The Radio Sky

Lecture 12

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PHY-236.3



H I at $z \approx 1$: too faint to detect one galaxy at a time

The numbers (Kaur et al. 2026)

- $M_{\rm HI} \sim 1.5 \times 10^{10}\, M_\odot$ at $z = 1.08$, $D_{\rm L} \approx 7.5$ Gpc.
- Inverting the mass formula, with a $1/(1+z)$ for the redshifted line: $\int S_\nu \, {\rm d}v \approx 2.4 \times 10^{-3}\, {\rm Jy\,km\,s^{-1}}$.
- Spread over a 280 $\rm km\,s^{-1}$ line: $S_\nu \approx 8.5\,\mu$Jy.
- GMRT Band-4 cube noise: 0.2–0.5 mJy per 24 kHz channel after 10–57 h per pointing.

Stacking

- Take many galaxies with known optical redshifts, shift each to its rest frame, and average.
- Noise averages down roughly as $1/\sqrt{N}$; the signal, common to all, does not.
- The result is the mean $M_{\rm HI}$ of the sample, not of any one galaxy.

Credit: Kaur, Kanekar, Chowdhury & Chengalur, GMRT CATz1-COSMOS, arXiv:2609.13382.

Stacking in the image cube: the recipe

1. Sample: 8122 star-forming COSMOS galaxies, $z = 0.875$–1.50, $M_* \geq 10^9\,M_\odot$, AGN removed.
2. Cut a $\pm 1900\ \mathrm{km\,s^{-1}}$ subcube around each galaxy.
3. Match resolution: convolve each to 90 kpc at its redshift.
4. Correct the primary beam; remove a baseline.
5. Average, weighting by $1/\sigma^2$, in luminosity units.
6. Integrate the spectrum over $\pm 200\ \mathrm{km\,s^{-1}}$.

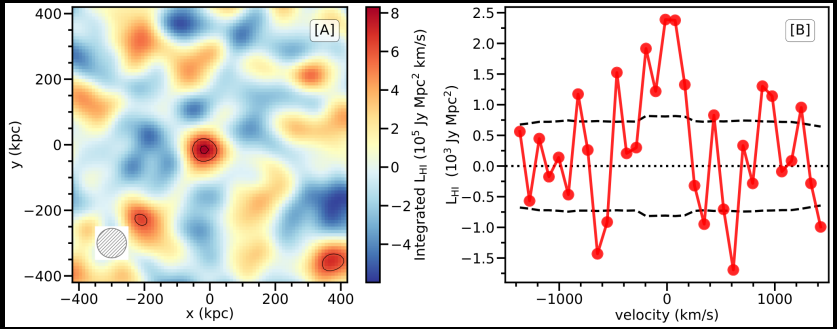
Why work in the cube?

Stacking positions, not just spectra, gives a stacked H I *image*, showing where the gas sits.

Guarding against false signals

- Drop subcubes with $> 20\%$ of channels flagged for RFI.
- Drop subcubes with $\geq 6\sigma$ spectral spikes.
- Noise from 10 000 stacks at randomised redshifts.

The stacked H I detection at $z \approx 1$



- [A] $\pm 200\ \mathrm{km\,s^{-1}}$ image: the 4σ peak sits at the stack centre; two weaker 3σ peaks show the field's noise.
- [B] Spectrum at that peak (90 $\mathrm{km\,s^{-1}}$ channels, dashed $\pm 1\sigma$): channels near zero velocity rise above the noise.

Credit: Kaur, Kanekar, Chowdhury & Chengalur, arXiv:2609.13382, Fig. 3.

What the stack measures at $z \approx 1$

$$L_{\rm HI} = \frac{4\pi \int S_\nu \, {\rm d}v \; D_{\rm L}^2}{1+z}$$

Then $M_{\rm HI} = \dfrac{2.36 \times 10^5}{4\pi} \, L_{\rm HI} \, M_\odot$, with $L_{\rm HI}$ in $\mathrm{Jy\,Mpc^2\ km\,s^{-1}}$.

- $L_{\rm HI} = (8.3 \pm 2.0) \times 10^5$ $\mathrm{Jy\,Mpc^2\ km\,s^{-1}}$: 4.2σ, FWHM 284 ± 33 $\mathrm{km\,s^{-1}}$.
- $\langle M_{\rm HI} \rangle = (15.5 \pm 3.7) \times 10^9 \, M_\odot$.
- Same galaxies in 680 MHz continuum (35σ): $\langle \mathrm{SFR} \rangle \approx 8.9 \, M_\odot \, \mathrm{yr^{-1}}$, so $t_{\rm dep} = M_{\rm HI}/\mathrm{SFR} \approx 1.7$ Gyr.

Sample	z	$M_{\rm HI}/M_*$	$t_{\rm dep}$
This work	1.08	1.15 ± 0.27	1.7 ± 0.5
DEEP2 (GMRT)	1.04	1.02 ± 0.16	1.5 ± 0.3
xGASS	≈ 0	0.42	4.3

Reading the comparison

At fixed M_*: $\sim 2.5\times$ the H I of local galaxies, used up $\sim 2.5\times$ faster ($t_{\rm dep}$ in Gyr).

Stacking: what it cannot tell you

- A mean, not a distribution: weighted by $1/\sigma^2$, so galaxies in the best-sampled regions of the field count most.
- Resolution costs signal: 90 kpc is chosen because gas resolved out at finer scales; the beam also blends neighbours, which is confusion unless galaxies are uncorrelated.
- Redshift errors (up to $\sim 100\ \mathrm{km\,s^{-1}}$) broaden the stacked line.
- Cosmic variance for a $\sim 1.4 \times 10^6$ cMpc^3 effective volume: up to $\sim 20\%$.
- Opacity corrections and the distance dependence are as in the worked example in Lecture 11: $M_{\mathrm{HI}} \propto D_{\mathrm{L}}^2$.

Interpretation (the authors')

Little extra H I and a short depletion time favour *insufficient gas accretion* as the reason the cosmic star-formation rate density falls at $z < 1$.

Opening question

Retrieval

An H_2O maser spot at 22 GHz has $T_\mathrm{b} > 10^{10}$ K, yet the gas it sits in has $T_\mathrm{k} \sim 10^{3}$ K. How can a line be brighter than the gas that emits it?

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- For thermal emission with no background, $T_\mathrm{b} = T_\mathrm{ex}\,(1 - \mathrm{e}^{-\tau}) \leq T_\mathrm{ex}$ (Lecture 3).
- In LTE $T_\mathrm{ex} = T_\mathrm{k}$, so $T_\mathrm{b} \leq T_\mathrm{k}$: a thermal line cannot exceed the gas temperature.
- $T_\mathrm{b} \gg T_\mathrm{k}$ therefore demands non-LTE level populations: here $T_\mathrm{ex} < 0$, amplification rather than emission.

Central question

How do masers probe compact energetic sites?

Maser amplification: negative excitation temperature

Recap:

$$\frac{n_\mathrm{u}}{n_\mathrm{l}} = \frac{g_\mathrm{u}}{g_\mathrm{l}} \mathrm{e}^{-h\nu/k_\mathrm{B}T_\mathrm{ex}}, \qquad \kappa_\nu \propto \frac{n_\mathrm{l}}{g_\mathrm{l}} - \frac{n_\mathrm{u}}{g_\mathrm{u}}$$

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Population inversion $n_\mathrm{u}/g_\mathrm{u} > n_\mathrm{l}/g_\mathrm{l}$:

- $T_\mathrm{ex} < 0$, $\kappa_\nu < 0$, $\tau_\nu < 0$.
- Transfer gives $I_\nu \approx I_{\nu,0}\, \mathrm{e}^{|\tau_\nu|}$: exponential gain.
- $|\tau| = 20$: gain $\mathrm{e}^{20} \approx 5 \times 10^8$.

Requirements

- A pump (radiative or collisional) out of LTE.
- Long velocity-coherent path.
- Saturation: the maser's own radiation depletes the inversion, so I_ν then grows only linearly with path, not exponentially.

Observable consequences

$T_\mathrm{b} \gg 10^{10}$ K in compact spots; narrow, variable lines; beamed along the longest gain path.

A maser zoo

Species	Frequency	Where it is found	Best observed with
OH	1.6–1.7 GHz	star-forming regions, OH/IR stars, SNR shocks, ULIRGs	MeerKAT, VLA, Parkes; VLBI: EVN, VLBA
H_2O $6_{16} \rightarrow 5_{23}$	22.235 GHz	protostellar outflows, AGB envelopes, AGN accretion discs	VLA, VLBA, Effelsberg; KVN, VERA
CH_3OH (class II)	6.668 GHz	exclusively massive star formation	Parkes, ATCA, Effelsberg; VLBI: EVN
SiO	43, 86 GHz	inner envelopes of AGB stars	VLBA, KVN (43 GHz); ALMA (86 GHz)

- Maser intensity is not a measure of column or mass: gain is exponential in path and inversion.
- What masers *do* measure well: positions and velocities of compact spots, with VLBI precision.

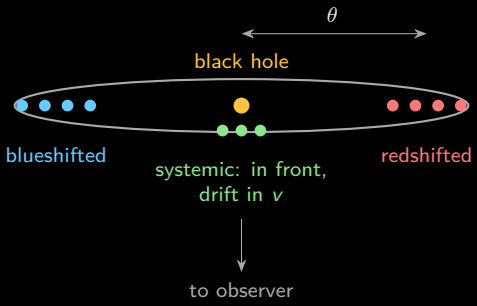
Masers as geometric rulers in the Milky Way

- VLBI positions of H_2O and CH_3OH masers to $\sim 10\,\mu$as yield trigonometric parallaxes: $\pi = 100\,\mu$as at $10\,\mathrm{kpc}$.
- Parallax + proper motion + v_{LSR} gives 3D positions and velocities of star-forming regions.
- Results: spiral-arm locations, $R_0 \approx 8.15\,\mathrm{kpc}$, $\Theta_0 \approx 236\,\mathrm{km\,s^{-1}}$, and direct tests of kinematic distances. Reid et al. 2014, doi:10.1088/0004-637X/783/2/130; 2019, doi:10.3847/1538-4357/ab4a11.

Why masers and not thermal lines?

Only a compact, extremely bright spot can be located to μas with VLBI: the non-LTE amplifier is what makes geometric astrometry possible.

Megamaser discs: a geometric distance to NGC 4258



Edge-on disc of H_2O masers, schematic.

- High-velocity masers: Keplerian $v(r)$, and hence $M_{\rm BH}$ (per unit D).
- Systemic masers: measured centripetal acceleration $a \approx v^2/r$ (times $\sin i$) gives the physical radius r.
- VLBI gives angular radius θ:

$$D = \frac{r}{\theta} = \frac{v^2 \sin i}{a\,\theta}$$

- $D = 7.60 \pm 0.23\,\mathrm{Mpc}$ (Humphreys et al. 2013, doi:10.1088/0004-637X/775/1/13; first: Herrnstein et al. 1999, doi:10.1038/22972).

Worked example: NGC 4258 with the published numbers

Humphreys et al. 2013 (Tables 1, 3)

- Systemic masers:
  $a_{\rm los} = 6.96$–$9.81\,\mathrm{km\,s^{-1}\,yr^{-1}}$
- High-velocity masers:
  $|v_{\rm los} - v_{\rm sys}| \approx 750$–$1170\,\mathrm{km\,s^{-1}}$
  ($v_{\rm sys} = 474.25\,\mathrm{km\,s^{-1}}$)
- Fit: $M_{\rm BH} = 4.00 \times 10^7\,M_\odot$, $i = 71.7^\circ$
- $D = 7.60 \pm 0.17 \pm 0.15$ Mpc (random, syst.)

Take $a = 9\,\mathrm{km\,s^{-1}\,yr^{-1}} = 2.85 \times 10^{-4}\,\mathrm{m\,s^{-2}}$ and $GM_{\rm BH} = 5.31 \times 10^{27}\,\mathrm{m^3\,s^{-2}}$ (SI):

$$r = \sqrt{\frac{GM_{\rm BH}\sin i}{a}} = 4.2 \times 10^{15}\,\mathrm{m} = 0.136\,\mathrm{pc}$$

$$v = \sqrt{GM_{\rm BH}/r} = 1120\,\mathrm{km\,s^{-1}}$$

$$\theta = \frac{r}{D} = 3.7\ \mathrm{mas} \quad (\text{for } D = 7.60\,\mathrm{Mpc})$$

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- v matches the observed high-velocity range. θ is *implied* by the fit (not quoted in the paper); VLBI measures it, and $D = r/\theta$.
- No distance ladder: only Kepler and geometry.

Concept test

Question

What population condition is necessary for maser amplification?

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Answer: population inversion

1. The upper level must be overpopulated relative to LTE: $n_{\mathrm{u}}/g_{\mathrm{u}} > n_{\mathrm{l}}/g_{\mathrm{l}}$.
2. Stimulated emission then exceeds absorption, so $\tau_\nu < 0$ and the intensity grows along the path.

Summary

- Stacking. Averaging the cube at known optical positions recovers the mean L_ν, hence $\langle M_{\rm HI}\rangle$, for galaxies too faint to detect singly; it gives a mean, not a distribution.
- Limits of a stack. Redshift errors broaden the line, and cosmic variance and selection set the uncertainty.
- Masers. Population inversion gives $T_{\rm ex} < 0$, $\tau < 0$ and exponential gain, until saturation makes growth linear; hence $T_{\rm b} \gg 10^{10}$ K in compact, narrow, variable spots.
- What masers measure. Positions and velocities, not column or mass: parallaxes in the Milky Way and Keplerian discs in megamaser galaxies.
- Megamaser distance. Velocity and acceleration of the disc spots give r and v, and with the VLBI angle θ a distance $D = r/\theta$ with no distance ladder.

Further reading

- **H I stacking at $z \approx 1$:** Kaur et al. 2026, arXiv:2609.13382.
- **Maser physics:** Elitzur 1992, *Astronomical Masers*; Gray 2012, *Maser Sources in Astrophysics*.
- **Masers as rulers:** Reid et al. 2014 (doi:10.1088/0004-637X/783/2/130); Reid et al. 2019 (doi:10.3847/1538-4357/ab4a11).
- **NGC 4258:** Humphreys et al. 2013 (doi:10.1088/0004-637X/775/1/13).