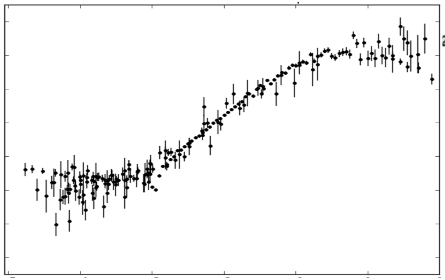
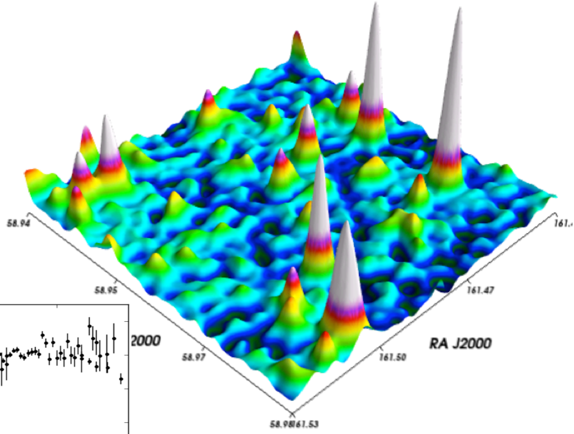
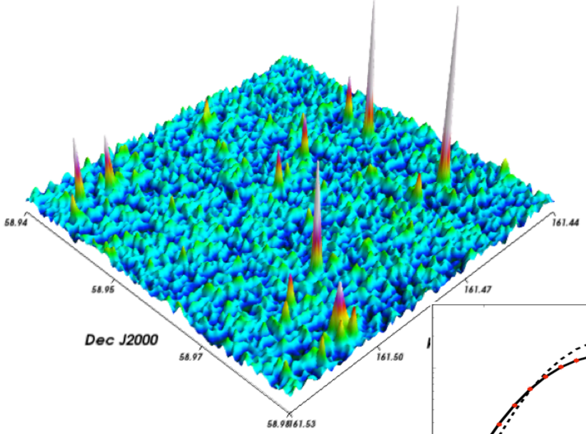
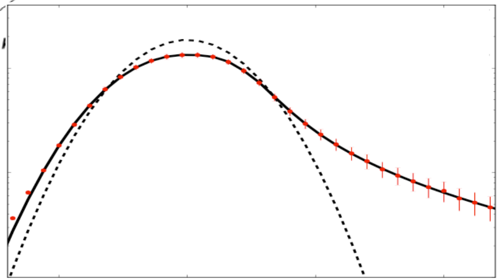
MicroJansky Radio Sources: Counts, Confusion, and Catalogues









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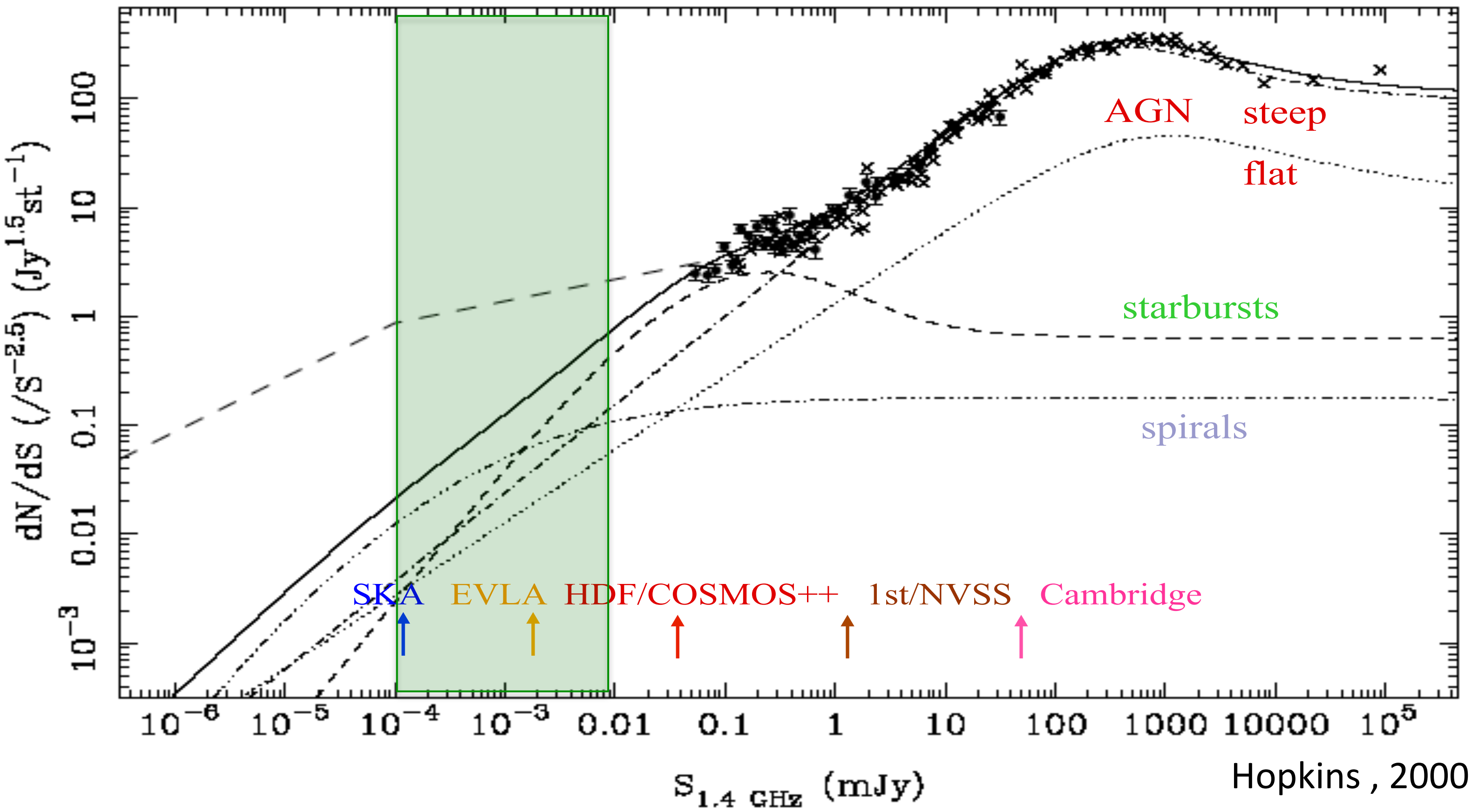
Rick Perley (NRAO/Soc), Ray Norris (CSIRO)

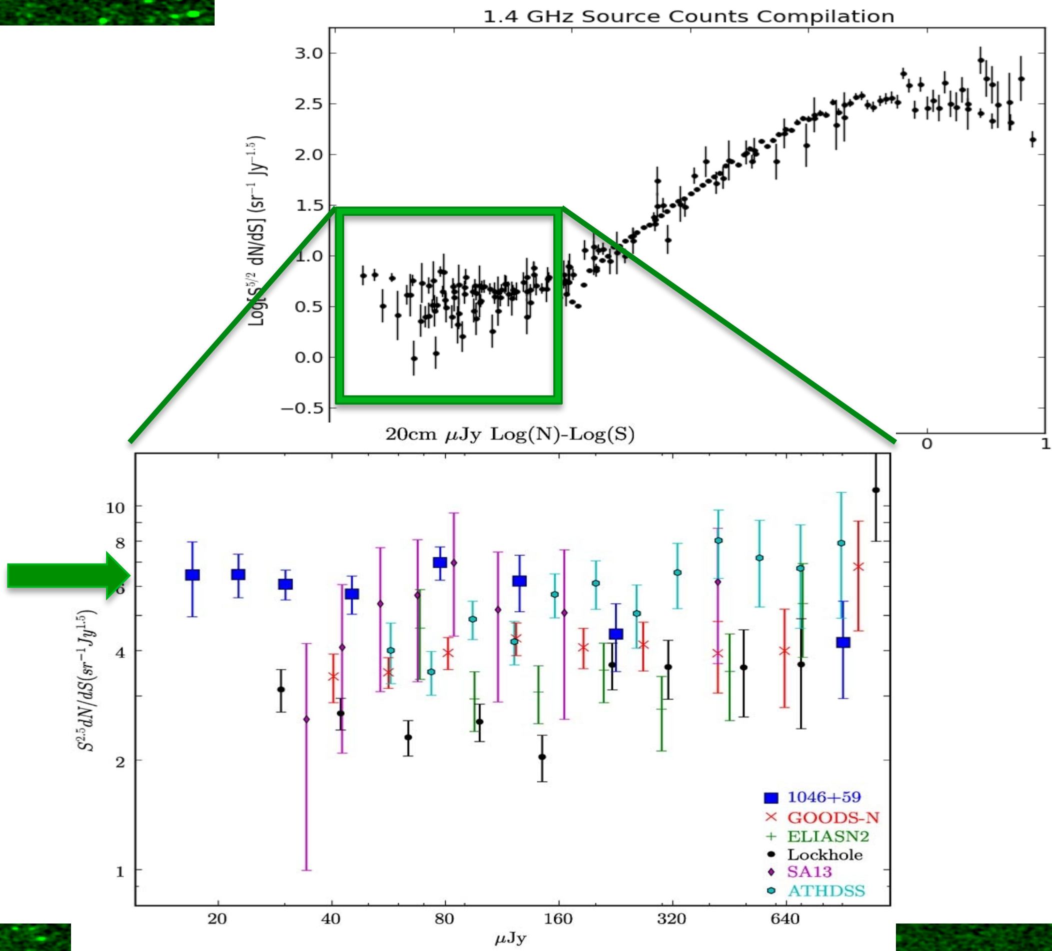
Background: Source Counts



Hopkins , 2000

Background: Source Counts

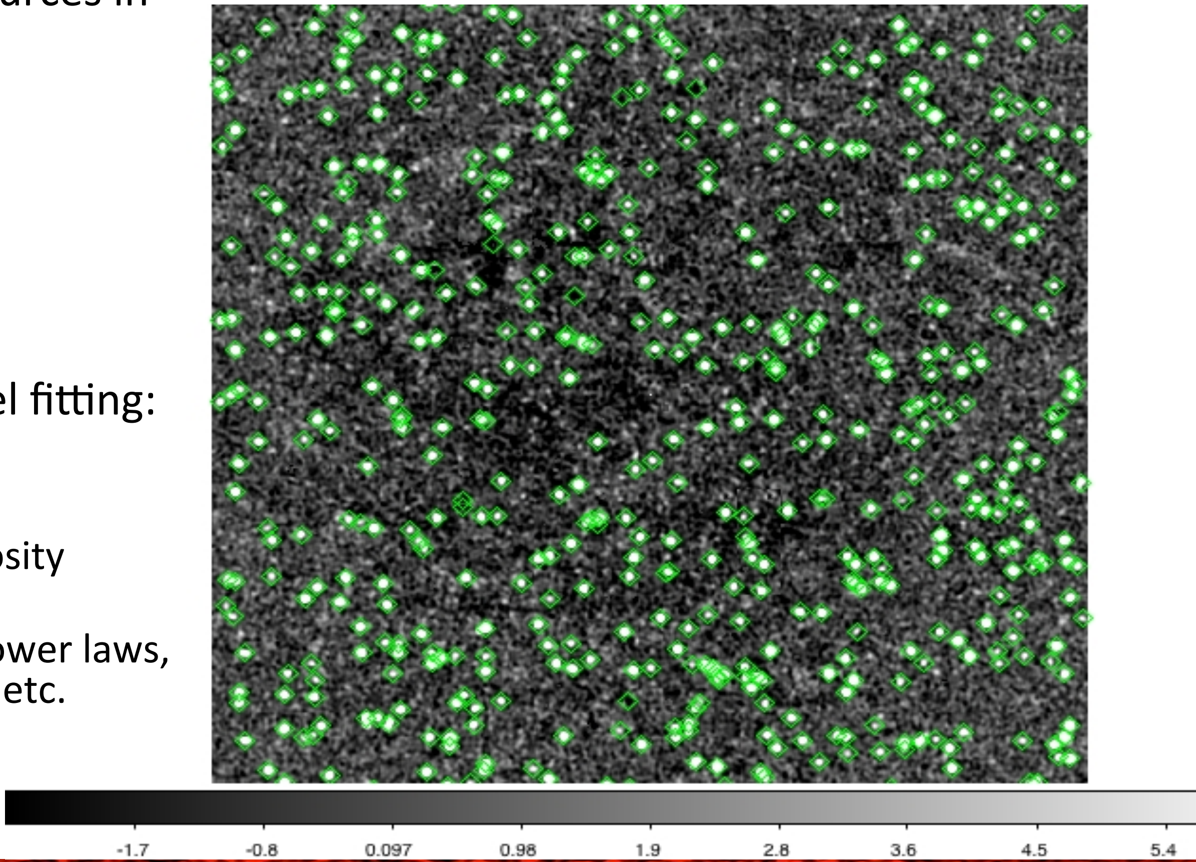
- Faint counts from high resolution surveys don't agree.
  - More scatter than due to Poisson or clustering
  - Faintest counts from Owen & Morrison 2008 show leveling off rather than downturn



Method: Source Counts

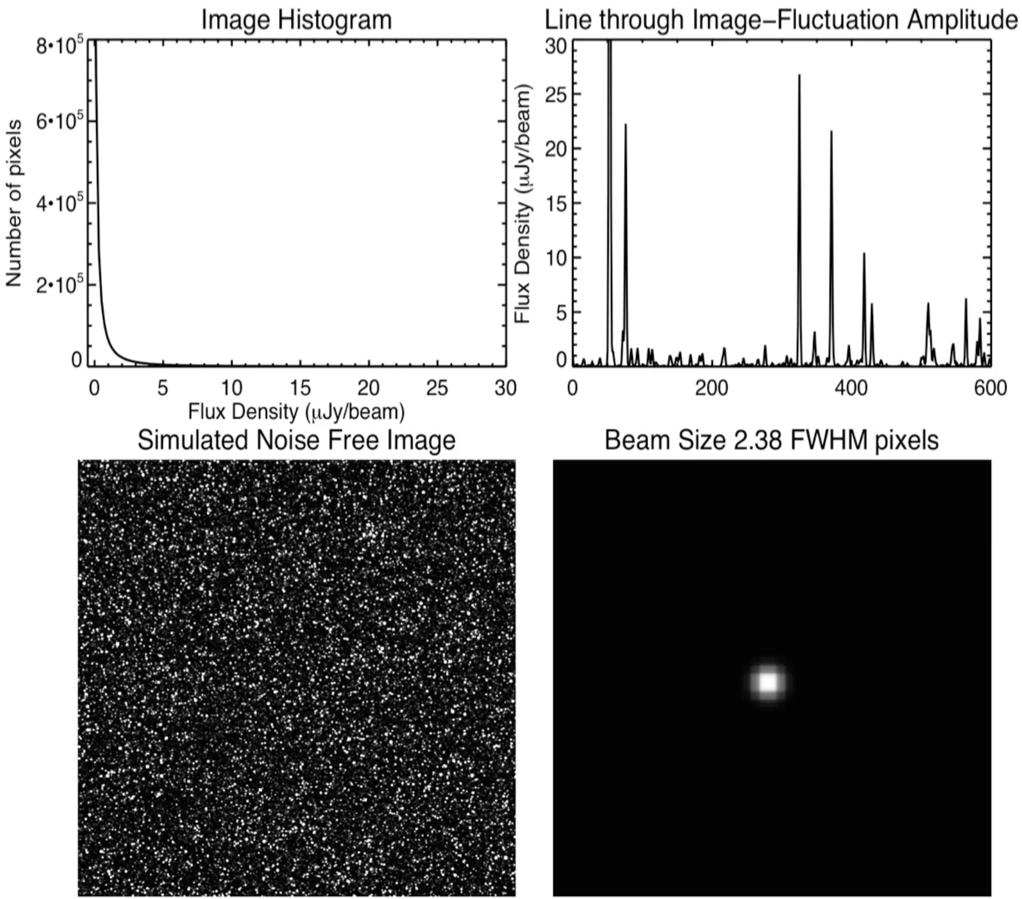
- Direct counting: count sources in survey with S > 5σ
  - Size corrections
  - Fit uncertainties
  - Completeness
  - False detections
  - Clean bias

- Statistical Estimate/model fitting:
  - Confusion analysis
  - → not limited by S>5σ
  - Physical models: Luminosity functions
  - Non-physical models: Power laws, polynomials, Gaussians, etc.



Method: Confusion

- Confusion = Blending of faint sources in beam
- Image pixel histogram (PDF) from confusion known as P(D)
- σ_c =width of P(D) governed by beam and source count
- **Want to know P(D)**



Method: 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 size
  - instrumental noise
- Mean density of observed flux, x

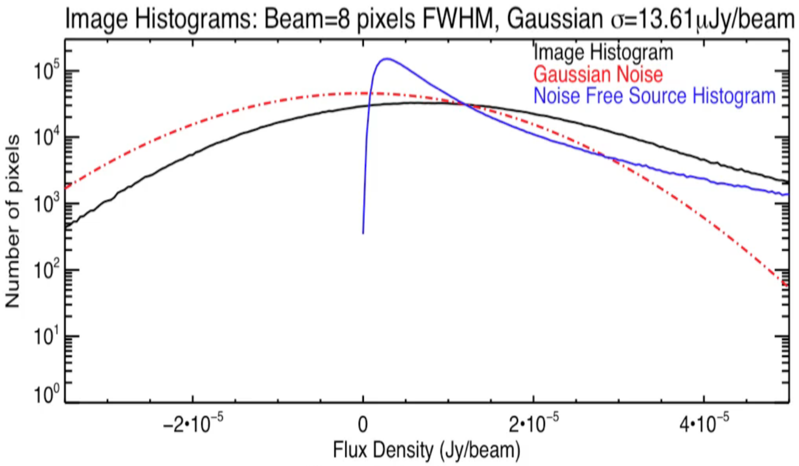
$$R(x)\,dx = \int_{\Omega} \frac{dN}{dS}\left(\frac{x}{b}\right) b^{-1}\,d\Omega\,dx$$

- P(D) is then:

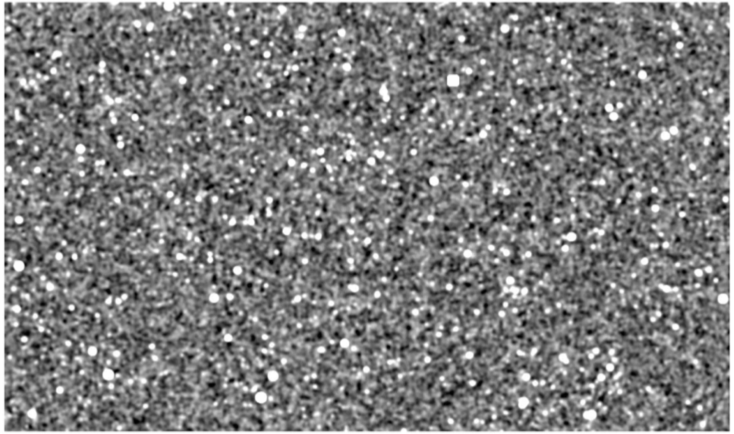
$$P(D) = \mathcal{F}^{-1}\left[\exp\left(\int_0^{\infty} R(x)\,e^{iwx}\,dx - \int_0^{\infty} R(x)\,dx - i\mu w - \frac{\sigma_n^2}{2}w^2\right)\right]$$

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

- Want $\boldsymbol{\sigma_c > \sigma_n}$

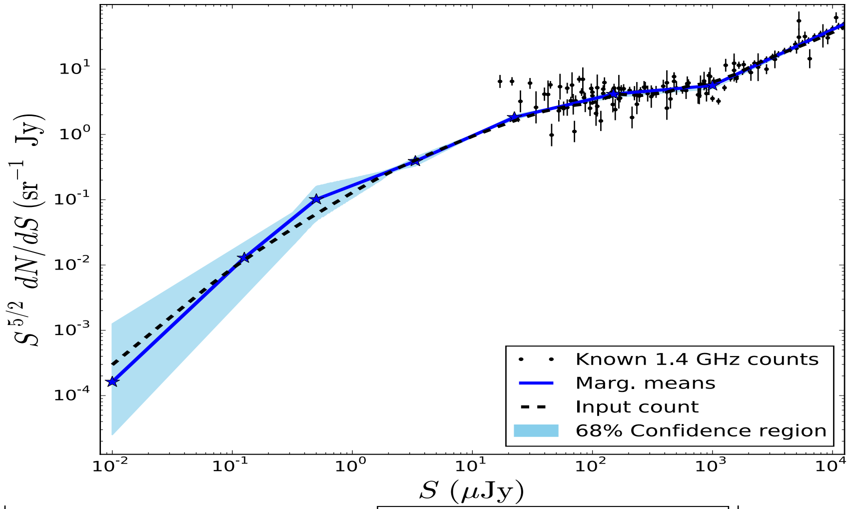


Simulated noisey Image

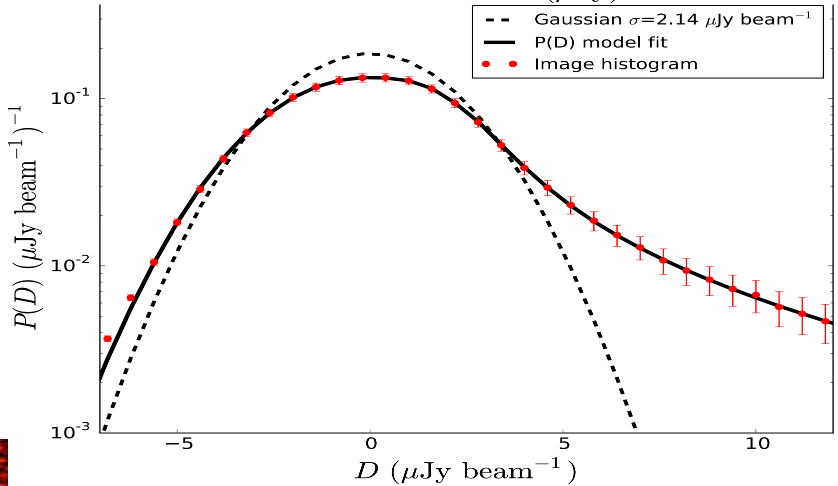


Method: Probability of Deflection

- Node Method (Patanchon, 2009):
  - Fixed node position in Log(S)
  - Fit amplitude of nodes in Log(dN/dS)
  - Interpolate between nodes
  - Use MCMC to find minimum log likelihood



- Example: Simulation data from SKADS S^3
  - 1 square degree
  - 1.4 GHz
  - Gaussian noise = 2.1 µJy/bm

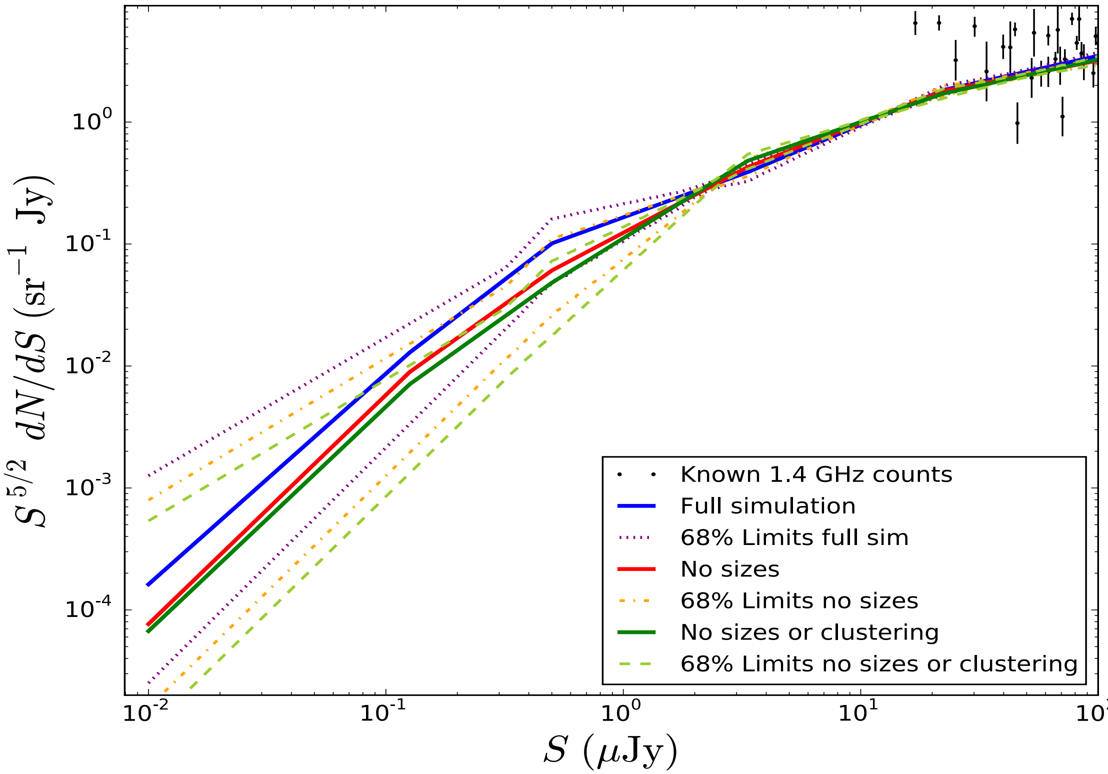


Method: Probability of Deflection

- P(D) does not account for
  - Clustering
  - Source Sizes

- Use simulation to test effect
  - Clustered sources with sizes
  - Clustered point sources
  - Random positions point sources

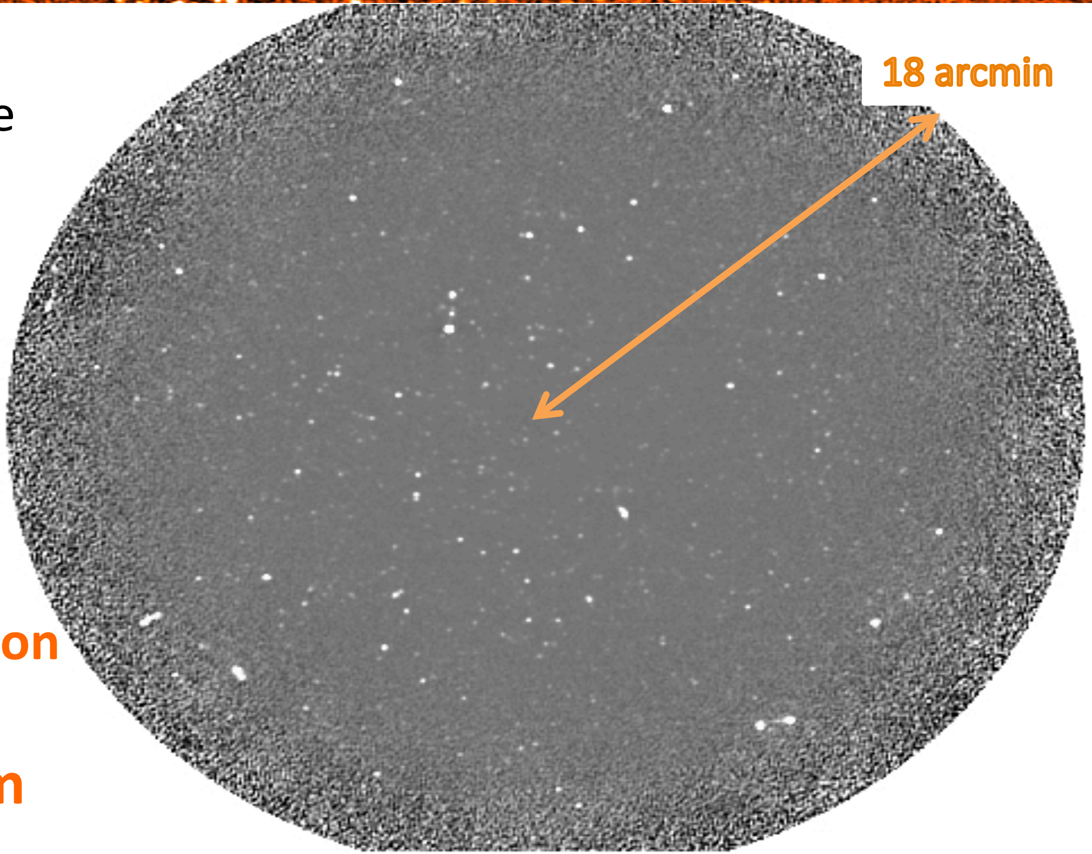
- Little effect on fitting except at faintest flux densities



VLA P(D): Data & Imaging

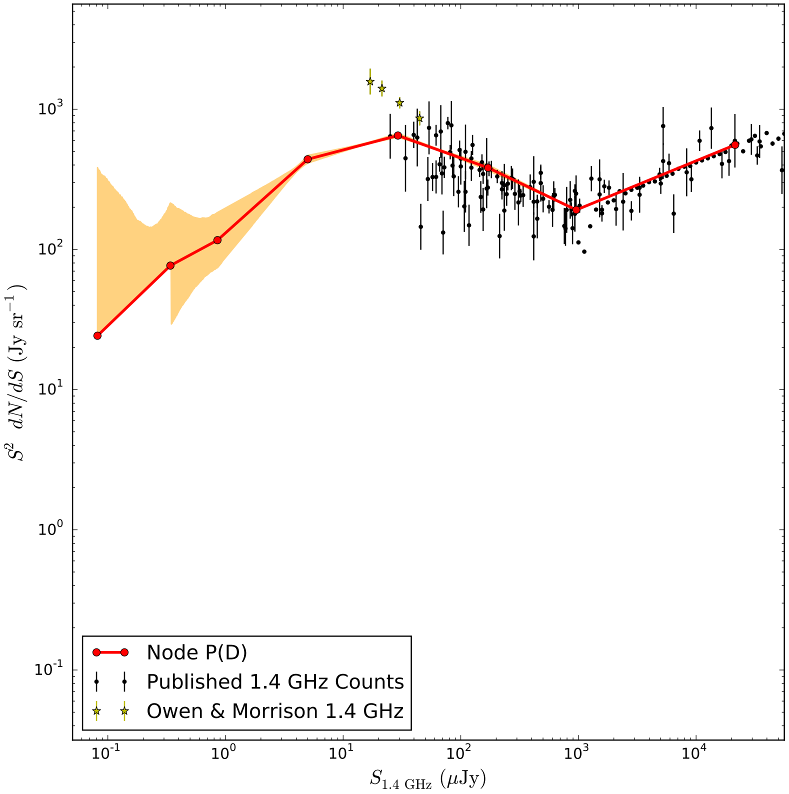
(J)VLA

- Lockman “Owen” Hole
- Time: **50h**
- S Band: **2 - 4 GHz**
- Beam size : **8’’**
- Array: **C - configuration**
- Noise: **1.08 μJy/bm**

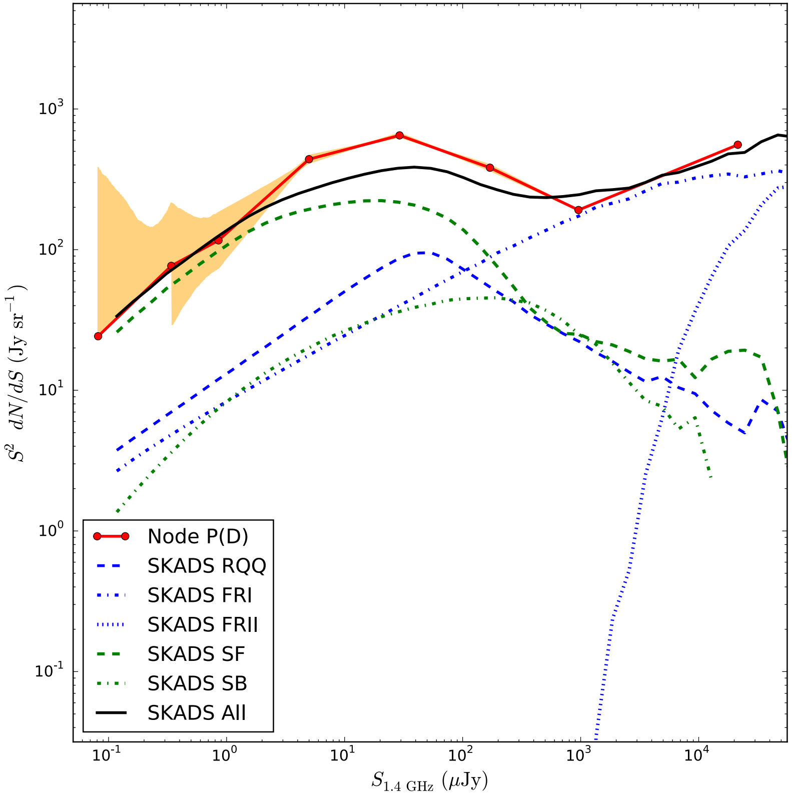


VLA P(D): Results – 1.4GHz

De Zotti Counts

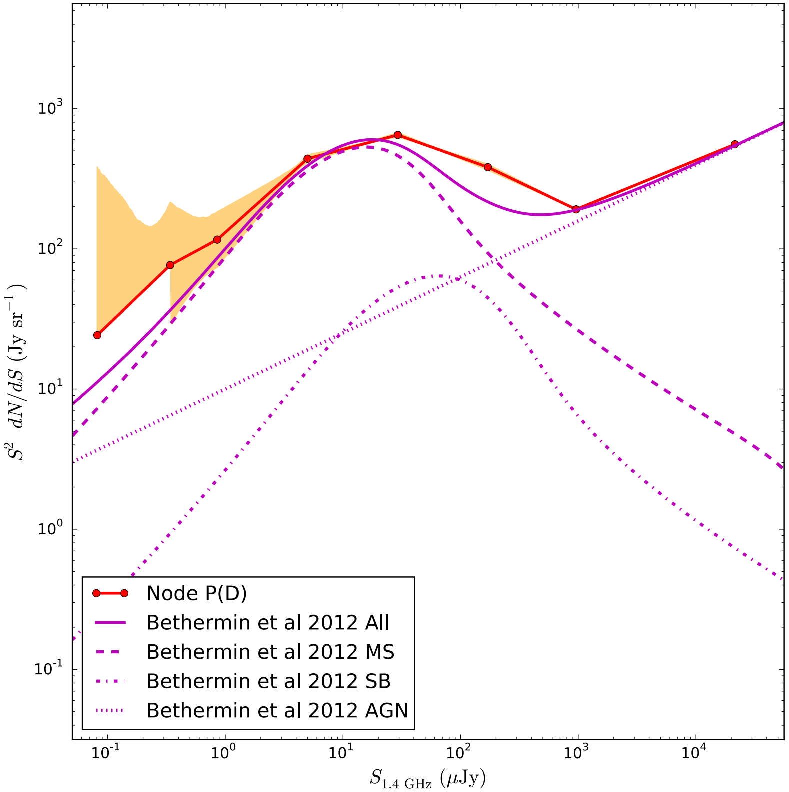


SKADS

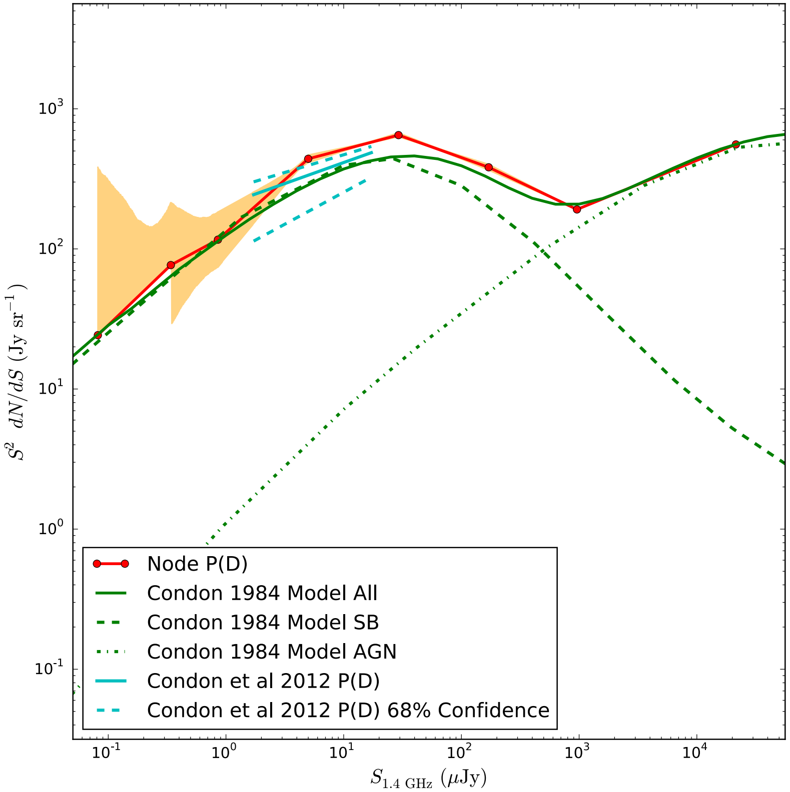


VLA P(D): Results – 1.4GHz

Bethermin+2012 – IR L Models

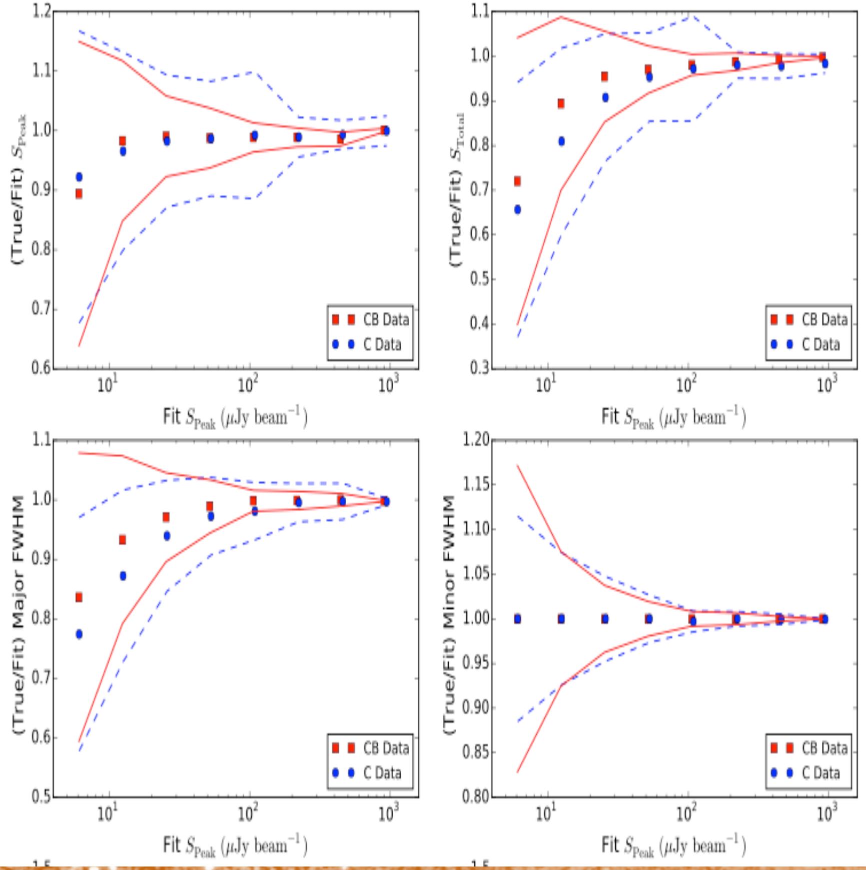


Condon 1984 – SB+AGN L Models



VLA Catalogue: Simulations

- 8” and 2.75” resolutions (VLASS vs SKA Pathfinders)
- OBIT and Aegean
- Simulations:
  - Simple case
  - “Realistic” case
  - Source blending
  - Source sizes
- To Test:
  - Effect of correlation noise
  - Software accuracy
  - Effect of resolution
  - Effect of source size
  - Effect of source blending
- Yields:
  - Parameter uncertainties
  - Completeness correction
  - False detection rate
  - “Flux boosting” correction



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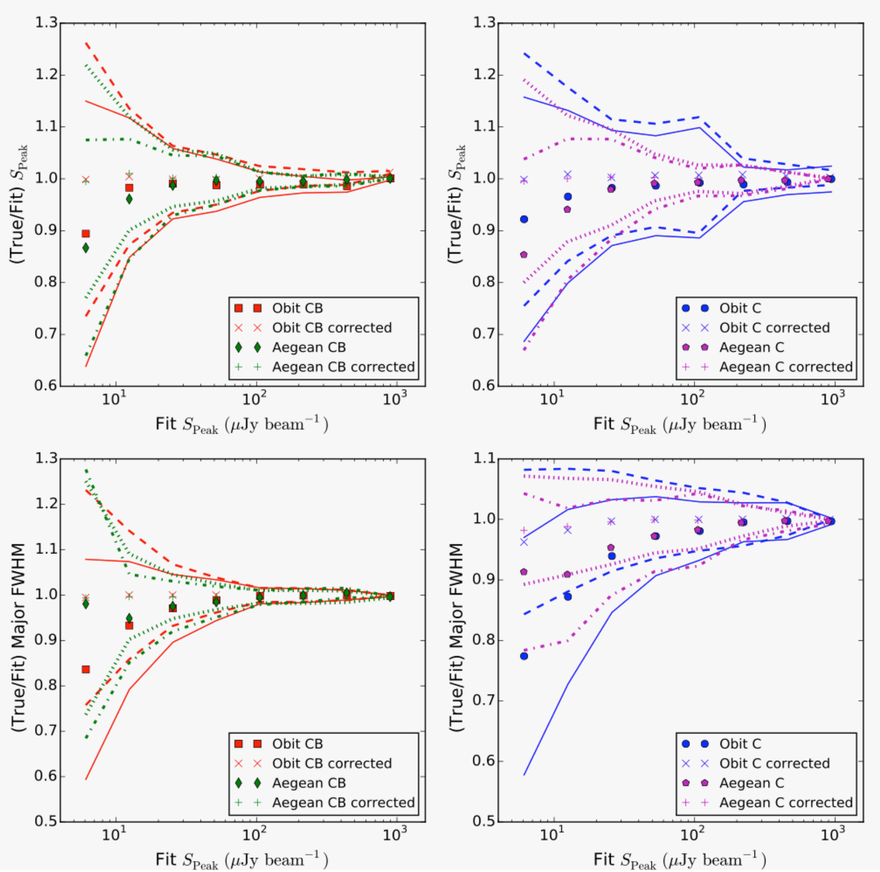
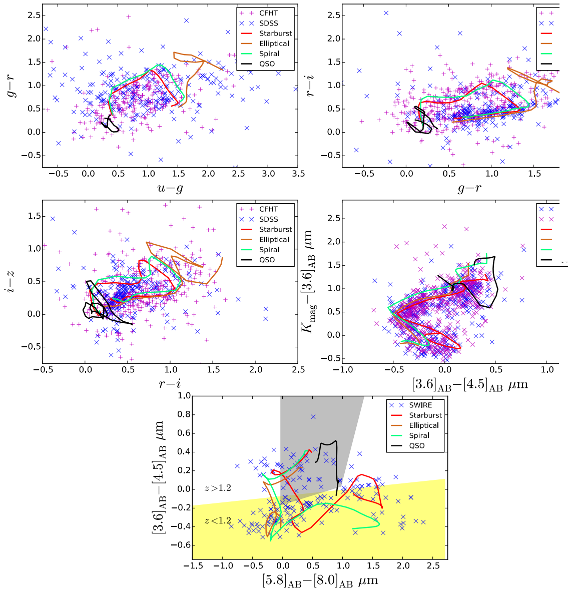
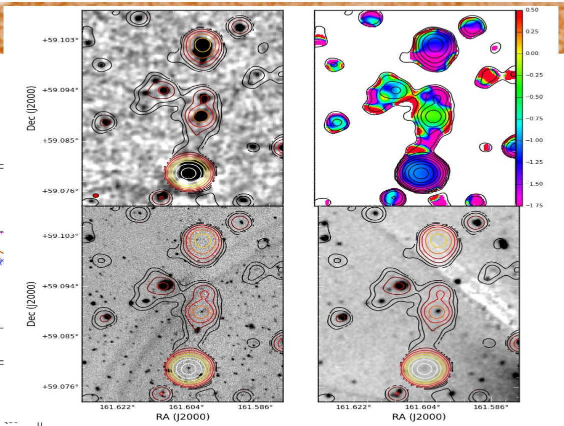
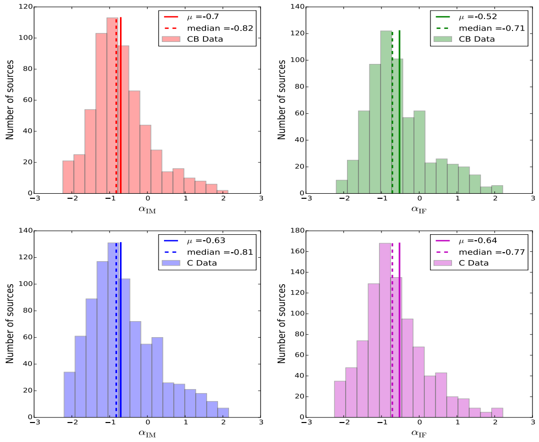


VLA Catalogue: Results

- Catalogue both resolutions down to 4σ
- Examine:
  - Angular size distribution
  - Source count
  - Spectral index
- ~25 other catalogs to cross match for:
  - Radio spectral index
  - Optical/IR colours
  - Redshifts



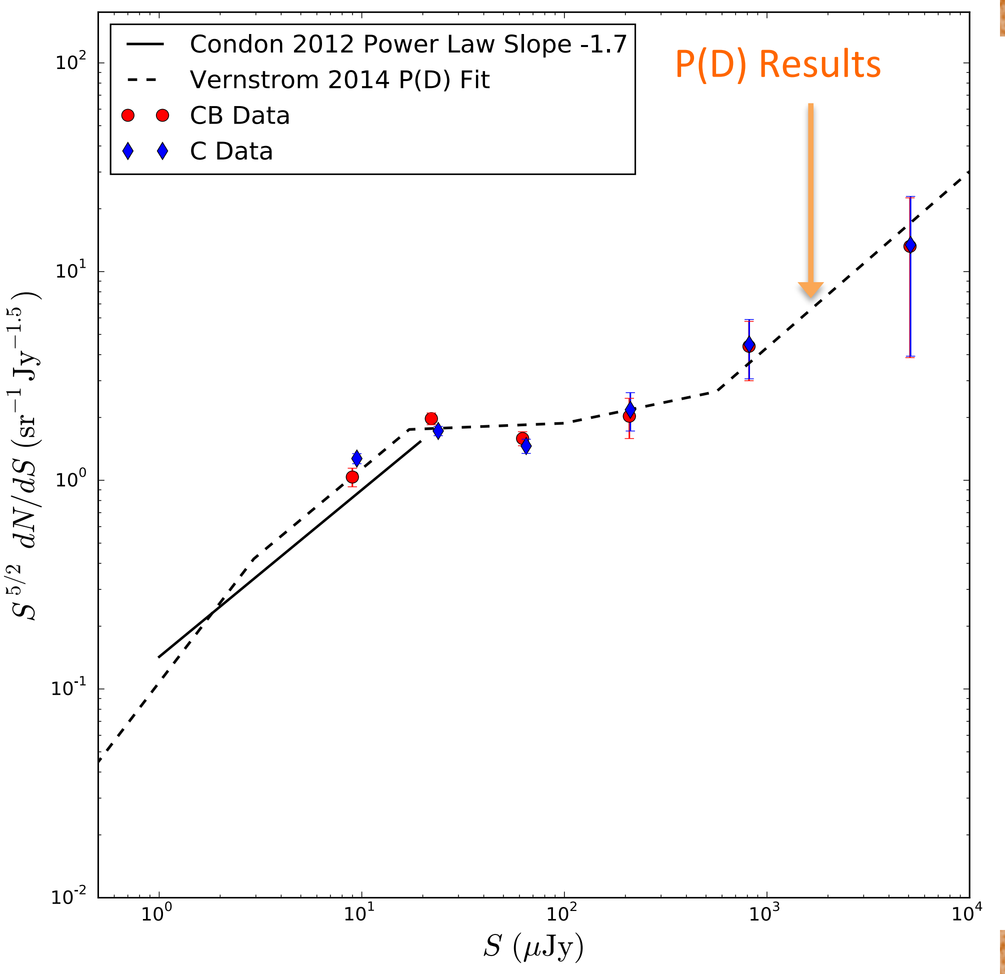




VLA Catalogue: Source Count

- Source count
  - Completeness and false detection corrections
  - Calculated in bins of fitted source size

✧ Very good agreement with P(D)



VLA Catalogue: Source Count

- Source count
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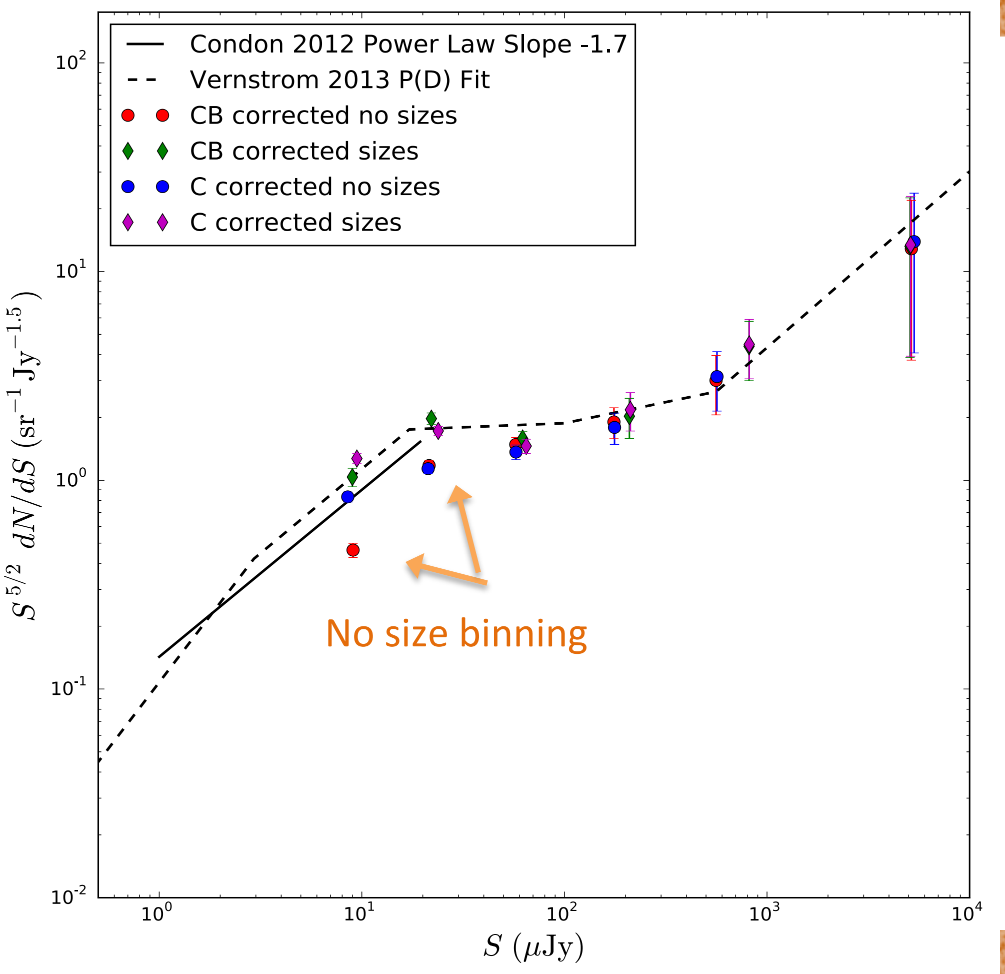
✧ Must be careful with corrections → very easy to overcorrect at faint end



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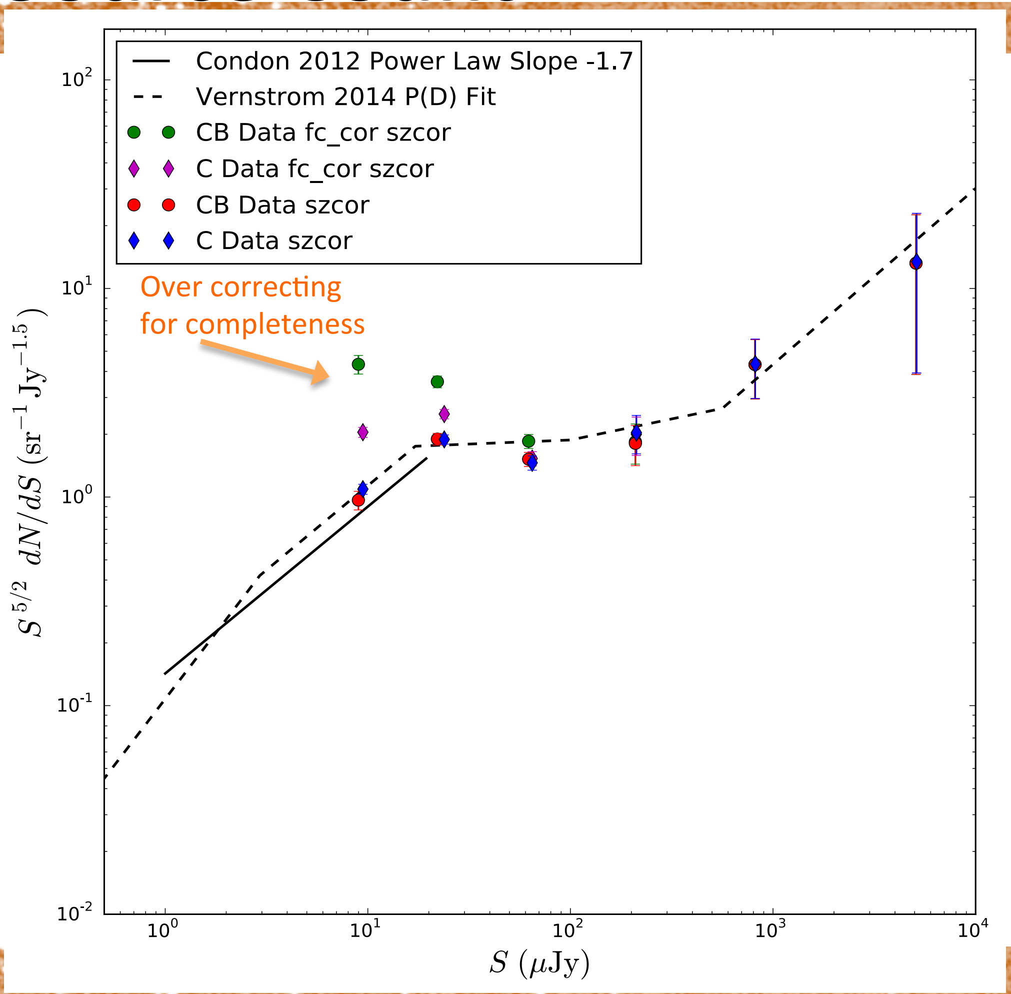
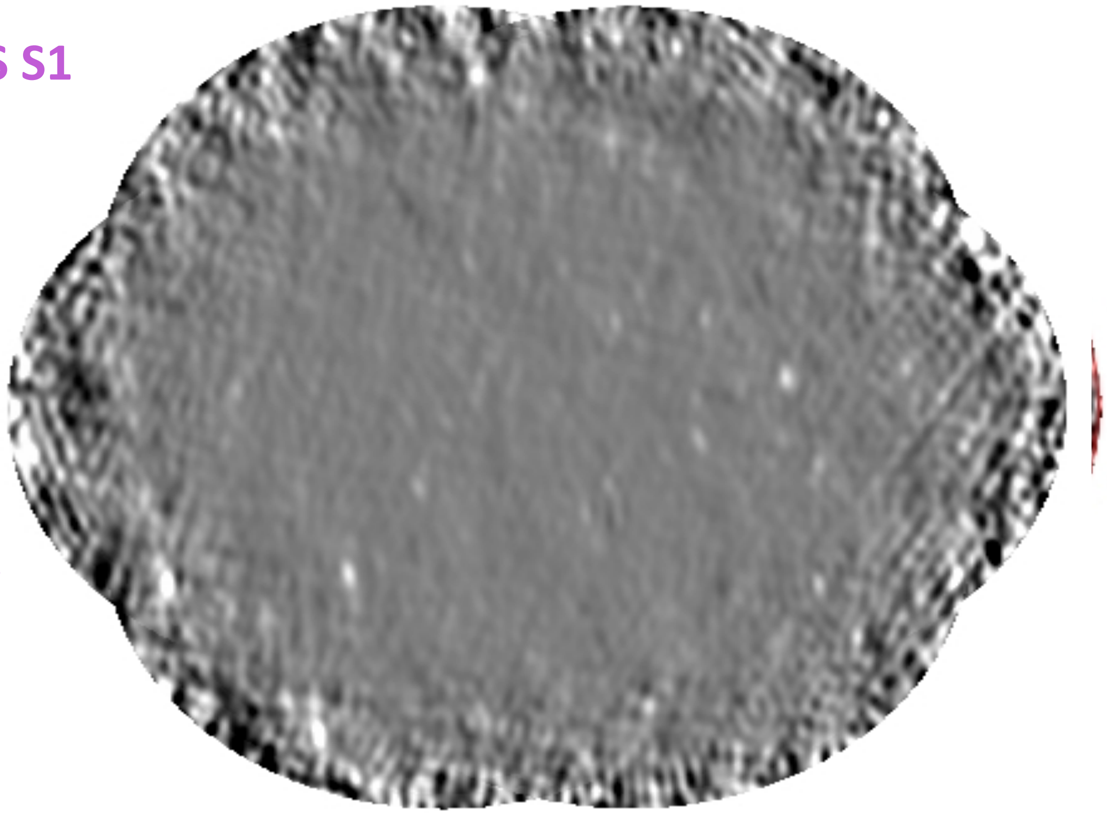


ATCA LSB: Data & Imaging

ATCA

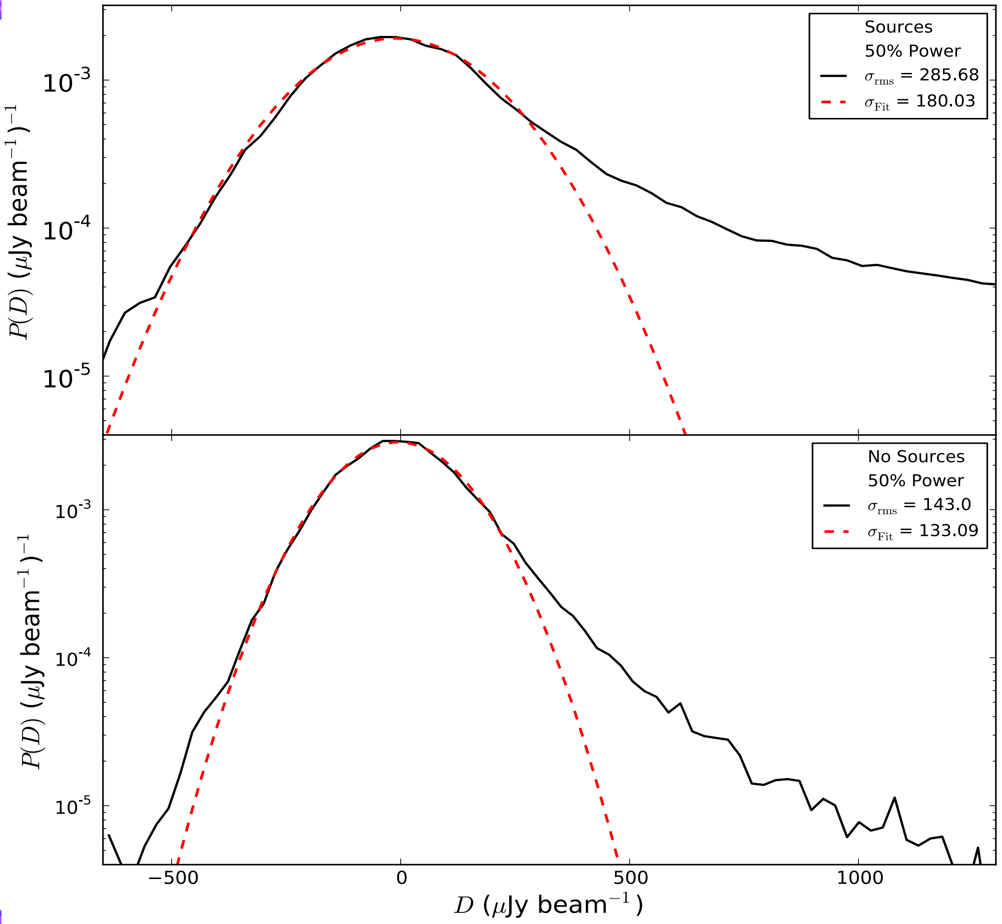
- 7 pointing mosaic: **ELAIS S1**
-
- Array: **EW 352**
- Time: **12h**
- Beam – **150'' x 60''**
- 16cm Band: **1.1-3.1 GHz** **<1.75 GHz>**
- Noise: <52> μJy/bm



ATCA LSB: Subtraction

No Subtraction Image Histogram

Subtraction Image Histogram

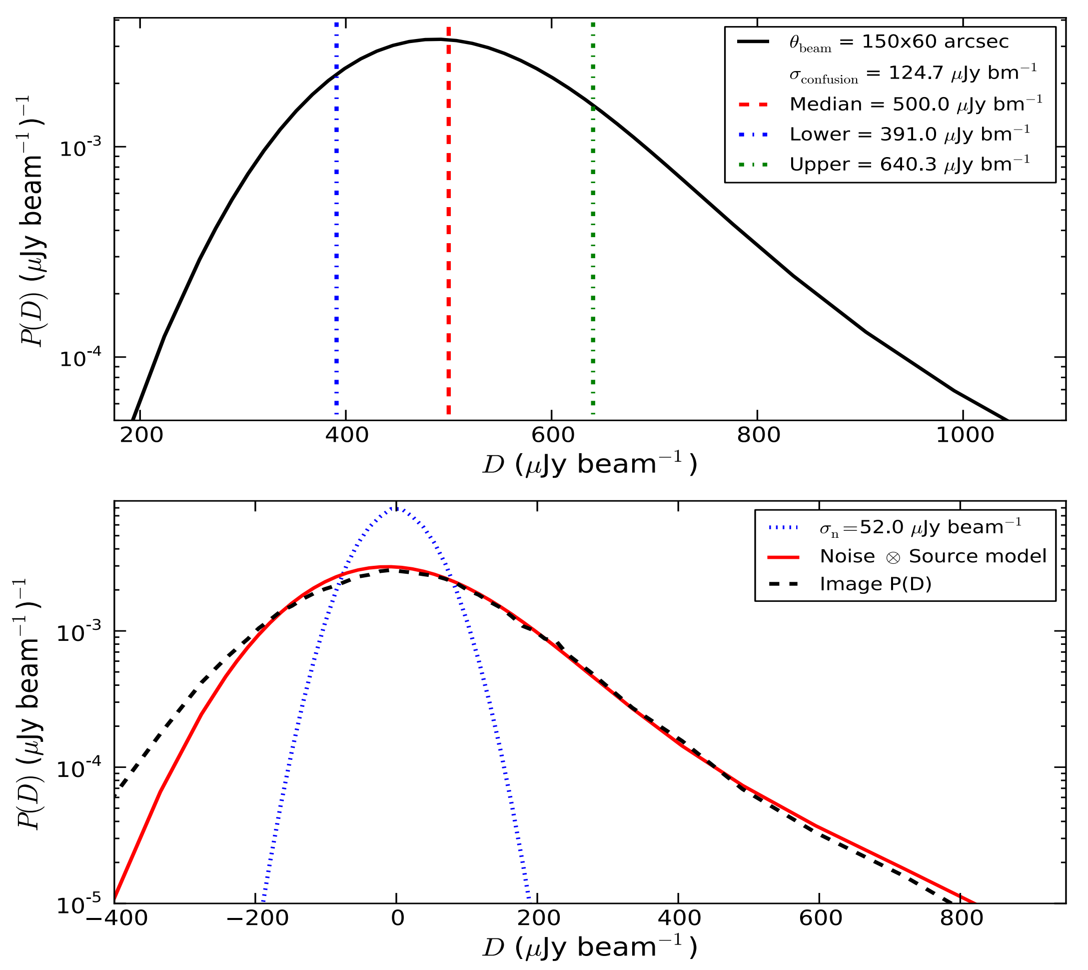


ATCA LSB: Subtraction

Model un-subtracted faint sources

Excess detected over model of noise + un-subtracted point sources:

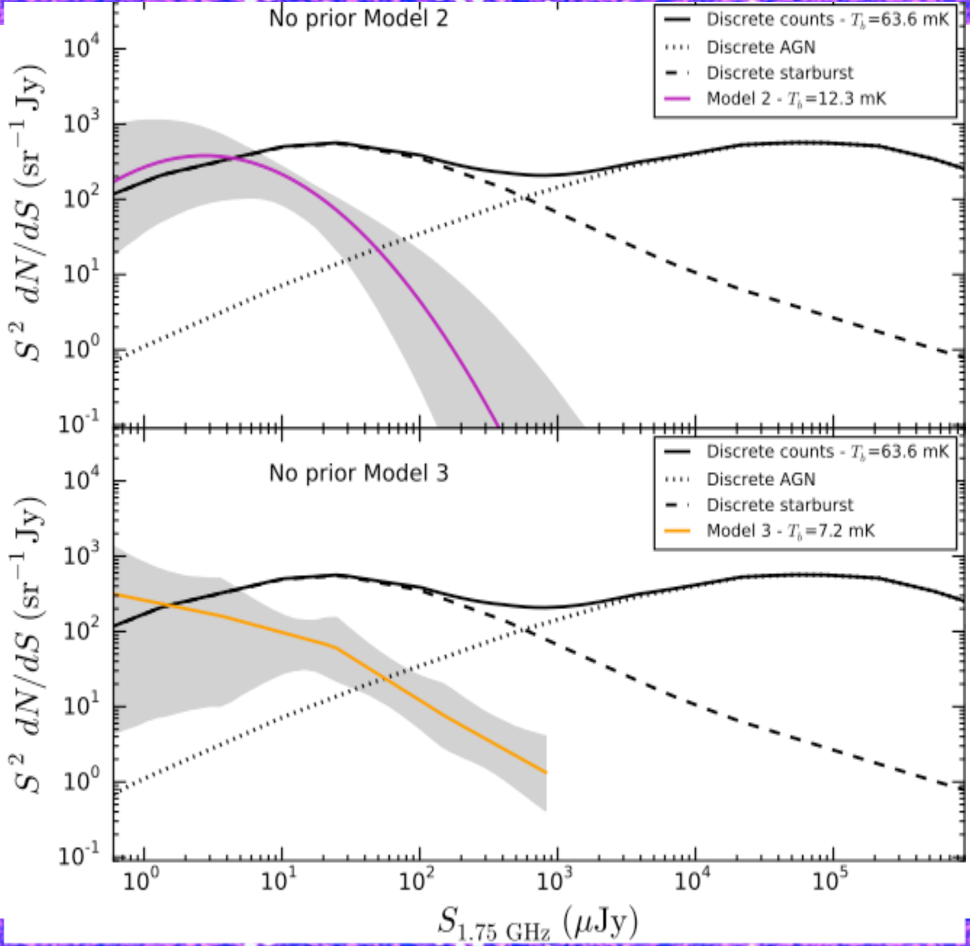
76 +\- 23 μJy/bm→ 3σ



ATCA LSB: Results – Counts

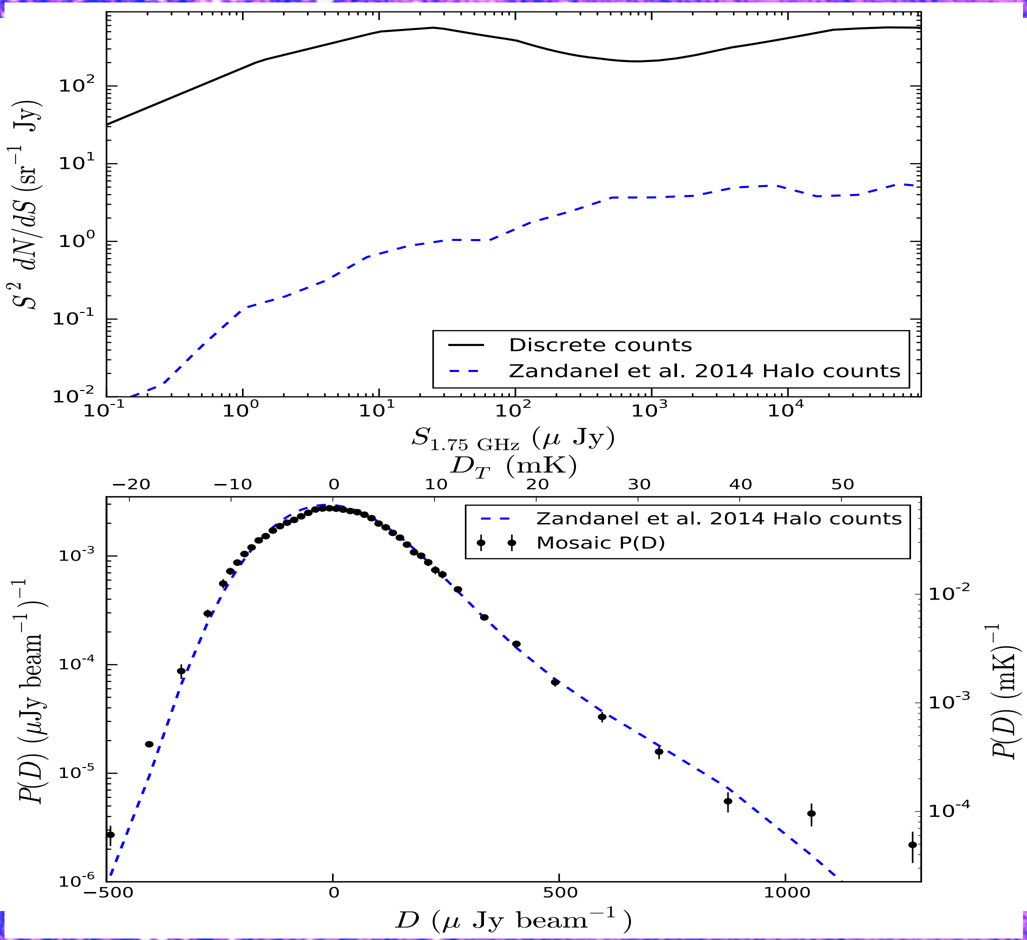
Model 1:
Parabola

Model 2: Nodes



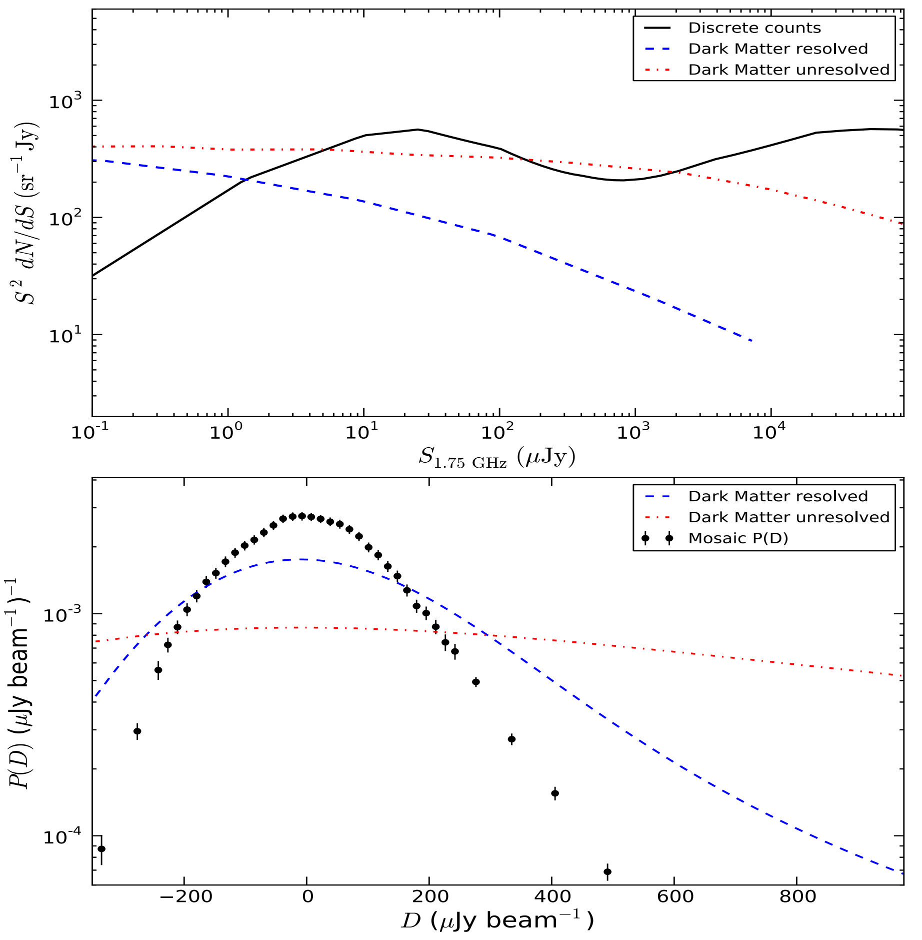
ATCA LSB: Clusters

- Cluster radio emission:
  - Giant/mini radio halos
  - radio relics
- Observations limited to bright halos (S > mJy)
- Simulated model from Zandanel et al 2014 – MultiDark cluster catalogue
- Reasonably good fit to our data
- Only goes to z=1

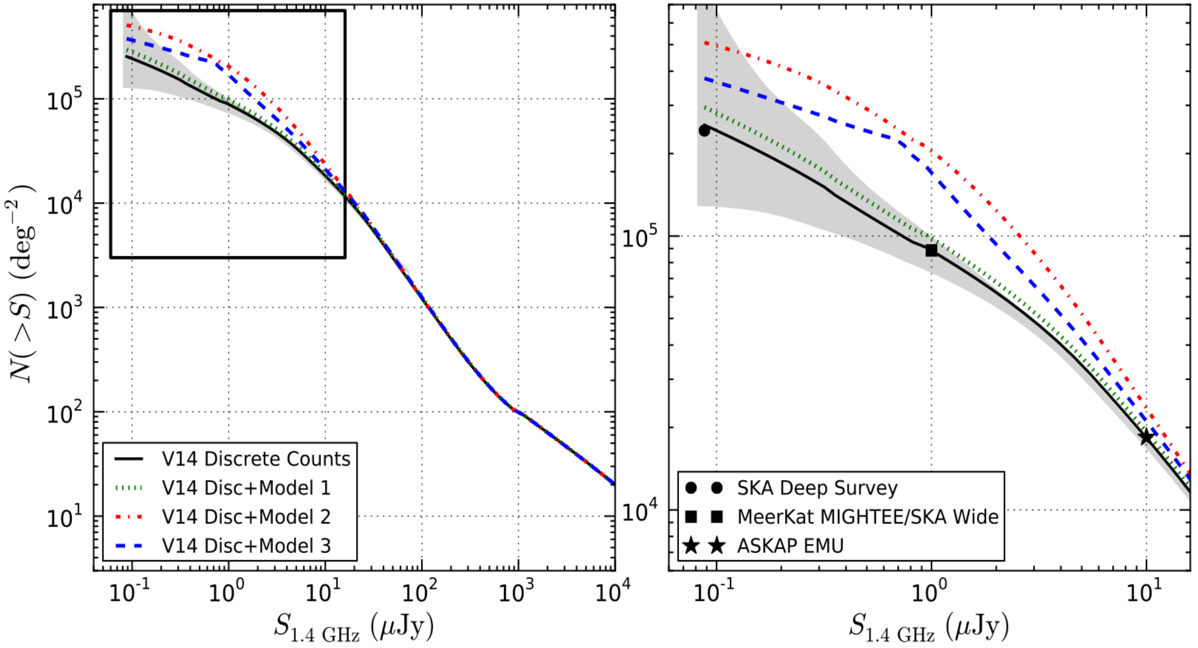


ATCA LSB: Dark Matter

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



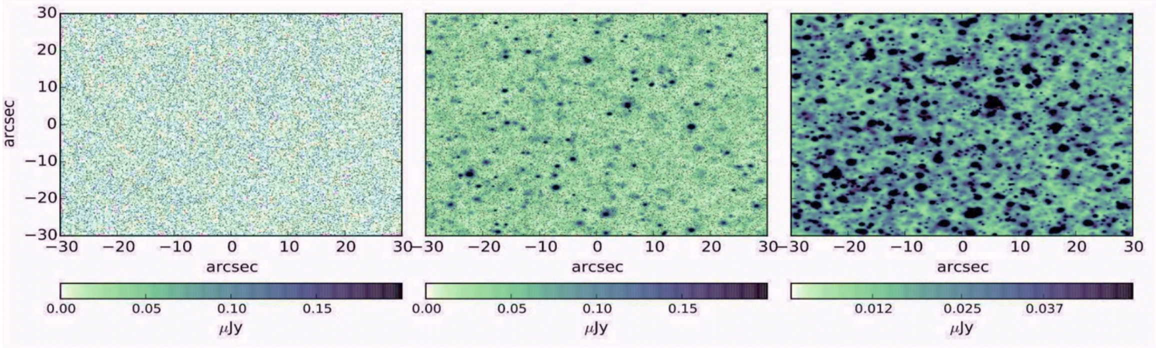
Integral Counts



	MeerKAT - MIGHTEE	ASKAP - EMU
No. of Sources	3.1×10^{6} / 9.7×10^{5}	9.0×10^{7}
Confusion level	2. - 3. μJy/bm (8”)	4. - 5. μJy/bm (10”)

Next Steps: Power Spectrum

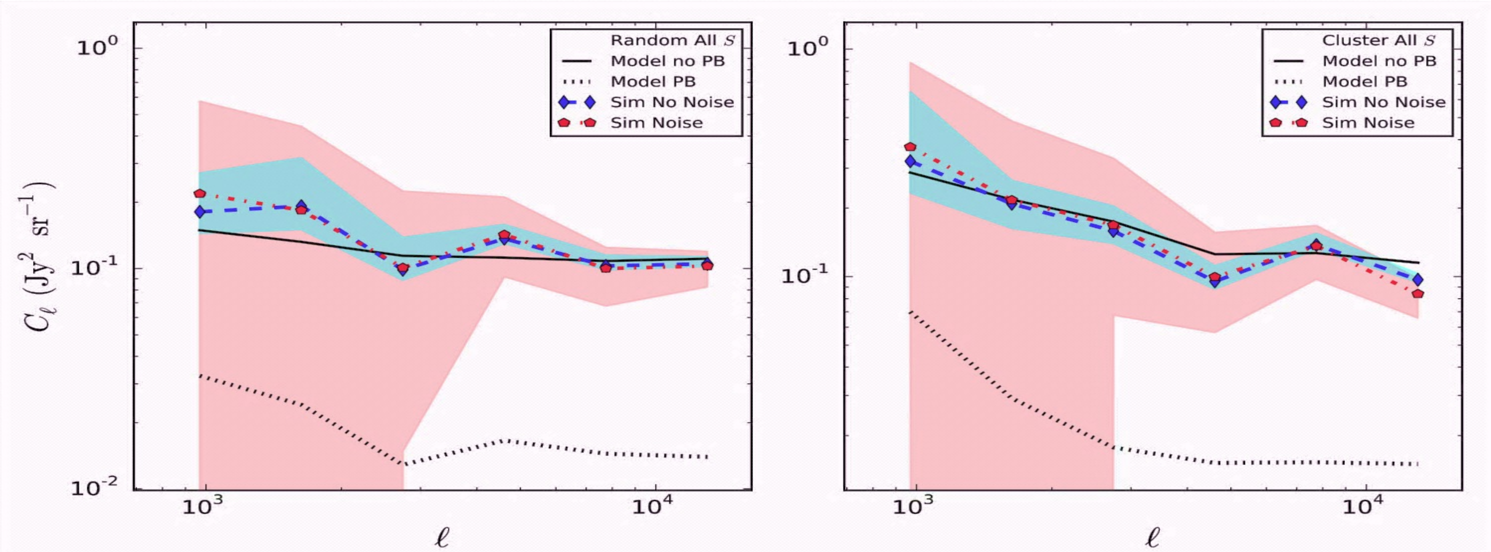
- Only upper limits to the unresolved radio background
- Simulations -- SKADS catalogues
  - Point Sources
  - Extended Halos
  - PS+Halos
  - Random Positions
  - Clustered Postions
  - Mosaic
- Simulations to test:
  - Frequency weighting
  - Primary beam
  - *uv* coverage
  - Noise
  - Mosaicking



Next Steps: Power Spectrum

Random positions
point sources

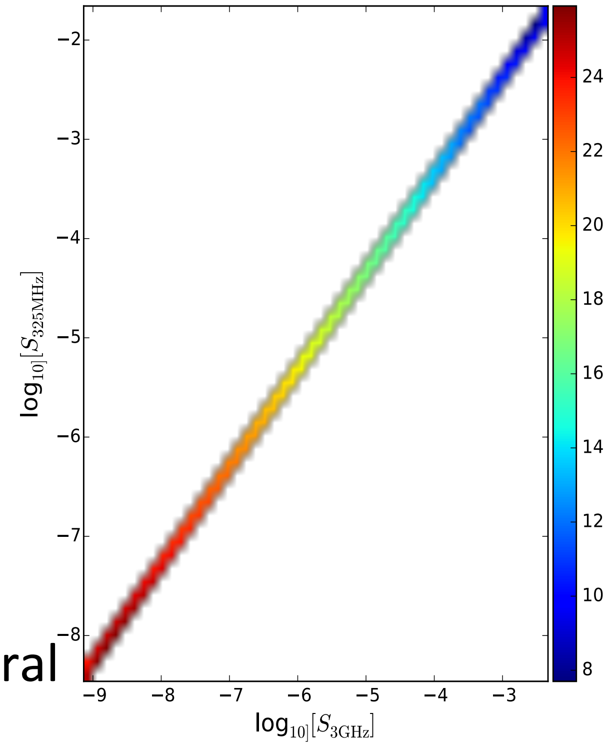
Clustered positions
point sources



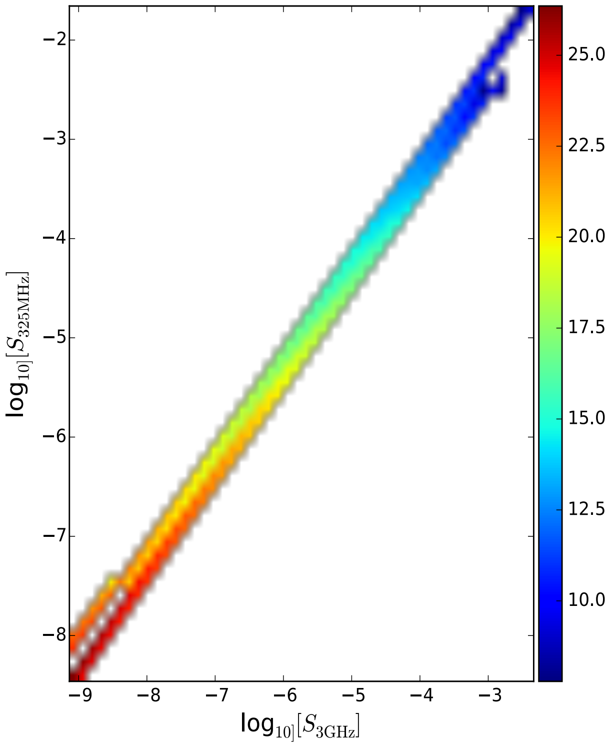
Next Steps: 2D P(D)

- 2D source count at 2 frequencies
- Fit 2D histogram
- Yields additional constraints
- Multiple populations/ luminosity functions+ spectral indices

Single population α=-0.7



2populations, AGN α=-0.85, Star-forming α=-0.6



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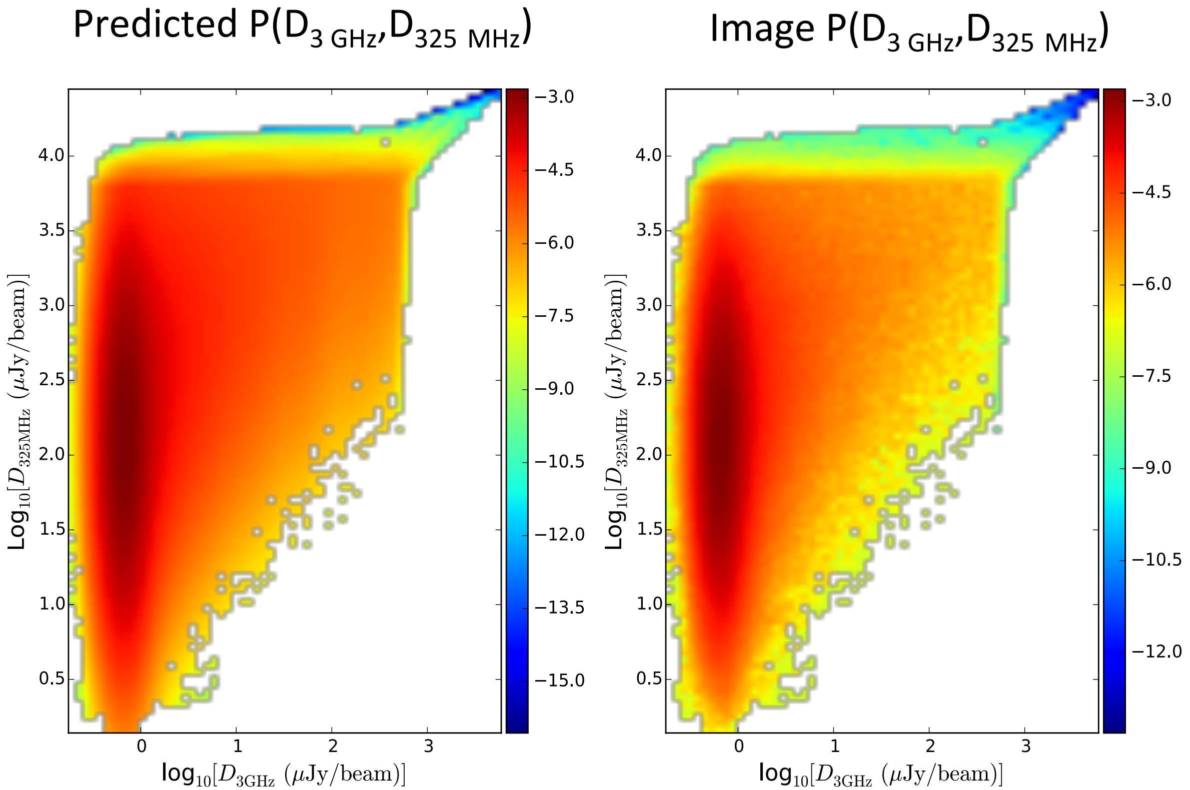


Conclusions

- P(D) and confusion:
  - Useful technique to estimate and constrain source count and confusion (EMU, MIGHTEE,….)
  - Best when confusion noise > instrumental noise (ASKAP, MeerKat, SKA)
  - Can be used for extended LSB as well → clusters, dark matter, cosmic web (EMU, MWA)
    - Requires careful point source subtraction
  - Can fit a wide range of models
  - Can be applied to MF and WF/Mosaic data
  - ❖ Need to know beam and noise very well
  - ❖ Valid as long as $\Omega_{source} < \Omega_{beam}$
  - ❖ Does not account for clustering
- Cataloguing for SKA surveys
  - Optimal source finding/fitting routine still a ?
  - Multiple deep resolutions best if possible
    - New imaging algorithms may be better at recovering all scales
  - SKA/Paths will be affected by blending
    - Machine learning/new algorithms for identification and de-blending
  - Need to be careful with source count corrections
  - WB coverage allows for α's
  - Still need to know the source size distribution as function of **S** (separate populations)
    - May not be as crucial for SKA (more optimal uv coverage)
  - ❖ Important to figure these issues out on smaller data sets/simulations now (before large surveys)

Continuing Work

- Radio Angular Power Spectrum – ATCA/EMU/ MWA
- High resolution catalog & Angular size distribution –VLA A config 40 mores hours LH
- Low frequency (2D P(D)) – 325 MHz GMRT LH– MWA
- Polarisation
- Luminosity function modelling
- SKA Simulations/Data challenge

Conclusions

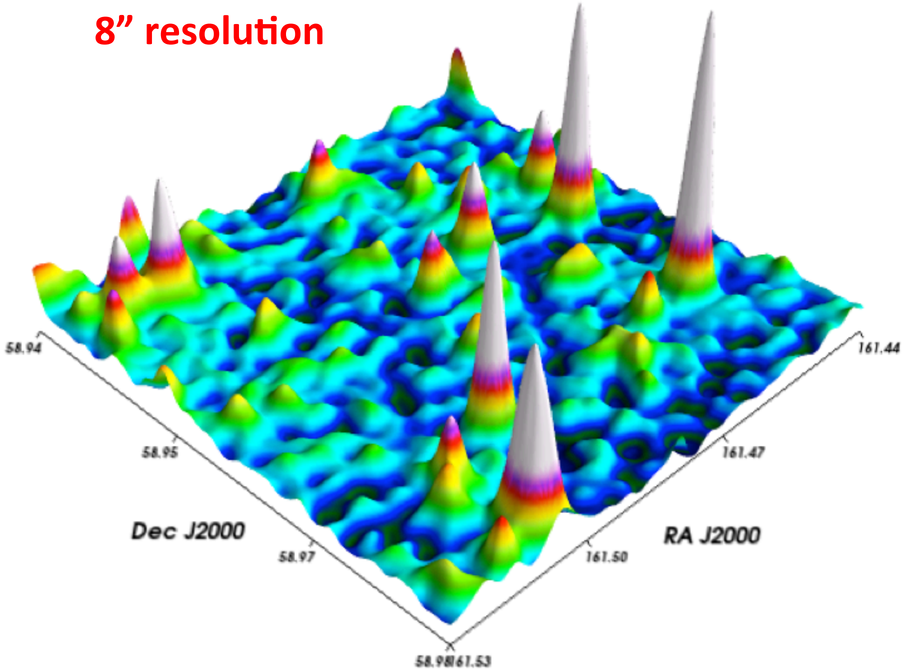
- Deepest:
  - single pointing 3GHz image
  - arcminute resolution image at ~1.4GHz
  - source count estimates & constraints
- Discrete count:
  - good agreement with most published data
  - Luminosity functions a bit lower in the 1-100 μJy range
- Extended count:
  - consistent with model of faint halo structures
  - rules out at least one model of dark matter annihilation
- Background temperatures:
  - Discrete only: 3GHz = **14 mK**
  - Discrete only: 1.4 GHz = **120 mK**
  - Discrete+ Extended: 1.75 GHz = **80 mK**

- Roughly 800 sources catalogued with:
  - Size measurements
  - Spectral Indices
  - Optical and IR colours
- Power Spectrum detection:
  - Poisson level
  - Possible clustering

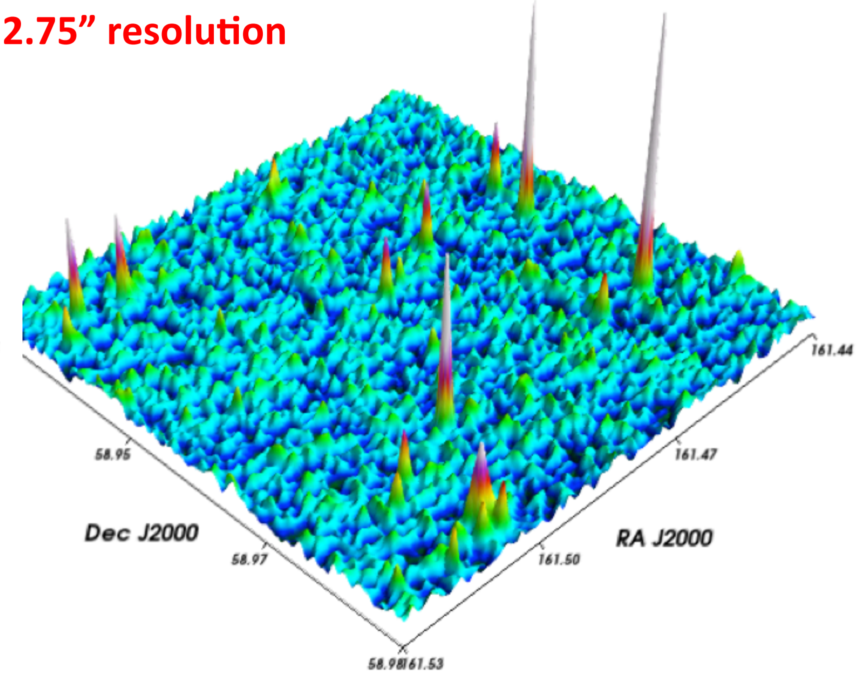
Method: Confusion

- Confusion = Blending of faint sources in beam

8” resolution



2.75” resolution



VLA P(D): Node Results