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Clarifying Confusion

SPARCS 2016 Goa

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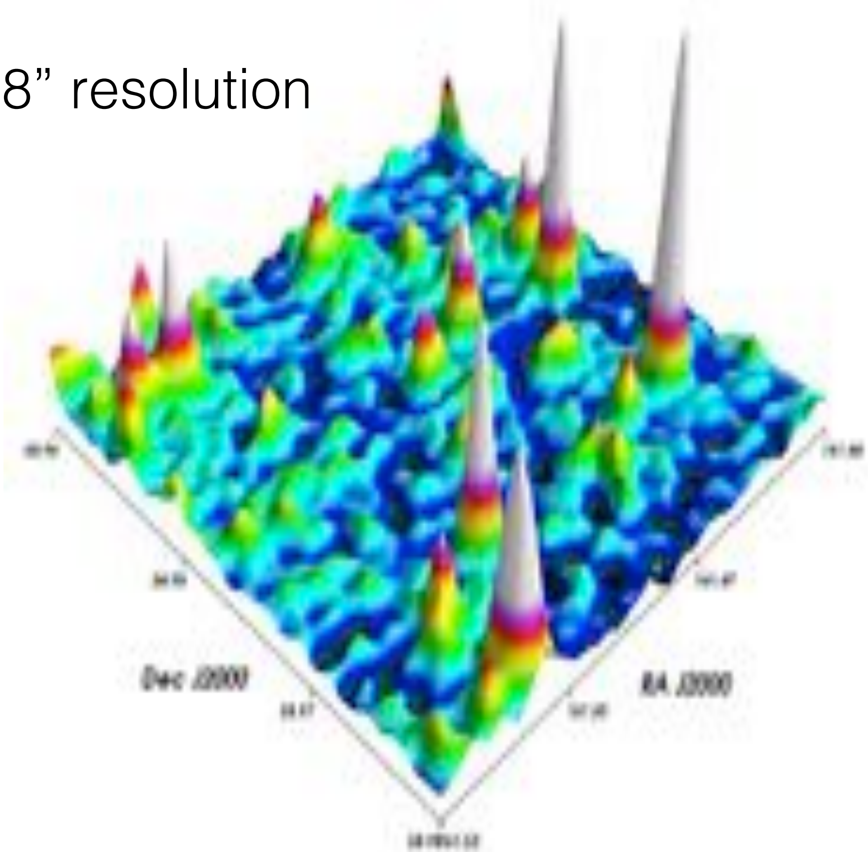
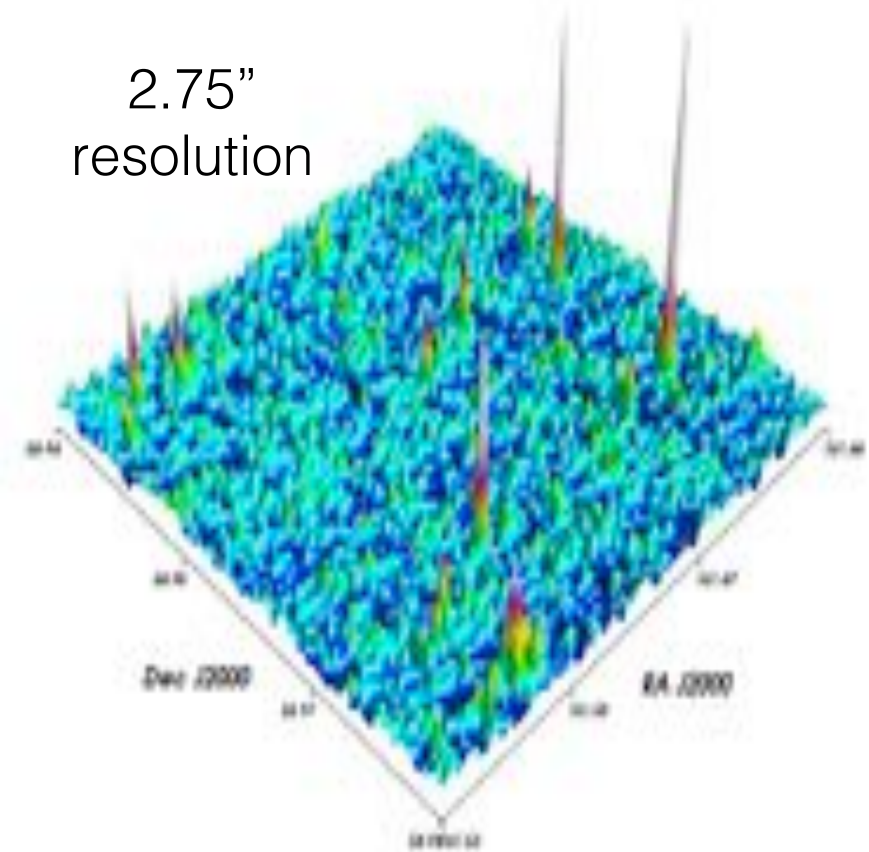
What is Confusion?

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

8" resolution

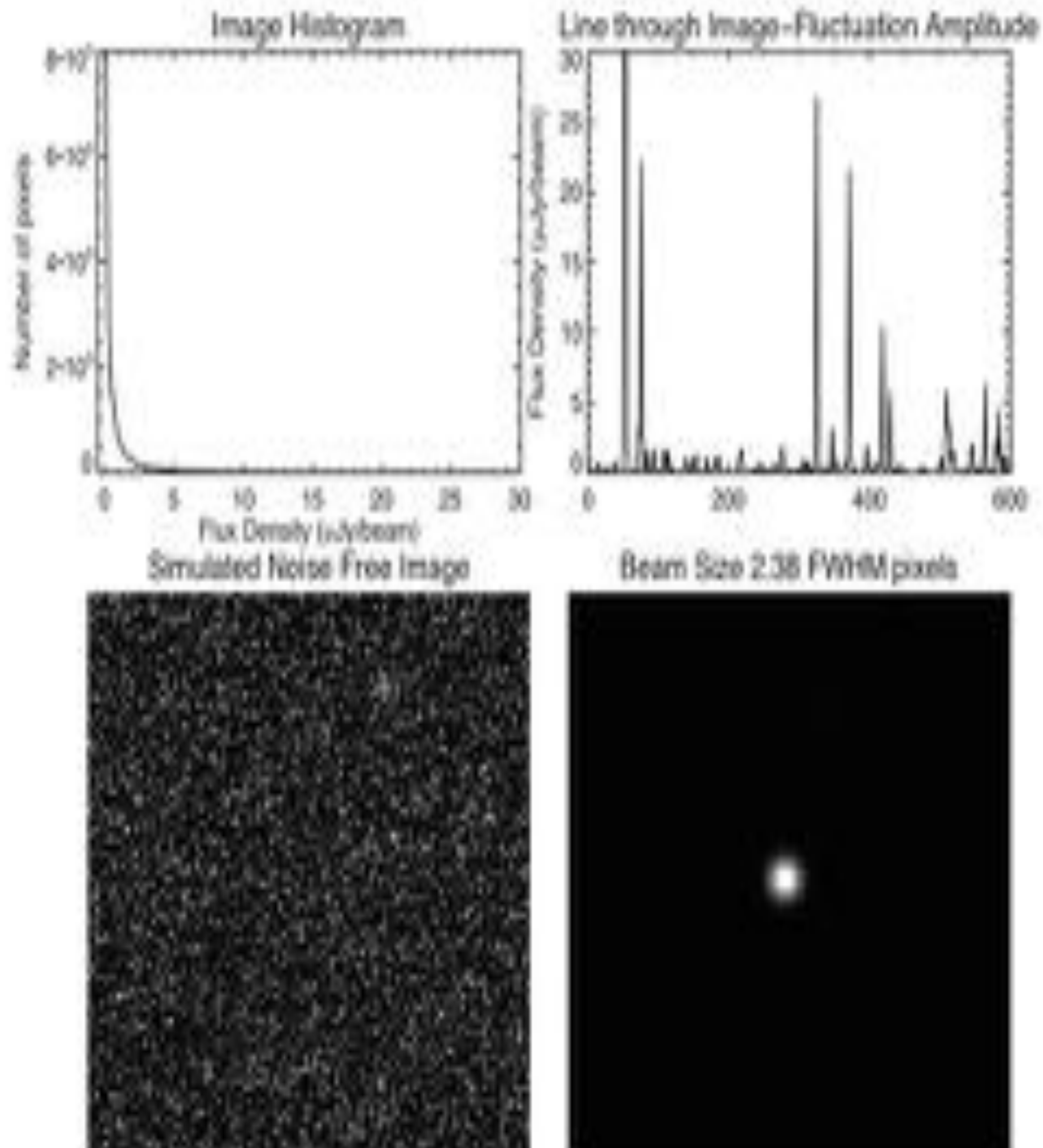


2.75" resolution



What is 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, $\boldsymbol{\sigma}_c$ (width of P(D))
  → governed by beam and source count



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Why is confusion important?

- Discrete source count
- Diffuse emission detection
- The cosmic radio background (CRB)
- Catalogue fit uncertainties
- Angular power spectrum / Fourier domain
- Luminosity functions / galaxy evolution and frequency dependence
- Foreground characterization

How? Probability of Deflection

- Fitting of Image histogram → statistical estimate of source counts as faint as ~ $\boldsymbol{\sigma}_c$
- Input
  - Source count model
  - Pixel size, beam shape
  - Instrumental noise
- Mean density of observed flux

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

- Can use any continuous source count model

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

- 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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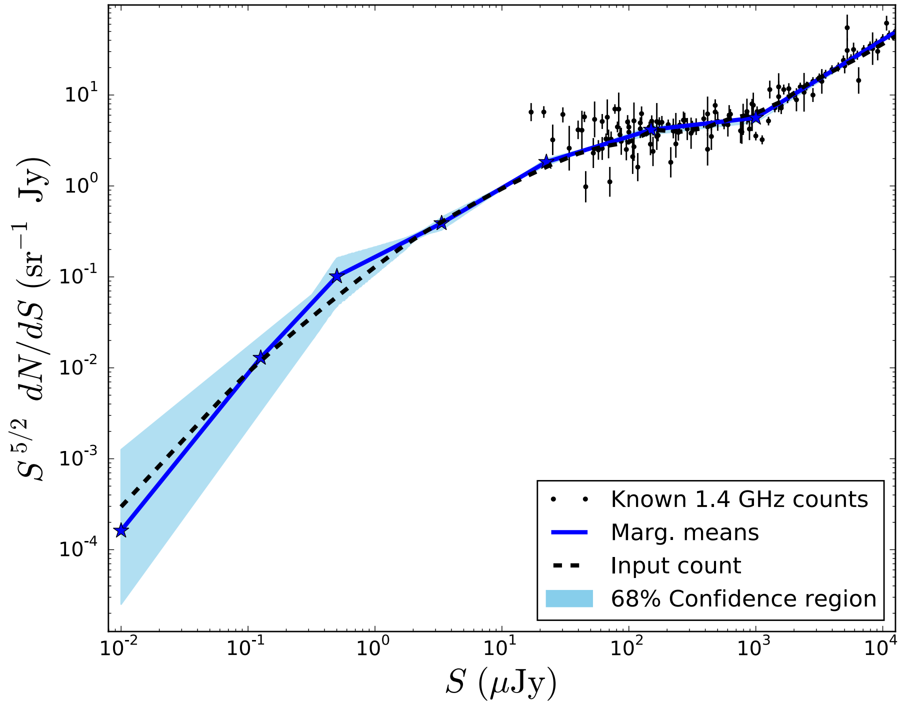

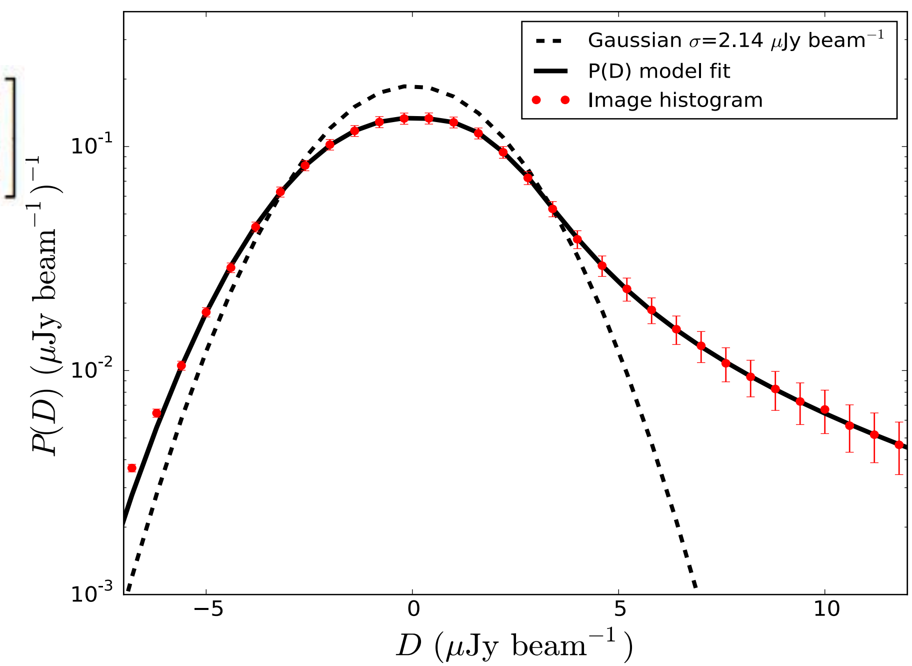

Discrete Source Count

- JVLA
  - Lockman Hole North
  - 3 GHz single pointing
  - Rms ~ 1 μJy/beam
  - 8 arcsec beam

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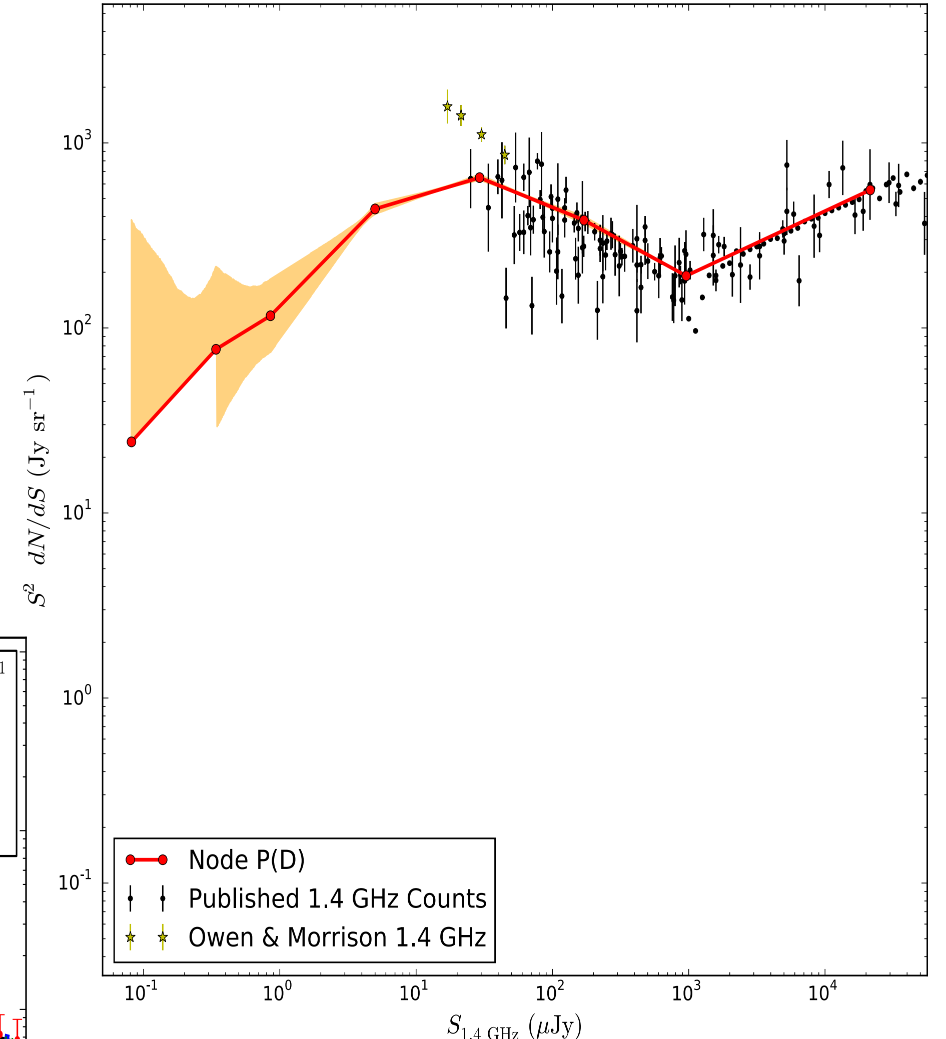

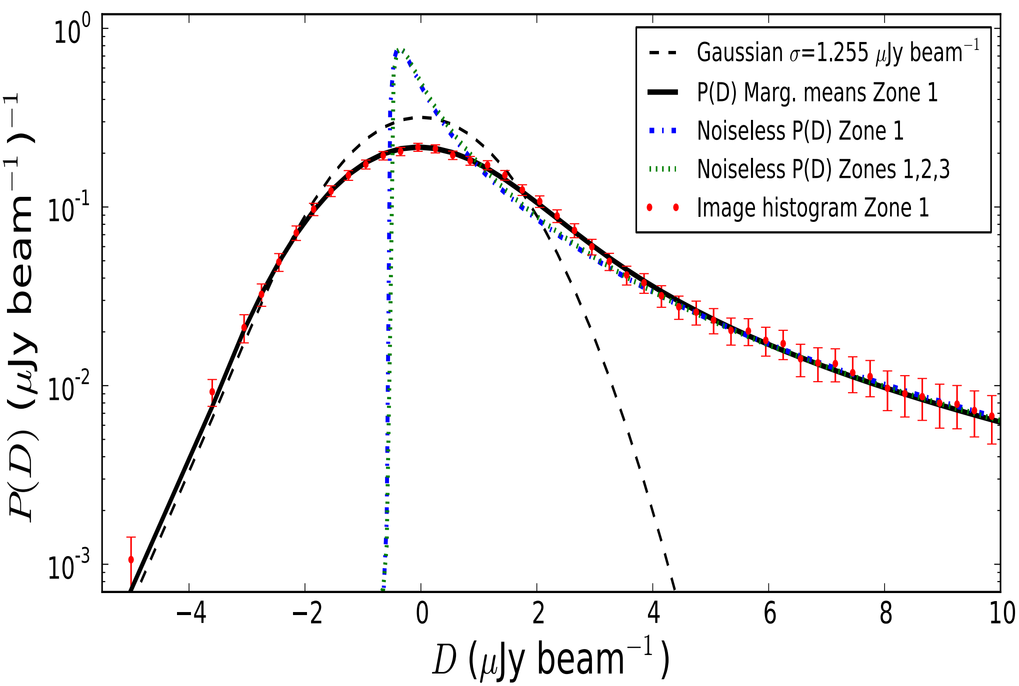

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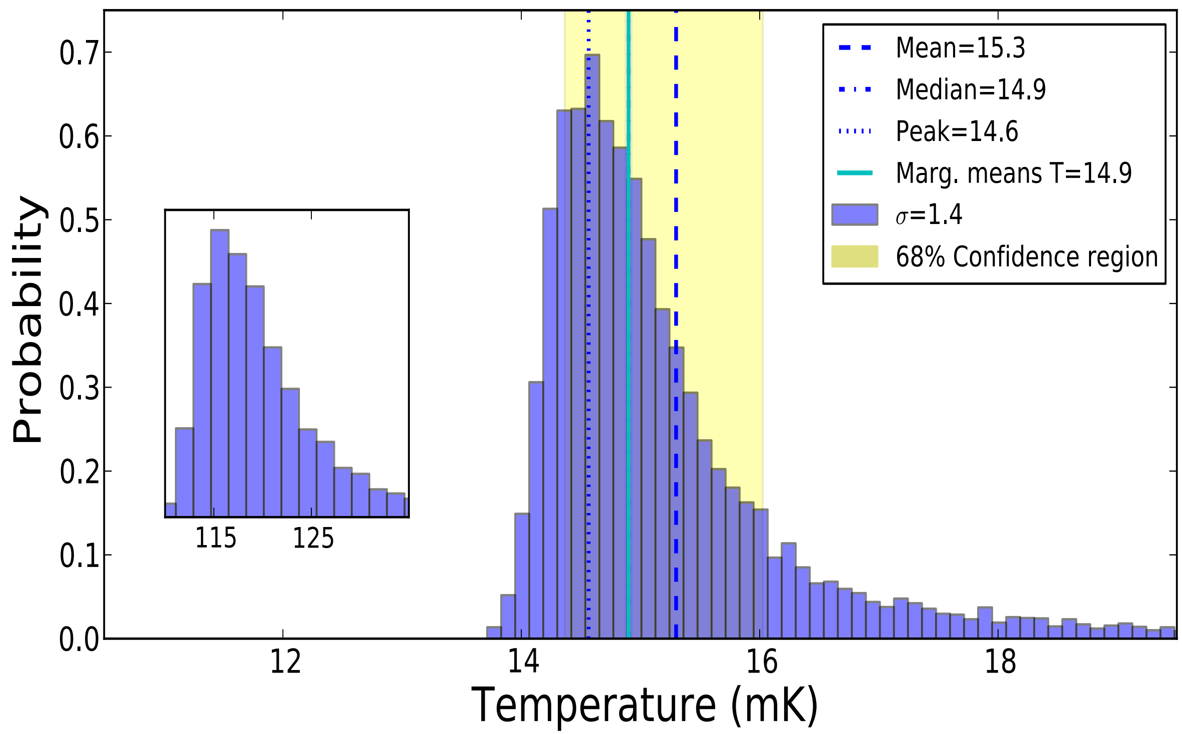
Cosmic Radio Background

- Background temperature, T_b , from extragalactic sources by integration source count

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



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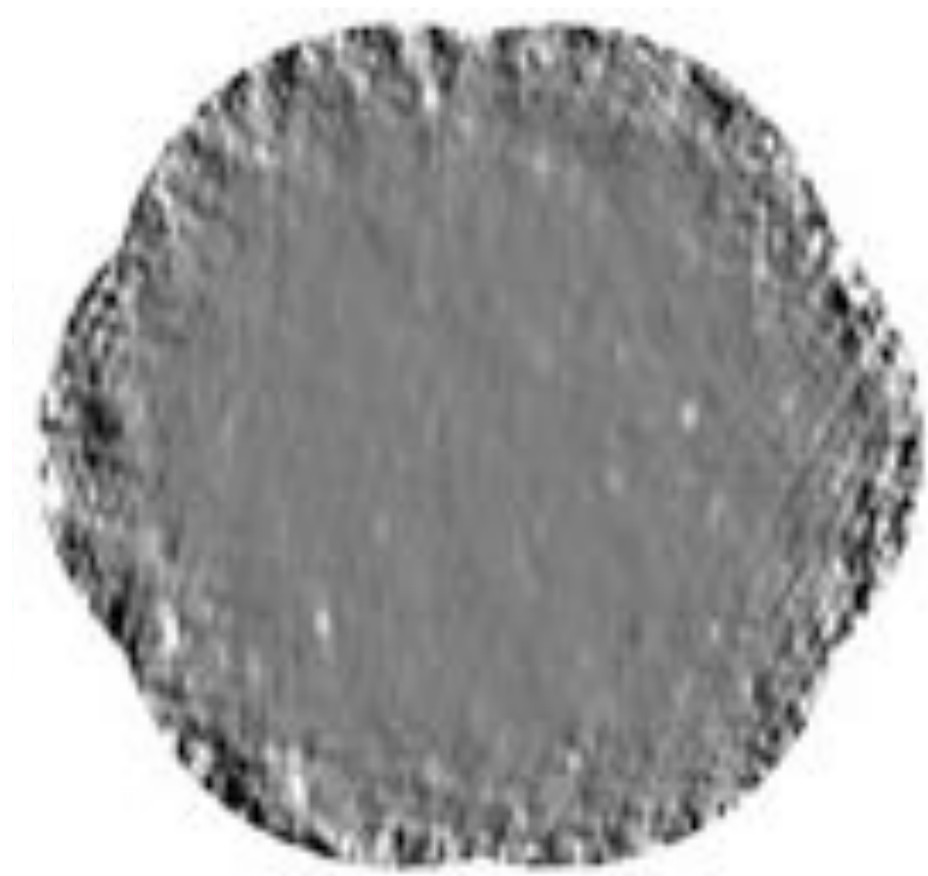
Diffuse Emission

- Can statistically detect presence of diffuse sources : galactic haloes, cluster haloes, relics, cosmic web
- Subtract point sources or use discrete source count model
- Example: ATCA
  - ELAIS S1
  - 7 pointing mosaic
  - 1.7 GHz
  - 150” x 60” beam
  - RMS ~ 50 μJy
- Use ATLAS point source models to subtract bright sources and JVLA discrete count for un-subtracted sources



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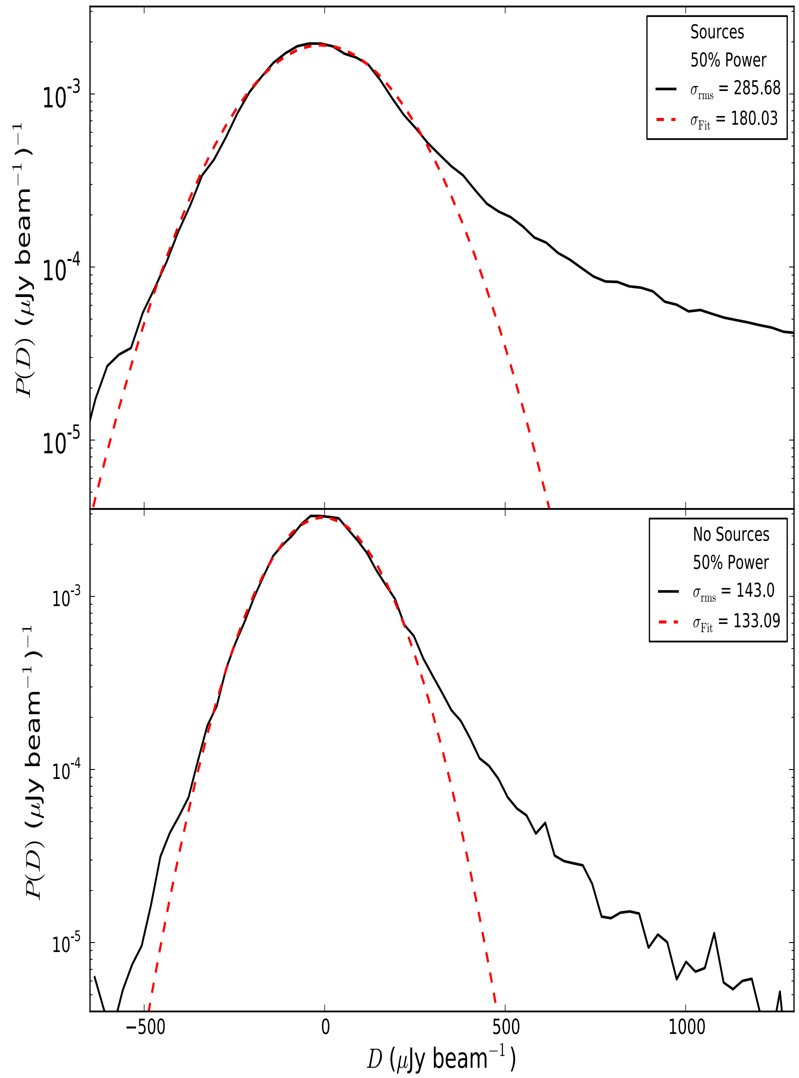

All Sources

Bright sources subtracted

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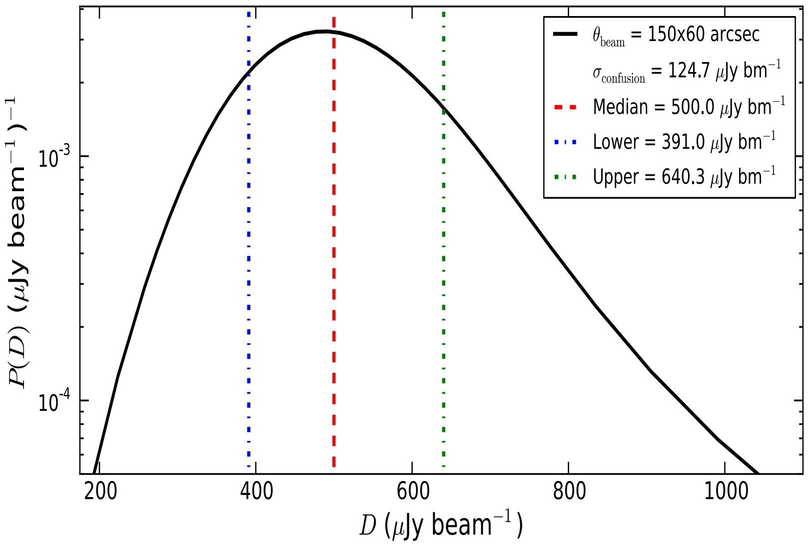

Model P(D) of faint sources

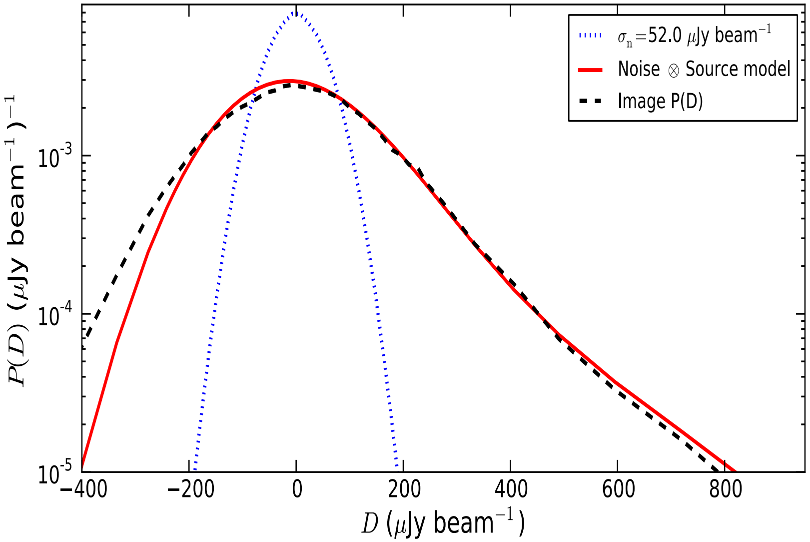

Image P(D) compared to model

← 3σ difference

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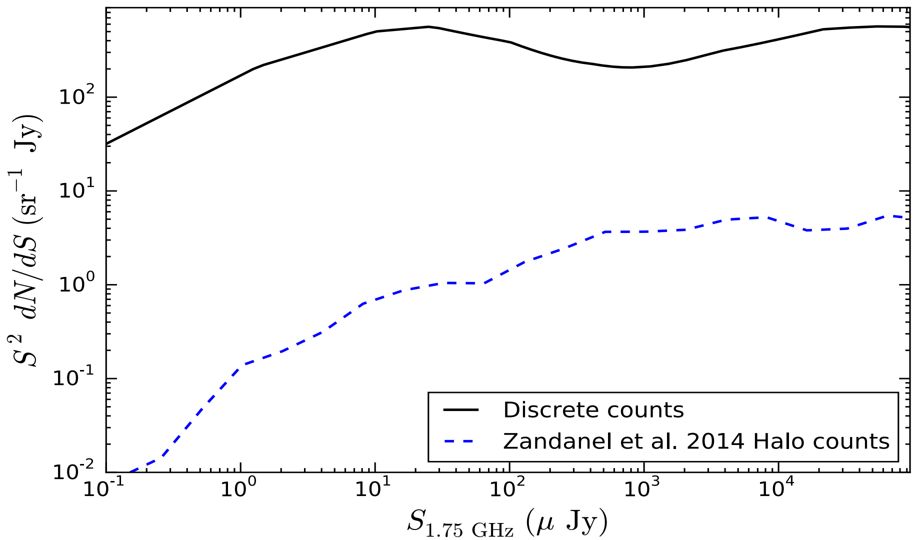
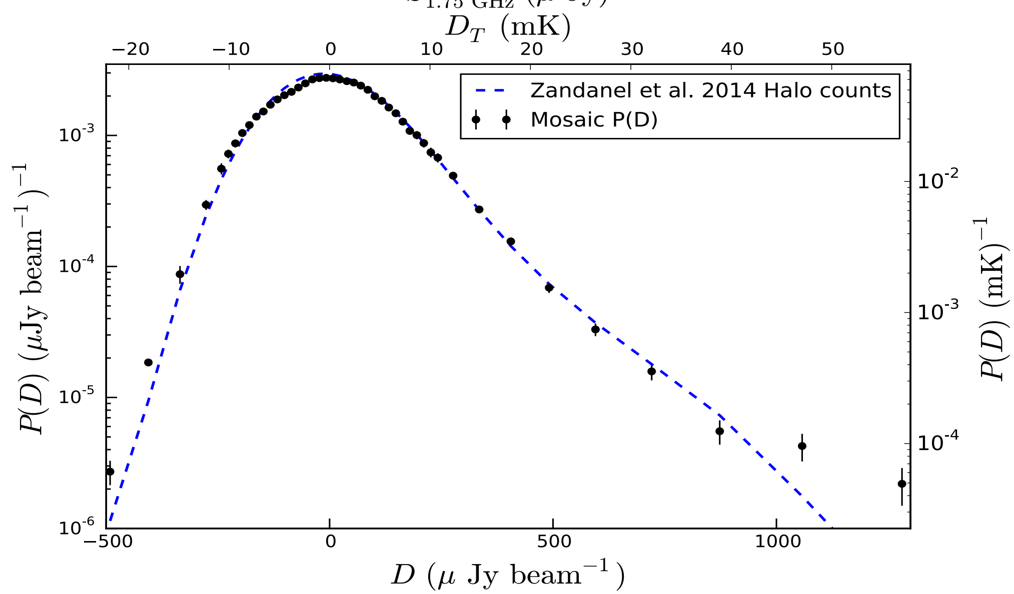
- Fit models of diffuse source count – dark matter haloes or clusters etc.



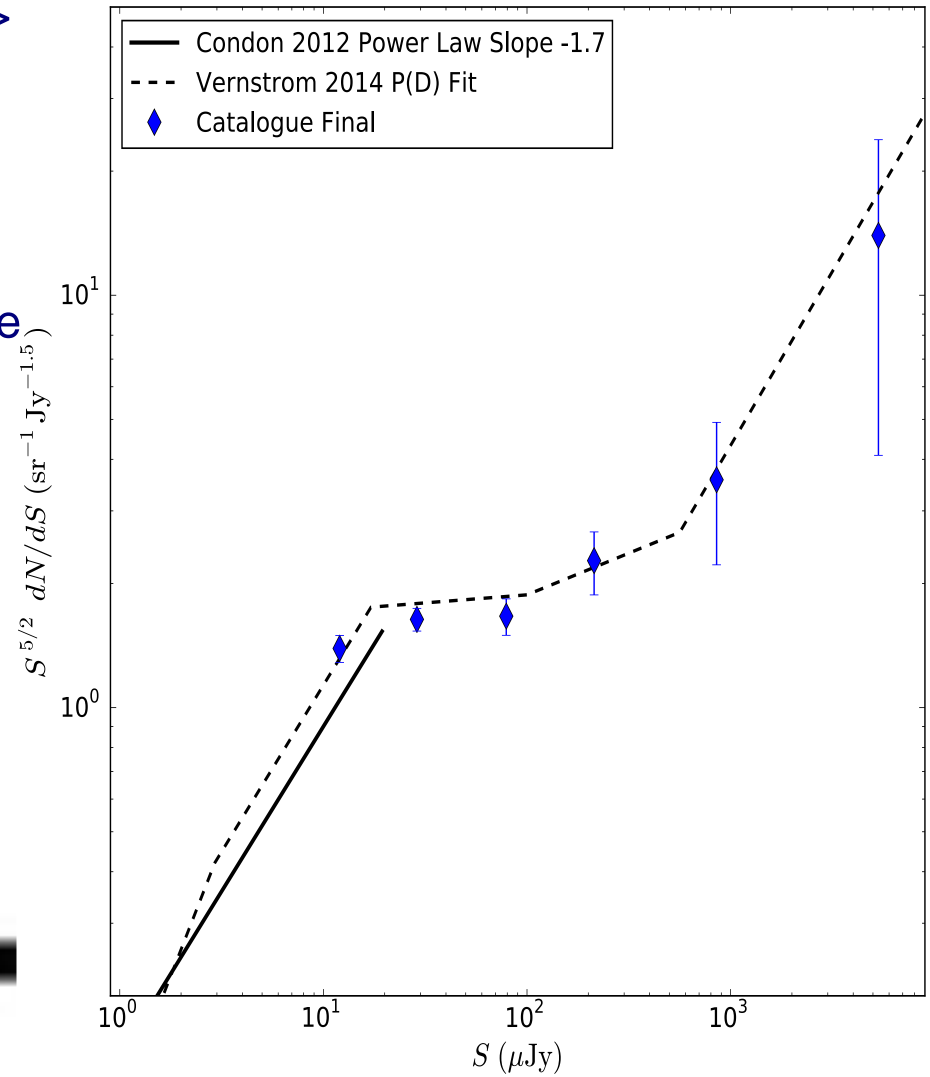


Catalogues and Counts

- Find, fit, and count number of source with S > 5**σ**
- But **σ** is total noise σ_{total}
  where $\sigma_{total}^2 = \sigma_{instrumental}^2 + \sigma_{confusion}^2$
  - Need to know confusion noise to determine cutoff
  - Also for fit uncertainties

$$p^2 = \frac{\pi}{8\ln 2}\frac{\theta_M \theta_m S_{peak}^2}{h^2 \sigma_{total}^2}$$

  - False detection rate
- Can also compare catalogue count and *P(D)* count



Angular Power Spectrum

- Can use the confusion noise to estimate Poisson contribution

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

- Where $\boldsymbol{\sigma}^2$ is the (flat) amplitude of the power from sources
- Also known as P(D) in the visibility plane
- Simulation: SKADS source fluxes at 1.4 GHz
  - Randomly distributed positions and fluxes
  - Positions and fluxes clustered according to a power law

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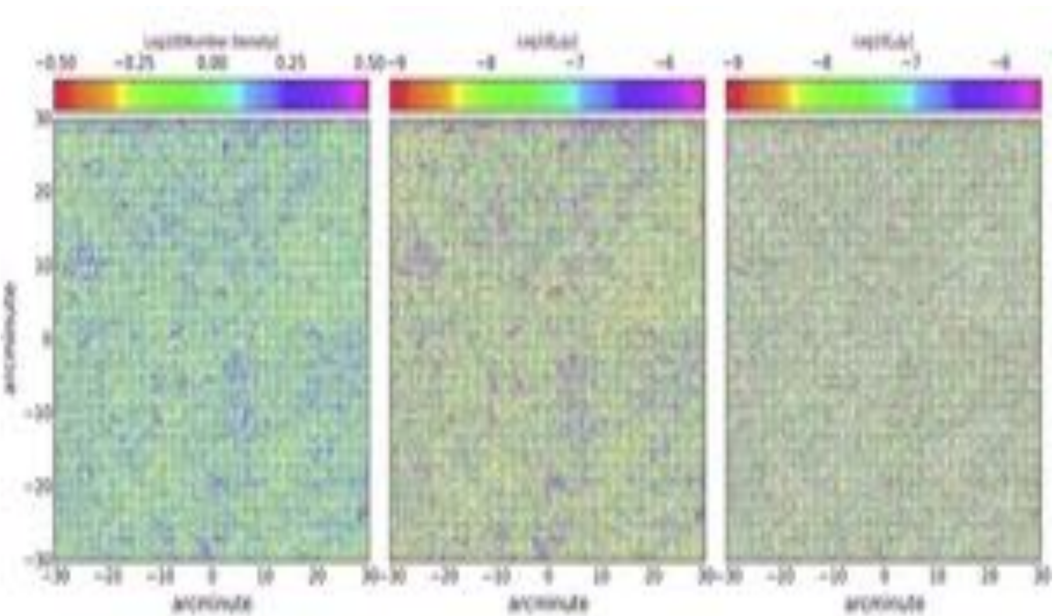
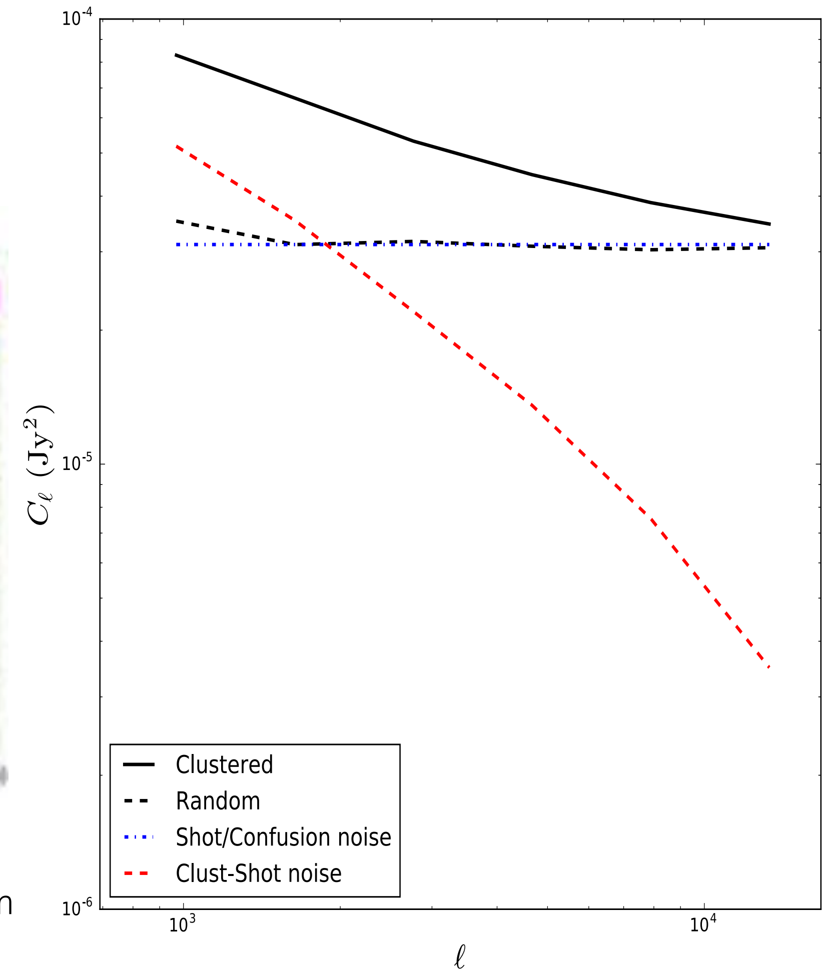


Number density clustered

Flux density distribution clustered

Flux density distribution random



2D P(D) – Luminosity, Evolution, Population M

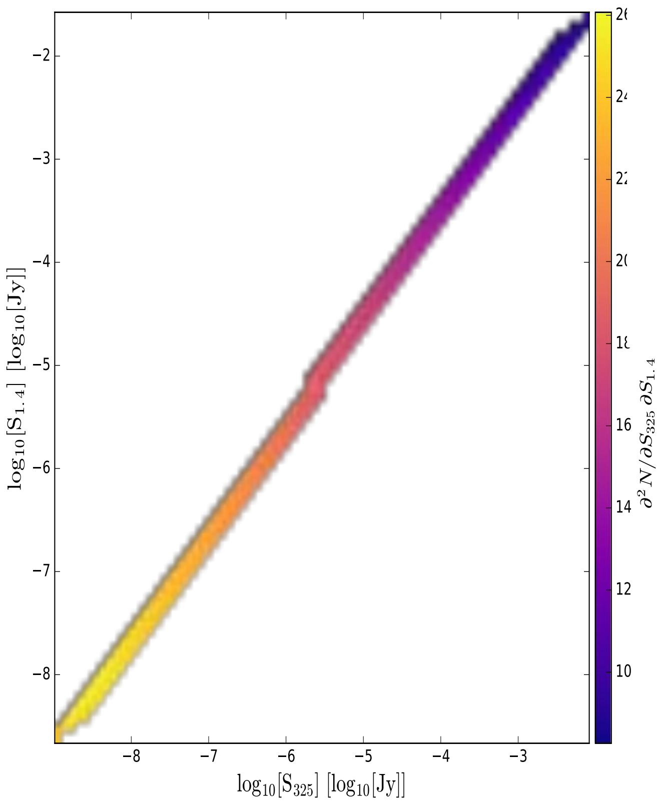
- Fit 2D histogram
  - Two Frequencies or Total & Polarised Intensity
  - How correlated is the confusion noise between frequencies
  - Uses more information to obtain tighter constraints

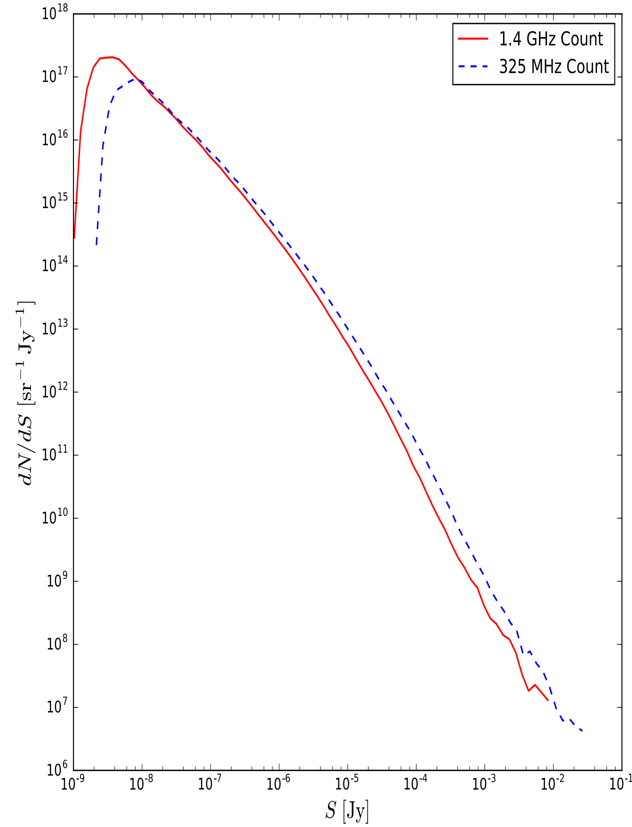
- Model: 2D source count at 2 frequencies
  - Can fit multiple population luminosity functions and spectra indices to predict source count at both frequencies

- Simulation using 1.4 GHz – 8 arcsec beam and 325 MHz – 15 arcsec beam (VLA vs GMRT)

Two populations, AGN **α**=-0.85, Star-forming **α**=-0.6

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





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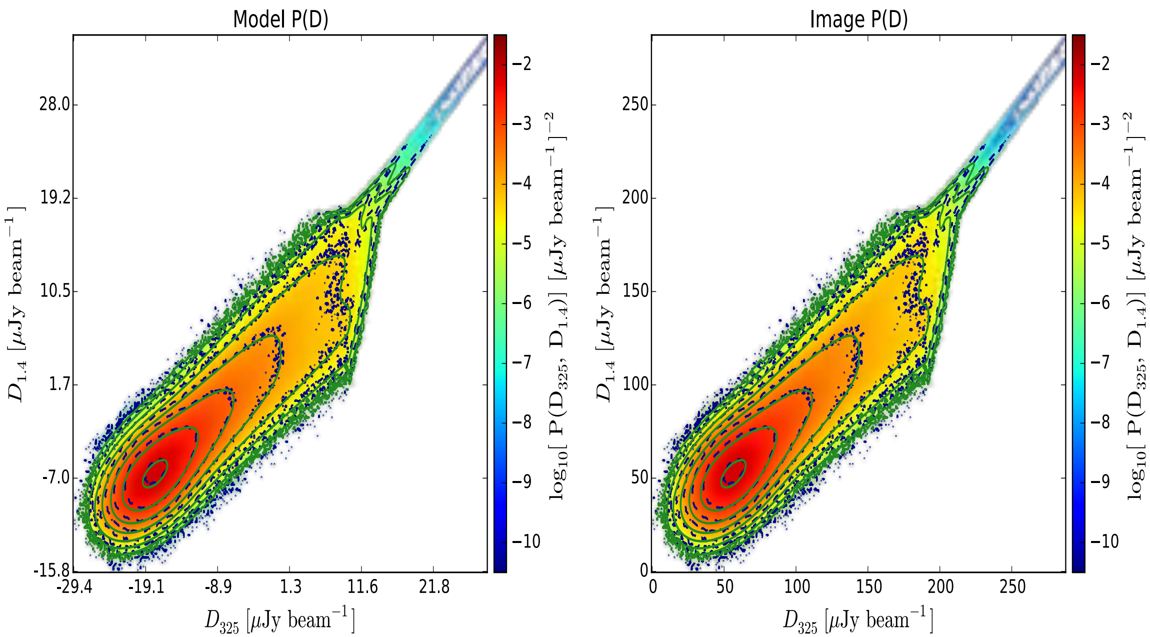

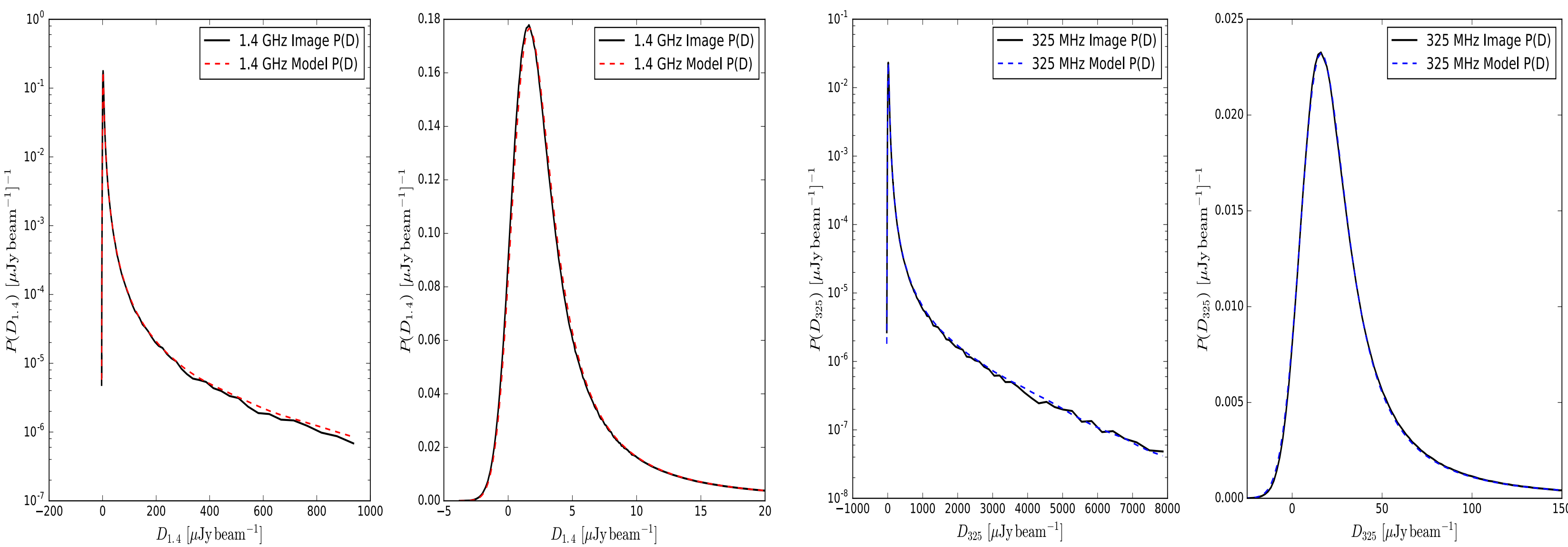

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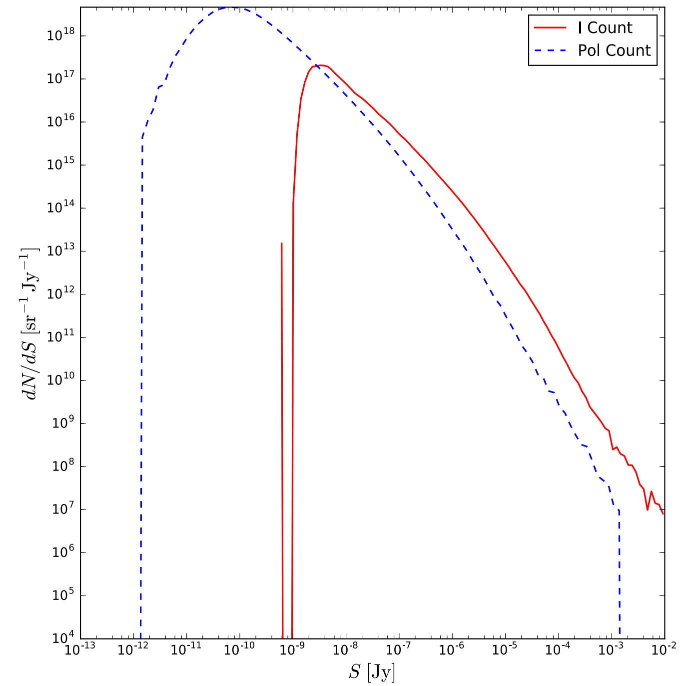
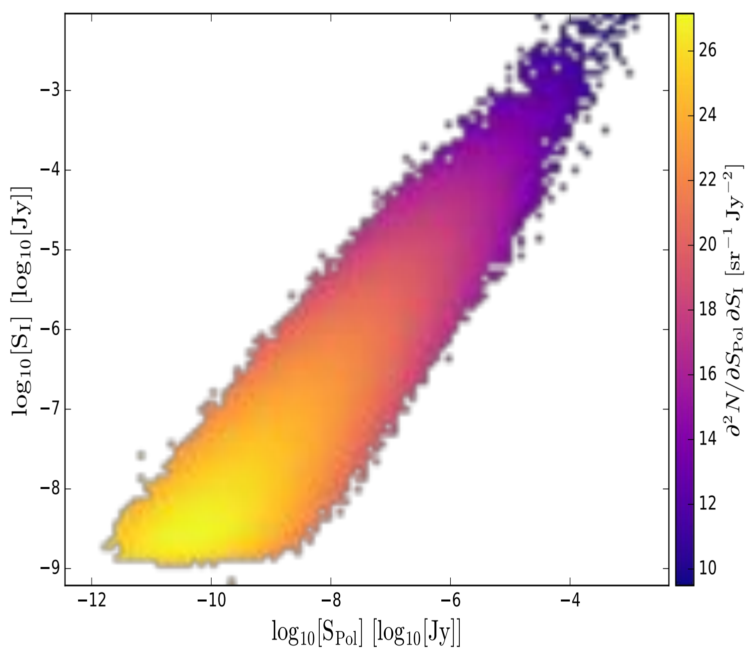
- Simulation using 1.4 GHz – 8 arcsec beam and Total intensity I and Polarised P

Total Intensity and Polarised Intensity – dN/dP(S)
Polarised count – 2 parameter function of Stokes I count

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





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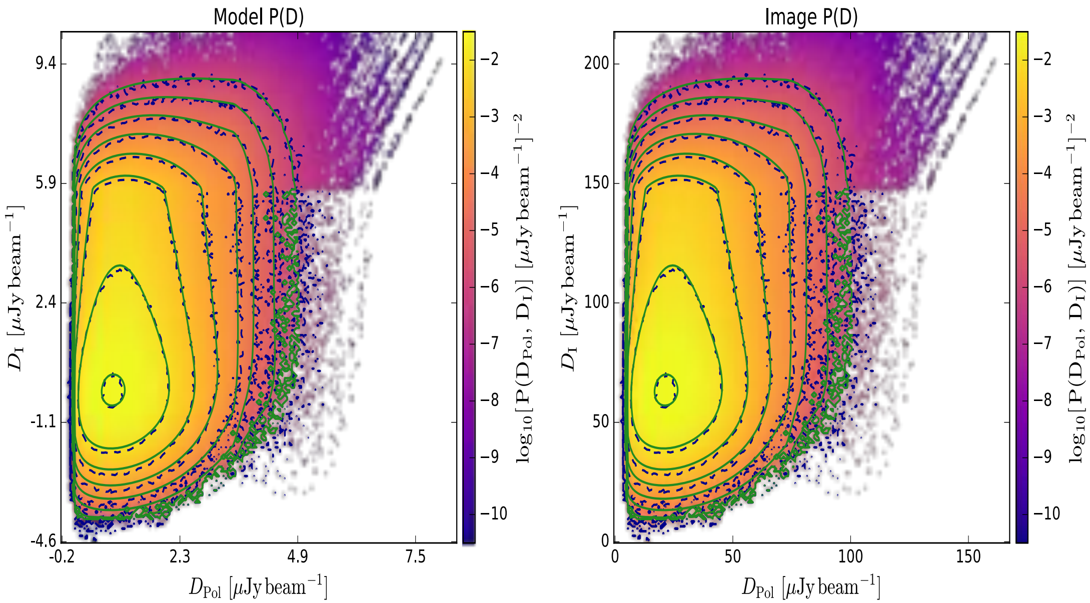

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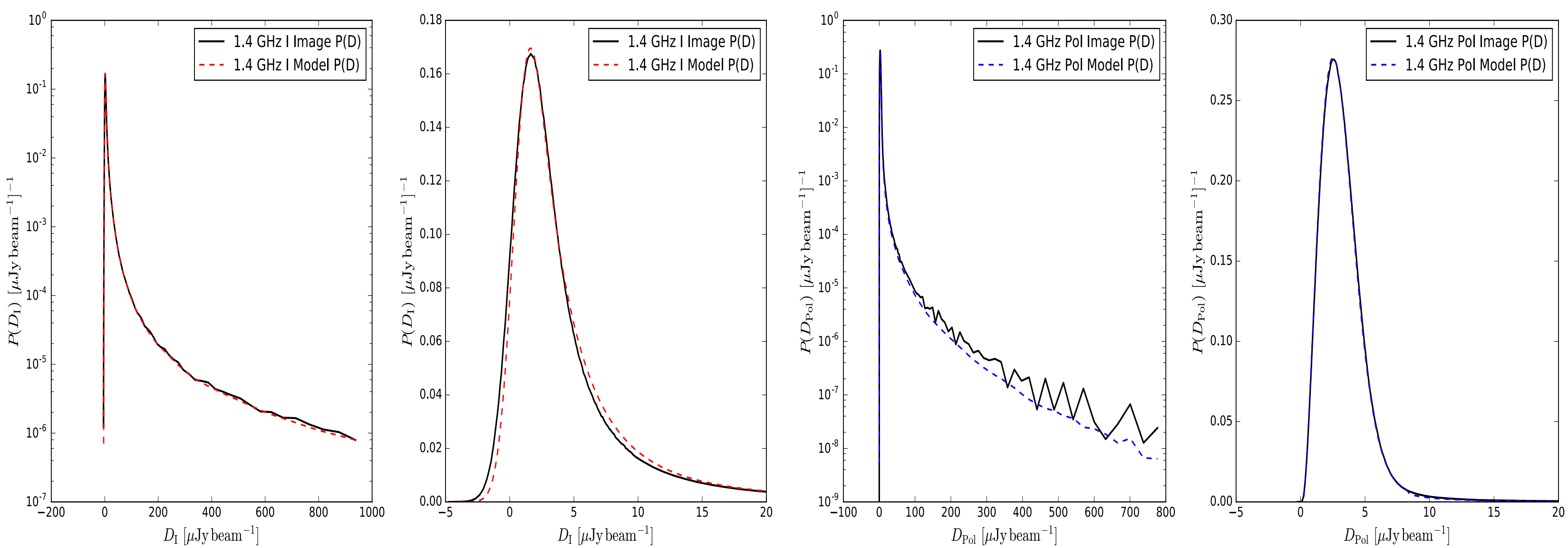

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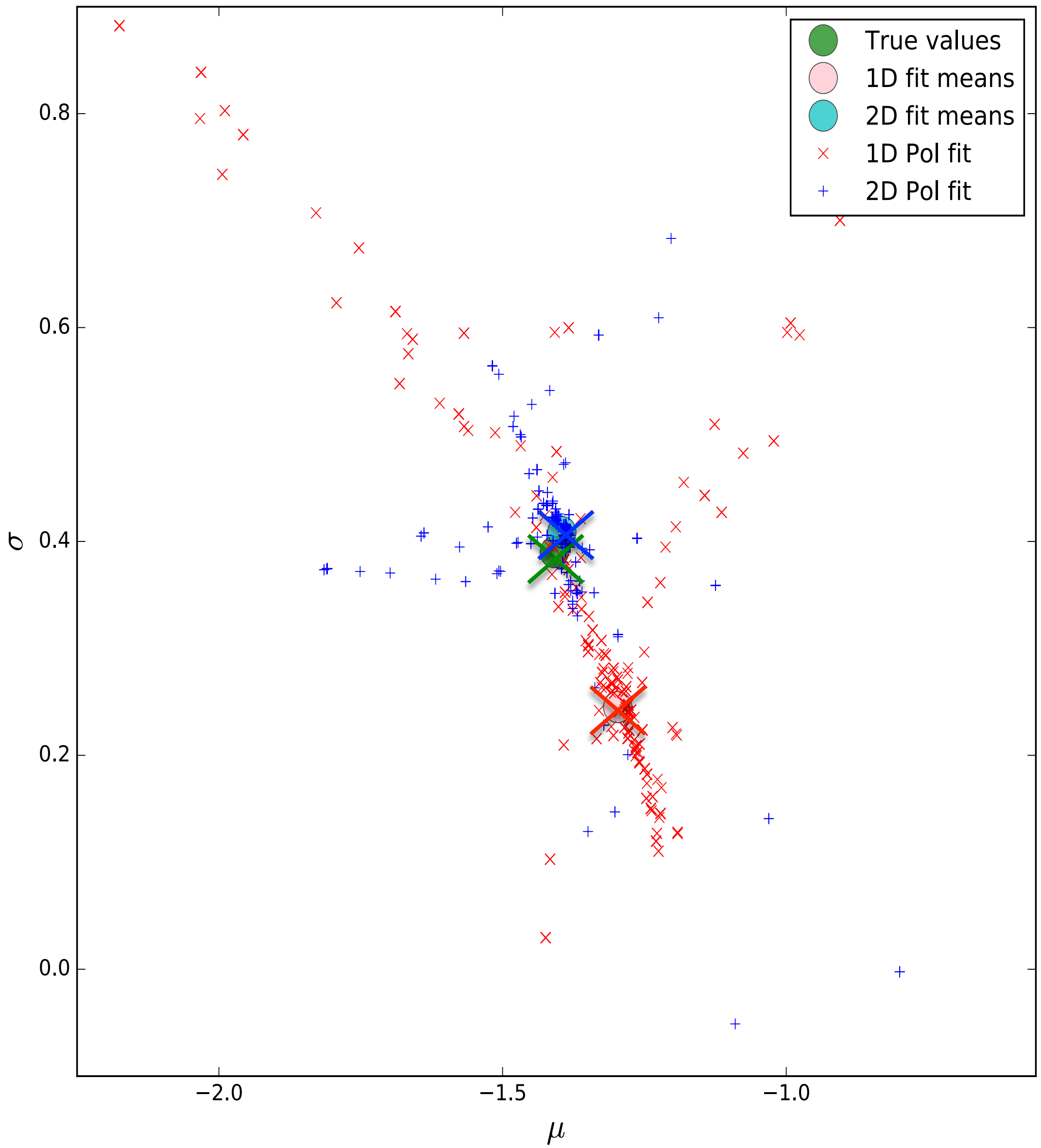

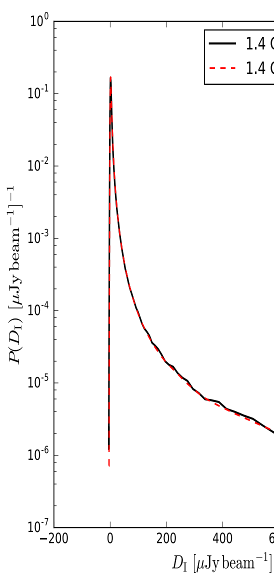

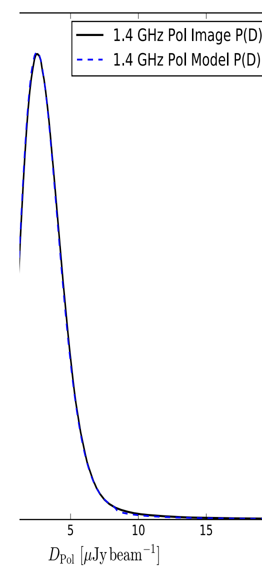

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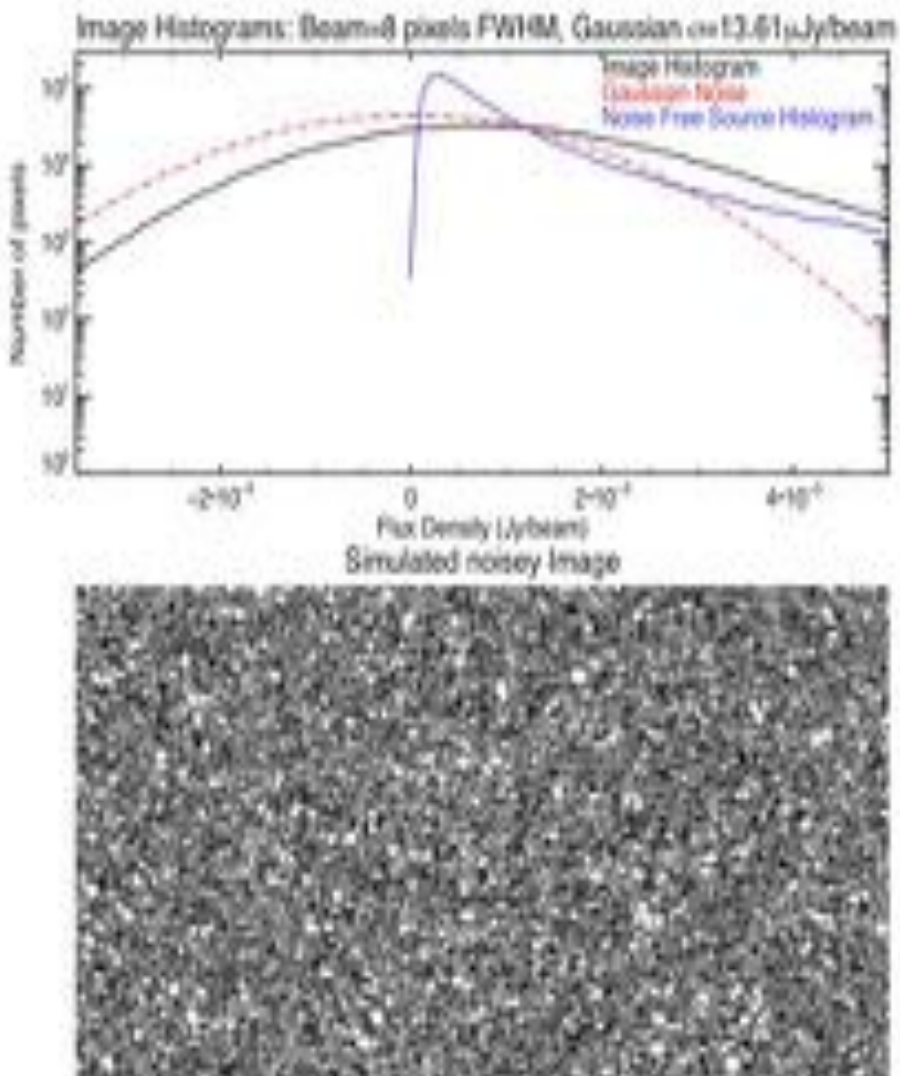
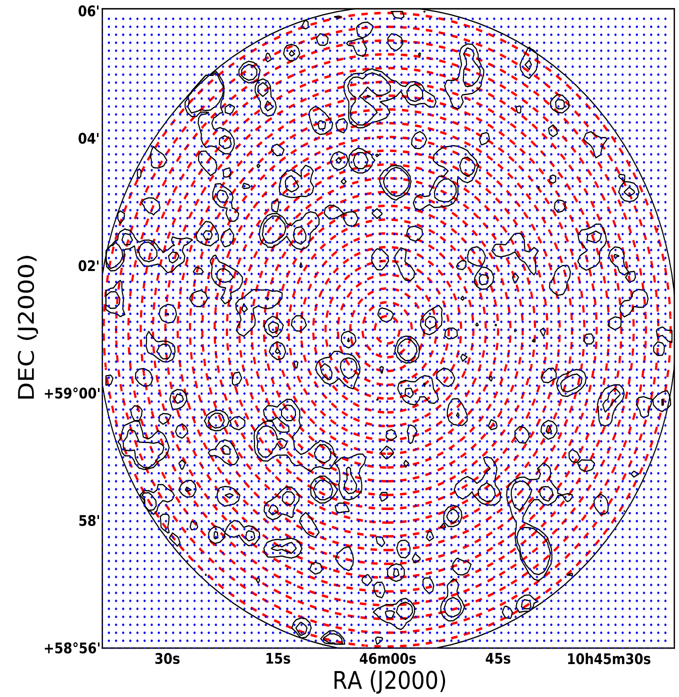
Issues – Instrumental Noise

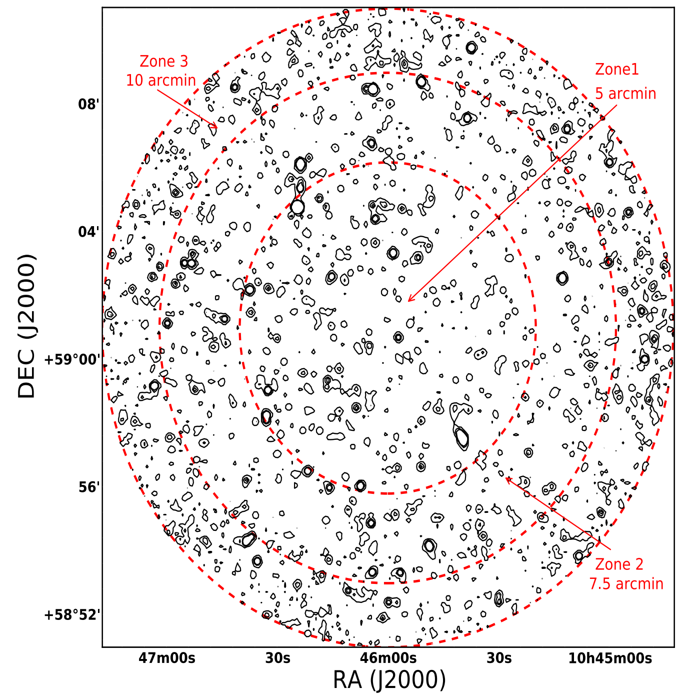
- $\boldsymbol{\sigma}_t^2 = \boldsymbol{\sigma}_n^2 + \boldsymbol{\sigma}_c^2$
- For faint counts want $\boldsymbol{\sigma}_c > \boldsymbol{\sigma}_n$



Issues – Instrumental Noise

- P(D) assumes constant instrumental noise
- Not the case with primary beam corrections or mosaics
  - Use multiple zones where change in noise is small
  - Within those zones create weighted histogram
    - Weights $\propto \frac{1}{\sigma_i^4}$
- Example: MWA/SKADS simulation
  - 150 GHz ~35^o
  - 2 arcmin Gaussian beam
  - Single 2 minute snapshot
  - **σ**=0.02 Jy





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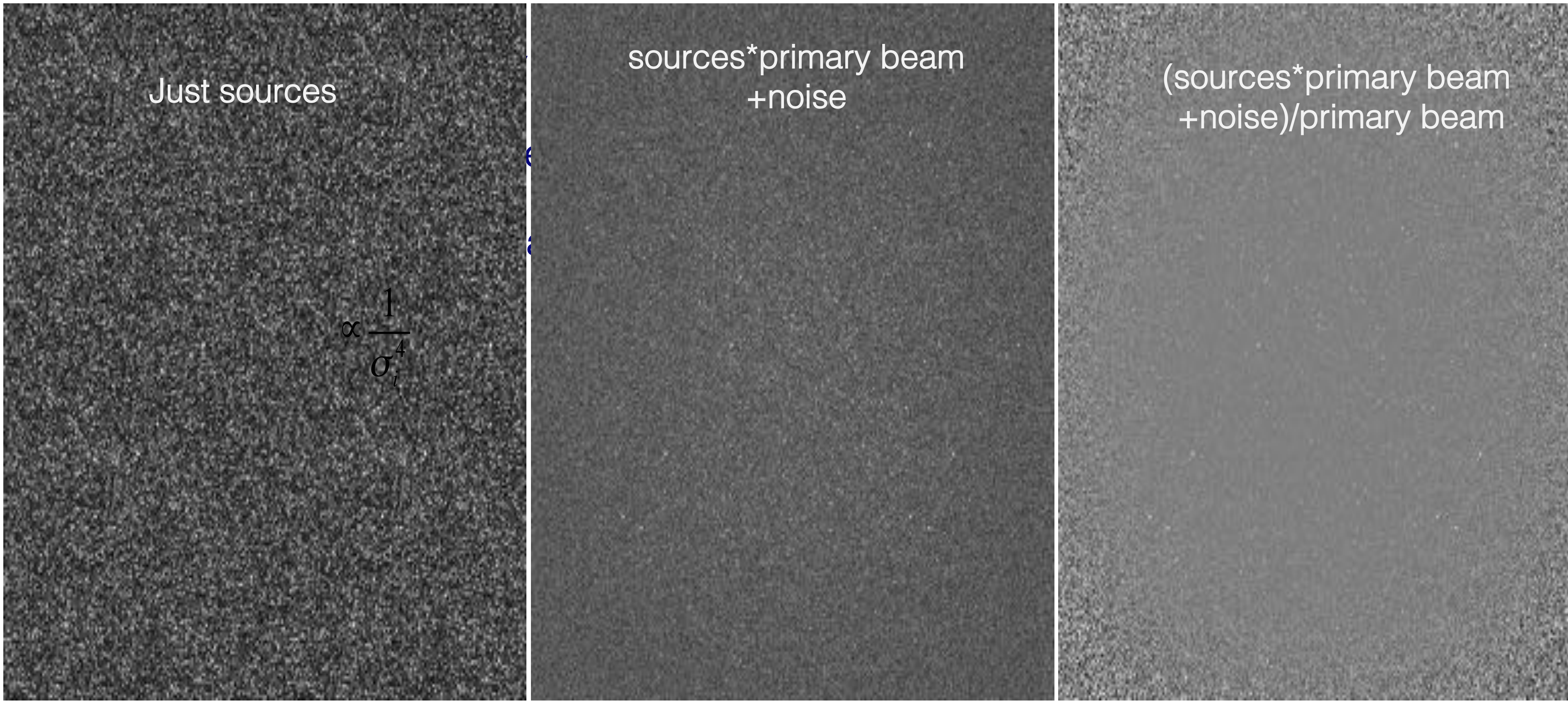

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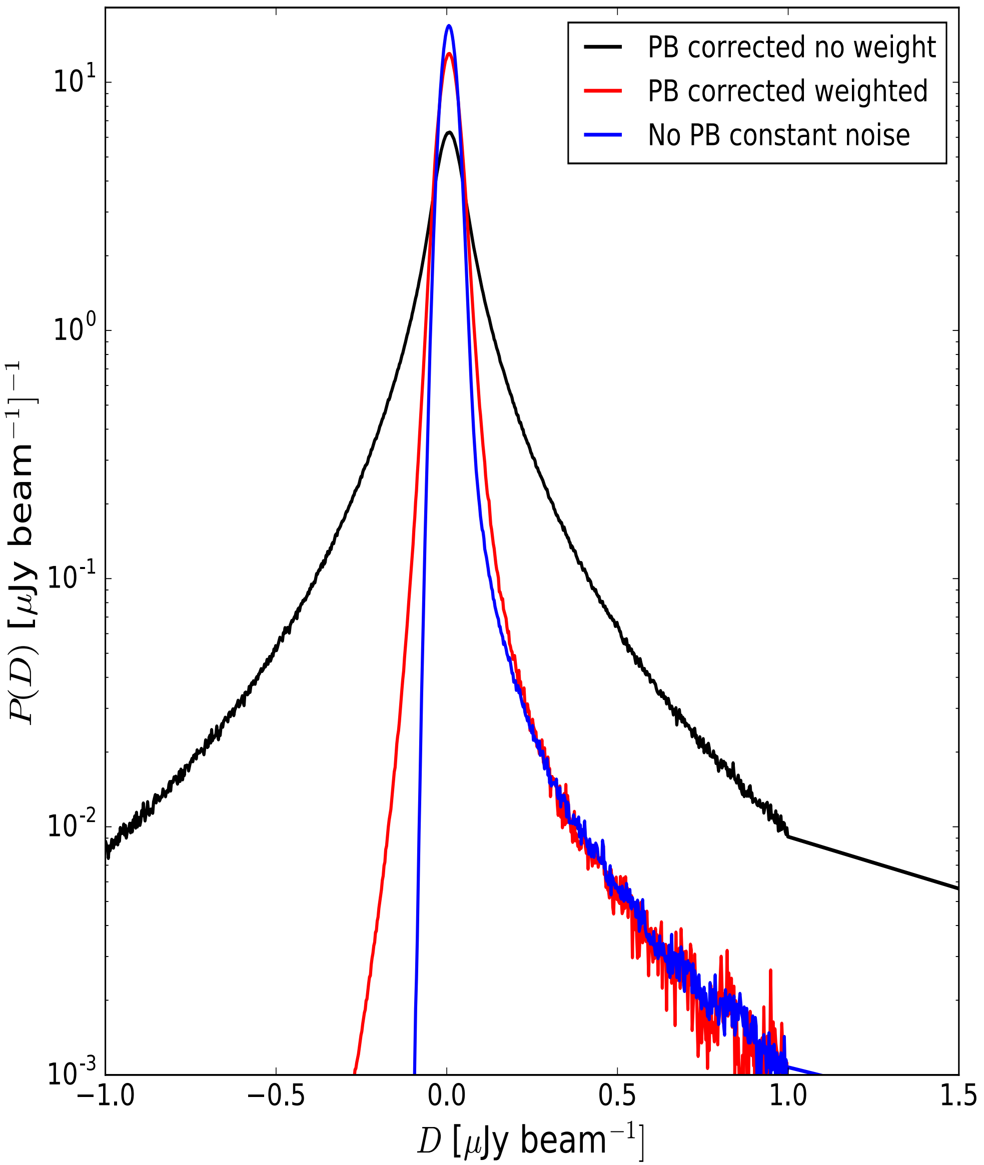
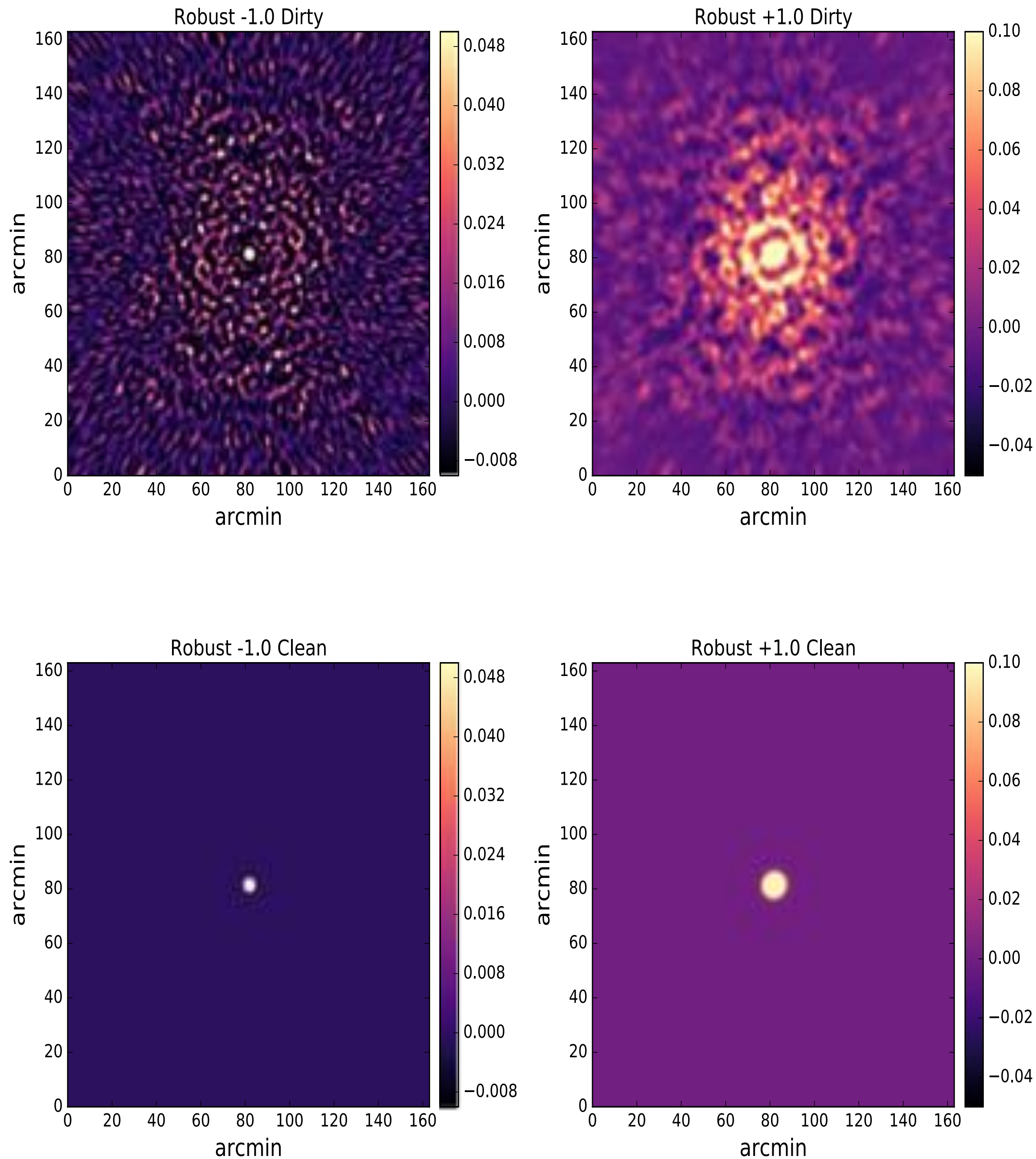


Issues – Dirty Beams

- Usually assume clean beam in P(D) calculation

→ very bad if clean and dirty beams very different !!!

MWA Beams 2-minute snapshot →



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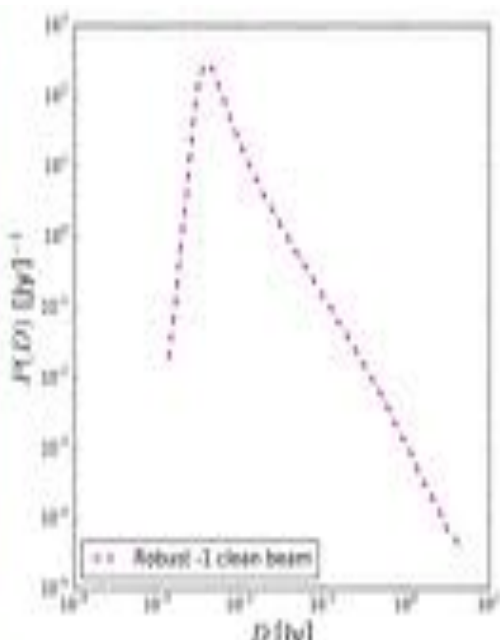
Issues – Dirty Beams

- Usually assume clean beam in P(D) calculation = very bad if clean and dirty beams very different !!!
  - Can calculate P(D) using just dirty beam or dirty beam for sources with S< cleaning limit and clean beam for S>clean limit
  - If ignored and fitting source count could discover a whole new population of sources (which are really sidelobes)
  - This also allows for an estimate of the noise contribution from sidelobes

Robust -1 Clean beam



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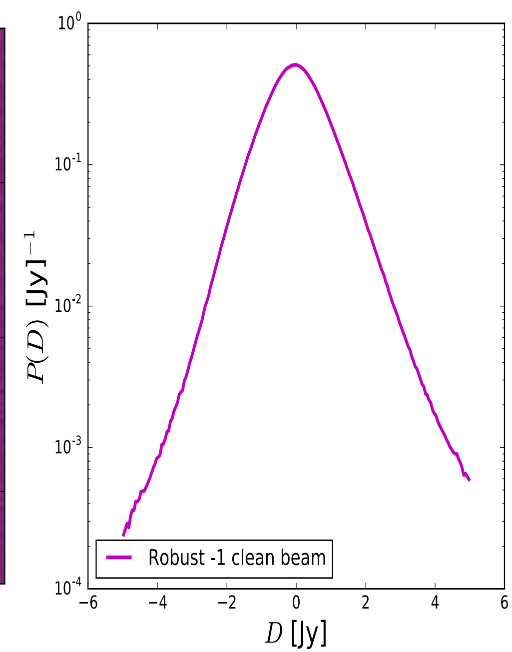

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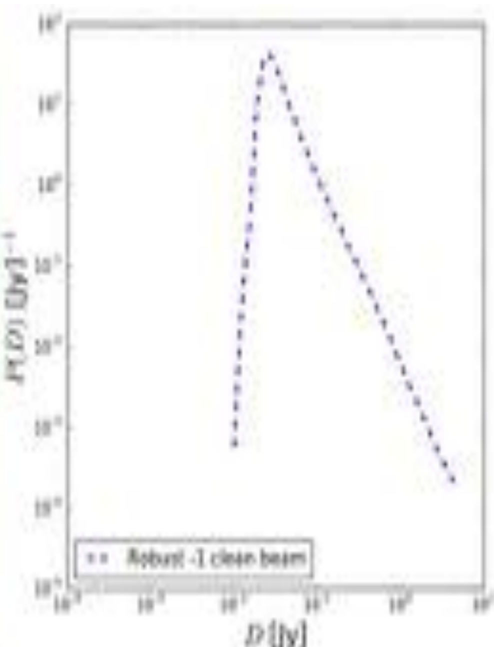

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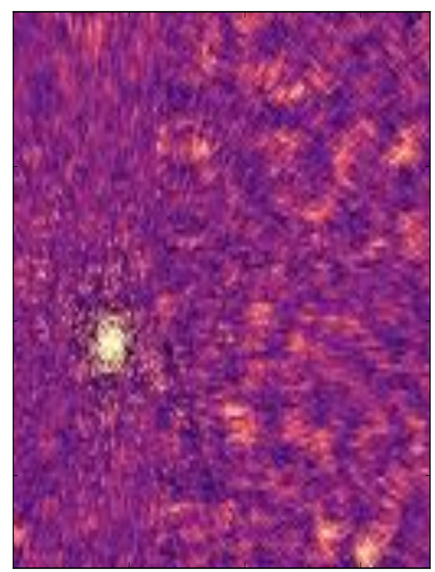

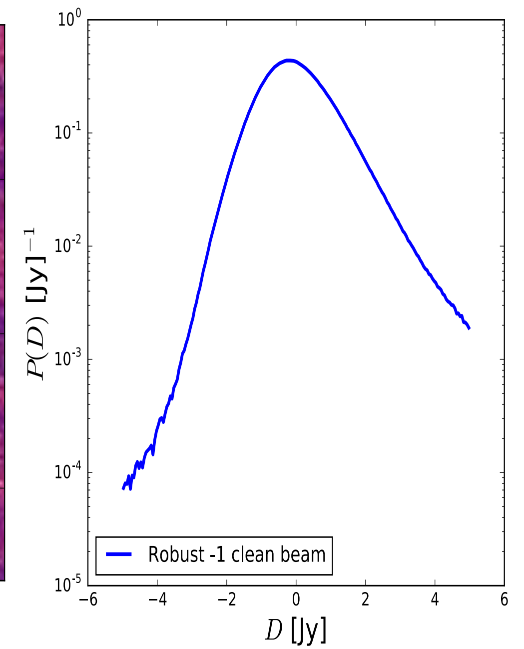

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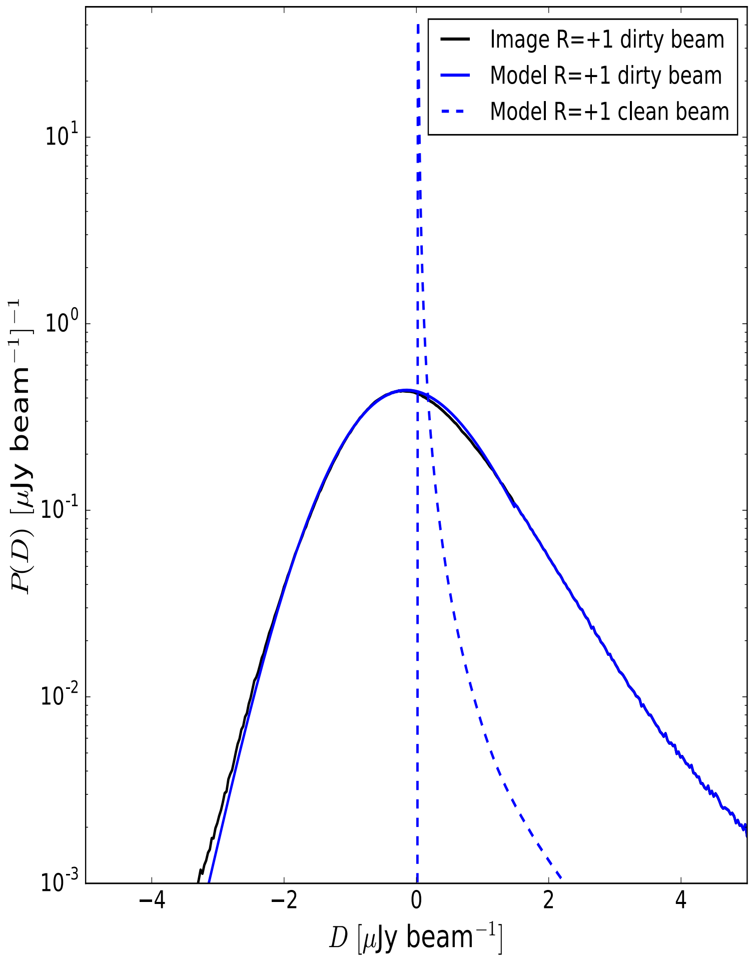

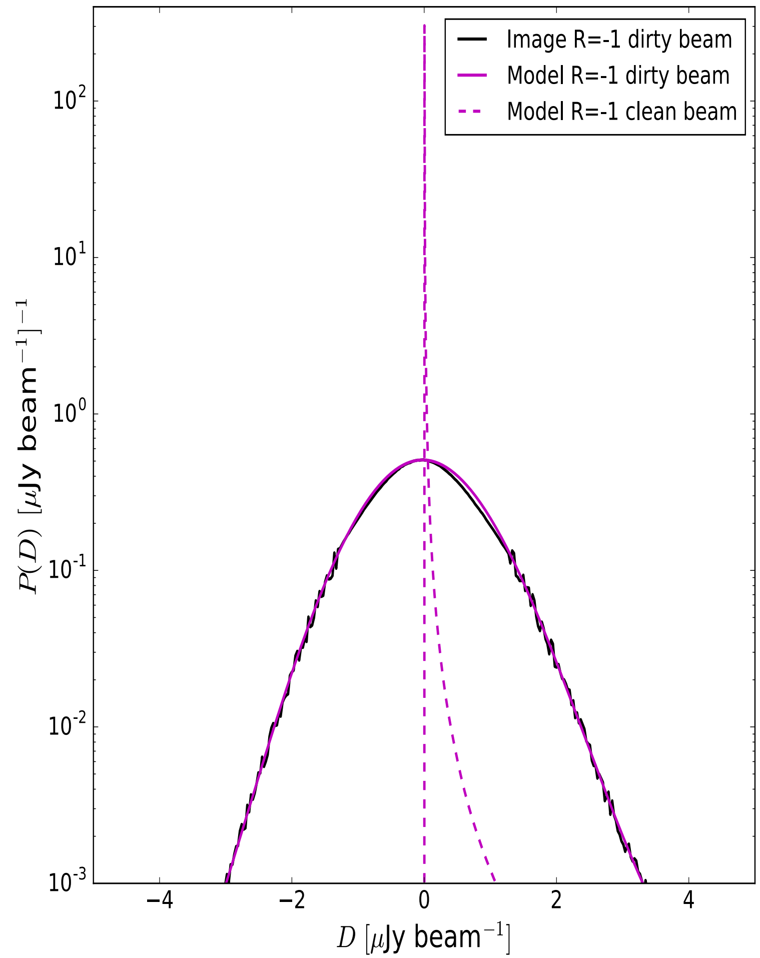

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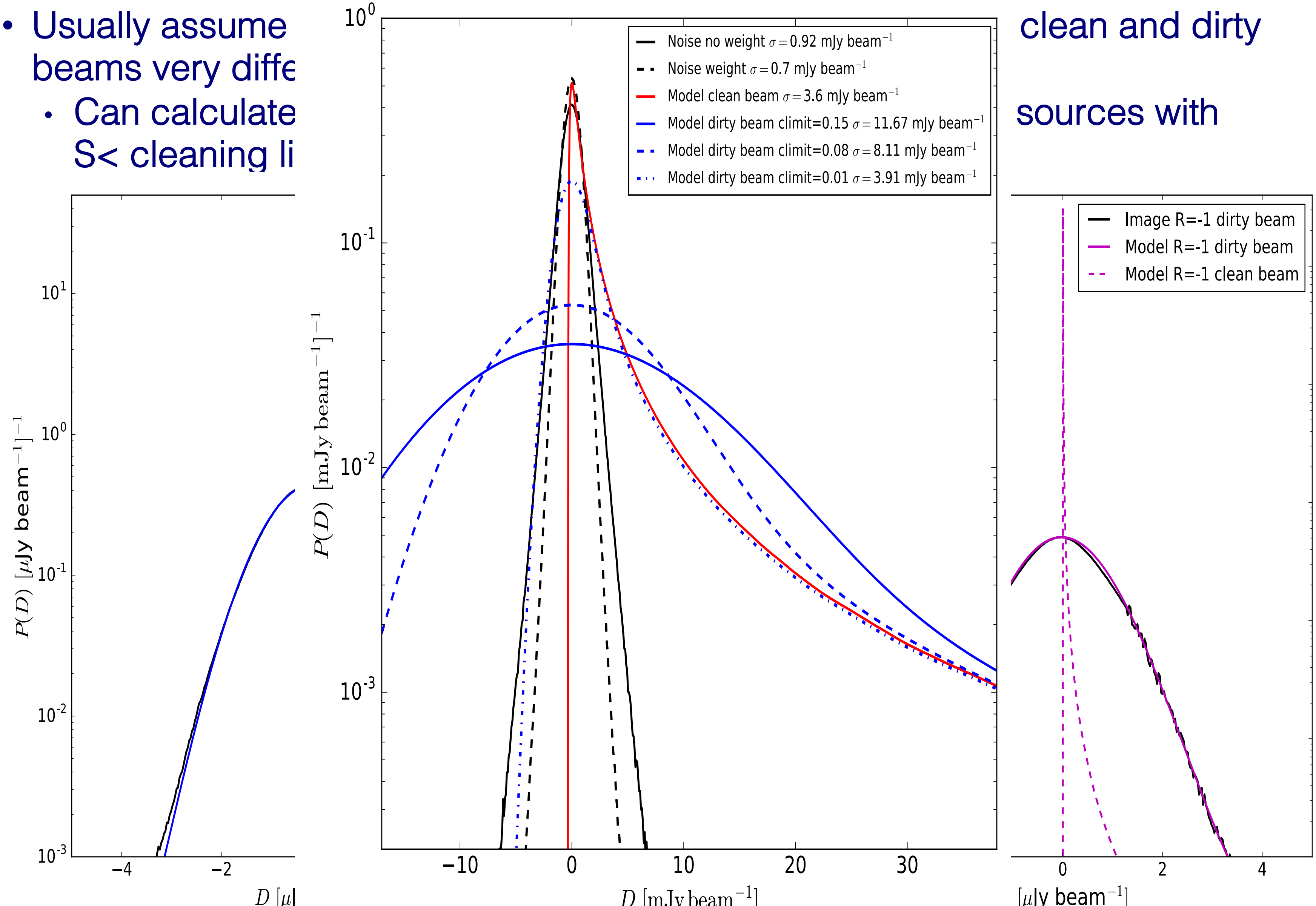
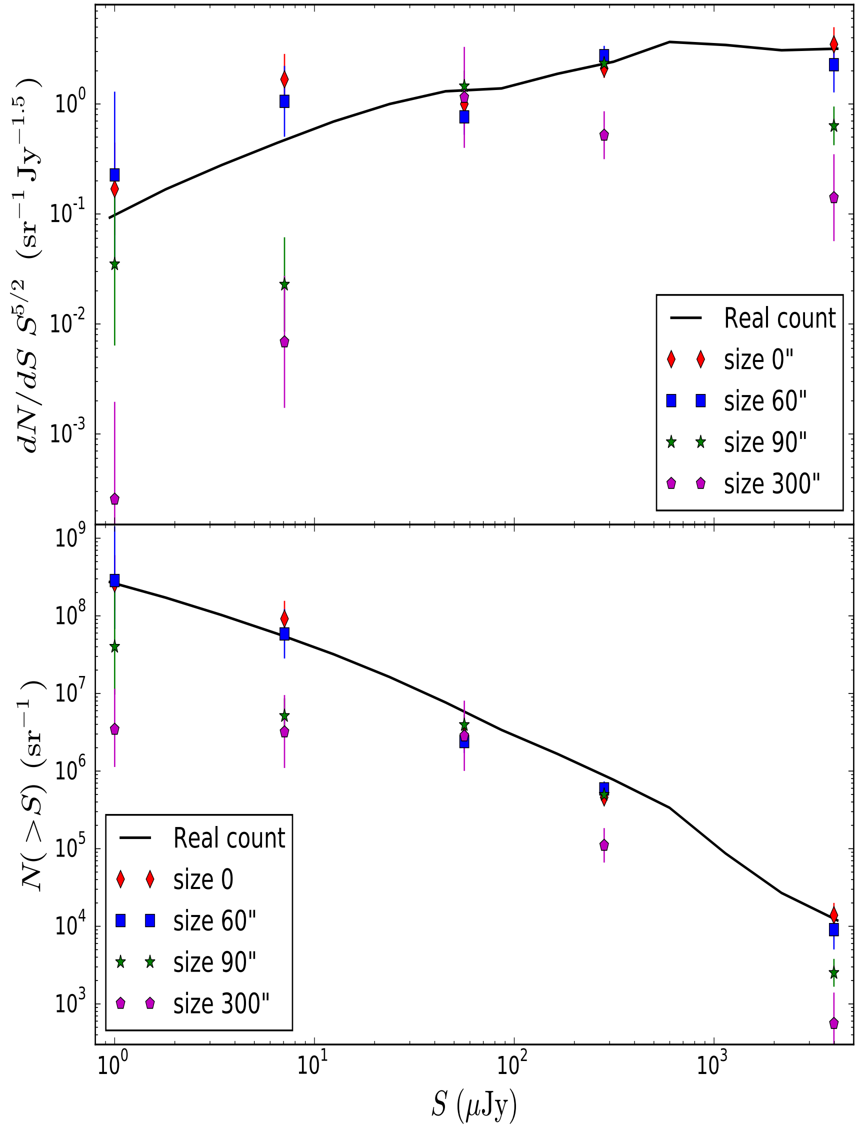


Issues – Source Sizes

- P(D) assumes point sources
- So what happens with extended sources?
- Simulation ATCA beam (~90"):
  - Point sources
  - 60" sources
  - 90" sources
  - 300" sources

- Fitting returns consistent results for sources with $\Omega_{size} <= \Omega_{beam}$
- Any larger source count is underestimated

→ P(D) works as long as sources are roughly beam size or smaller



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Conclusions

- Confusion analysis is important and can be a powerful tool

- Can be used:
  - to estimate discrete source count below confusion and instrumental noise levels
  - to estimate cosmic radio background temperature
  - to estimate the contribution from diffuse emission
  - to model source population luminosity functions and spectral indices
  - to look at the correlation between frequencies
  - to obtain confusion noise contribution (and sidelobe contribution) to total noise for cataloguing
  - to obtain Poisson contribution to angular power spectrum
  - Polarisation as well as total intensity

- Things to remember:
  - Want instrumental noise < confusion noise
  - P(D) assumes constant noise → use noise zones and weighted histograms
  - Need to use the right beam shape in calculation
  - P(D) assumes point sources → need beam size such that source size <= beam
  - Other issues to be aware of: beam changes from ionosphere, non-Gaussian noise and artifacts

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