Radio Continuum Surveys: Lessons Learned

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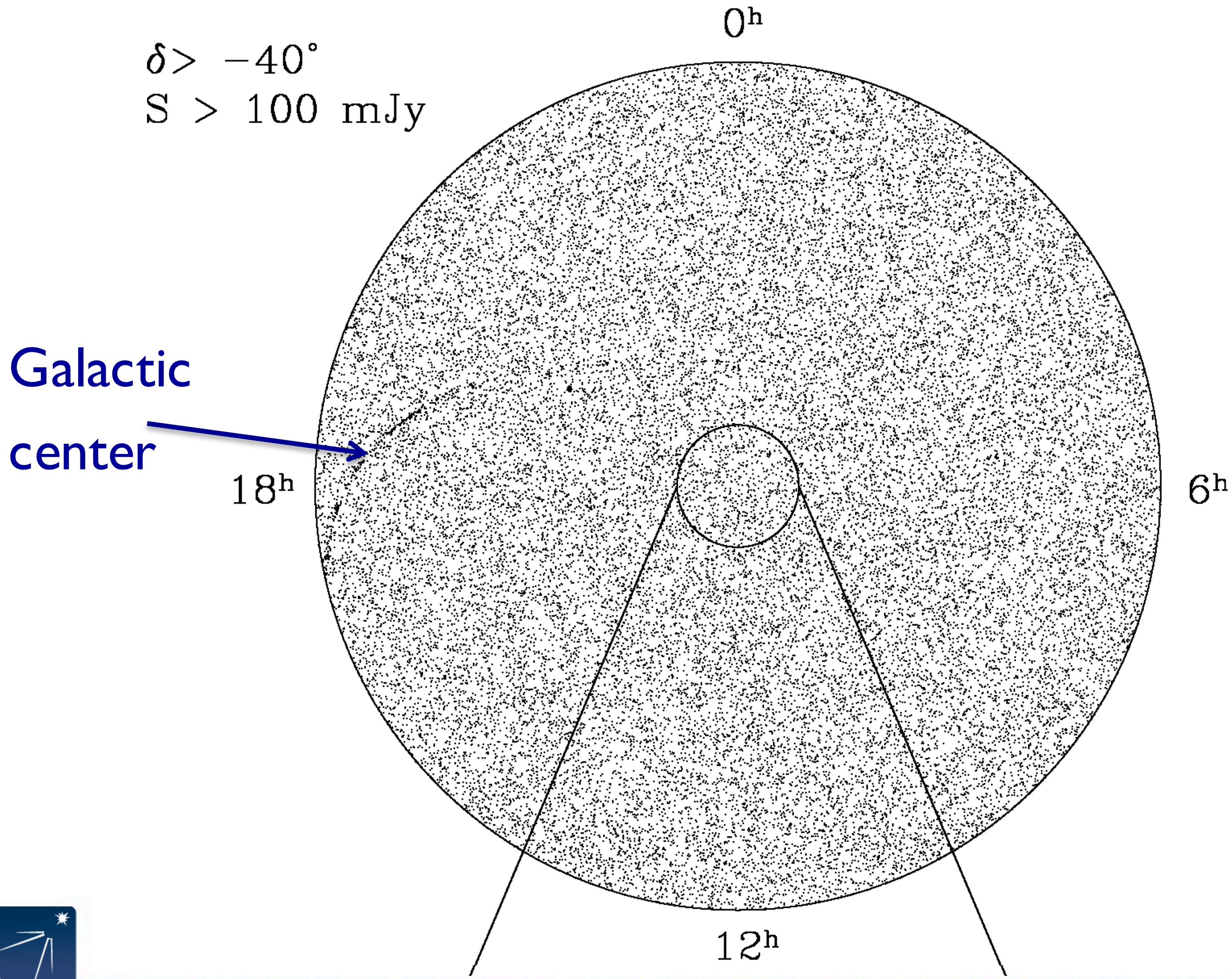
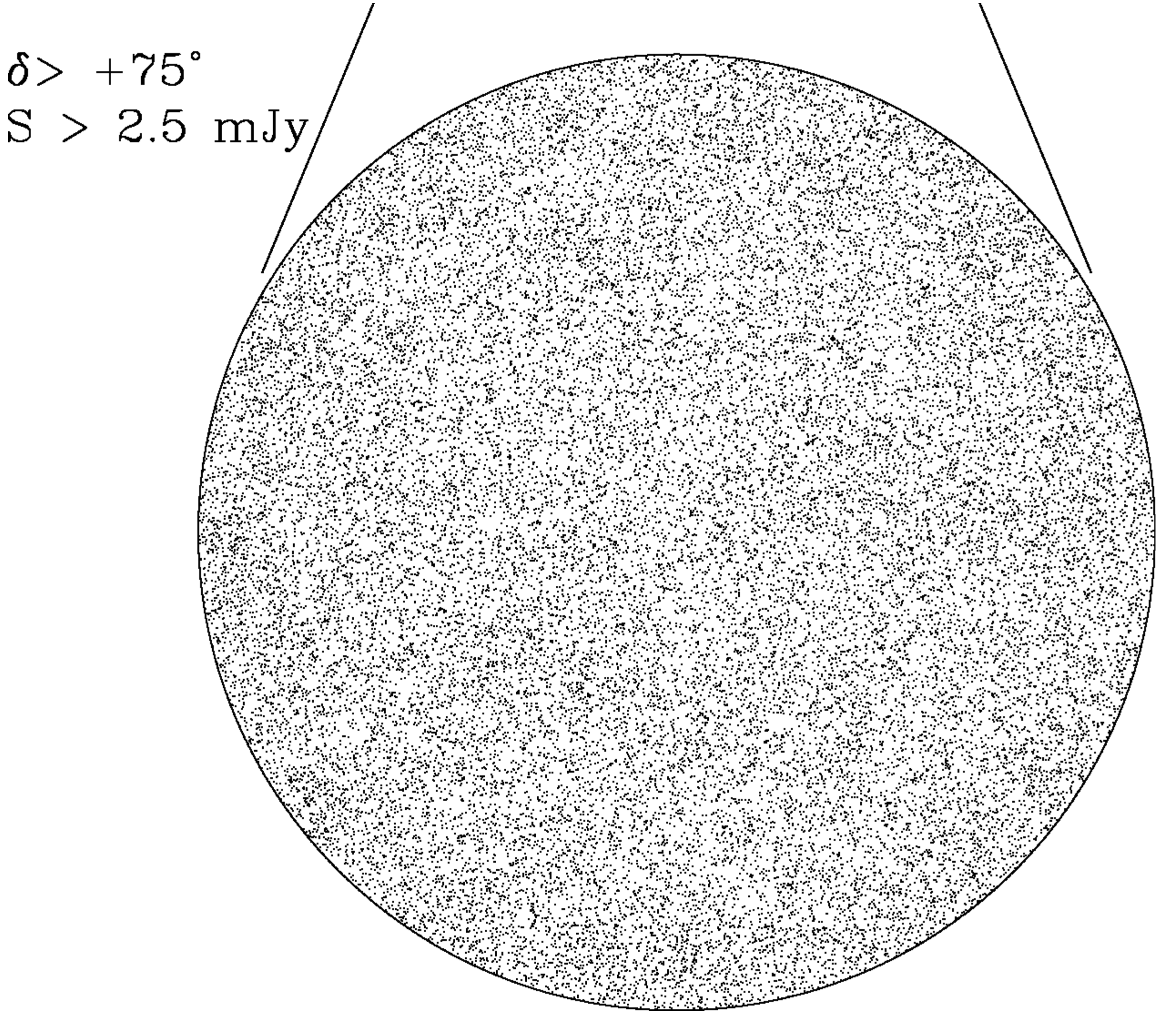
Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

The radio universe is mostly extragalactic,



very isotropic and hence very distant,



and neither static nor Euclidean.

10 × luminosity evolution

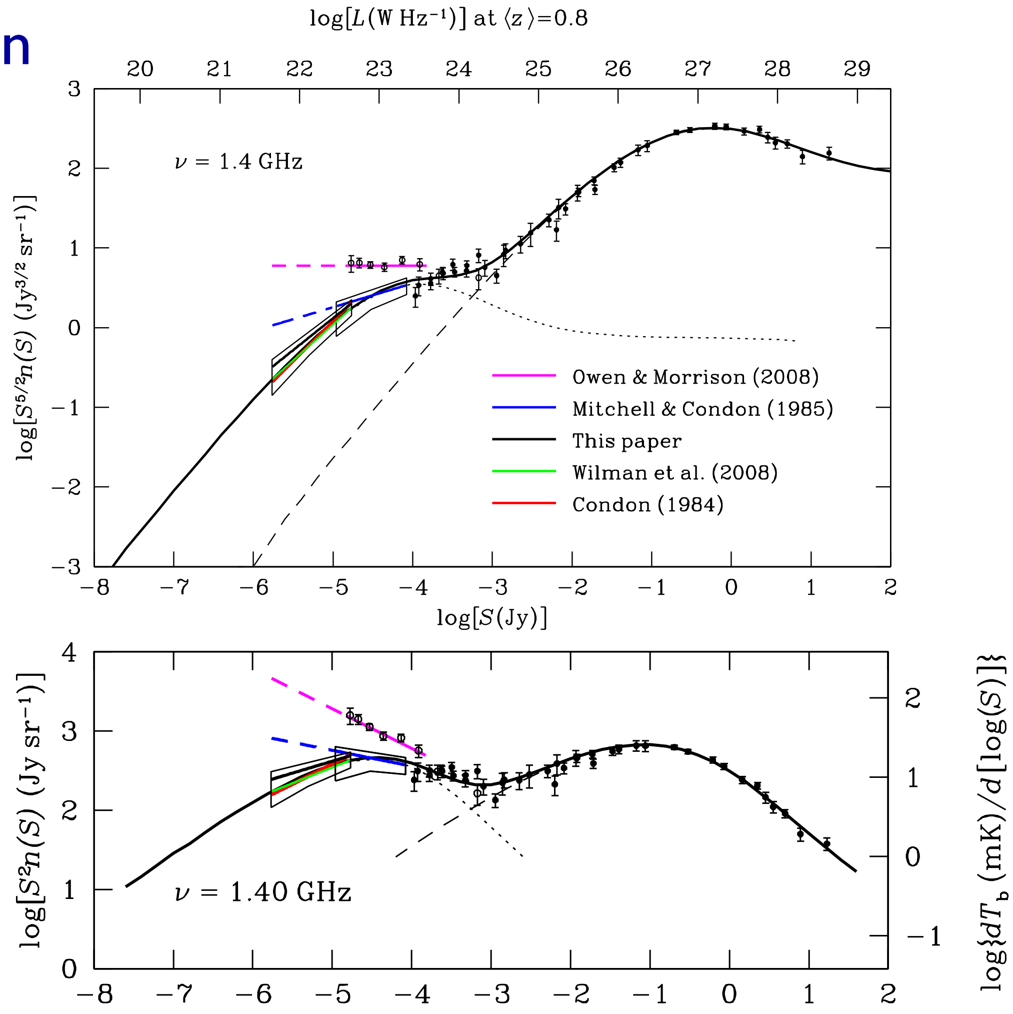
and S ~ $\nu^{3.7}$ ➔

<z> ~ 0.8 shell, S ~ L,

finite sky brightness

Static Euclidean weighting

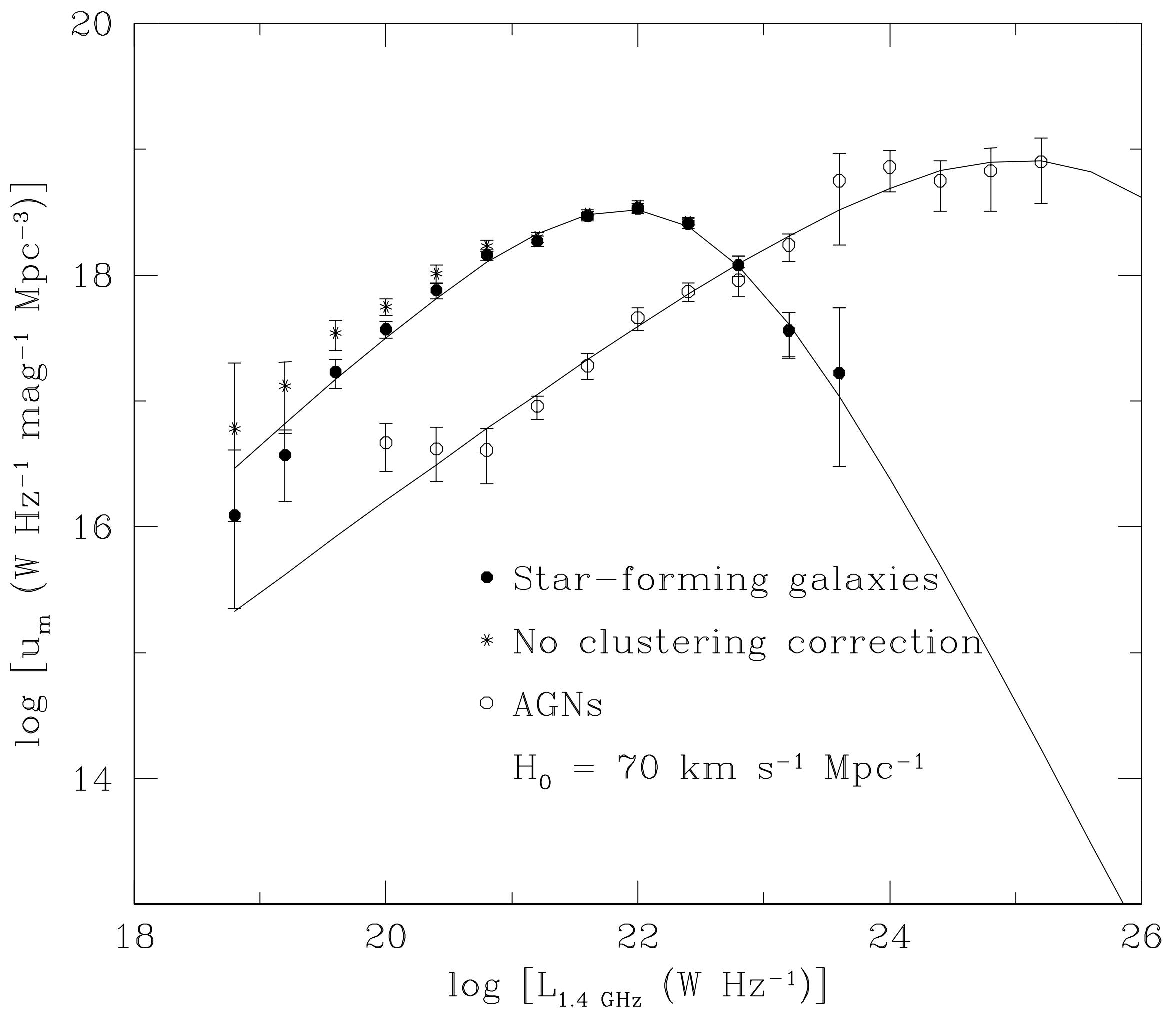
Brightness weighting



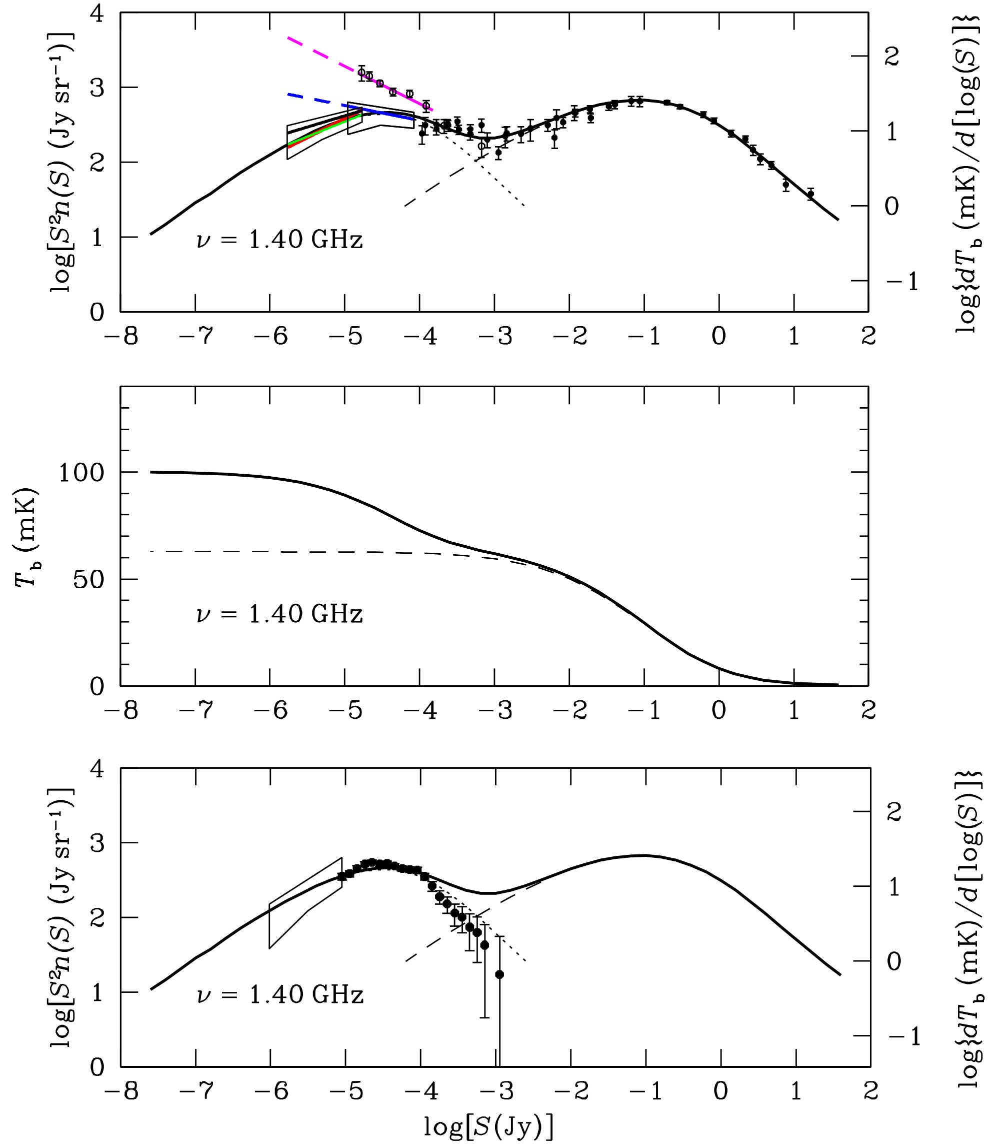
Local 1.4 GHz Spectral Power Density

Two populations (AGNs and star forming galaxies)

With no major "new population" (energy source or spectral index) since 3CR



96% of the radio source background is resolved by $S_{1.4\ \mathrm{GHz}} \sim 1.7\ \mu\mathrm{Jy}$



Data points and box: 160 μm Herschel counts converted to 1.4 GHz by the FIR/radio ratio $q = \log(S_{160\ \mu\mathrm{m}})/\log(S_{1.4\ \mathrm{GHz}}) = 2.5$

Confusion: “rms” confusion plot

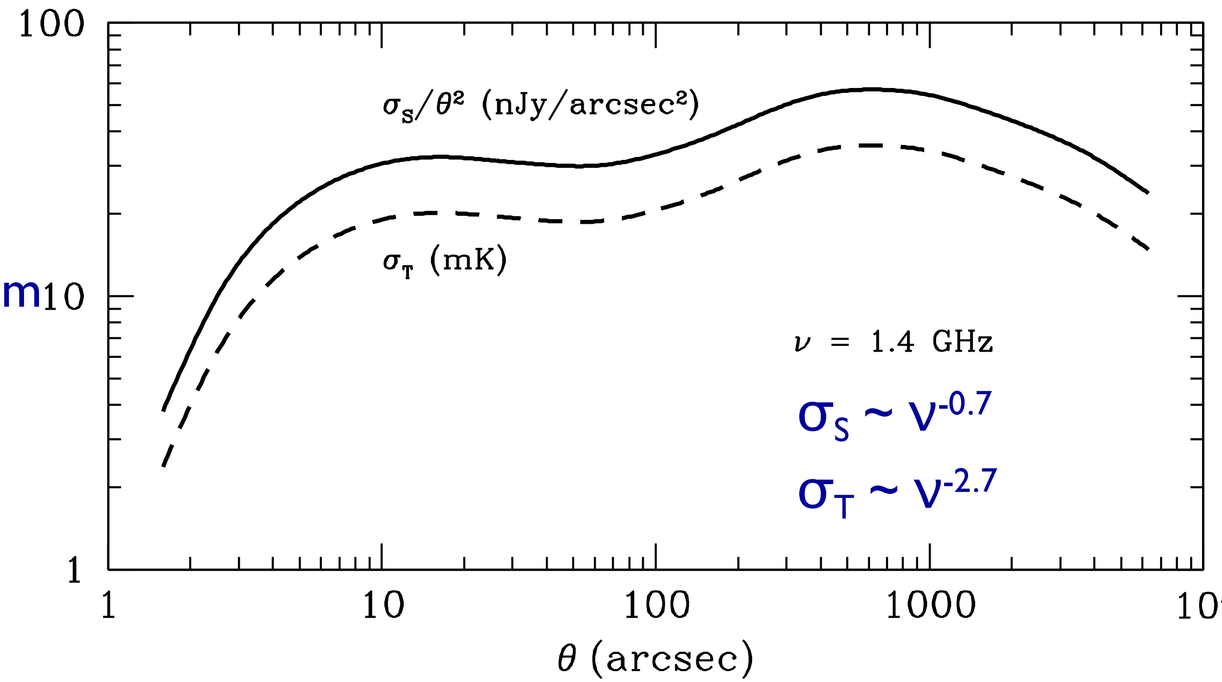
Example: EMU

θ = 10 arcsec FWHM

at ν = 1.4 GHz so

$\sigma_S \approx 31 \times 10^2$ nJy/beam

≈ 3.1 μJy/beam



Example: JVLA C-array

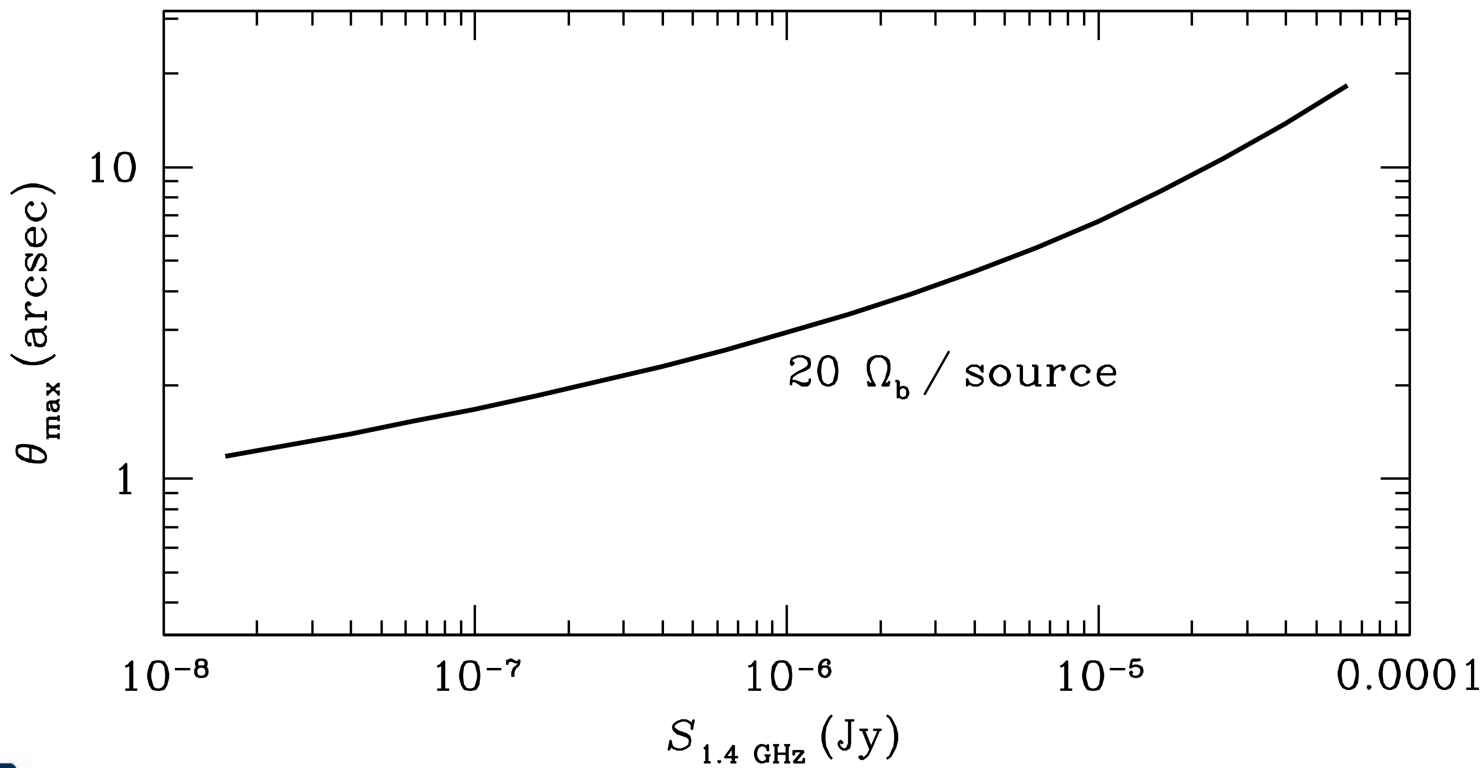
θ = 8 arcsec FWHM

at ν = 3 GHz so

$\sigma_S \approx 27 \times 8^2 \times (3/1.4)^{-0.7}$ nJy/beam

≈ 1.0 μJy/beam

Largest beamwidth θ_{max} for a given source detection limit



Good news:

Confusion won't limit the SKA continuum sensitivity, so

Bad news:

Dynamic range will. The faster the survey telescope, the sooner it hits the wall:

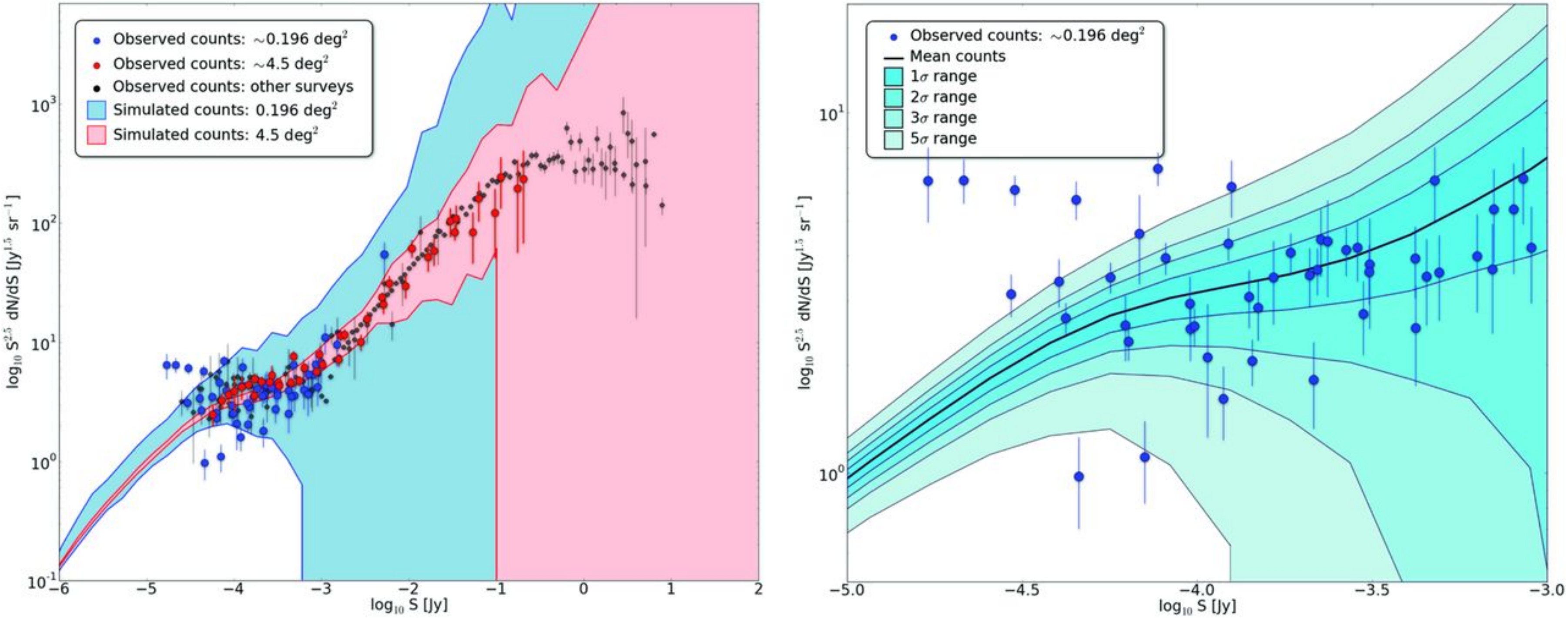
$\tau \sim (A_e / T)^{-2} (\Omega_{fov} B)^{-1}$

(e.g., NVSS, FIRST, EMU, VLASS… noise, reliability, transients)

<u>Quantity needs quality</u>

Trouble in paradise!

Left-hand panel: the data points and the corresponding error bars show the observationally derived Euclidean-normalized differential source counts at 1.4 GHz from the publications listed in Section 2.



Ian Heywood et al. MNRAS 2013;432:2625-2631

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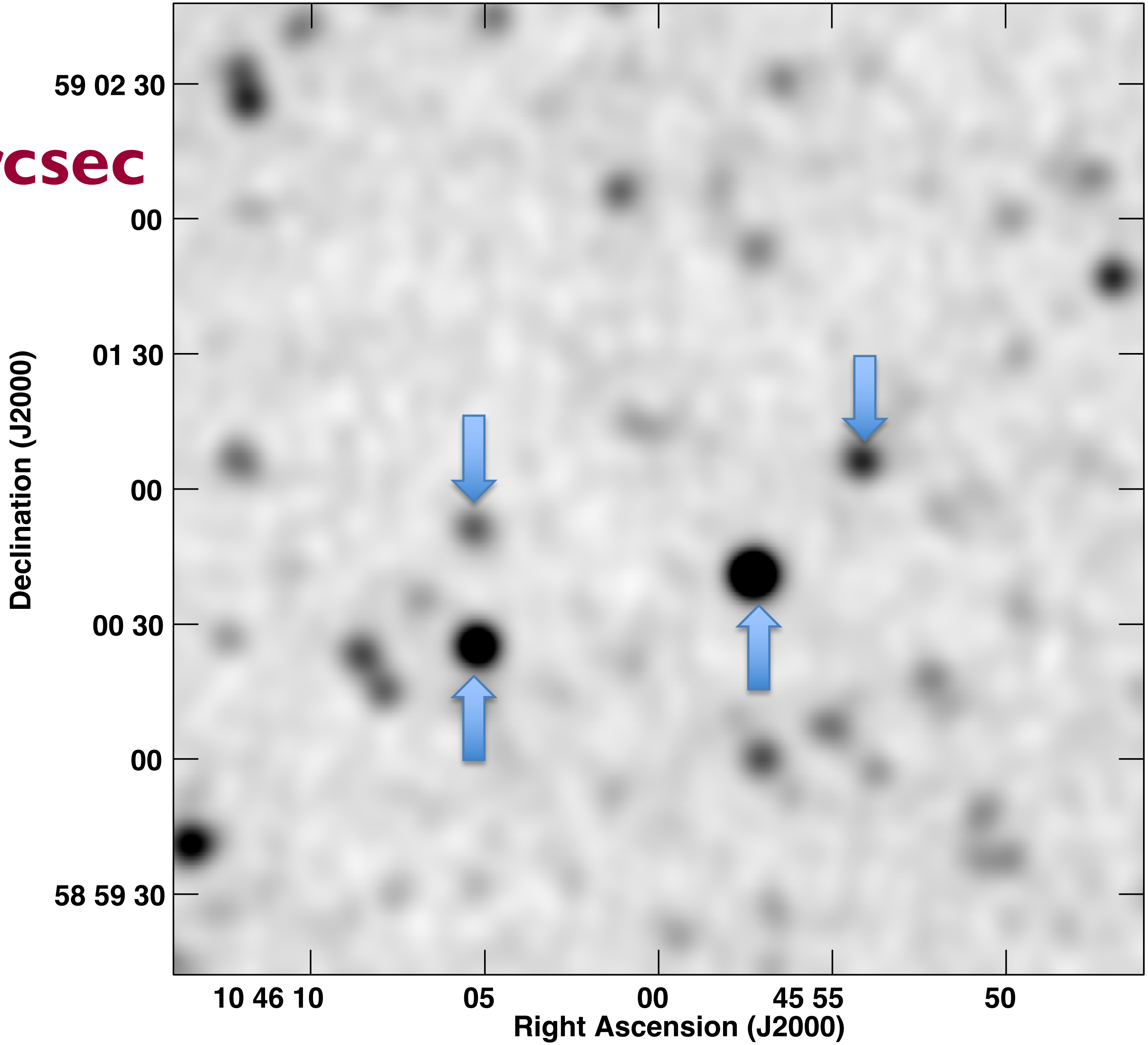
The fault, dear Brutus, is not in our stars, But in ourselves, …

Source clustering cannot explain the large observed scatter.
Multiple pointings observed on the same day with the VLA, then calibrated and analyzed by the same procedure, agree within Poisson statistical errors.
Different surveys by different observers using different telescopes suggest that errors in corrections for partial resolution and primary-beam attenuation cause most of the scatter.

8 arcsec


59 02 30
00
01 30
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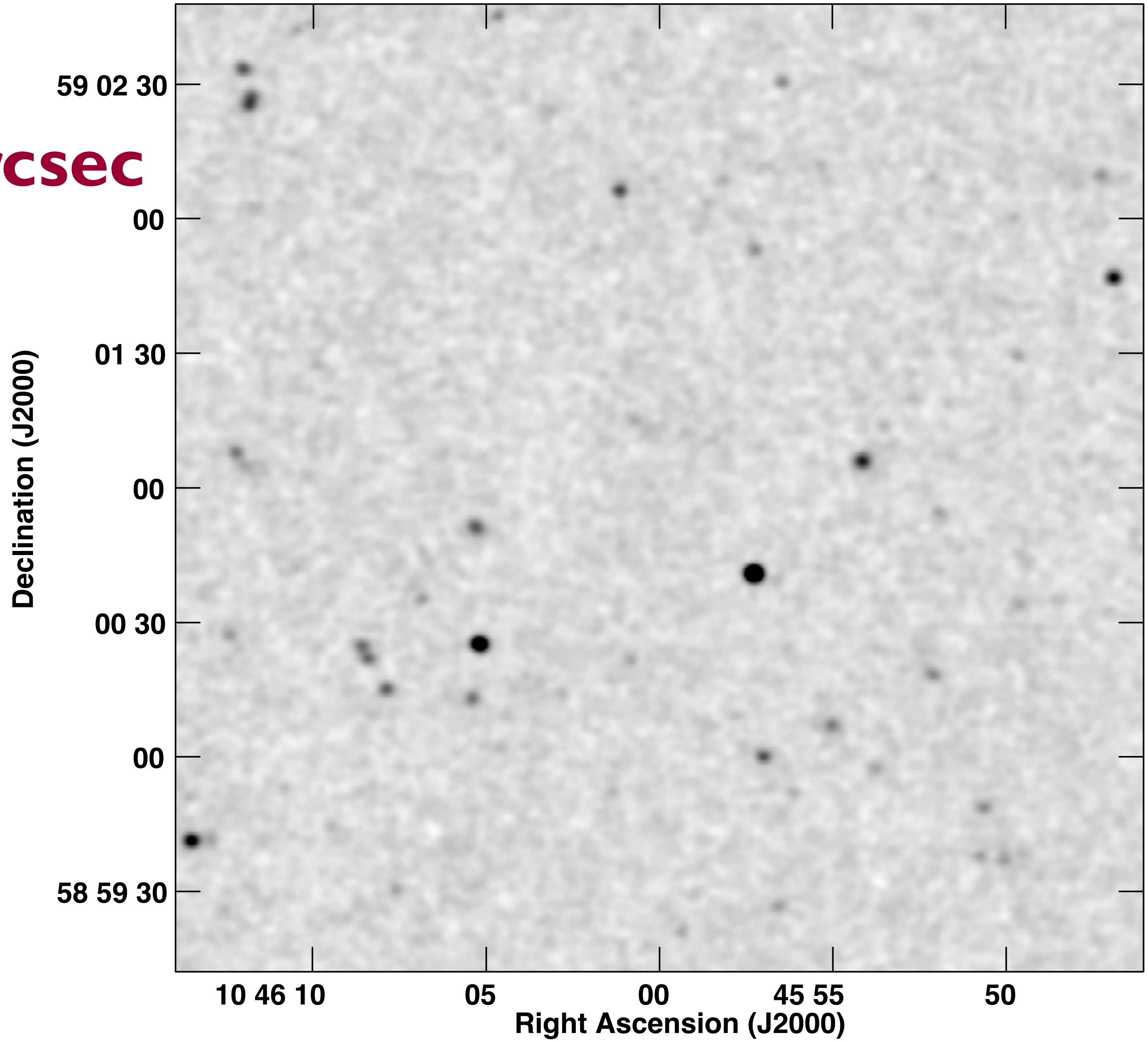
00
58 59 30
Declination (J2000)
10 46 10
05
00
45 55
50
Right Ascension (J2000)

2.8 arcsec



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58 59 30
Declination (J2000)
10 46 10
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45 55
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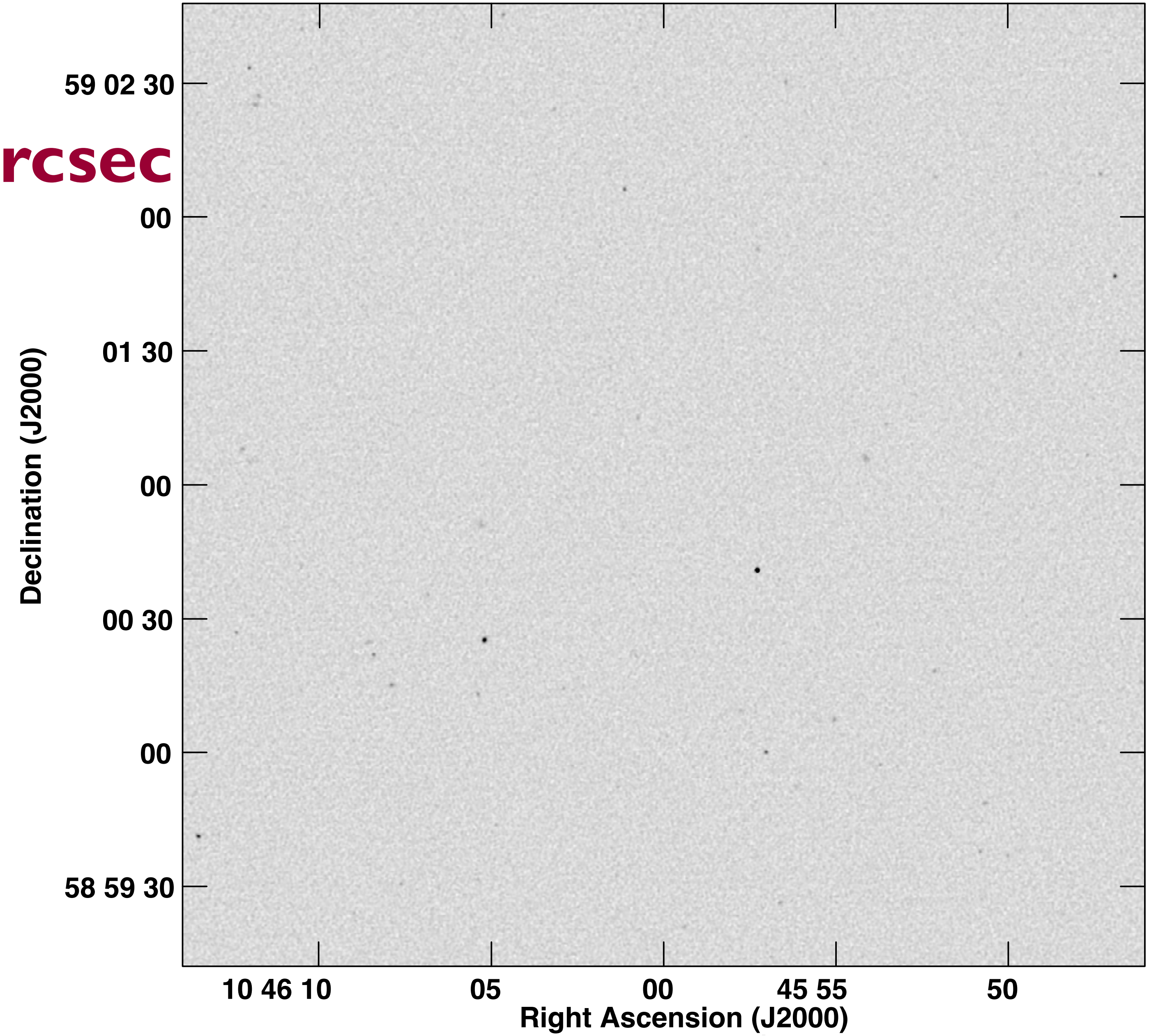
Right Ascension (J2000)

0.65 arcsec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58 59 30
Declination (J2000)
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45 55
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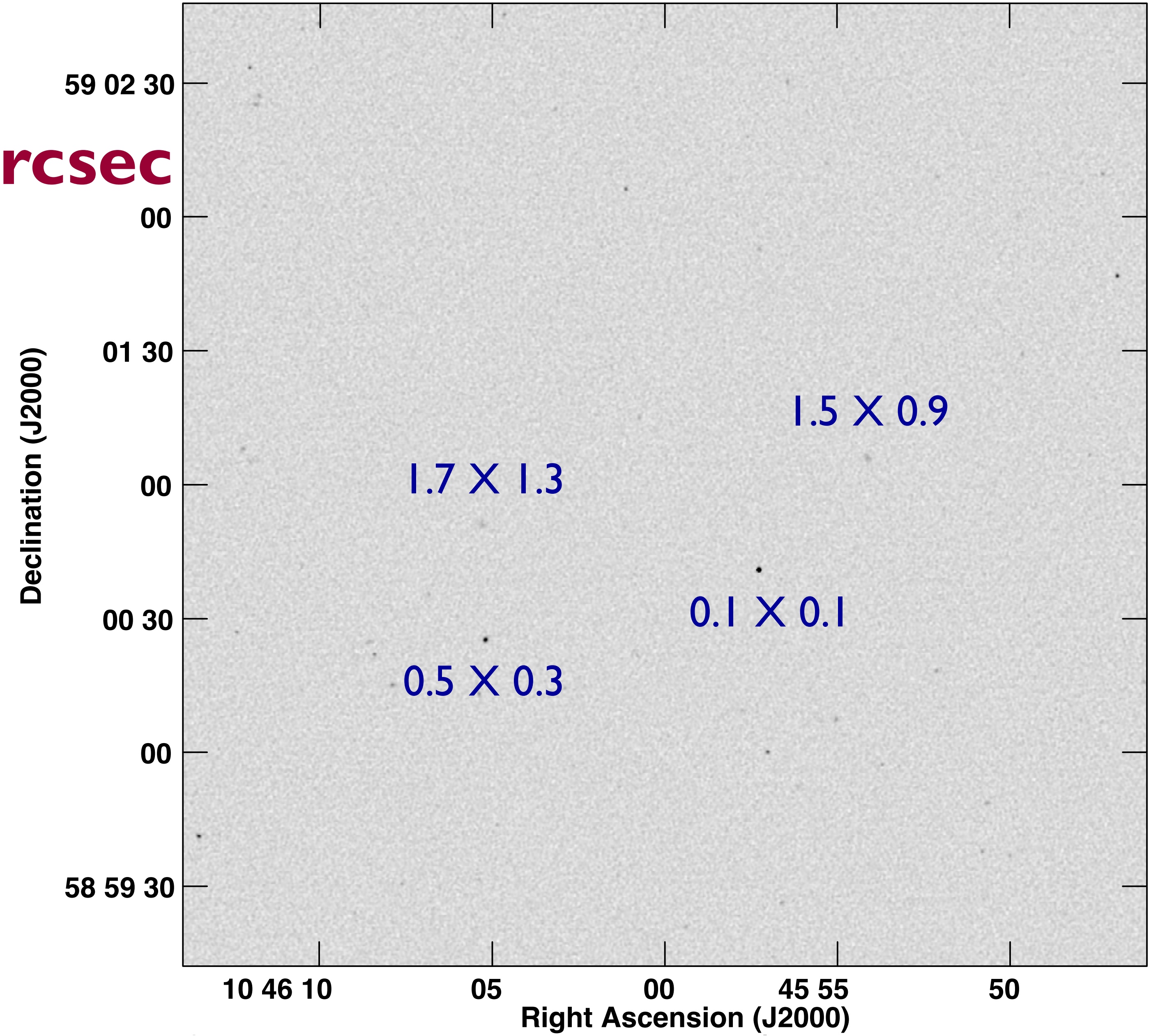
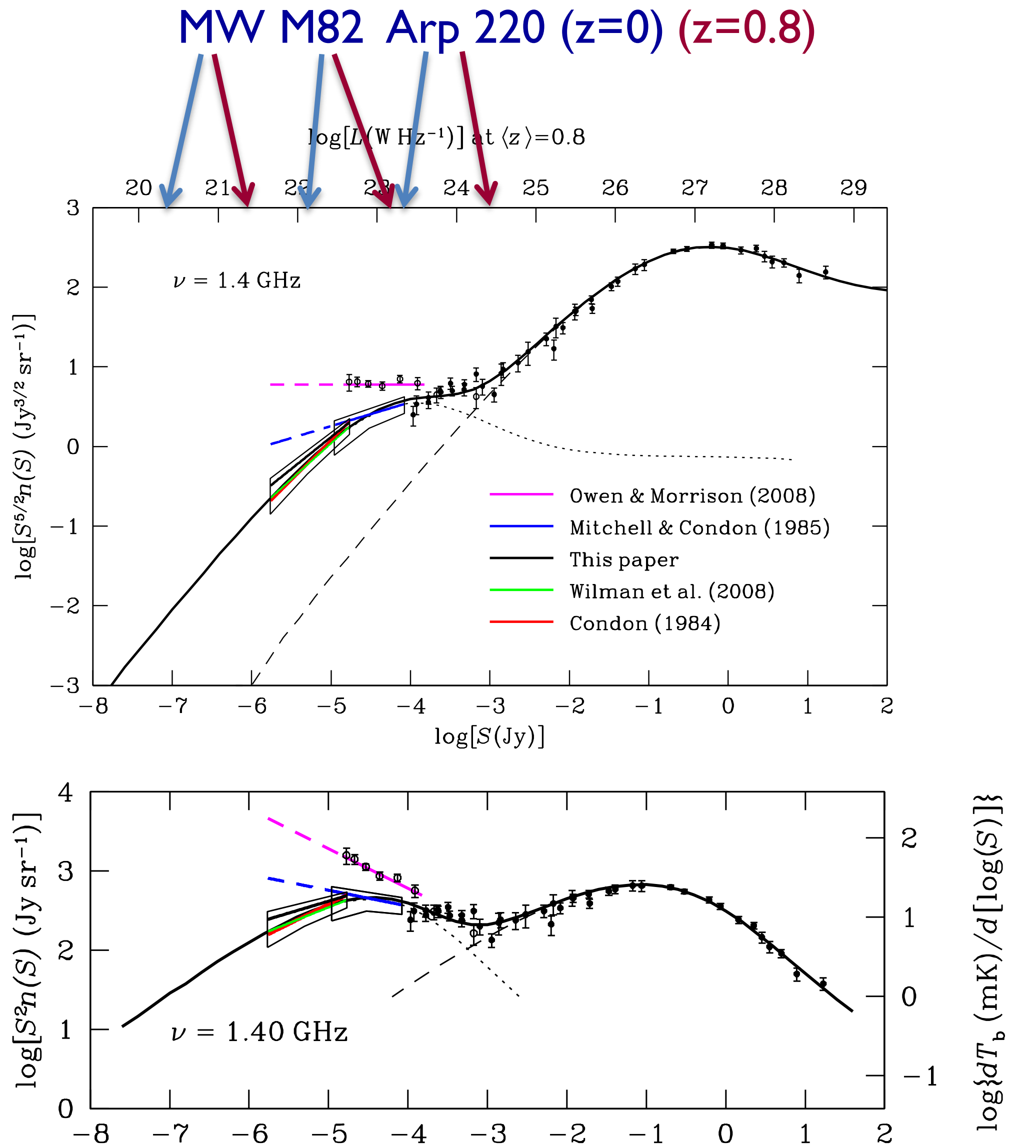
Right Ascension (J2000)

0.65 arcsec


59 02 30
00
01 30
00
00 30
00
58 59 30
Declination (J2000)
1.5 X 0.9
1.7 X 1.3
0.1 X 0.1
0.5 X 0.3
10 46 10
05
00
45 55
50
Right Ascension (J2000)

A wedding-cake survey to study the evolving z < 3 SFRD



$$\left[\frac{dT_b}{d\log(S)}\right] = \left[\frac{\ln(10)c^2}{2k_B\nu^2}\right] S^2 n(S)$$

Near $S^2n(S)$ peak,

$\Delta N / \Delta \log(S) \sim \Omega S_{min}$

and $\Delta\tau \sim S_{min}^{-1}$

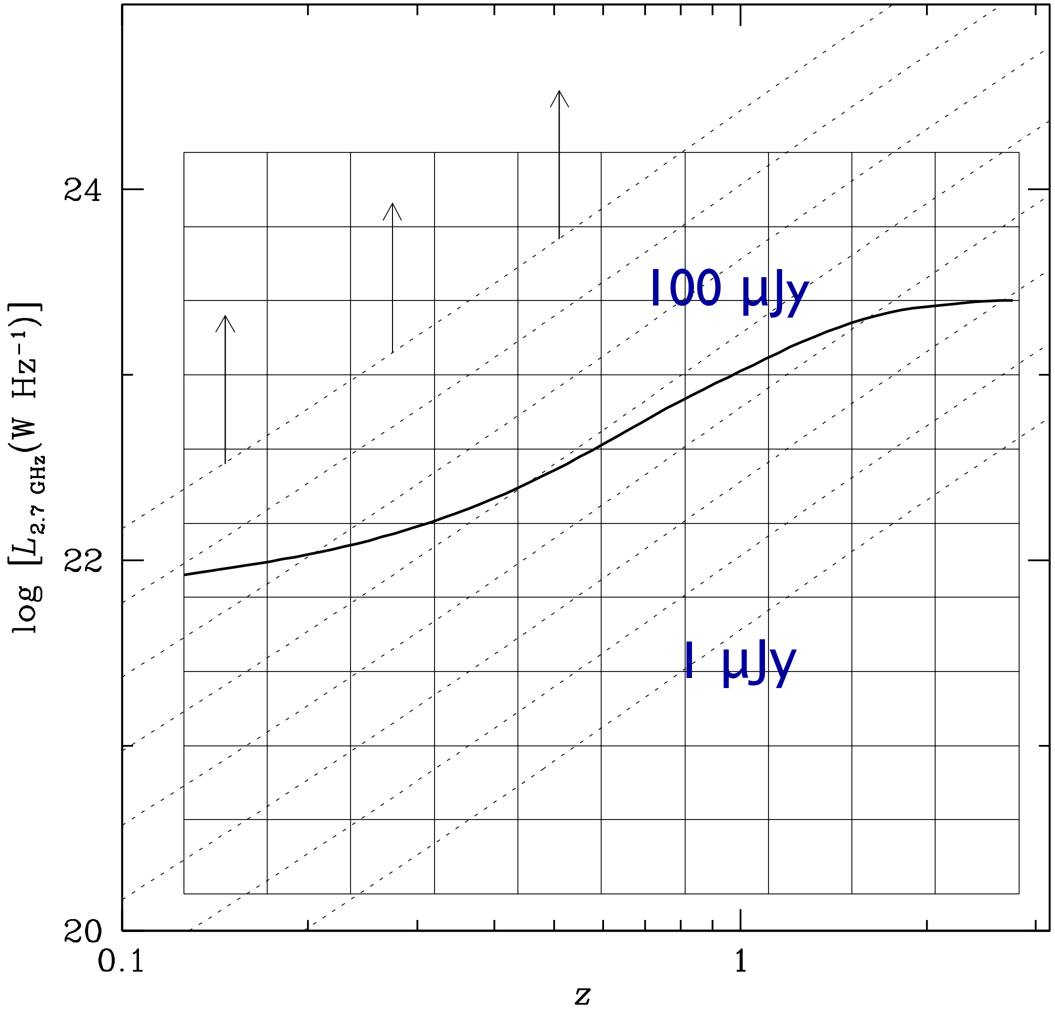
The Evolving Star-forming Galaxy Population at 2.7 GHz

Layer	$\log(S_{\rm min})$ (Jy)	$\log(S_{\rm max})$ (Jy)	$S^2 n(S)$ (Jy sr^{-1})	ΔN (sr^{-1})
1	-6.0	-5.6	129	7.52×10^7
2	-5.6	-5.2	194	4.55×10^7
3	-5.2	-4.8	256	2.41×10^7
4	-4.8	-4.4	275	1.05×10^7
5	-4.4	-4.0	221	3.50×10^6
6	-4.0	-3.6	129	8.60×10^5
7	-3.6	-3.2	59	1.64×10^5

The 2.7 GHz L-z plane for star-forming galaxies

Solid curve = evolving u_m peak luminosity

Dotted lines show Log[S(μJy)] = 0 to 2.8 by 0.4



Surface-brightness sensitivity and flux-density limit: resolution can kill!

$$\frac{\langle T_{\rm b}\rangle}{\rm K} \approx 2.5\left(\frac{\nu}{\rm GHz}\right)^{-2.7} \qquad T_{\rm b} = \frac{2\ln(2)c^2 S_{\rm p}}{\pi k \theta^2 \nu^2}$$

$$\left(\frac{\theta}{\rm arcsec}\right)^2 \geq 2.44\left(\frac{\sigma_{\rm n}}{\mu{\rm Jy\ beam}^{-1}}\right)\left(\frac{\nu}{\rm GHz}\right)^{+0.7}$$

JVLA S-band ($\nu \approx 2.7$ GHz)

Array	θ(arcsec)	σ_n(μJy/beam)
D	24	< 118
C	8	< 13
B	2.5	< 1.3
A	0.7	< 0.10

An S-band JVLA "Wedding Cake" Survey of Star-forming Galaxy Evolution

Layer	$\sigma_{\rm n} = S_{\rm min}/5$ (μJy beam^{-1})	θ (arcsec)	$\sigma_{\rm c}$ (μJy beam^{-1})	$N_{\rm p}$	$\Delta\tau$ (hours)	Ω (deg^2)	ΔN
1	0.20	2.5	0.04	1	860	0.044	1.0×10^3
2	0.50	2.5	0.04	1	138	0.044	6.1×10^2
3	1.26	2.5	0.04	3	66	0.132	9.7×10^2
4	3.17	8	1.1	7	24	0.31	9.8×10^2
5	7.96	8	1.1	19	10.3	0.83	8.9×10^2
6	20.0	24	12	91	7.8	4.0	1.0×10^3
7	50.0	24	12	500	6.9	22.0	1.1×10^3

Note that 3 JVLA configurations are required to reach the needed surface-brightness sensitivity while avoiding the confusion limit.

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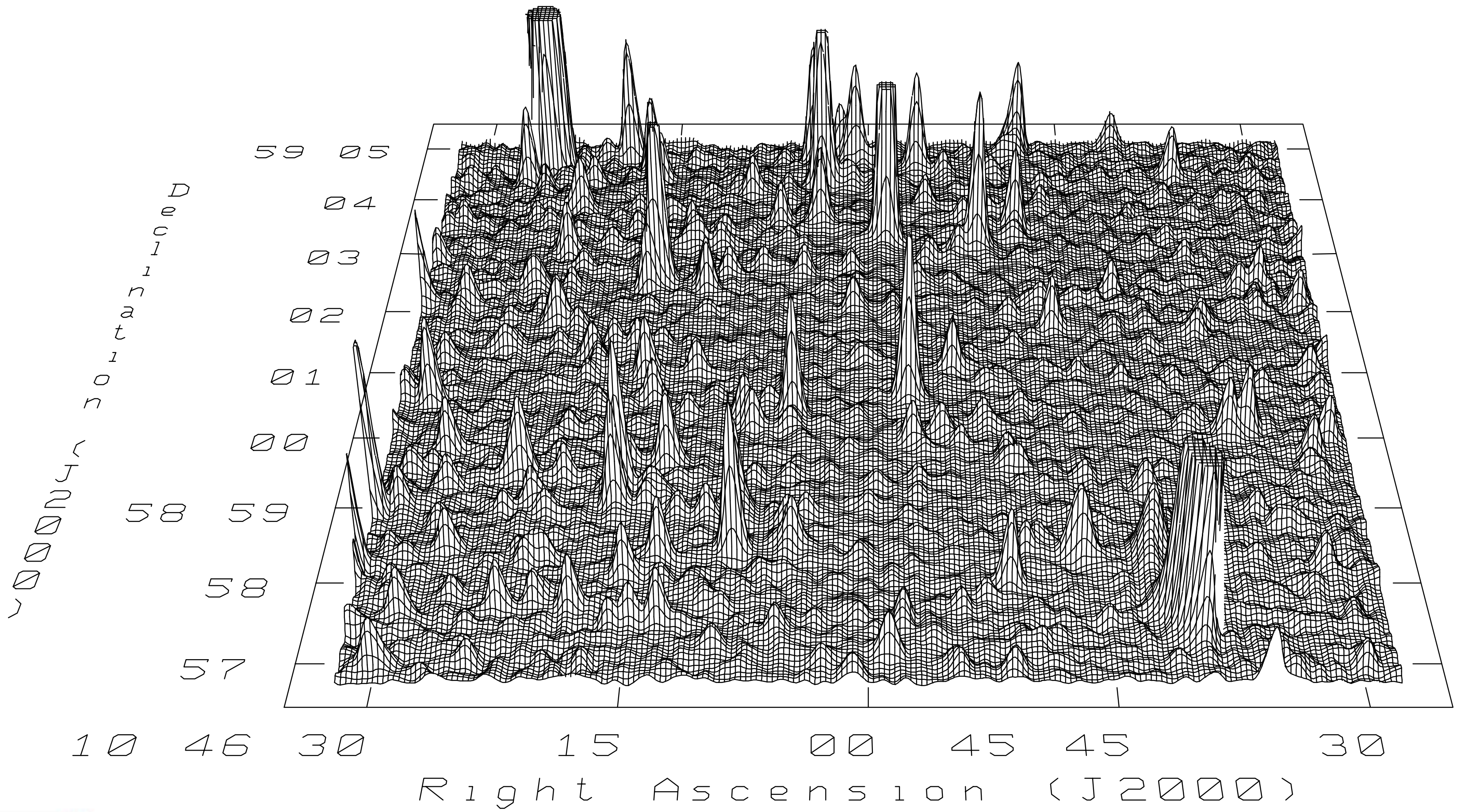
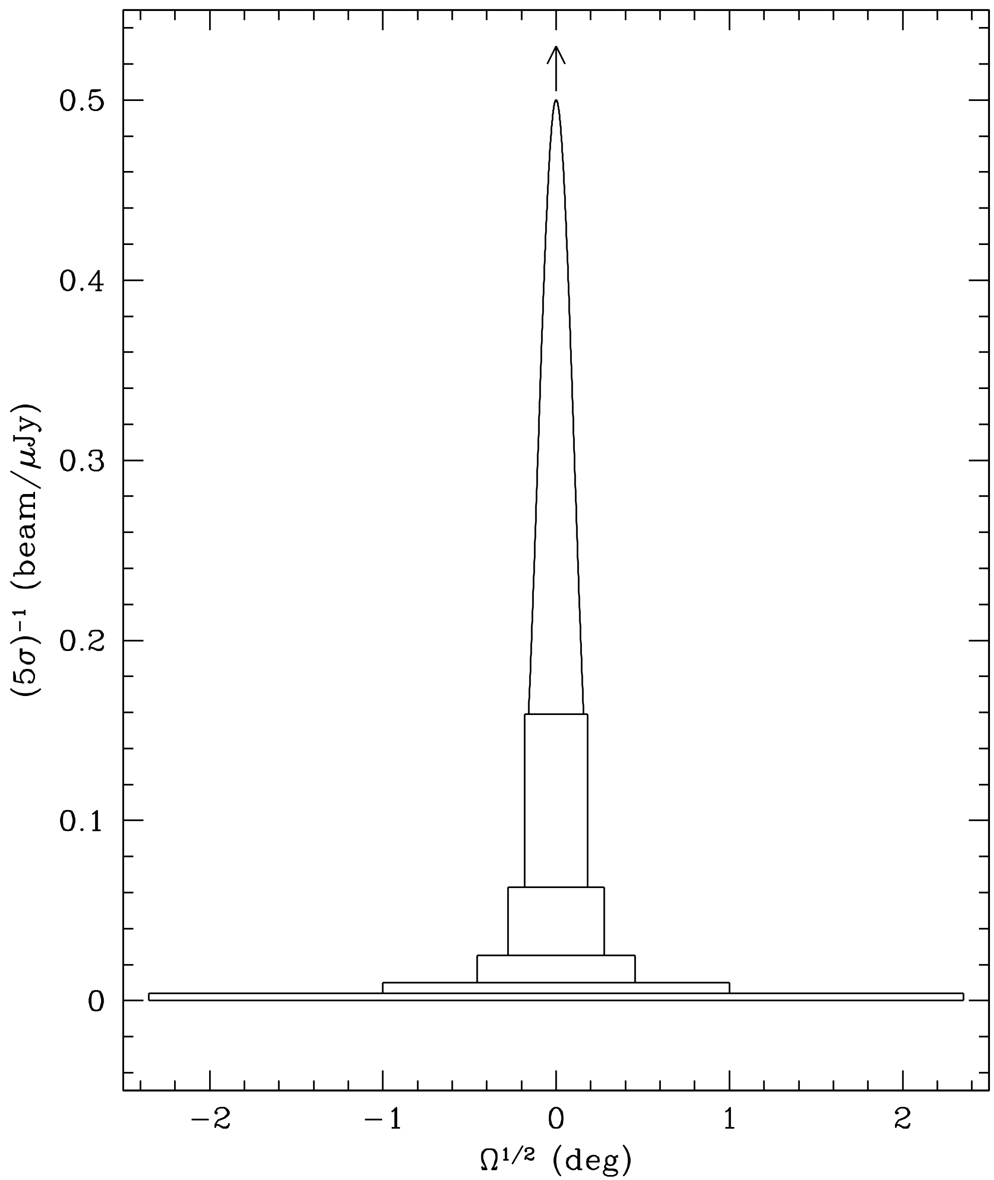
5× Deeper understanding through confusion



A JVLA S-band Wedding Cake Survey for Star-formation History



Lessons learned:

- 10 × luminosity evolution, <z> ~ 0.8 shell, S ~ L
- Confusion 'melts away' below S ~10^{-5} Jy (good news for SKA), so high dynamic range and accurate resolution corrections when θ < 1 arcsec will be required (bad news for SKA).
- The faster the survey speed, the sooner the survey hits the wall of systematic errors (confusion, primary beam errors, resolution corrections, dynamic range,…).
- Systematic errors already dominate, so quality is needed for quantity.
- The universe is not a vacuum. Survey parameters (resolution, sensitivity, dynamic range, position accuracy, sky coverage,…) should be matched to source properties (surface brightness, redshift range, angular size, spectral index, sky density, confusion, optical/IR IDs,…).
- Making a wedding-cake survey is a mathematical problem, not an art.
- Because it can be reconfigured, the JVLA could already make an SKA-class wedding-cake survey to constrain the SFRD up to z ~ 3.

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A Simple and Accurate Liquid Dielectric Variable Delay Line

Braccesi et al. 1966, Proc. IEEE, 54, 69

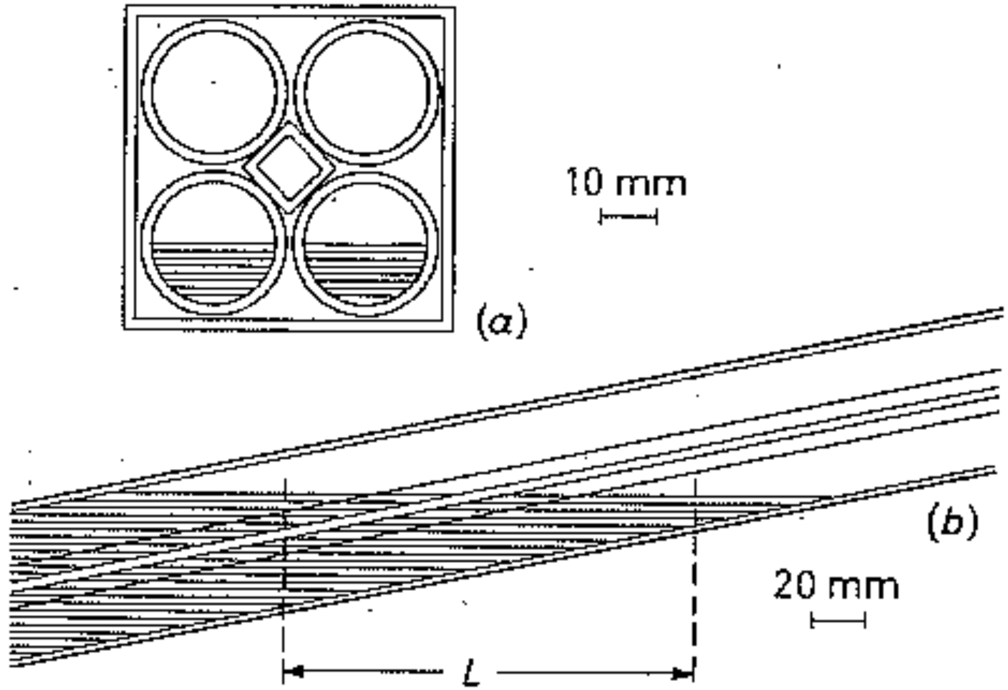

Fig. 2.