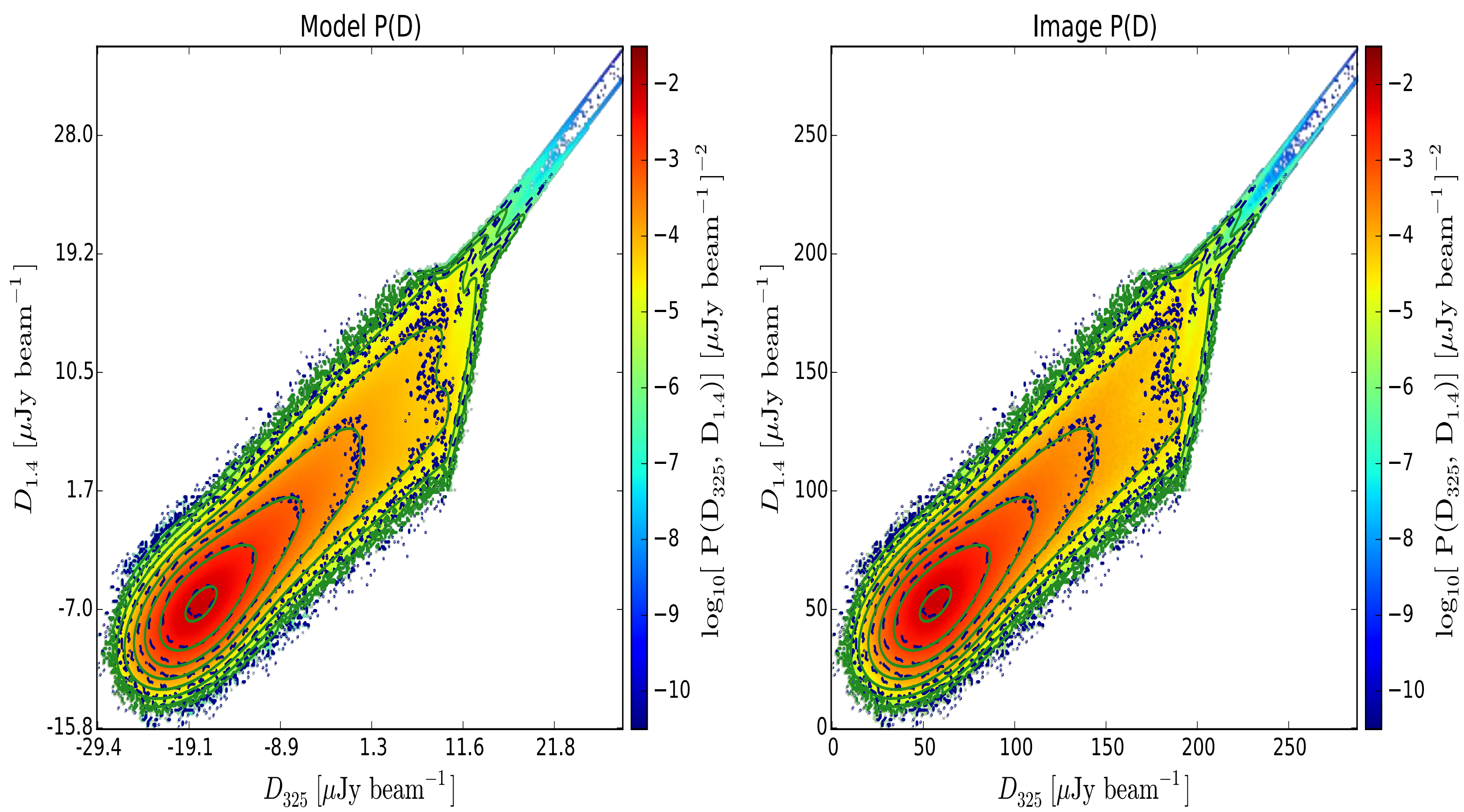




Other Methods

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

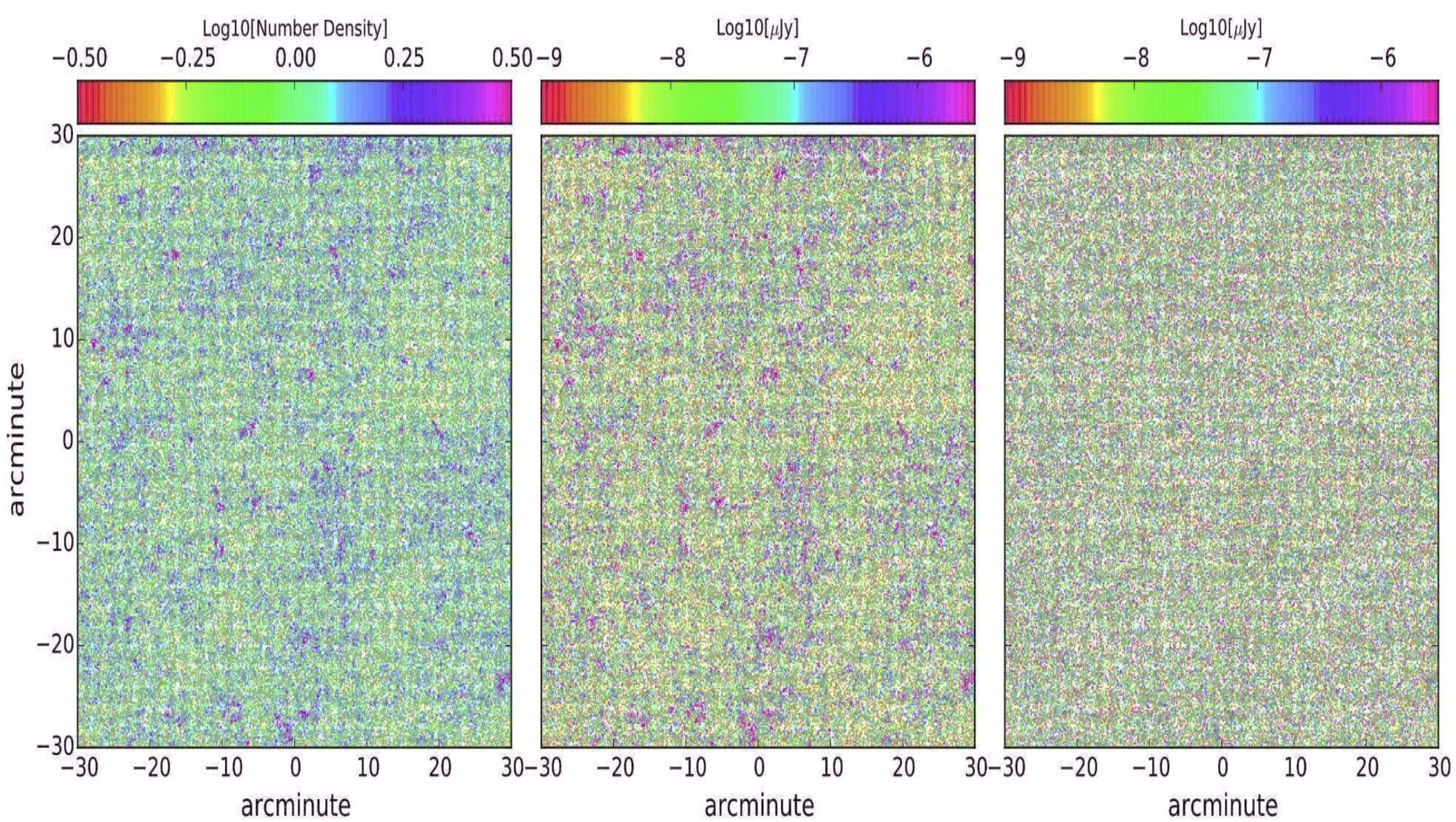
- **2D Angular power spectrum & P(D) in the visibility plane**

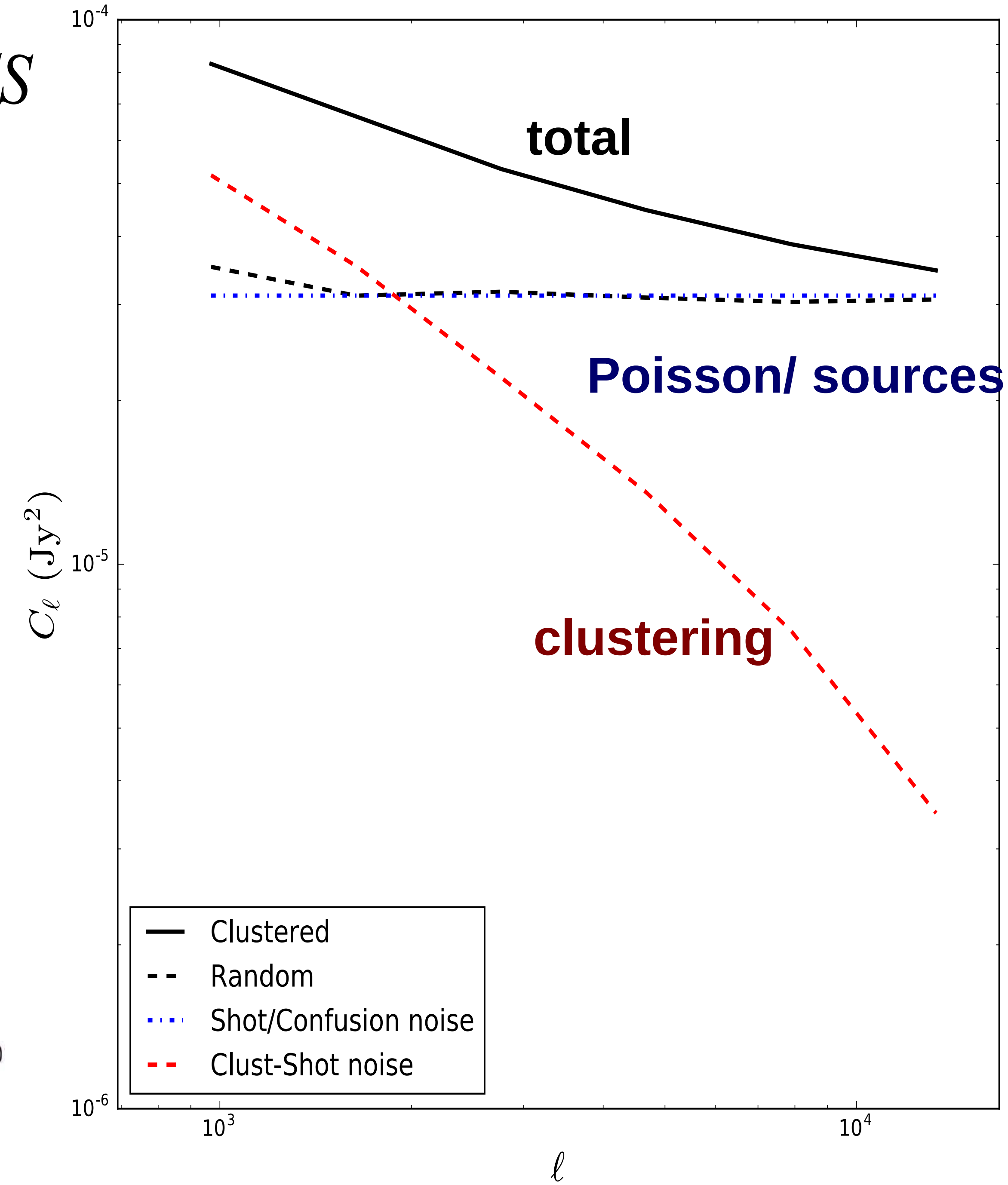
- **Can use the confusion noise to estimate Poisson contribution**

$$\sigma^2 = \int S^2 \frac{dN}{dS} dS$$

- **Where σ^2 is the (flat) amplitude of the power from sources**

- **Also known as P(D) in the visibility plane**





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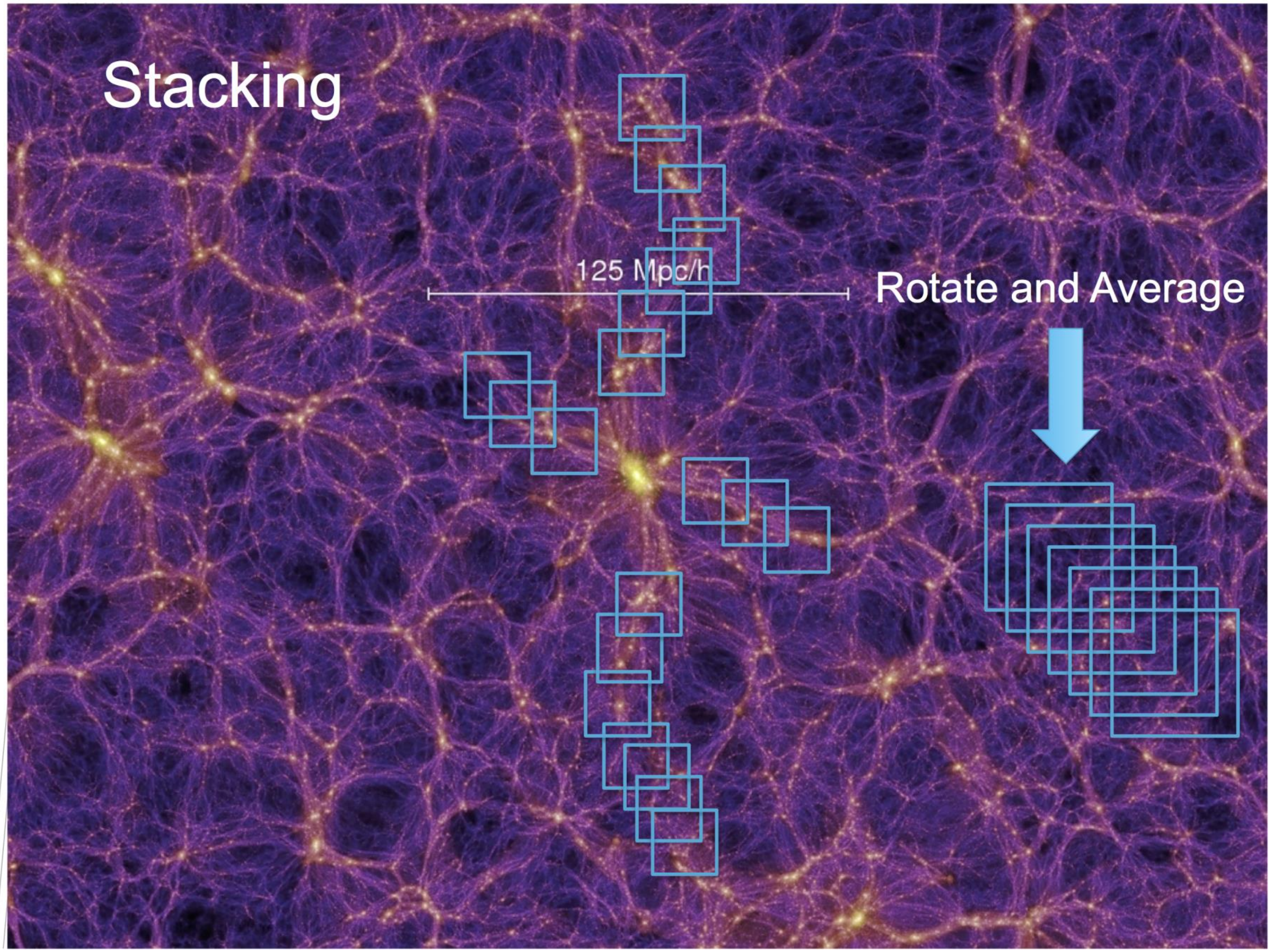
- **Stacking (diffuse emission/ filaments, e.g. Rudnick, Vazza, Farnes)**



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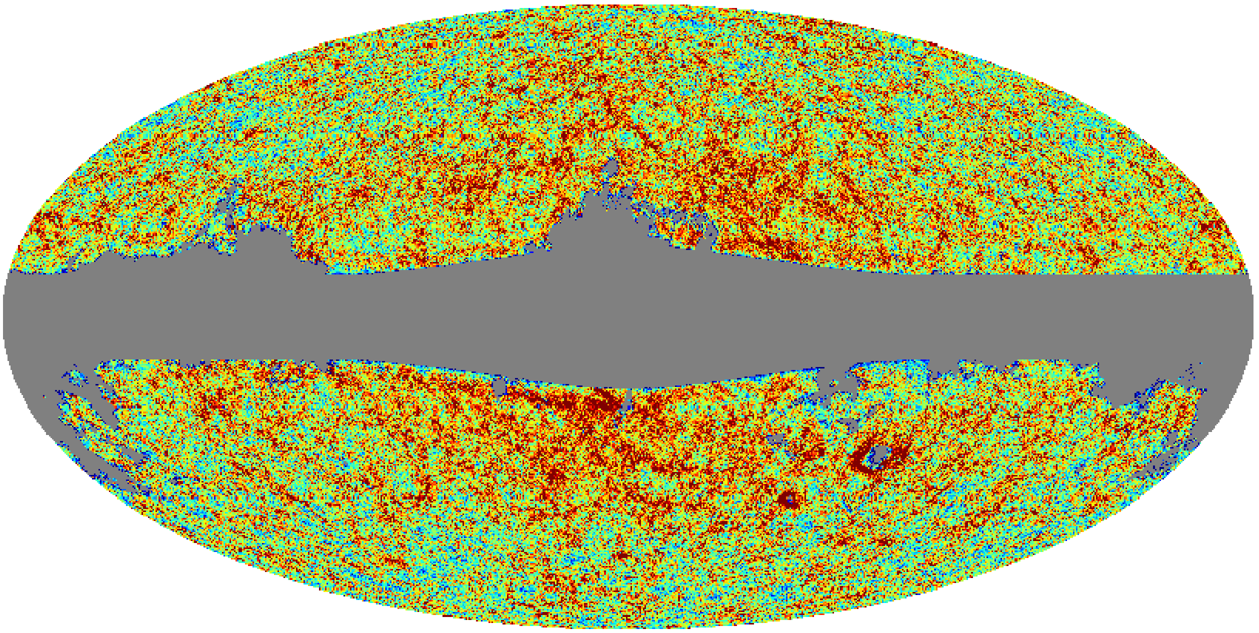
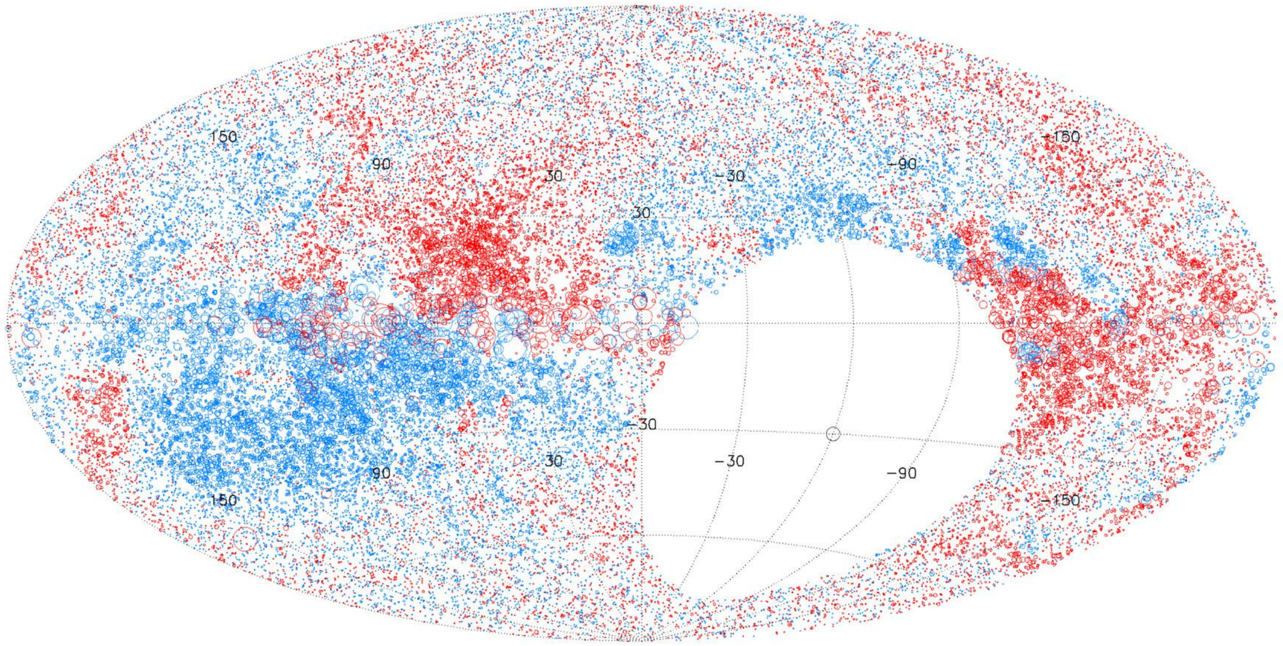


X



WISExsuperCOSMOS galaxy redshift catalog

Taylor et al. (2009) RM catalogue

Other Methods

- **2D P(D) analysis**
- **2D Angular power spectrum & P(D) in the visibility plane**
- **Stacking (diffuse emission/ filaments, e.g. Rudnick, Vazza, Farnes)**
- **Rotation measure cross correlation (cosmic web, Lee, Amaral, Gaensler et al)**
- **Cross power spectrum (cosmic web)**
- **Wavelet covariance (cosmic web)**
- **Combinations, e.g. confusion analysis + cross correlation**

Total Background Temperature

At ~1.4 GHz

Source counts **~115 mK** + **Diffuse cluster** **~10 mK** + **Cosmic web** **~1 mK**

=

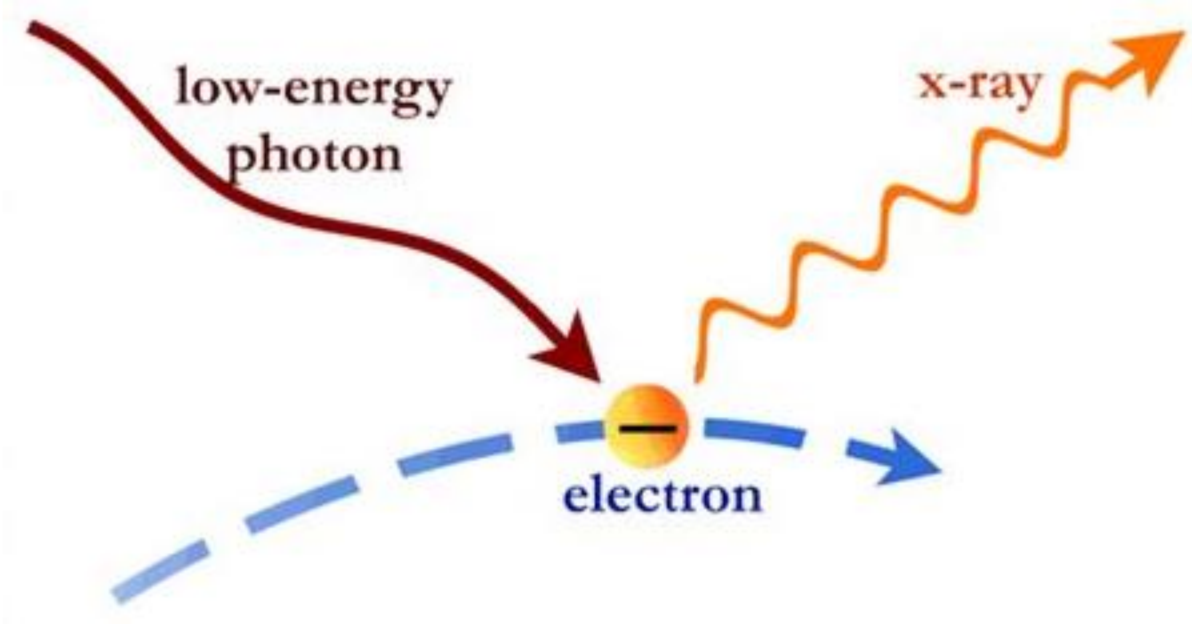
126 mK ± 15 mK

Total Background Temperature – X-ray limits

- **Radio emission related to X-ray emission**
  - **Low energy CMB photons up-scatter from electrons giving off synchrotron emission**

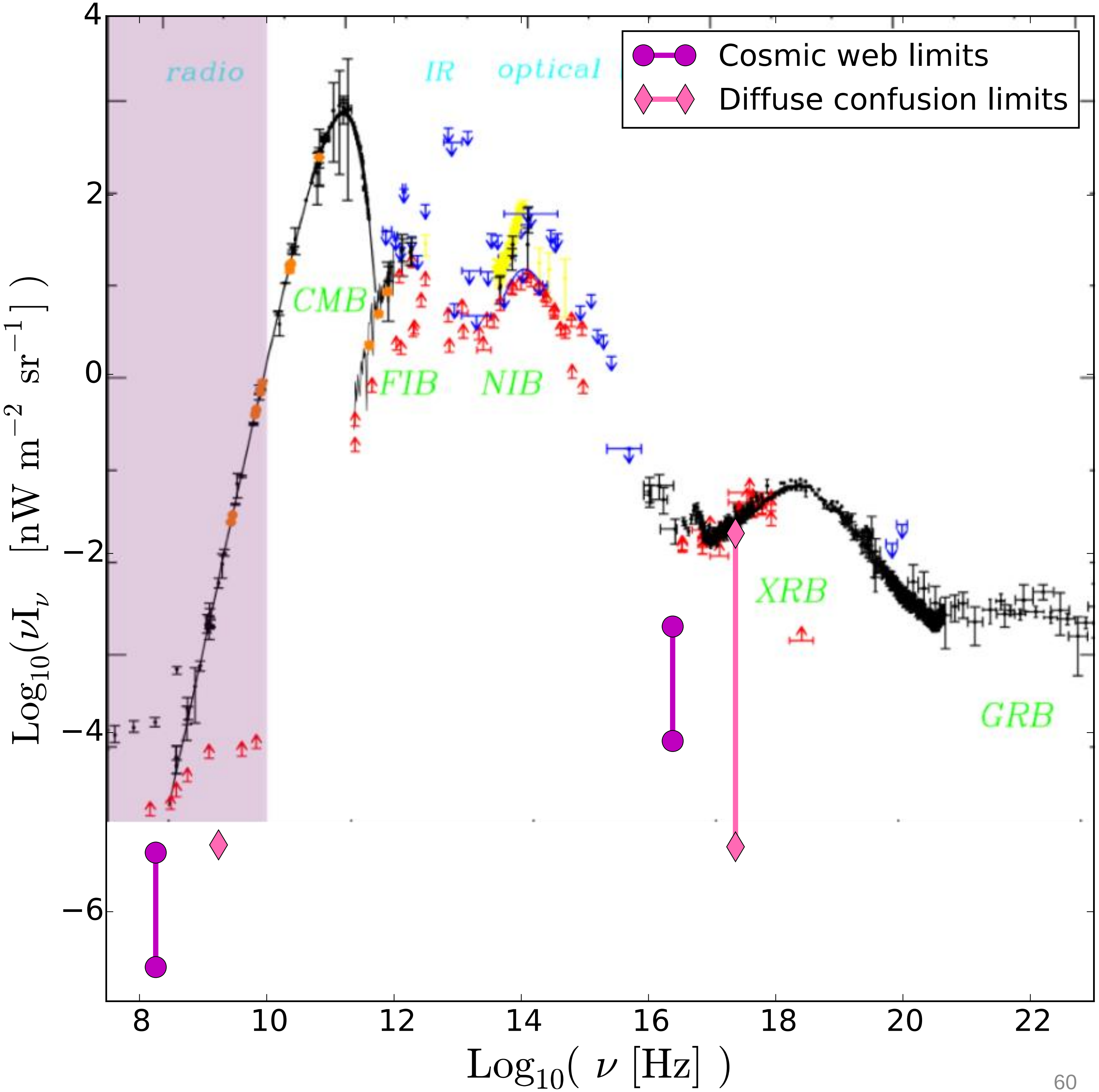
$$\frac{L_{\rm IC}}{L_{\rm sync}} = \frac{U_0(1+z)^4}{U_{\rm B}}$$

  - **Can use measurements of X-ray background to constrain radio**



Total Background Temperature

- **Assume ultra-relativistic**
  - **ϒ = 10⁴**
- **Use median redshift**
  - **z = 0.3**
- **For cosmic web use flux and magnetic field limits**
- **For diffuse confusion limit use a range for B of**
  - **0.1 < B [μG] < 6**



Total Background Temperature

At ~1.4 GHz

Source counts **~115 mK** + **Diffuse cluster** **~10 mK** + **Cosmic web** **~1 mK**

=

Upper Limit → **126 mK ± 15 mK**

≠

ARCADE 2
450 mK

Total Background Temperature

- **Assume ultra-relativistic**
  - **ϒ = 10^4**
- **Use median redshift**
  - **z = 0.3**
- **For cosmic web use flux and magnetic field limits**
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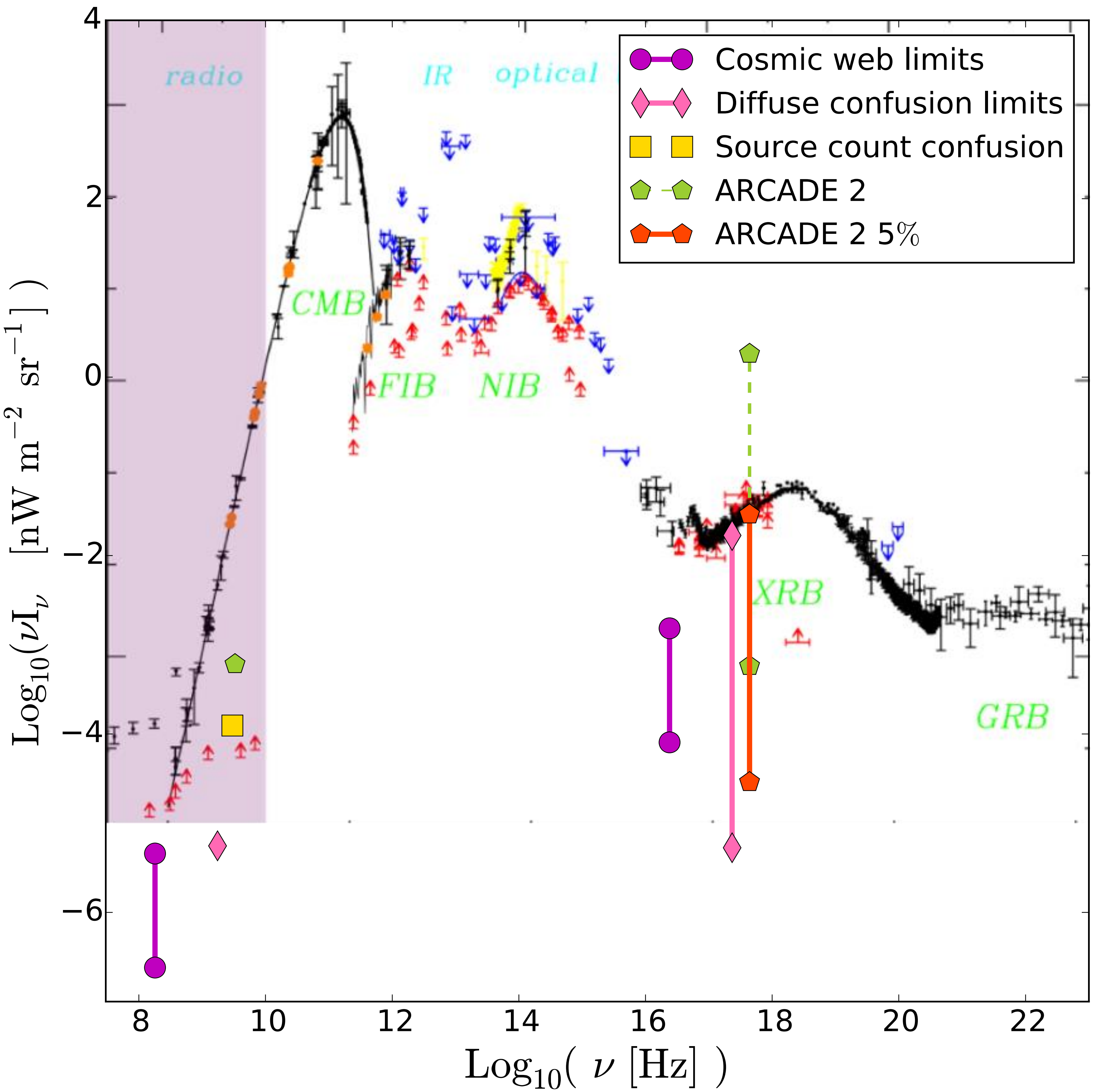

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Summary & Conclusions

- Extragalactic CRB temperature at 1.4 GHz ~ 120mK upper limit
  - Predominantly from individual sources
  - Up to ~10% from diffuse emission (2-3% of Arcade value) – upper limit of ~ 5-15 mK
- 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
    - Which can be used to constrain models of faint radio haloes/relics or dark matter
- Cross correlation technique yields upper limits on IGM of ~0.5 microG
  - Need more/better models to interpret results
- Statistical techniques can be powerful tools for reaching below the noise
- Understanding current and developing new techniques crucial for fully utilizing new large surveys