First prototype ammonia maser and inventor Charles H. Townes (1953). The ammonia nozzle is at left in the box, the four brass rods at center is the quadrupole state selector, and the resonant cavity is at right. The 24 GHz microwaves exit through the vertical waveguide Townes is adjusting. At bottom are the vacuum pumps.
Stimulated Emission, Einstein 1917

Interaction of light and atoms: absorption, spontaneous emission, stimulated emission

Two emitted photons are coherent
population inversion

red, excited atoms blue atoms in ground state
cascade of coherent photons
3 and 4 level schemes for lasers. Require pumping to achieve population inversion.

Principle of the three-level laser.

Easier to achieve in practice is 4-level

Principle of the four-level laser.
1. ratio of stimulated to spontaneous

\[ \frac{W_{st}}{W_{sp}} = \frac{1}{e^{\Delta E/kT} - 1} \]

\[ = 25 \text{ @ 1mm} \]

\[ = 10^{-35} \text{ visible} \]

2. size of \( \Delta E \)

\[ \frac{N_{E_2}}{N_{E_1}} = e^{-\Delta E/kT} \]

\[ \text{masers } \Delta E \approx 10^{-5} \text{ eV} \]

\[ \text{thermal energy } 0.025 \text{ (} T/300 \text{K)} \]
observed maser molecules

OH (hydroxyl)
H₂O (water)
SiO
CH
H₂CO
CH₃OH (methanol)
NH₃ (ammonia)
HC₃N
HCN (cyanide)

Astronomical masers have much smaller line widths (5-10) than due to thermal motions. Over 200 methanol lines have been detected between 360 and 834 GHz. Over 20 of those display maser emission. Other characteristics are intensity of emission and high polarization.

What causes population inversion? Ask Prof. Pihlström
Orion nebula

In 1962 it was discovered that radio molecular lines from interstellar clouds had huge intensities (blackbody $T \sim 10^{12}-10^{15}$ K) but very narrow doppler line widths (equivalent to $T<100$ K). Explained by maser.
A chandra X-ray image (blue) has been combined with Hubble's optical image (red and green) to compose this stunning and revealing picture of the spiral galaxy NGC 3079. The location of the water maser studied with the SMA is marked on the inset. Towering filaments consisting of warm (about ten thousand degrees Celsius) and hot (about ten million degrees C) gas blend to create the bright horseshoe-shaped feature near the center. The correlation of the warm and hot filaments suggests that they were both formed as a super-wind of gas rushed out from the galaxy's center. Such a super-wind originates either from activity generated by a central supermassive black hole, or by a burst of supernova activity. NASA/CXC/G. Cecil (UNC)
VLBA can measure distances via parallax out to few kpc (to 10%)
A foreground galaxy distorts the quasar MG J0414+0534 into four images; two reveal water maser emission. Seen from nearby, the quasar might look similar to the galaxy M87 (inset at lower right). 

(Illustration: Milde Science Communication/HST Archive data/CFHT/J-C Cuillandre/Coelum)
NGC 4258 (shown in optical + X-ray in blue) the first galaxy whose distance was measured using the maser technique in 2000. The latest galaxy measured by the technique is seven times more distant and is a step towards providing astronomers with a new estimate of the expansion rate of the universe.

We report a new geometric maser distance estimate to the active galaxy NGC 4258. The data for the new model are maser line-of-sight velocities and sky positions from 18 epochs of Very Long Baseline Interferometry observations, and line-of-sight accelerations measured from a 10-year monitoring program of the 22 GHz maser emission of NGC 4258. The new model includes both disk warping and confocal elliptical maser orbits with differential precession. The distance to NGC 4258 is $7.60 \pm 0.17 \pm 0.15$ Mpc, a 3% uncertainty including formal fitting and systematic terms. The resulting Hubble Constant, based on the use of the Cepheid Variables in NGC 4258 to recalibrate the Cepheid distance scale (Riess et al. 2011), is $H_0 = 72.0 \pm 3.0$ km/s/Mpc.