“Mr. Osborne, may I be excused? My brain is full.”
How can synthesis imaging help me do better science?
Science benefits of synthesis imaging

• Higher angular resolution: diffraction limited by the size of the array, not by the size of each telescope
• Correlation zeros or differentiates out most unwanted effects (e.g., varying atmospheric emission, ground radiation, “1/f” noise, RFI, …)
• Higher sensitivity is reached via longer practical integration times and lower “confusion” caused by unresolved background sources
• Higher spectral resolution: lag correlators measure frequencies very accurately with clocks, not wavelengths with rulers.
• Higher dynamic range is possible because the point-source response can be controlled and modified (e.g., selfcal, clean) and is nearly independent of mechanical pointing errors.
• Higher astrometric accuracy by using clocks instead of rulers to determine angles, and eliminating plane-parallel atmospheric refraction
Beating Confusion
(GB 300-ft at 1.4 GHz)
NVSS (45 arcsec beam) grayscale under GB 300-ft (12 arcmin beam) contours

\[ \sigma_c \sim 1 \mu\text{Jy/beam} \times \left( \frac{\theta}{5 \text{ arcsec}} \right)^2 \times \left( \frac{\nu}{1.4 \text{ GHz}} \right)^{0.7} \]
22 GHz $\text{H}_2\text{O}$ maser disk imaging and astrometry with the HSA = GBT + VLBA

Angular resolution: 0.0003 arcsec
Spectral resolution: 1 km/s
Differential astrometric precision: 0.000002 arcsec $\approx 10^{-11}$ radians
Maser rotation curve of UGC 3789

Distance = 50 ± 7 Mpc
so $H_0 = 69 \pm 11$ km/s/Mpc

$1.09 \times 10^7$ solar mass BH
or dense “star” cluster?

Plummer distribution:
$\rho(r) = \rho_0 \left(1 + \frac{r^2}{c^2}\right)^{-5/2}$

1. Evaporation if $N$ small
2. Collisions if $N$ large

$\rho_0 > 4 \times 10^{11} \ M_{\odot}/\text{pc}^3$
$m_* < 0.08 \ M_{\odot} \ N_* > 10^8$

Science costs of synthesis imaging

• Loss of “zero spacing” flux on extended sources (this is primarily a problem for nearby Galactic sources)
• Poor surface-brightness sensitivity at high angular resolution because the array area “filling factor” is low
• Computational costs may limit total bandwidth, spectral resolution, time resolution, field-of-view, … Complexity also limits multibeaming, pulsar observations, etc.
• Quantum noise limits sensitive synthesis imaging to radio frequencies!
Resolution versus surface-brightness sensitivity
The quantum noise limit for coherent amplification

\[ \frac{T}{\nu} = \frac{h}{k} = 48 \text{ K/THz} \]
e.g., \( \sim 150 \text{ K at } \lambda = 100 \text{ \(\mu\)m} \)
\( \sim 15000 \text{ K at } \lambda = 1 \text{ \(\mu\)m} \)

**Fig. 2:** An illustration of quantum noise in a maser amplifier. This (fictitious) maser amplifier consists of a tube filled with a gas of molecules or atoms, which are pumped in a way that causes some transition with frequency \( \nu \) to be inverted. A signal arriving at the input with power \( P_s \) is amplified by stimulated emission and emerges with power \( GP_s \), where \( G \) is the power gain of the amplifier. However, due to spontaneous emission, noise photons emerge from the amplifier output even when \( P_s = 0 \).
What is the main limitation of radio astronomy?
Normal galaxies example: Mouse vs. elephant
VLBA/HSA Image of the Starburst Nuclei in the ULIRG Arp 220
Jet Energy via Radio Bubbles in Hot Cluster Gas
Radio Spectral Lines: Cold Gas
The EOR Quasar at $z = 6.42$

J1148+5251: Coeval formation of a super massive black hole and giant elliptical galaxy within 870Myr of the Big Bang
EVLA and ALMA together

- EVLA continuous frequency coverage from 1 GHz to 50 GHz
- Detect CO at almost any redshift
- Study excitation of star-forming gas in distant galaxies
Parts of external galaxies: SNe and GRBs
Take-away message: Synthesis imaging is the secret weapon of radio astronomy
The end ...

Not!