The Nature of the Radio Sky: What Will VLA Sky Surveys Find?

Jim Condon
NRAO, Charlottesville

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

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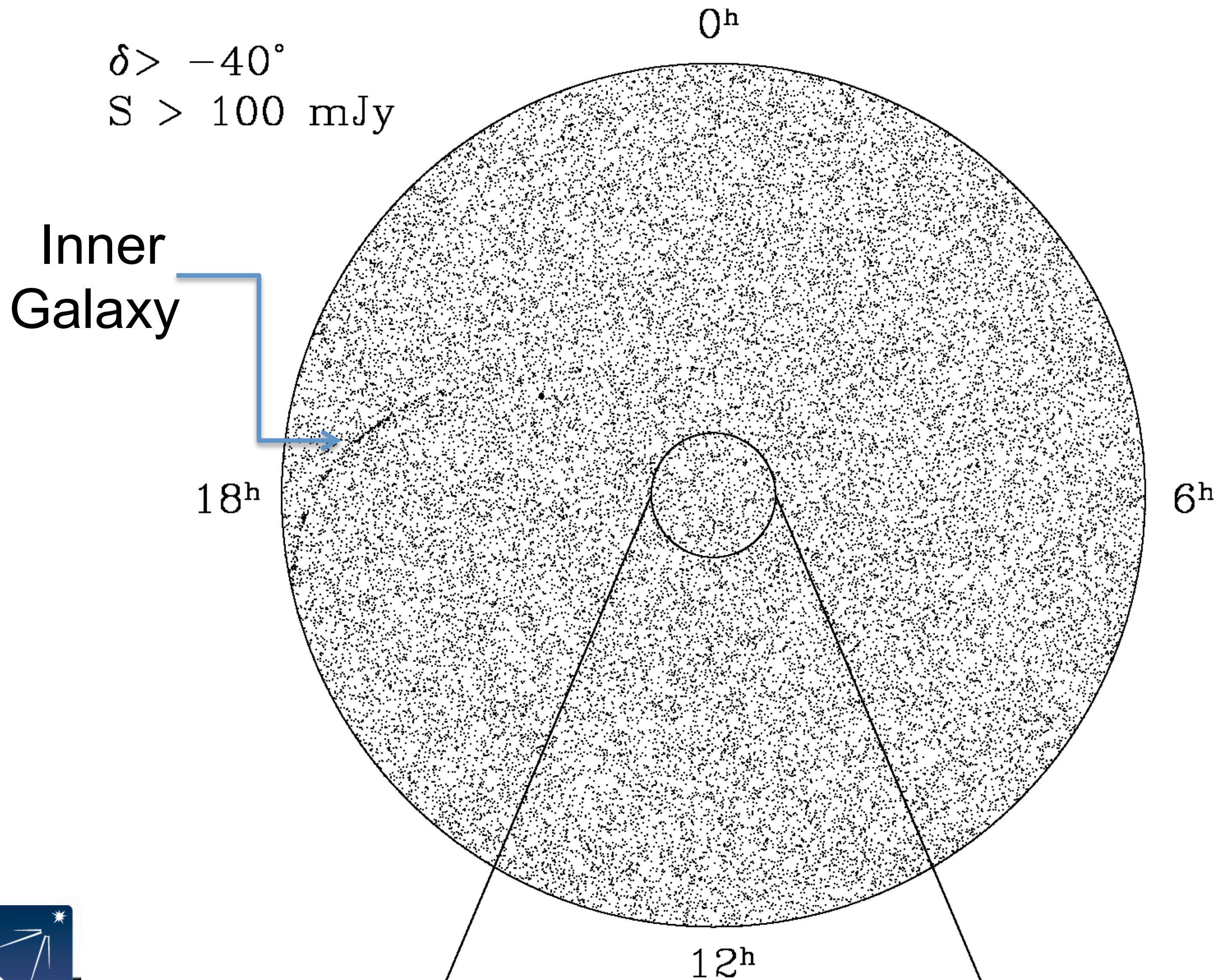
The universe is not a vacuum

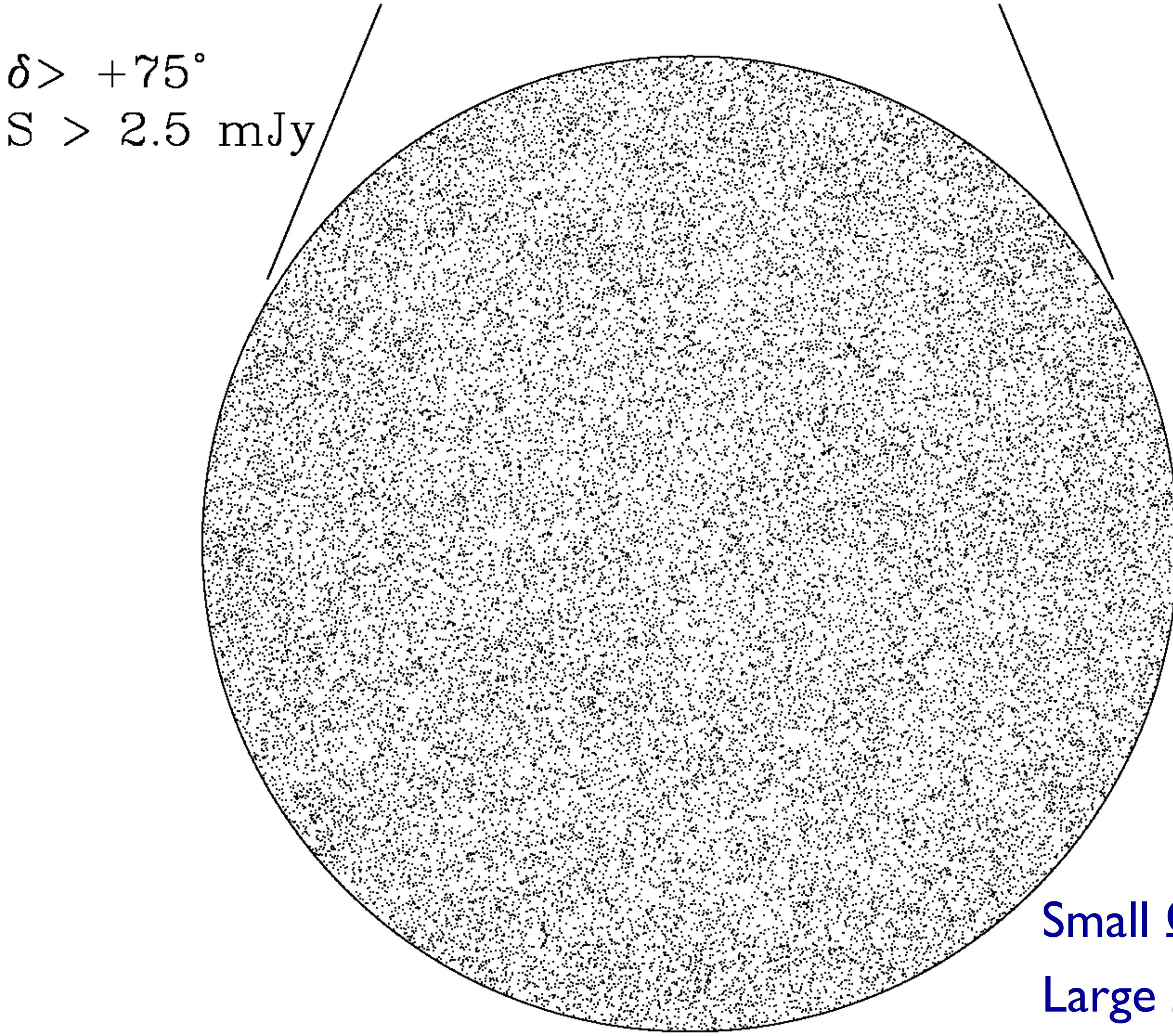
Survey parameters (sensitivity, resolution, frequency, …) should be chosen with known source properties in mind. For example, the widely used "survey speed" is a purely instrumental parameter that ignores the median spectral index $<\alpha> \sim -0.7$ of faint radio sources. The source detection rate or "effective survey speed" ESS = survey speed / $\nu^{1.4}$ favors lower frequencies.

ν(GHz)	SS (deg^2/hr)	ESS = SS/$\nu^{1.4}$
1.5	13.9	7.9
3.0	16.5	3.5
6.0	7.2	0.6
10	3.0	0.1

Nearly all radio sources are extragalactic



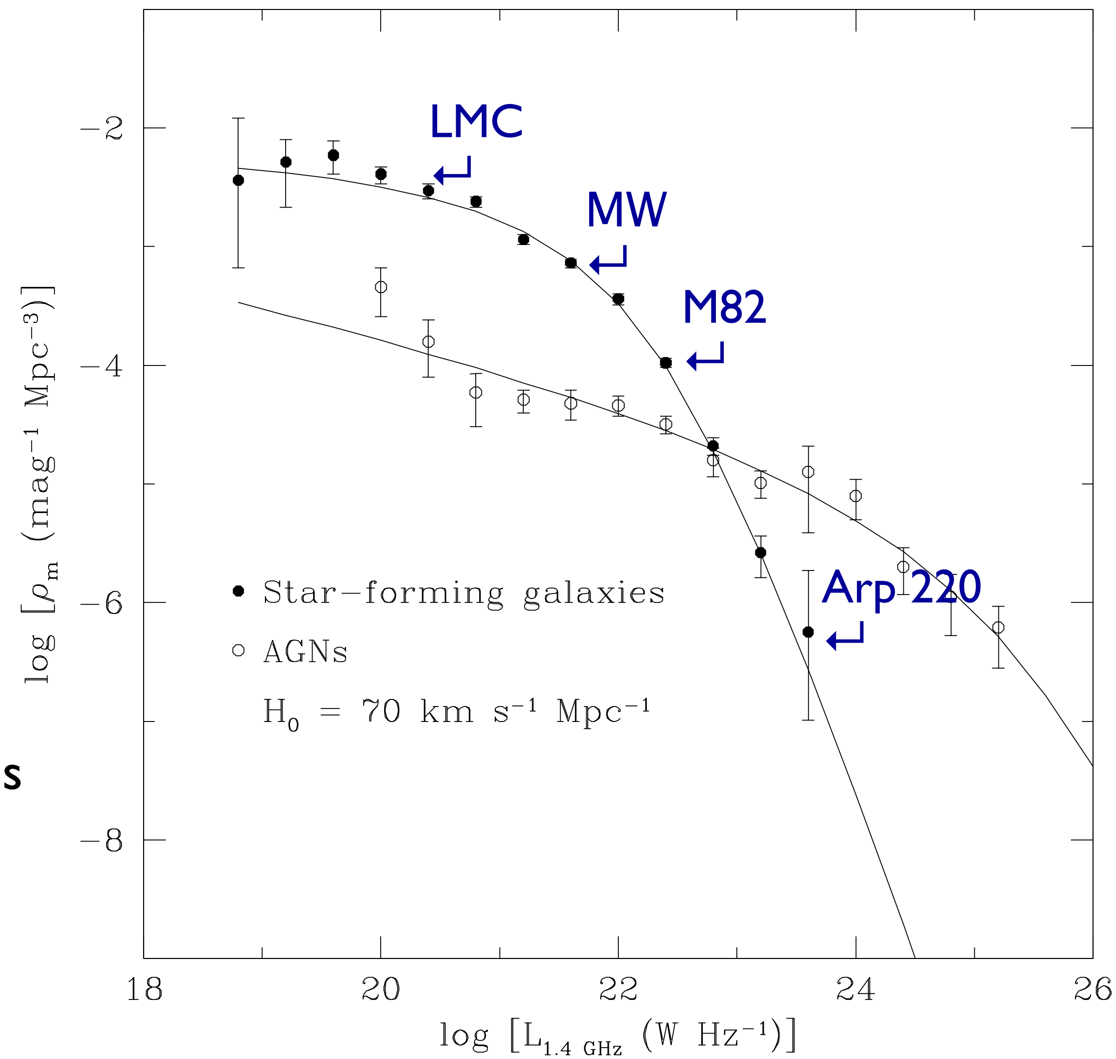
… very extragalactic: <z> ~ 1, all *S*



Small Ω ➔ fair sample

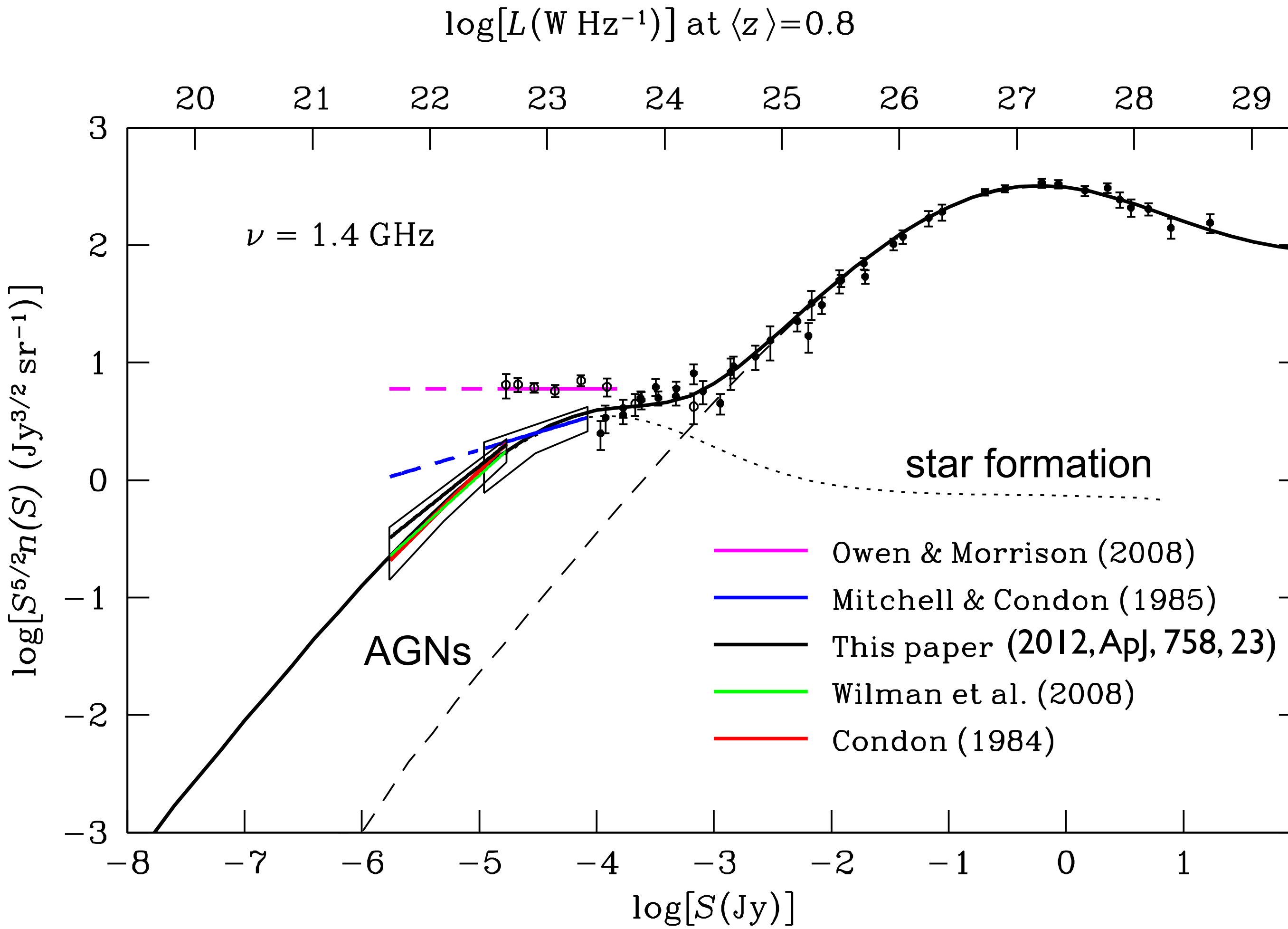
Large Ω ➔ cosmology, if $N^{-1/2}$ calibration

Radio sources powered by star formation and by AGN



1.4 GHz luminosity functions of star-forming galaxies and AGNs at z ~ 0

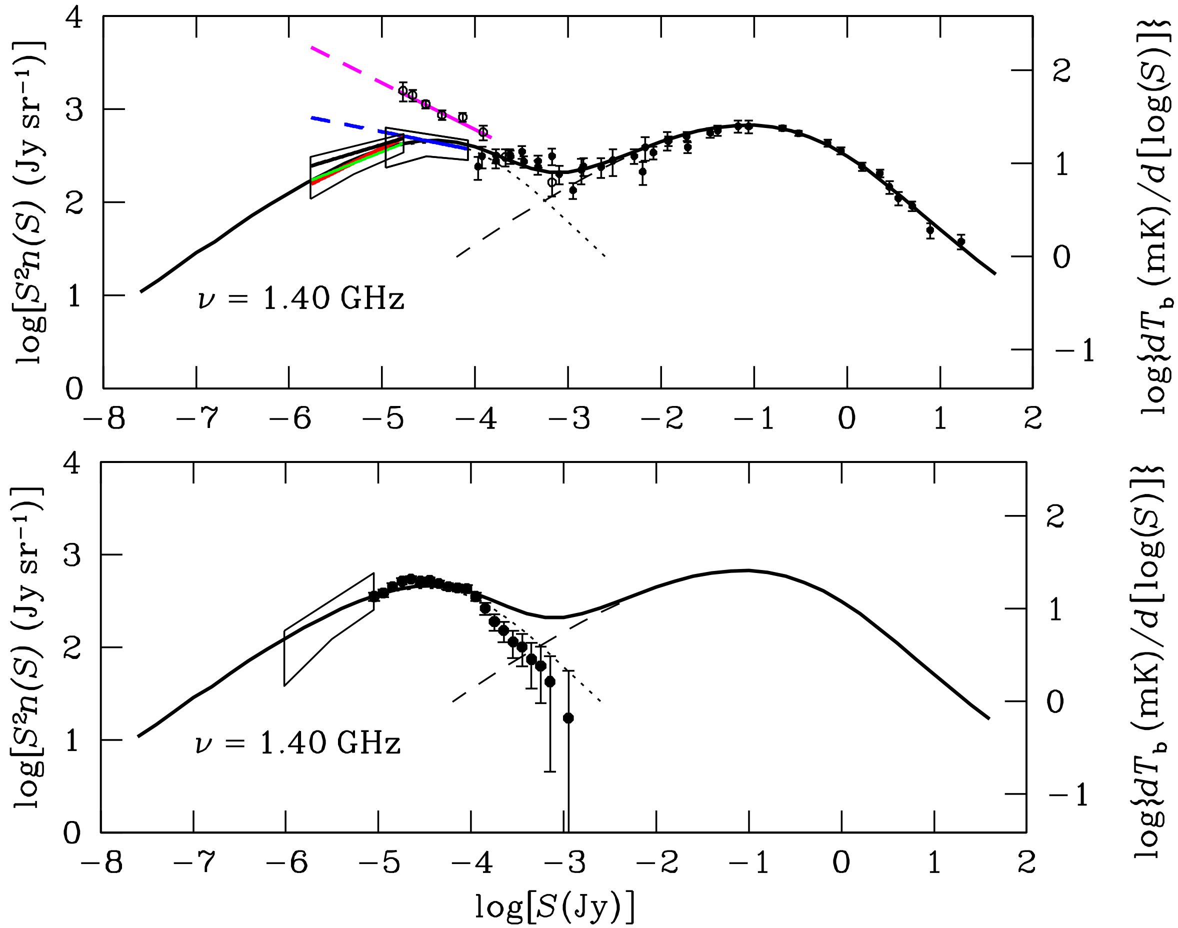
Source counts, luminosities, and types



μJy radio sources obey the FIR/radio correlation

1.4 GHz source count

160 μm source count converted to 1.4 GHz by the FIR/radio correlation



Faint-source median angular size Φ

<Φ> ~ 0.5″ ? Nelson et al. 2013, ApJ, 763, L16

<Φ> ~ 1.2″ ? Owen & Morrison 2008, AJ, 136, 1889

Want PSF θ > source <Φ> for μJy detection surveys

Want PSF θ ~ source <Φ> for μJy lensing surveys

<Φ> is not well known and should be measured before making a big high-resolution survey.

Brightness and flux-density limits

Rayleigh-Jeans brightness temperature (Gaussian PSF):

$T_b = 2 \ln(2)\, c^2 S / (\pi k \theta^2 \nu^2) = 1.22\, S(\mu Jy) \times [\theta(arcsec)\, \nu(GHz)]^{-2}$ (K)

"Normal" star-forming galaxies have

$<T_g> \approx 2.5\, \nu(GHz)^{-2.7}$ (K) ~ 1 K at 1.4 GHz

To <u>detect</u> (5σ) them, the survey beamwidth θ should be larger than

$$[\theta(arcsec)]^2 \geq 2.44\, \sigma(\mu Jy/beam)\, \nu(GHz)^{0.7}$$

Ex: EMU 1.4 GHz $\sigma(\mu Jy/beam) = 10 \Rightarrow \theta \geq 6$ arcsec; actual $\theta = 10$ arcsec

Ex: VLASS $\theta(arcsec) = 5$ at $\nu(GHz) = 1.5 \Rightarrow \sigma(\mu Jy/beam \leq 8$

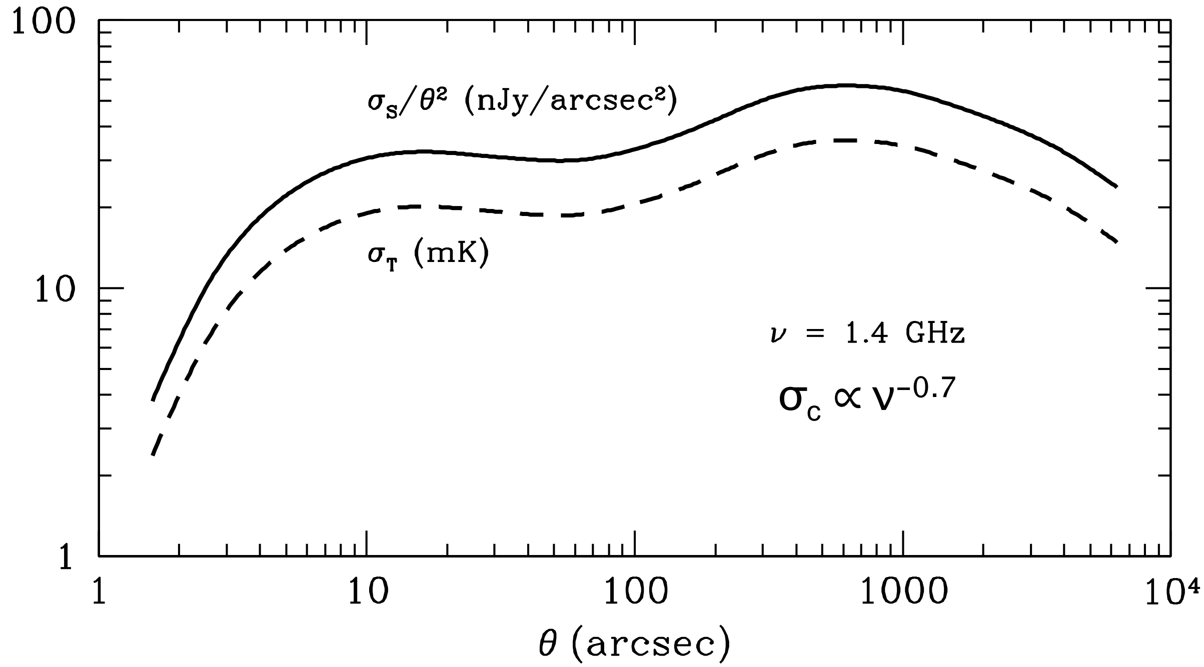
Ex: VLASS $\theta(arcsec) = 2.5$ at $\nu(GHz) = 3 \Rightarrow \sigma(\mu Jy/beam \leq 1.2$

Note: $\tau \propto \theta^{-4}$, or 100X per configuration jump. If $\sigma(\mu Jy/beam) = 100$, the biggest usable array for a "new NVSS" is C at L band (18″) or D at S band (23″).

Confusion (Gaussian PSF)

Instrumental confusion "melts away" for FWHM θ ≤ 10 arcsec

Ex: EMU θ = 10 arcsec, ν = 1.4 GHz, σ_s ~ 3 μJy/beam



Θ (″)	$\sigma_{1.4\,\mathrm{GHz}}$ (μJy/bm)
1.6	0.009
2.5	0.06
4.0	0.3
6.3	1.0
10	3
16	8
25	20
40	50
63	120

"Natural" confusion will not be a problem even at nanoJy levels if the faint source median angular size <Φ> ~ 0.5 arcsec FWHM, typical of faint star-forming galaxies (Nelson et al. 2013, ApJ, 763L, 16).

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Dynamic range

DR $\propto \nu^{-2.7}$ is a problem, especially for small dishes at low frequencies

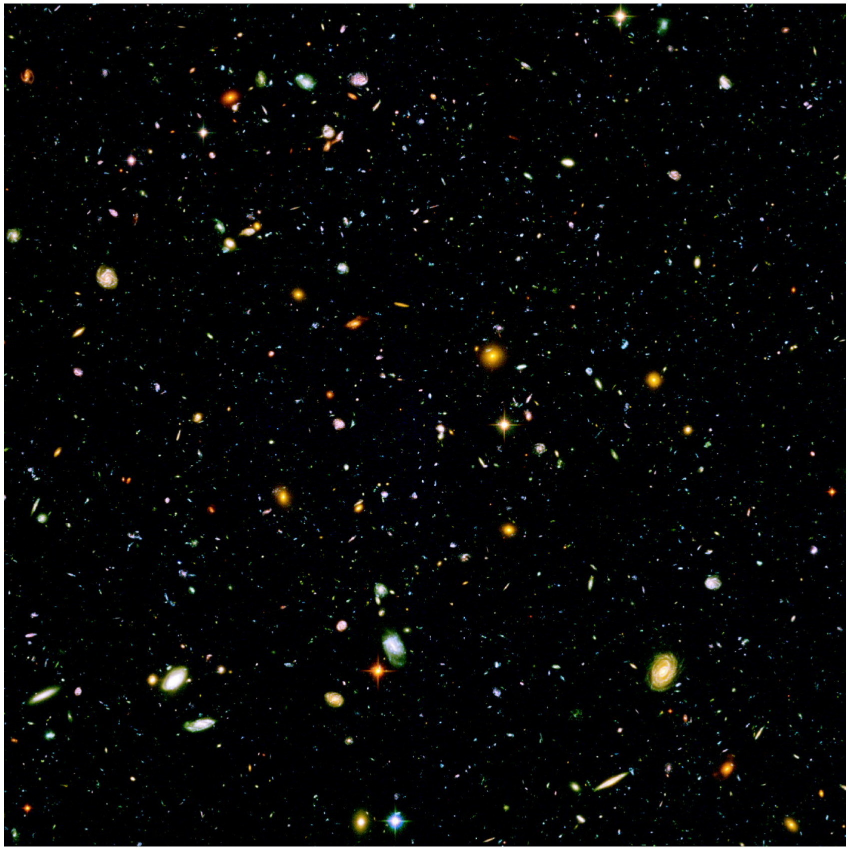
Braun, R. 2013, A&A, 551, A91

Condon 2009, SKA Memo 114

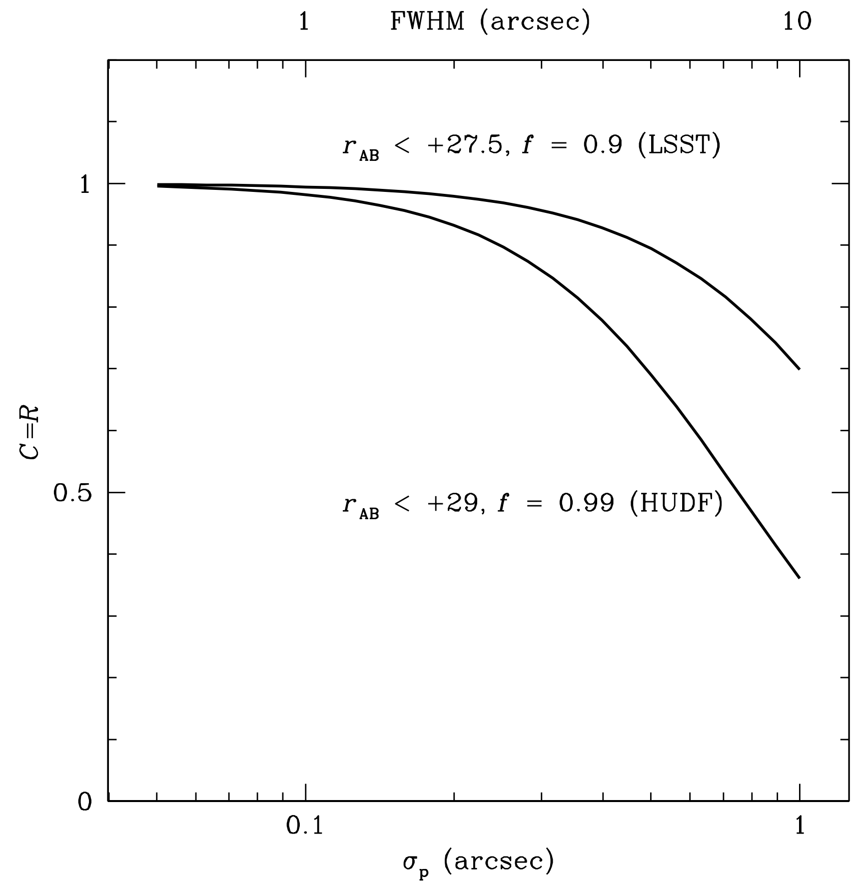
Ex: EMU 1.4 GHz, FoV $\Omega \sim 1$ deg^2, $\langle S_{eff} \rangle \leq 1$ Jy over 90% of the sky, $\sigma = 10$ μJy/beam requires DR ~ 100,000:1

Ex: VLA Large dishes help, but DR is still a huge problem at P band, significant at L band when $\sigma < 10$ μJy/beam, and affects S band when $\sigma < 1$ μJy/beam

Optical identifications



HUDF $r_{AB} < +29$



Completeness C = Reliability R
given f = fraction with IDs
$\sigma_p \sim \theta/(2\times\text{SNR}) \leq \theta/10$

Could one VLASS do it all?

$[\theta(\mathrm{arcsec})]^2 \geq 2.44\ \sigma(\mu\mathrm{Jy/beam})\ \nu(\mathrm{GHz})^{0.7}$ (detect most faint sources),
$\theta(\mathrm{arcsec}) < 5$ (optically identify most faint sources), and
avoid DR limitation

Ex: L band, A configuration: $\theta \sim 1.5$ arcsec, $\sigma(\mu\mathrm{Jy/beam}) < 0.7$, DR $> 10^5$
Ex: L band, B configuration: $\theta \sim 5$ arcsec, $\sigma(\mu\mathrm{Jy/beam}) < 8$, DR $\sim 3\times10^4$
Ex: S band, B configuration: $\theta \sim 2.5$ arcsec, $\sigma(\mu\mathrm{Jy/beam}) < 1.2$, DR $\sim 10^4$

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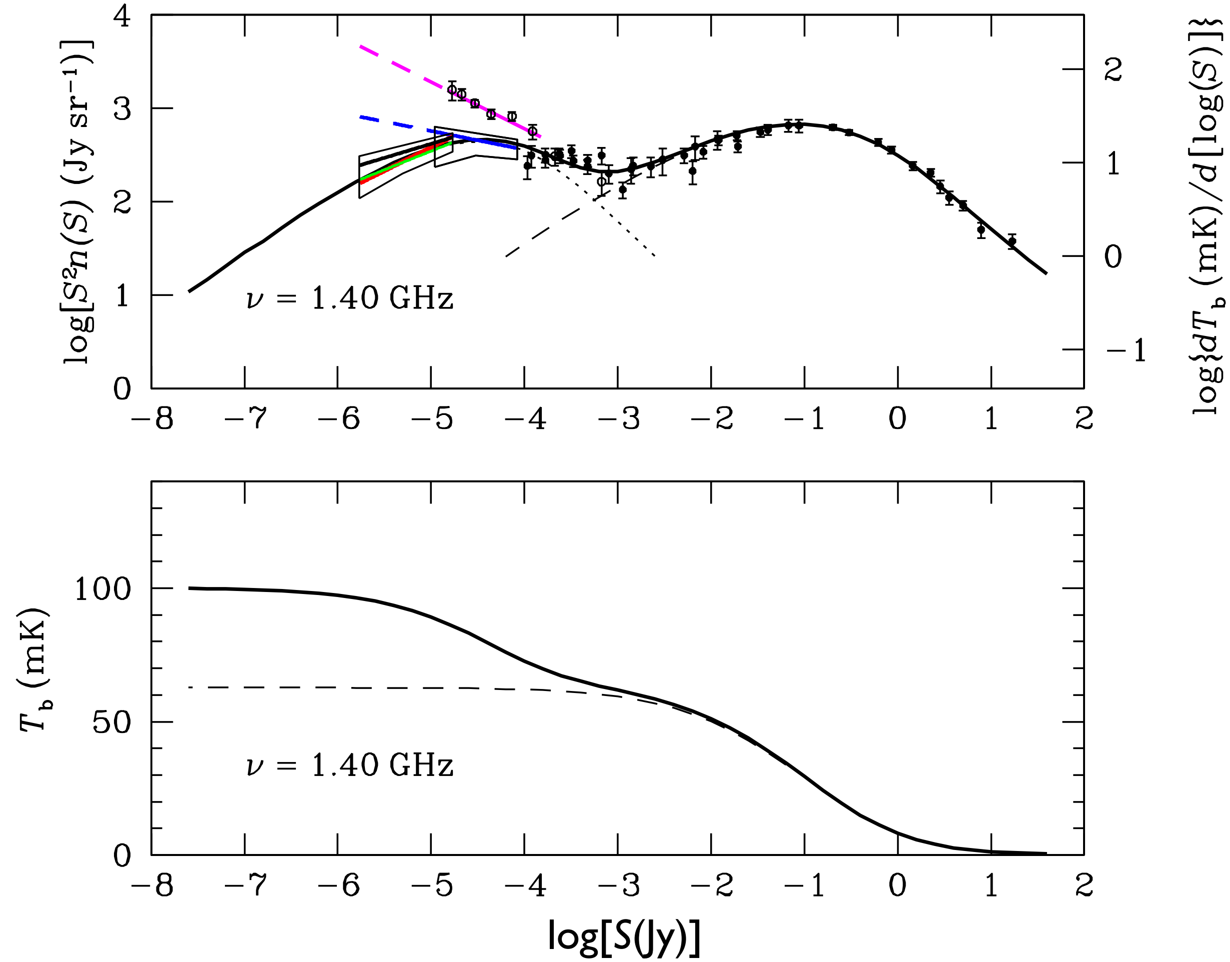
Resolving the radio source background

Differential source count, sky brightness normalization

Cumulative sky brightness contributed by radio sources

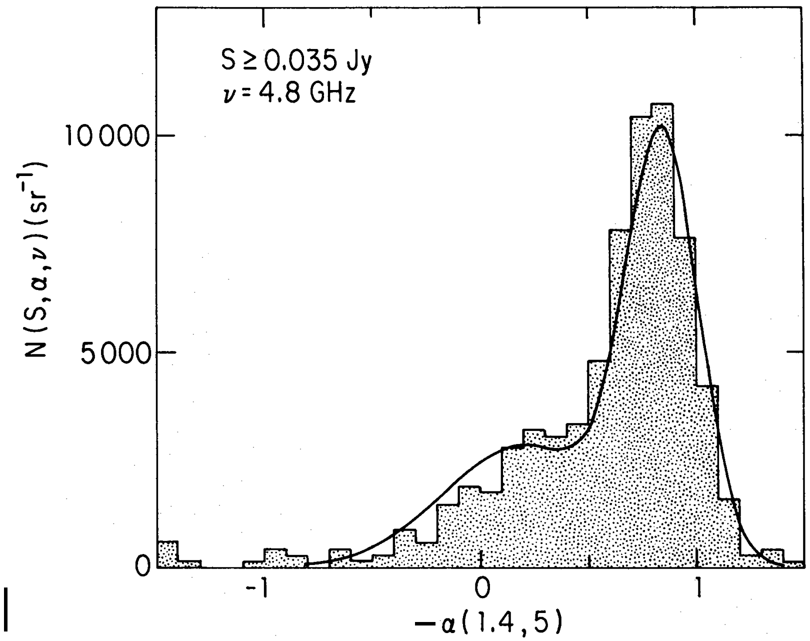


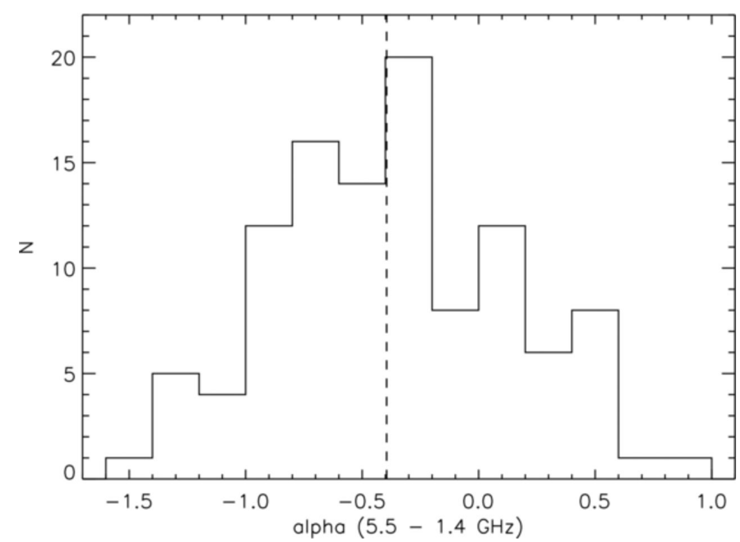
Radio source spectra

Narrow ($\langle\sigma_\alpha\rangle \sim 0.15$) steep-spectrum component
Broader flat-spectrum component from compact sources in AGN
Combined $\langle\alpha\rangle \approx -0.7$

Noise error in two-point α:
$\sigma_\alpha = [(\sigma_1/S_1)^2+(\sigma_2/S_2)^2]^{1/2} \, / \, | \ln(\nu_1/\nu_2) |$
Best case: (SNR independent of ν)
$\sigma_\alpha \sim (\sqrt{2}/\mathrm{SNR}) \, / \, | \ln(\nu_1/\nu_2) |$
Noise error in broadband α:
$\sigma_\alpha \sim (\sqrt{6}/\mathrm{SNR}) \, / \, \ln(\nu_{max}/\nu_{min})$

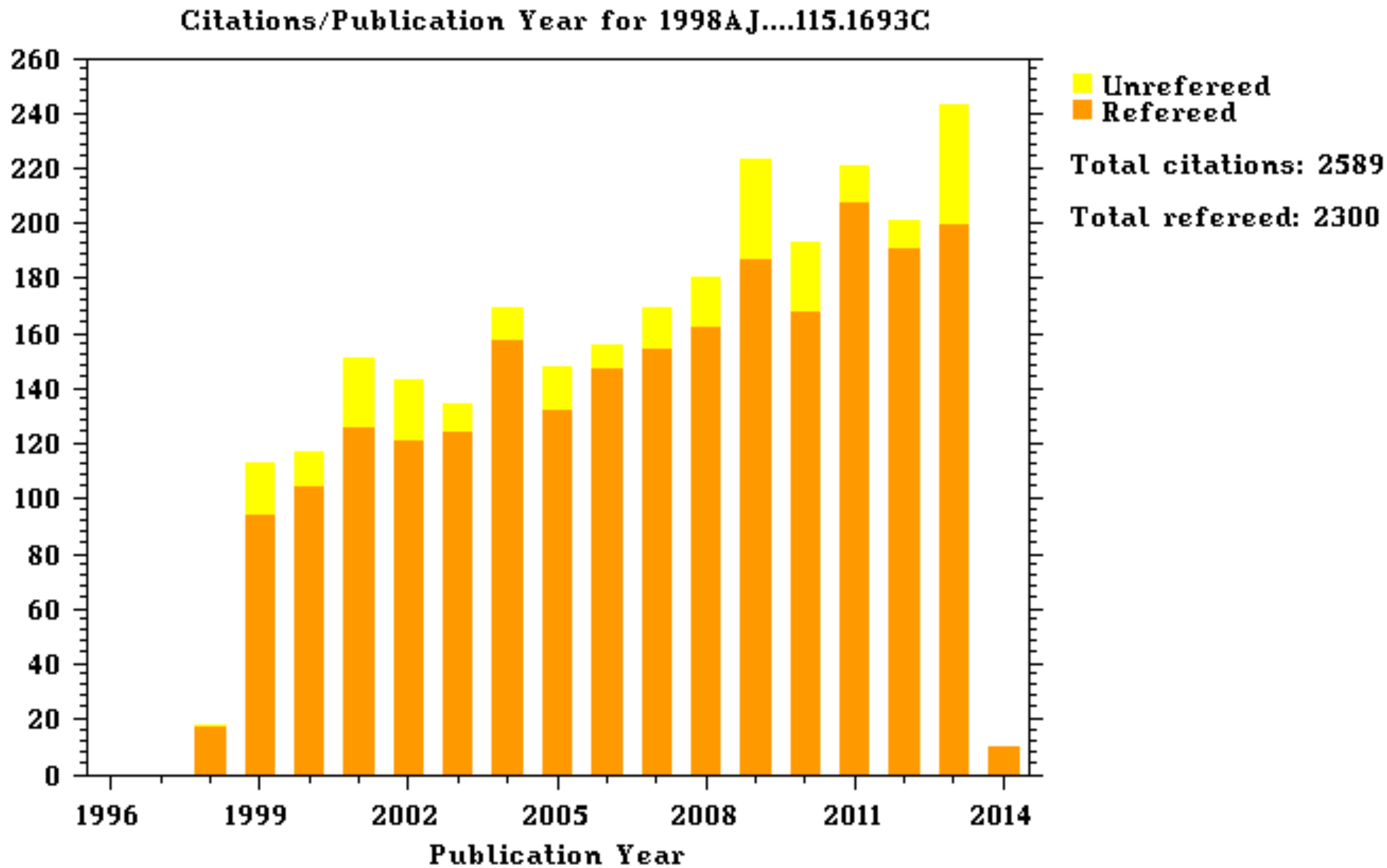
➔ need $| \ln(\nu_1/\nu_2) | > 1$,
not "in band" spectra unless SNR >> 5



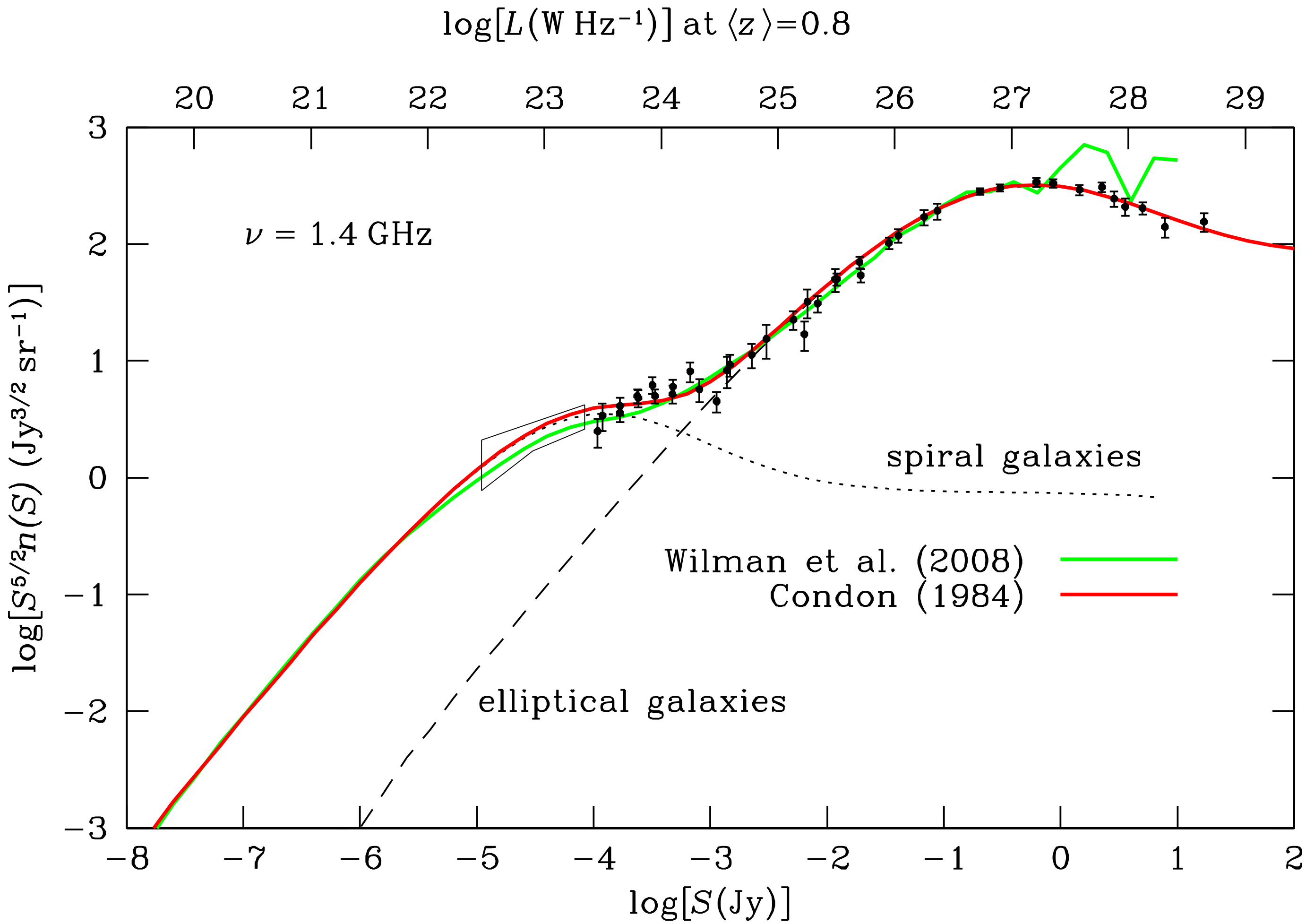


Report of the NRAO Large Proposals Committee - Alan Bridle et al. 1997

- The committee considered whether the NRAO should explicitly solicit proposals for large projects via Announcements of Opportunity, targeted either to specific disciplines or to special deadlines (other than those of the regular proposal process.)
- It was our unanimous opinion that this would be undesirable.
- It would separate "opportunities" for proposing large projects from the regular proposal process, whereas we see merit in keeping the processes for large and small proposals well-coupled. It is also hard to see what benefit would come by encouraging the whole user community to think about large proposals simultaneously.
- It is particularly undesirable to create an artificial imbalance between the pressures for large and regular proposals when our ultimate goal is to find an appropriate balance. We believe that balance is more likely to be achieved through a proposal process that is driven mainly by the scientific interests of individual investigators, rather than through one driven by ad hoc deadlines.


Citations/Publication Year for 1998AJ....115.1693C
260
240
220
200
180
160
140
120
100
80
60
40
20
0
1996
1999
2002
2005
2008
2011
2014
Publication Year
Unrefereed
Refereed
Total citations: 2589
Total refereed: 2300

Comparison of simulations



Good agreement ➔ both right?

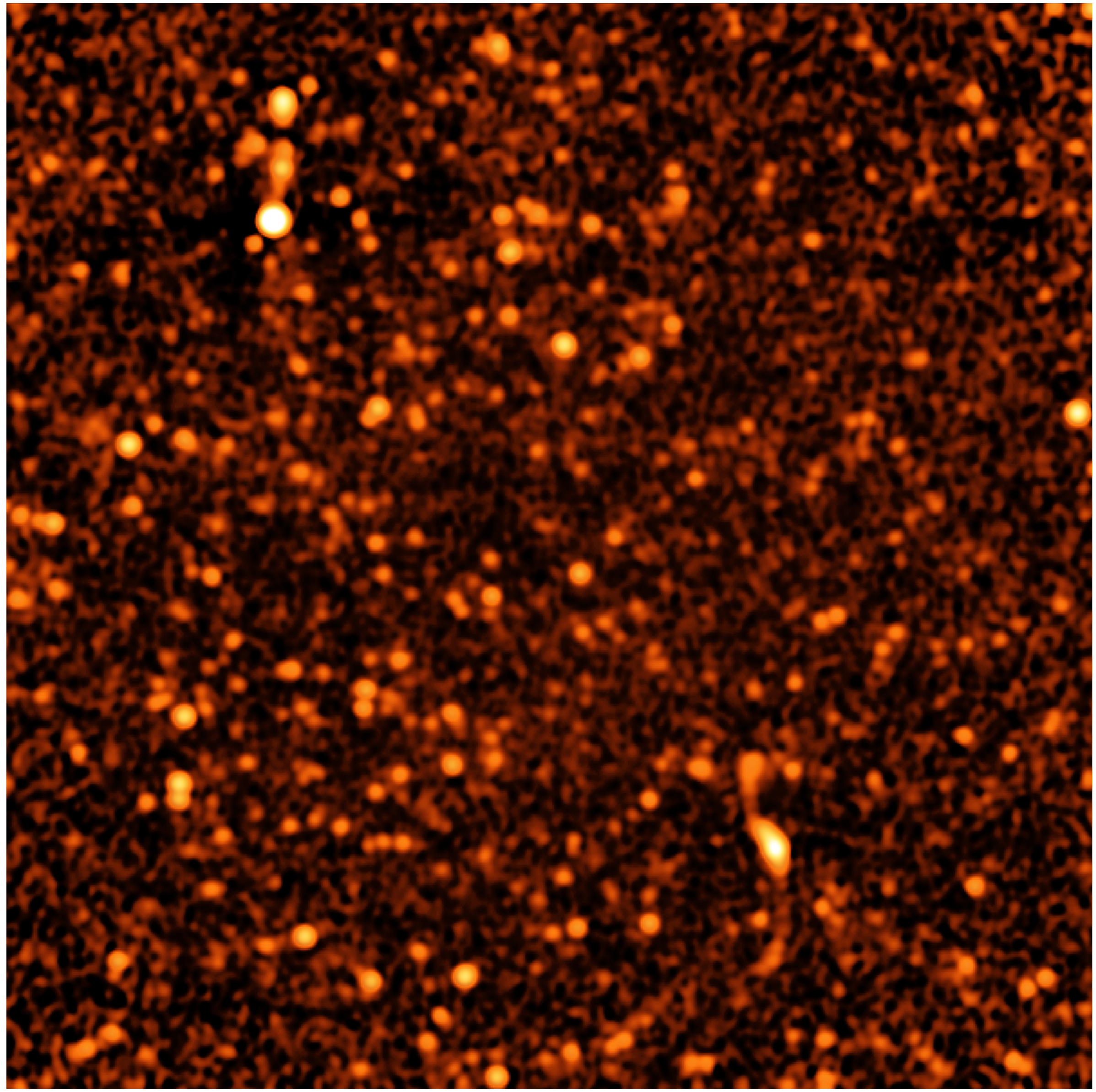
Confusion
(Gaussian PSF)

- Instrumental
- Natural

(12 arcmin)^2 image
ν = 3 GHz

8 arcsec resolution
σ_c = 1 μJy/beam
(Condon et al. 2012, ApJ, 758, 23)

➔ the μJy sky is dark



FIR/radio correlation

1. Radio luminosity is an extinction-free measure of star-formation rate
2. Radio and FIR flux-limited samples of star-forming galaxies are nearly identical