Masers

One of the most interesting, and in many cases a very useful, type of molecular feature is a maser. Radio version of laser. These lead to very bright, compact sources, often around protostars or giants that have circumstellar material from stellar winds, but also around some supermassive black holes.

methanol   ammonia   hydrogen cyanide

Typical molecules → OH, H_2CO, CH_3OH, SiS, H_2O, NH_3, SiO, HCN

1.6 GHz   22 GHz   43 GHz, 86 GHz

formaldehyde

Tend to be time variable.

But are often excellent targets for VLBI → compact, radio, relatively bright → much information in positions & angular motions.

Let's remind ourselves what causes masing.

Recall the equation of radiative transfer in the context of a two level system:

$$\frac{dI_\nu}{ds} = \underbrace{-\frac{h\nu}{4\pi}\left(n_1 B_{12} - n_2 B_{21}\right)\phi(\nu)}_{\alpha_\nu} I_\nu + \frac{h\nu}{4\pi} n_2 A_{21}\phi(\nu)$$

$$\alpha_\nu = \frac{h\nu}{4\pi} n_1 B_{12}\left(1 - \frac{g_1 n_2}{g_2 n_1}\right)\phi(\nu)$$

Normally (eg in thermodynamic eq'm):

$$\frac{g_1 n_2}{g_2 n_1} < 1 \quad \left(\text{eg } \frac{n_2}{n_1} = \frac{g_2}{g_1}\underbrace{e^{-h\nu_{21}/kT}}_{<1}\right)$$

so $\alpha_\nu > 0$ "absorption"

can be quantified as a "negative" temperature

But we can obtain "inverted populations" where:

$$\boxed{\frac{g_1 n_2}{g_2 n_1} > 1} \longrightarrow \text{upper state more populated "per multiplicity"}$$

Then $\alpha_\nu < 0 \longrightarrow$ amplification!

Conditions to observe:

- inverted population (kept out of thermodynamic eq'n)
- long enough path length
- not a lot of Doppler shifts (otherwise this blurs $\phi(\nu)$ and effectively reduces optical depth)

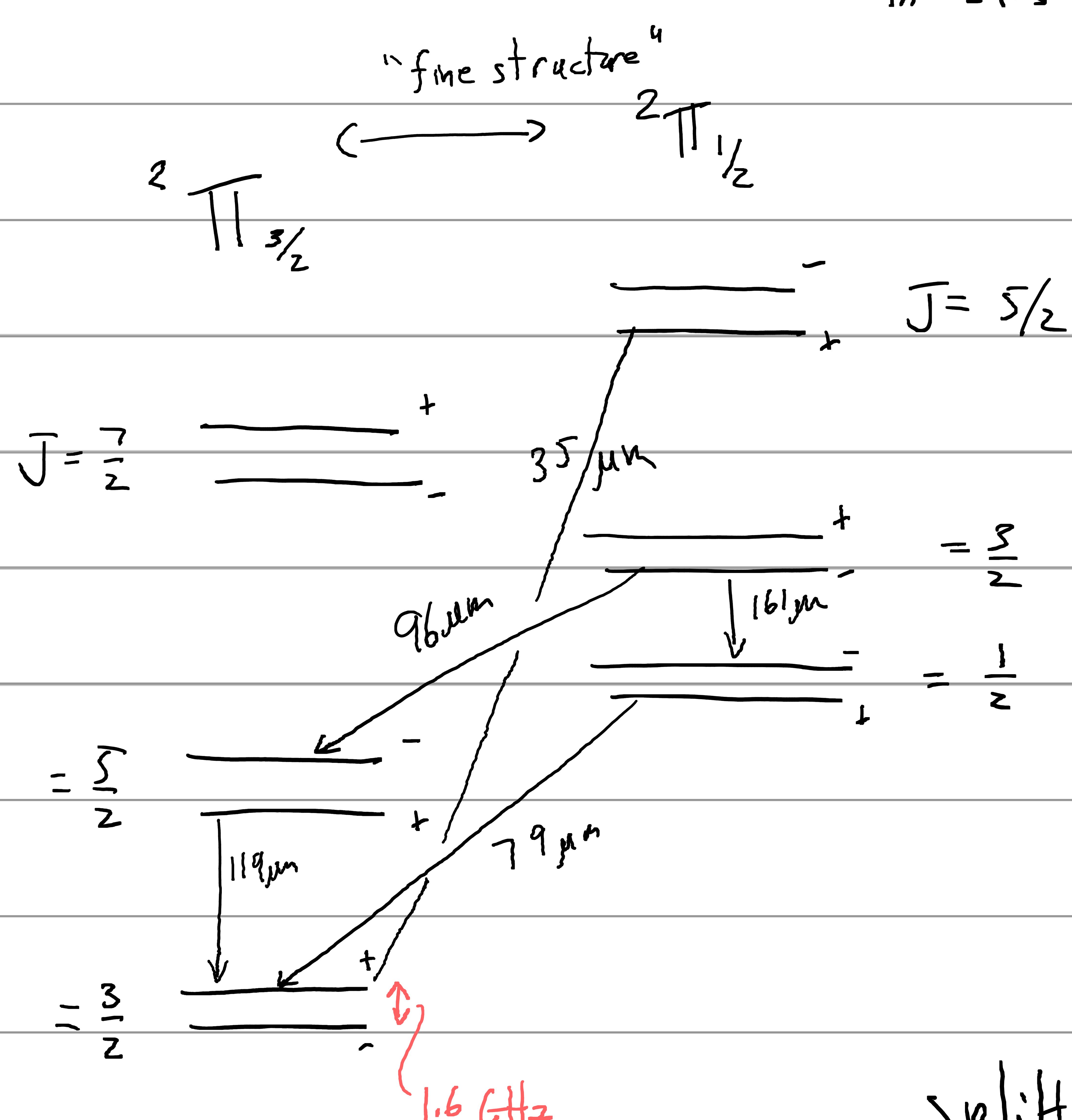
Inverted populations are often associated with optical pumping. However, collisional excitation can play a role if the gas is not in equilibrium with the levels.

Optical pumping occurs when incident light excites the molecule and the combination of the relative degree of excitation and the particulars of the decay paths lead to a population inversion.

To see an example, let's consider the rotational levels of OH in more detail.

OH is special because its ground electronic state is $\Lambda = 1$, $S = \frac{1}{2}$. The total electronic ang. mom. projected on the diatomic axis is:

$$\Omega = |\Lambda - S|,\ \Lambda + S = \underbrace{\tfrac{1}{2}, \tfrac{3}{2}}_{\text{in this case}}$$



$\oplus \to \ominus \sim$ cm

"lambda doubling" because $\Lambda \neq 0$ can have two signs

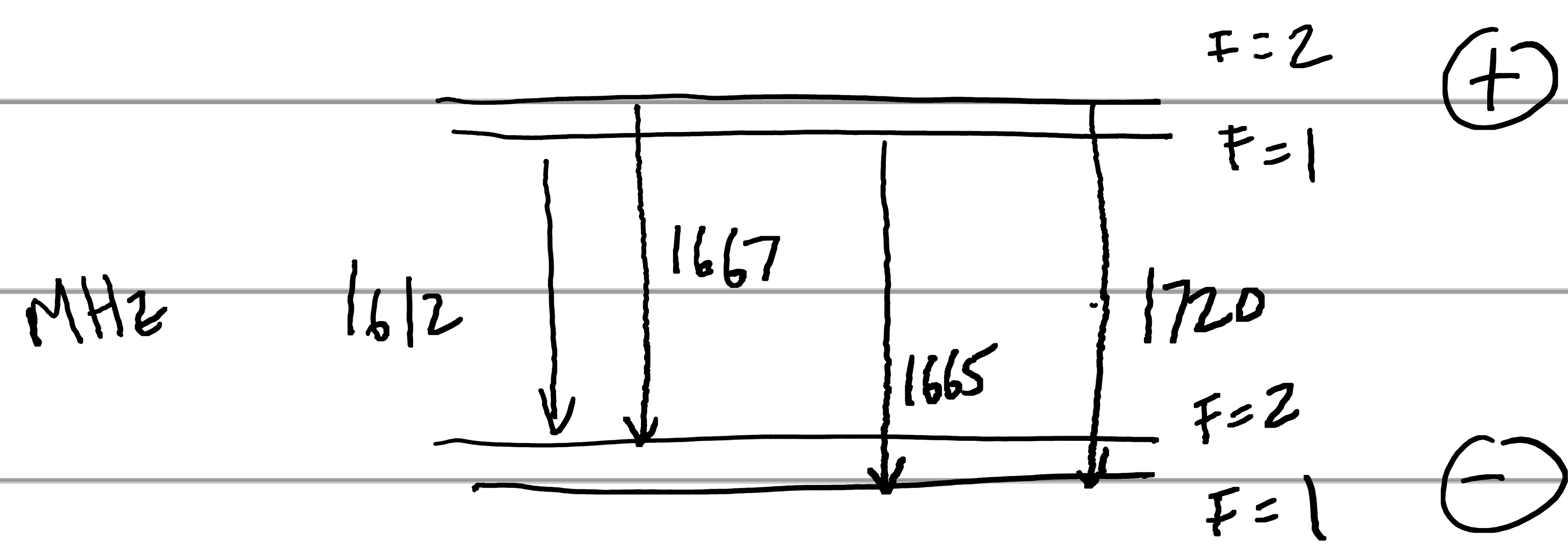
i.e. electronic angular momentum comes in

splitting is of order

$$\frac{\Delta E}{E_J} \sim \frac{m_e}{\mu} \quad \text{(ratio of a.m.)}$$

Note each state has also hyperfine structure associated with the nuclear spin. So in the ground state:

$^2\Pi_{3/2}$ $J = \frac{3}{2}$ $F = 2$ or 1



"main lines" 1667, 1665 MHz

"satellite lines" 1612, 1720 MHz

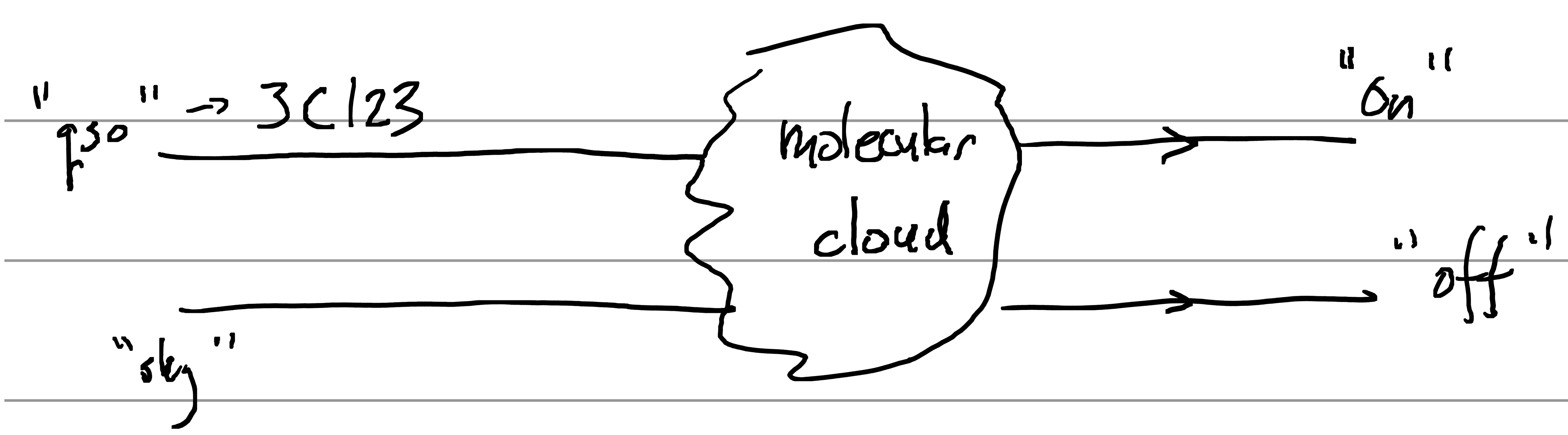
So what happens? If there is sufficient IR flux, it populates the upper rotation levels. They decay at rates that depend on their specific A-coefficients. Under the right IR flux — ie. ratio of 119, 79, 53, 35 μm light — the result can lead to decays to ⊕ states that exceed ⊖.

The exact conditions (IR flux & spectrum, velocity distribution of OH) are critical to determining masing — and are expected to vary (as masing is observed to do).

Fun summary: Elitzur (2007) IAU Proceedings
and Elitzur (1991) ARA&A is still useful.

Classic demonstration of stimulated emission from
Rieu et al (1976), A&A, 46, 413

Used method we discussion in the context of measuring
spin temperatures:



Recall: $I_\nu^{off} = I_\nu^{sky} e^{-\tau_\nu} + B_\nu(T_{OH})(1-e^{-\tau_\nu})$

$I_\nu^{on} = I_\nu^{qso} e^{-\tau_\nu} + B_\nu(T_{OH})(1-e^{-\tau_\nu})$

$$T_{OH} \propto B_\nu(T_{OH}) = \frac{I_\nu^{off} I_\nu^{qso} - I_\nu^{on} I_\nu^{sky}}{(I_\nu^{qso} - I_\nu^{sky}) - (I_\nu^{on} - I_\nu^{off})}$$

↑ R-J limit

In 3C123, for 1720 MHz line → $T < 0$!

Weisberg et al (2005) saw same enhancement of 1720 MHz in a galactic maser in front of a pulsar. Here you don't need to look on-off in different directions — just time-resolve "on pulse" & "off pulse."

Other Galactic masers (eg CH_3OH) can be used to measure precise distances & motions in the MW. Eg. Reid (2012) IAU Proceedings.

Example: OH Mega Masers — extremely luminous masers at centers of luminous IR galaxies. (See Lockett & Elitzur 2008)

"main lines" 1667, 1665 MHz

"satellite lines" 1612, 1720 MHz

Fraction & luminosity correlates w/ IR luminosity (which makes sense). Seem to be mostly in "warm" LIRGs — 35 μm & 53 μm pumping lines are key. Dust needs to be at least ~ 40K.

Note the calculation is involved & cannot ignore collisions to predict level populations.

Other masing molecules occur in mega-variety, eg. methanol (12 GHz) & H_2O (22 GHz). In these cases the amplified radiations arises from a continuum source at the galactic centers.

H_2O masers are of great importance because of the role played in the extragalactic distance ladder of NGC 4258.

The inversion in this case is due to collisional excitations of fairly high level rotational states. The specific 22 GHz line is detectable because it avoids atmosphere absorption lines in mm range.