Discovery of Terahertz Water Masers with SOFIA/GREAT

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Outline

- Motivation for studying water masers
- Physics of maser amplification
- Discovery of Terahertz masers with SOFIA

Water masers

- First detection of interstellar water reported by Cheung et al. (1969):

  $6_{16} – 5_{23}$ transition at 22 GHz

- Brightness temperatures often > 10^{10} K and can even reach 10^{14} K

  ➔ maser amplification

Motivation

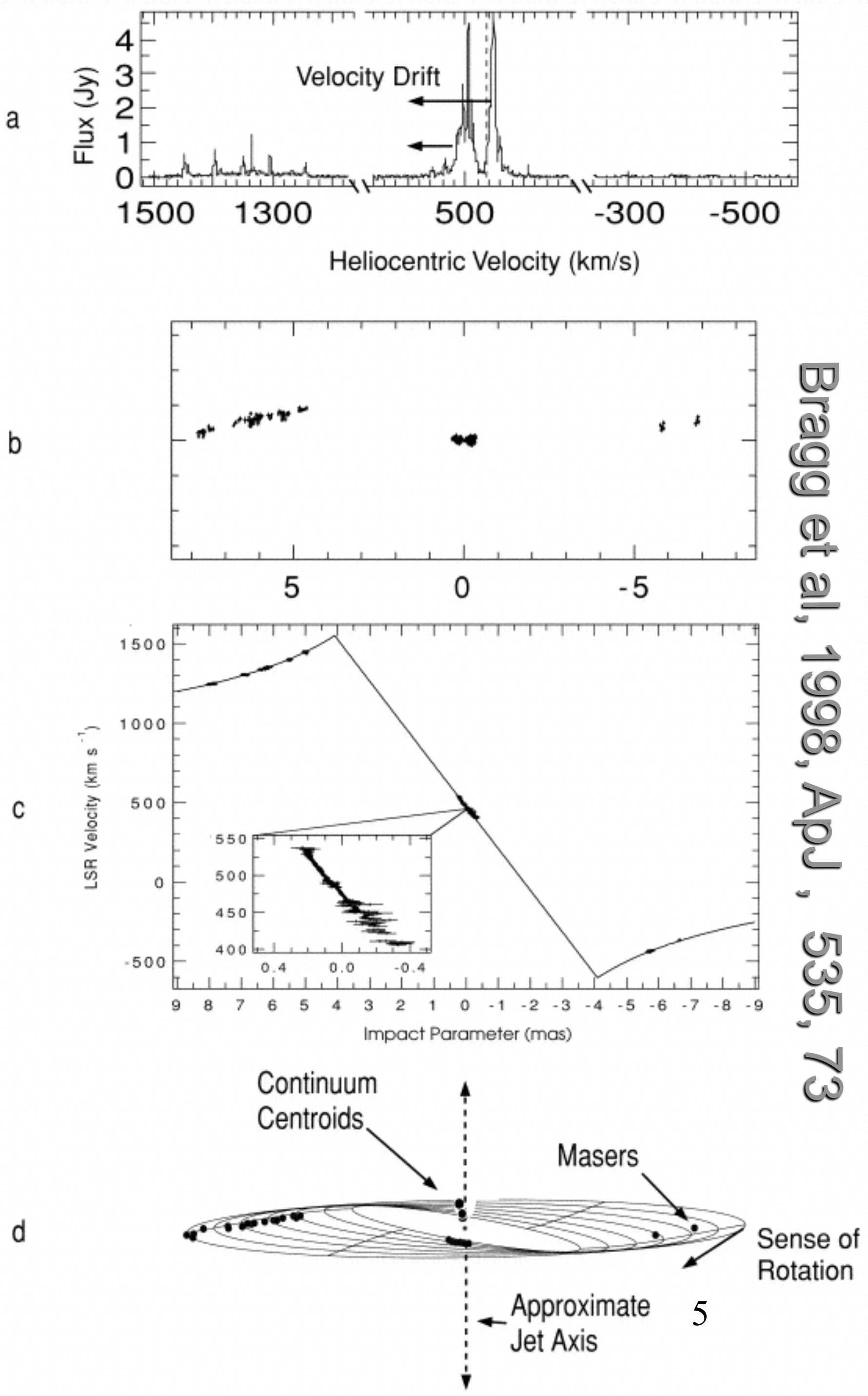
- All ground-based water observations target transitions that are – or can be – inverted
- Extraordinarily high brightness temperatures often permit VLBI

  ➔ sub-milliarcsec resolution
- Clumpiness of maser emission allows proper motion studies
  - Best evidence for a supermassive black hole at the center of an active galaxy (Miyoshi et al. 1995)
  - Beautifully accurate determinations of parallax to regions of high mass star formation (many papers by Menten, Reid and collabs)

AGN accretion disks

Water maser observations provide some of the best evidence we have for the existence of supermassive black holes

Derived dynamical mass in NGC 4258 is 4 x 10^7 $M_\odot$ within a region of radius 0.13 pc.



Bragg et al, 1998, ApJ , 535, 73

Motivation

- Water masers provide a unique tracer of extremely dense gas ($n_H \sim 10^9 – 10^{11}\ \mathrm{cm}^{-3}$)
- Water masers provide unique probe of the magnetic field in dense regions
- Maser amplification is a fundamental physical process of intrinsic interest
  - dramatic manifestation of Bose-Einstein statistics
- Multitransition studies (since 1990) place constraints upon the physics of the masing gas

Maser environments

Warm dense molecular gas in:

1) Shocked regions (protostellar outflows)
2) Circumstellar outflows
3) AGN accretion disks

Observational opportunities

- Recent and upcoming observational opportunities available in the submillimeter region
  - HIFI: access to additional maser transitions (600 – 1000 GHz), and unobscured access to previously-observed emissions
  - Interferometry with ALMA
  - SOFIA: access to the highest-frequency transitions

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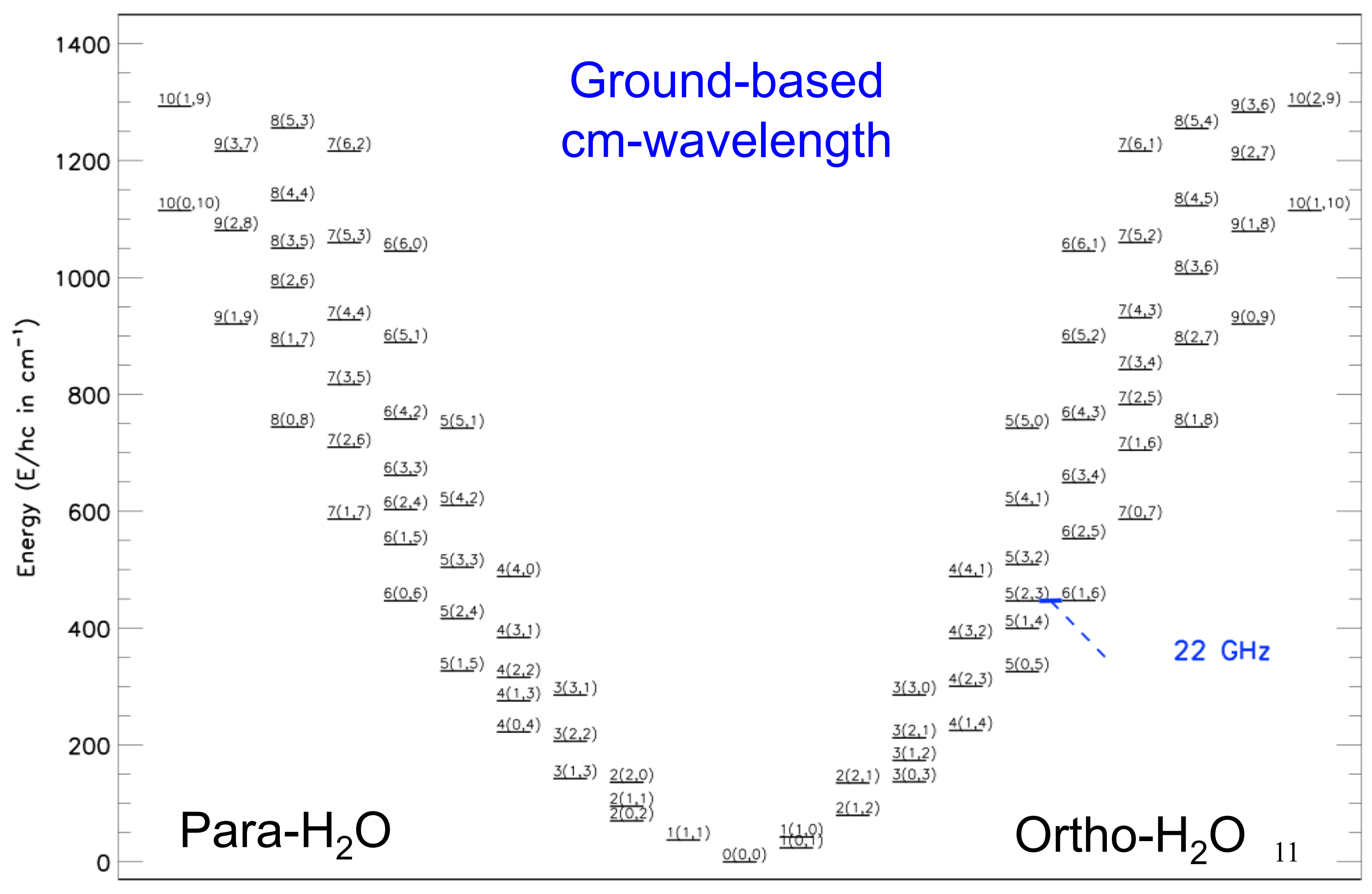
Underlying physics

- Maser amplification requires a “population inversion”
  $n_{upper}/g_{upper} > n_{lower}/g_{lower}$
  which can never happen in thermal equilibrium. (The larger the frequency, the larger the required departure from thermal equilibrium)
- When this criterion is met
  stimulated emission rate > absorption rate
- Line intensity increases in proportion to its current value
  exponential amplification instead of attenuation

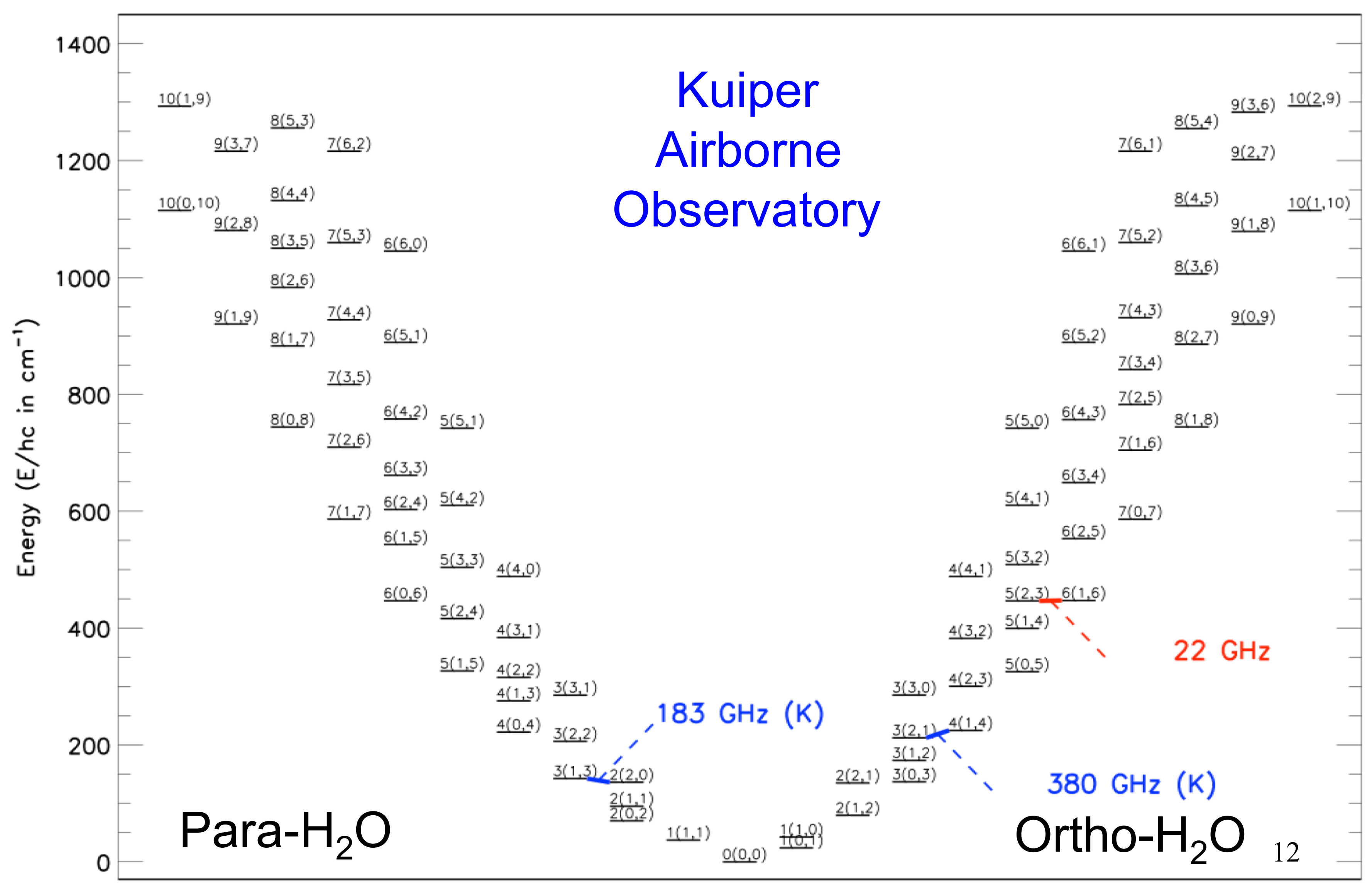
- Key question: how does the population inversion arise, and what physical conditions are required?

Water maser transitions observed (as of 1969)

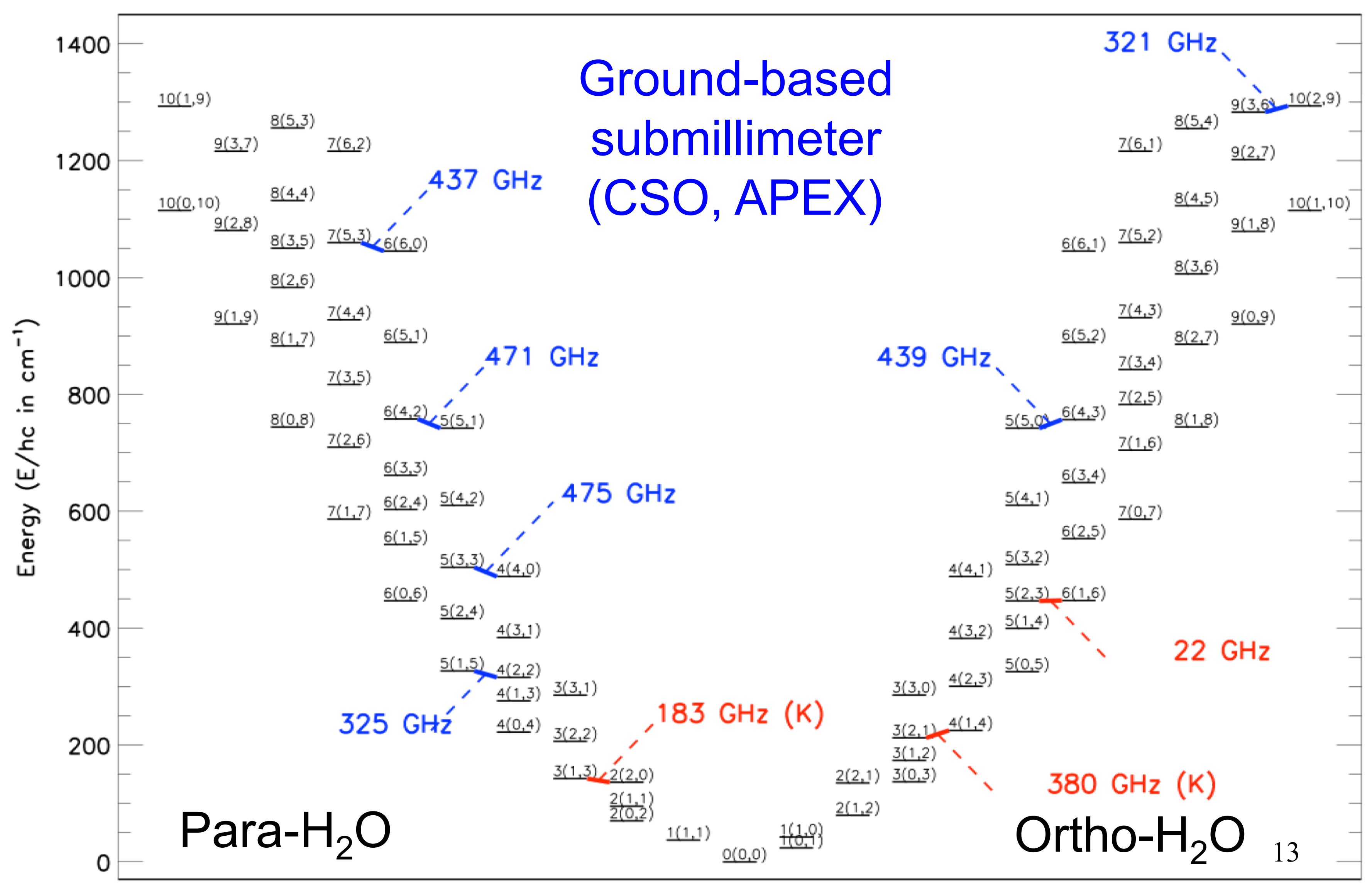


Ground-based cm-wavelength

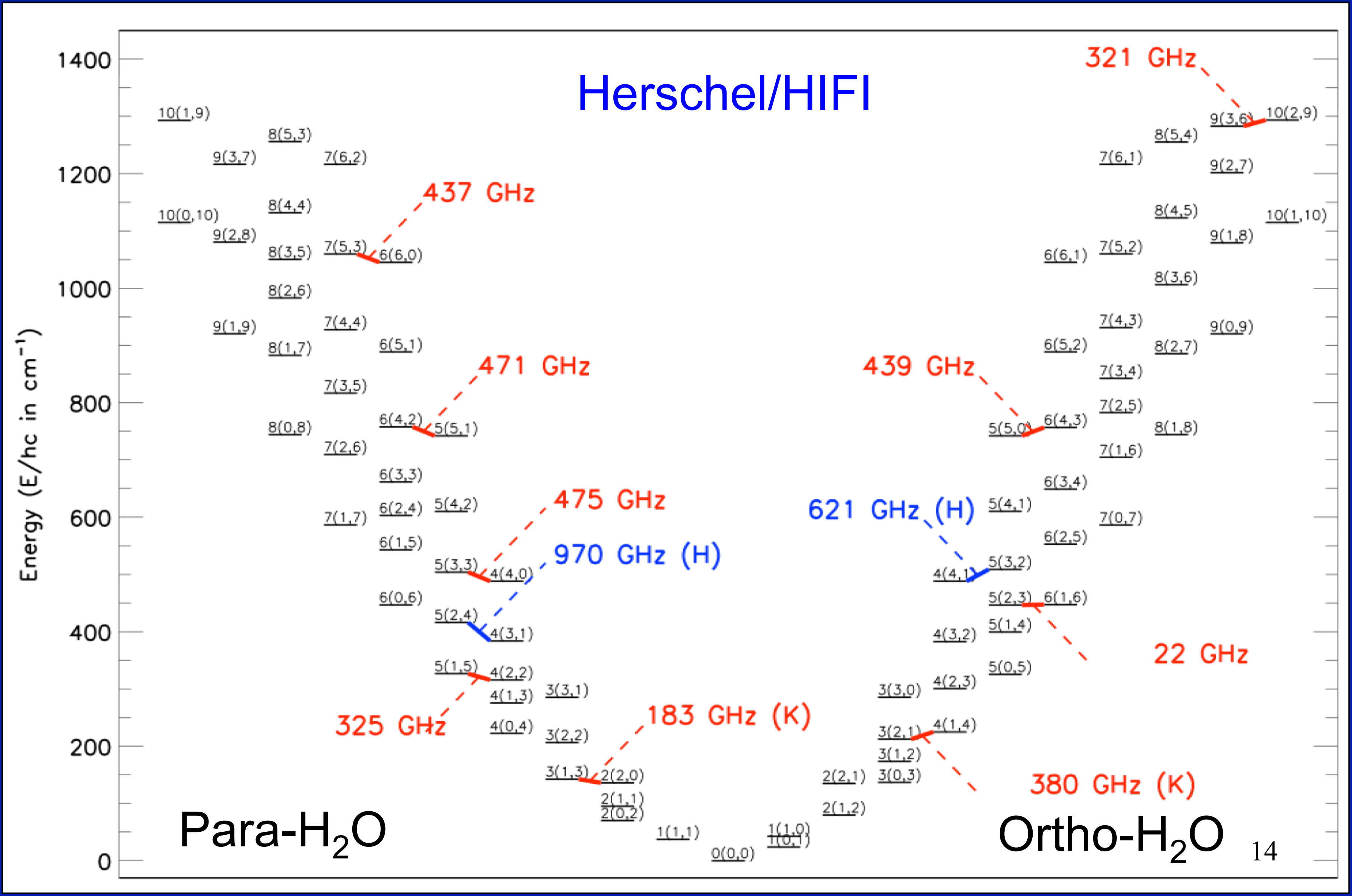
Water maser transitions observed (as of 1980)



Water maser transitions observed (as of 2008)



Water maser transitions observed (as of 2015)



Origin of the population inversion

All masing transitions have

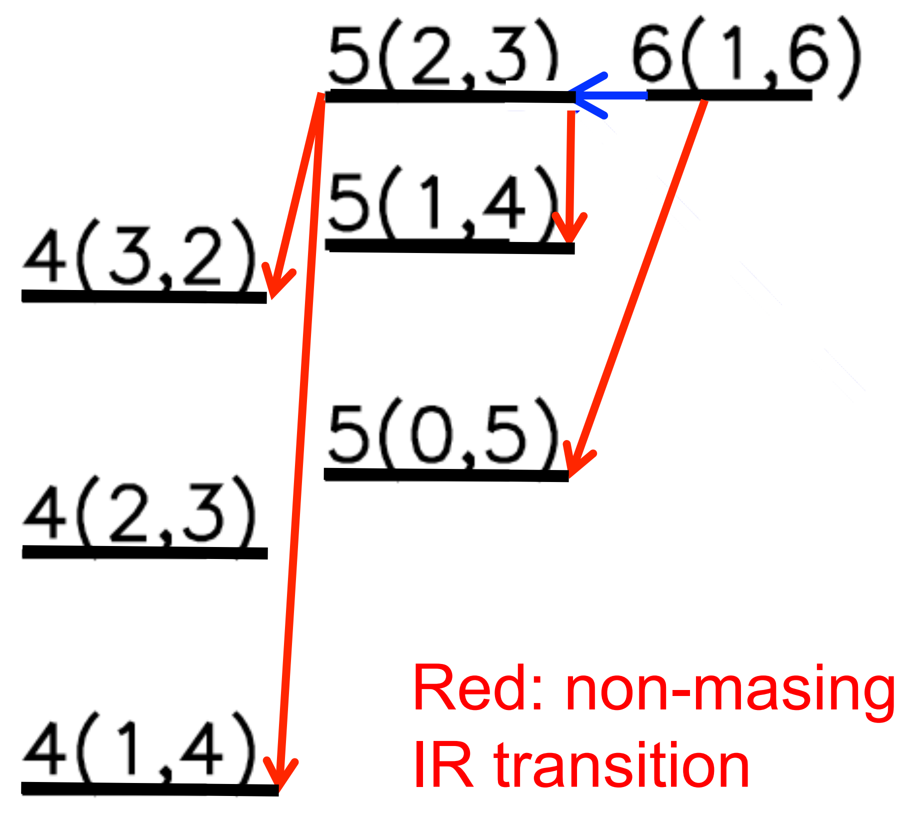
$\Delta J = -1$, $\Delta K_A = +1$

For these pure-rotational transitions within the ground vibrational, a population inversion can arise naturally from the combined effects of collisional excitation and radiative decay

Upper and lower states are populated by collisions at roughly the same rate.

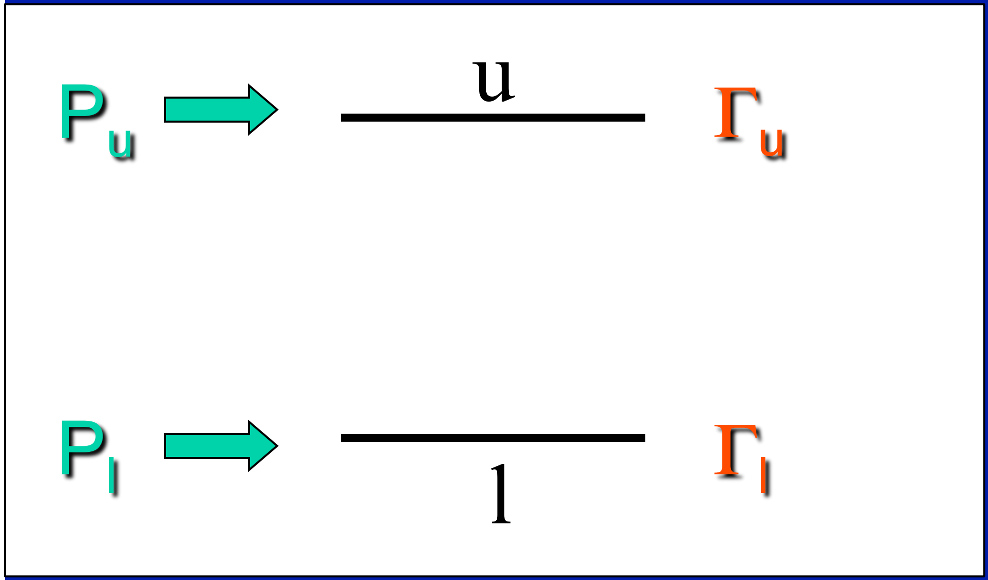
Upper state has fewer IR radiative decay routes

- ➔ longer lifetime
- ➔ larger population



Unsaturated limit ($\Phi \sim 0$)

Pump rates Decay rates



Negative opacity:

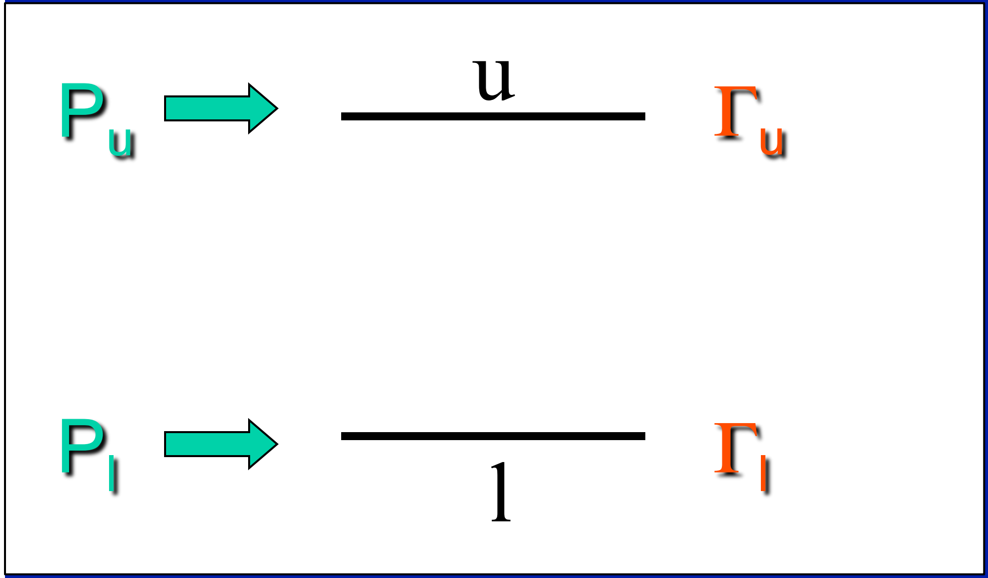
$$-\alpha_\nu^{\text{unsat}} \propto f_u/g_u - f_l/g_l$$

$$\propto P_u/(\Gamma_u g_u) - P_l/(\Gamma_l g_l)$$

Unsaturated limit ($\Phi \sim 0$)

Pump rates

Decay rates

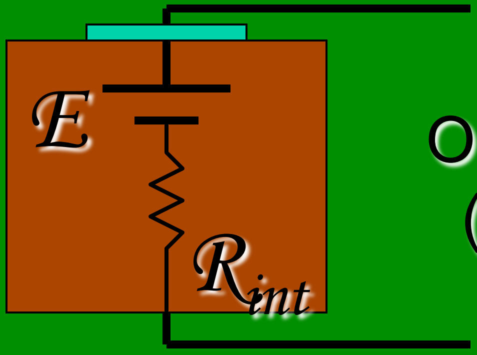


Negative opacity:

$$-\alpha_\nu^{\text{unsat}} \propto f_u/g_u - f_l/g_l$$

$$\propto P_u/(\Gamma_u g_u) - P_l/(\Gamma_l g_l)$$

Battery analog



Open circuit
(no load)

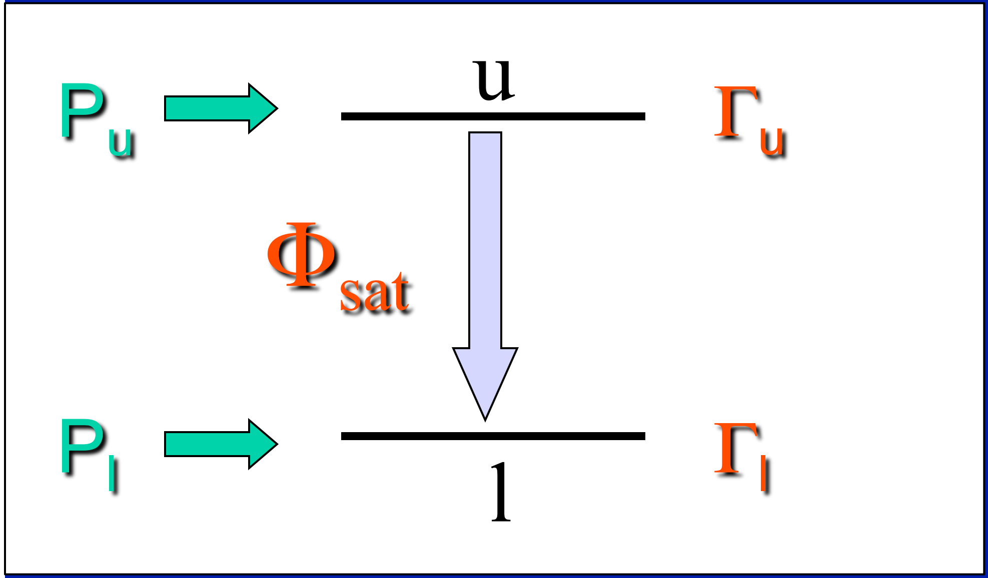
Potential difference:

$$V = \mathcal{E}$$

Saturated limit ($\Phi \sim \Phi_{sat}$)

Pump rates

Decay rates

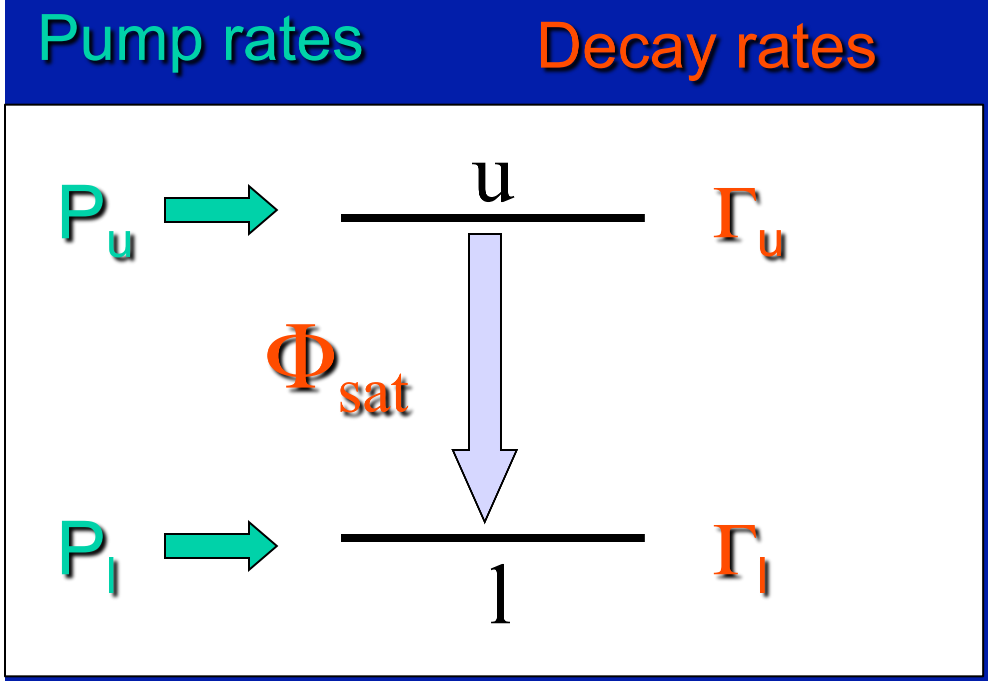


Stimulated emission rate:

$$\Phi_{sat} \propto \frac{[P_u/(\Gamma_u g_u) - P_l/(\Gamma_l g_l)]}{[1/(\Gamma_u g_u) + 1/(\Gamma_l g_l)]}$$

Opacity, $\alpha_\nu \rightarrow 0$

Saturated limit ($\Phi \sim \Phi_{sat}$)

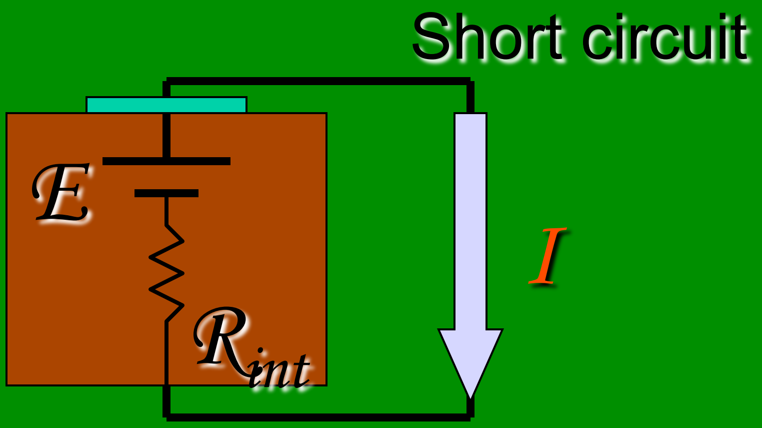


Stimulated emission rate:

$$\Phi_{sat} \propto \frac{[P_u/(\Gamma_u g_u) - P_l/(\Gamma_l g_l)]}{[1/(\Gamma_u g_u) + 1/(\Gamma_l g_l)]}$$

Opacity, α_ν → 0

Battery analog



Current:

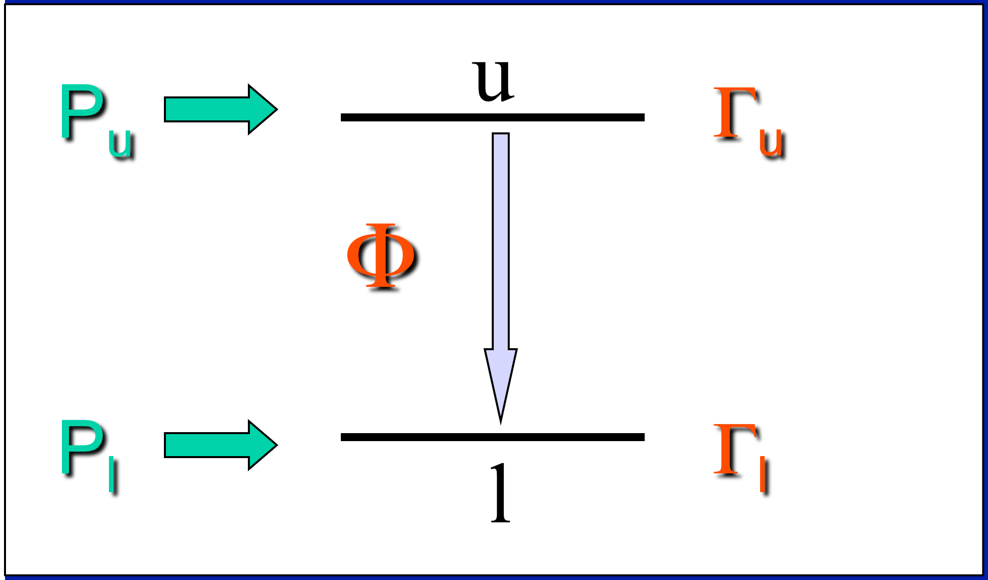
$$I_{max} = \mathcal{E} / \mathcal{R}_{int}$$

Potential difference, V → 0

General case ($\Phi < \Phi_{sat}$)

Pump rates

Decay rates



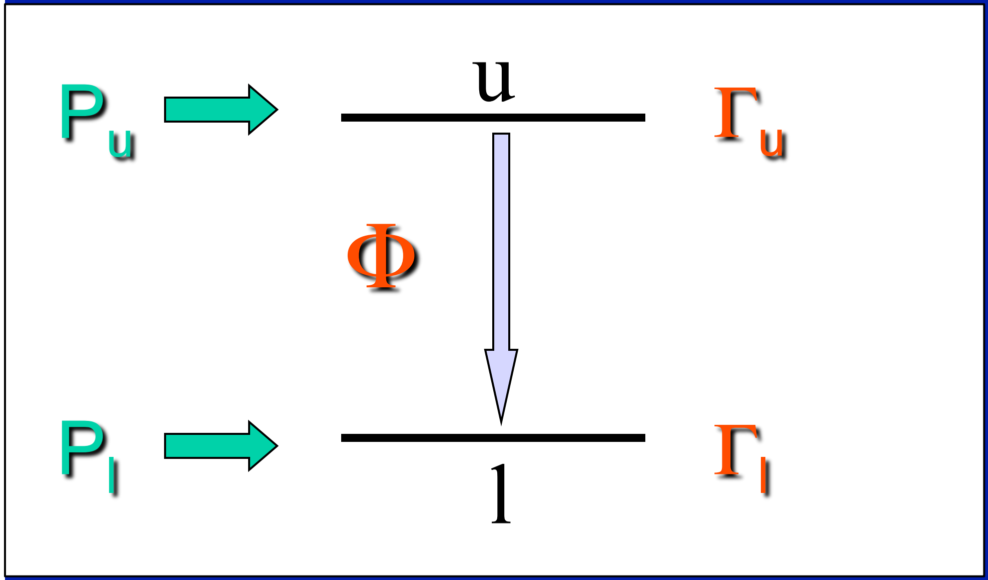
Opacity:

$$\alpha_\nu = \alpha_\nu^{unsat}\,(1 - \Phi/\Phi_{sat})$$

General case ($\Phi < \Phi_{sat}$)

Pump rates

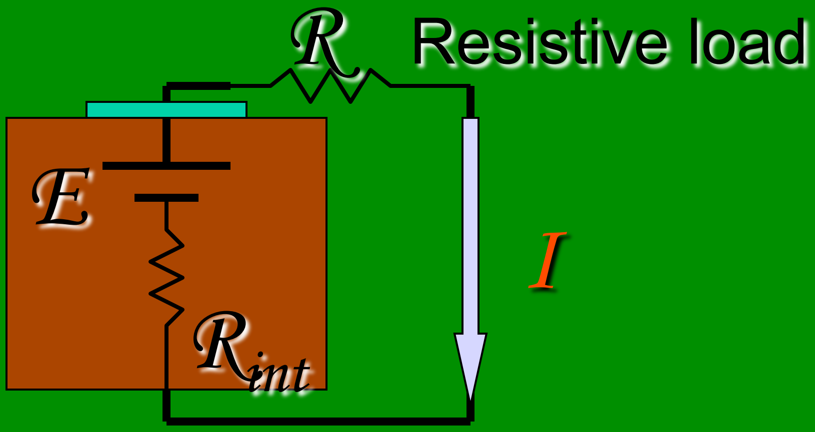
Decay rates



Opacity:

$$\alpha_\nu = \alpha_\nu^{unsat}\,(1 - \Phi/\Phi_{sat})$$

Battery analog

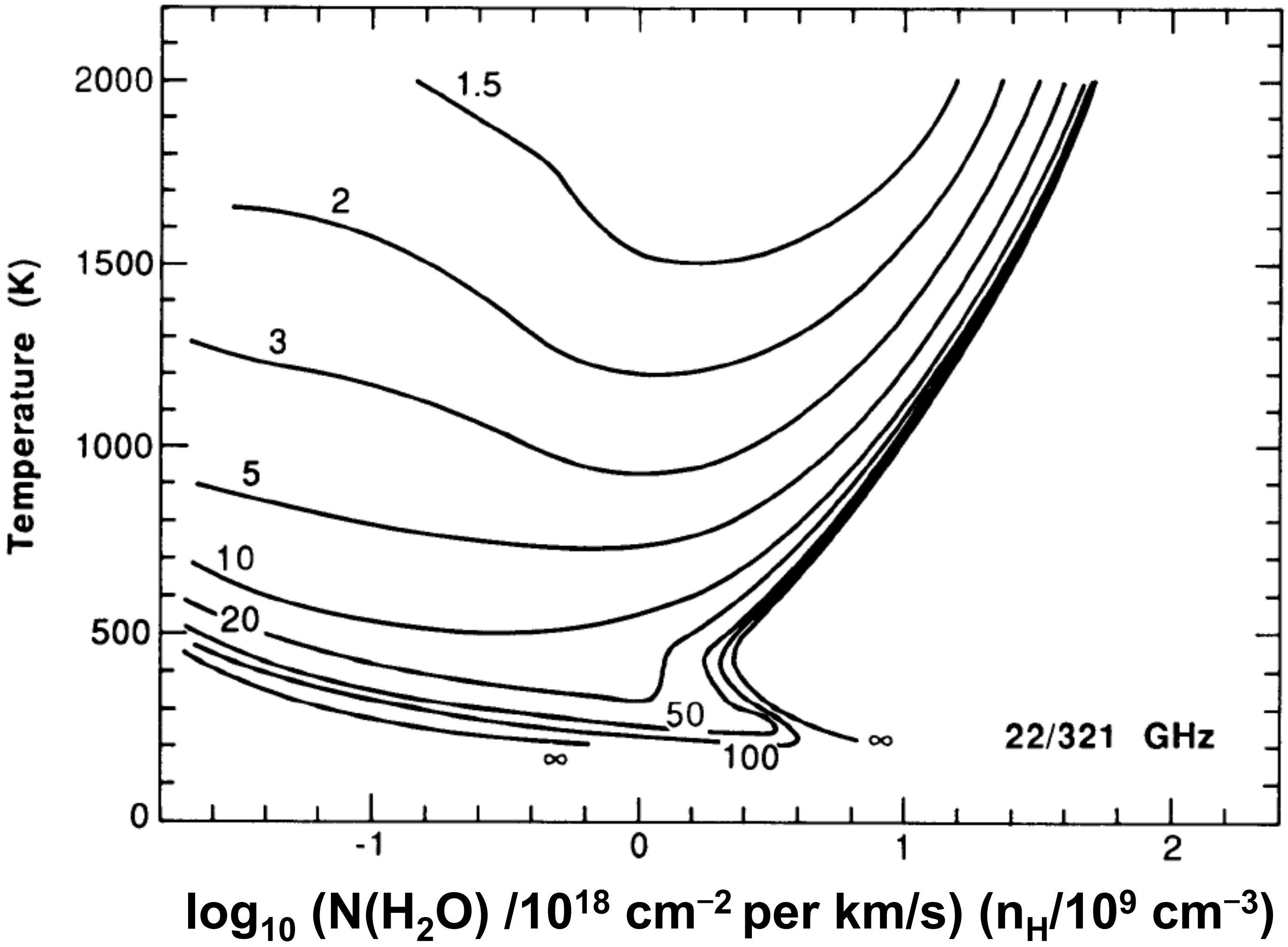


Potential difference:

$$V = \mathcal{E} - I\mathcal{R}_{int}$$
$$= \mathcal{E}\,(1 - I/I_{max})$$

Line ratios probe physical conditions

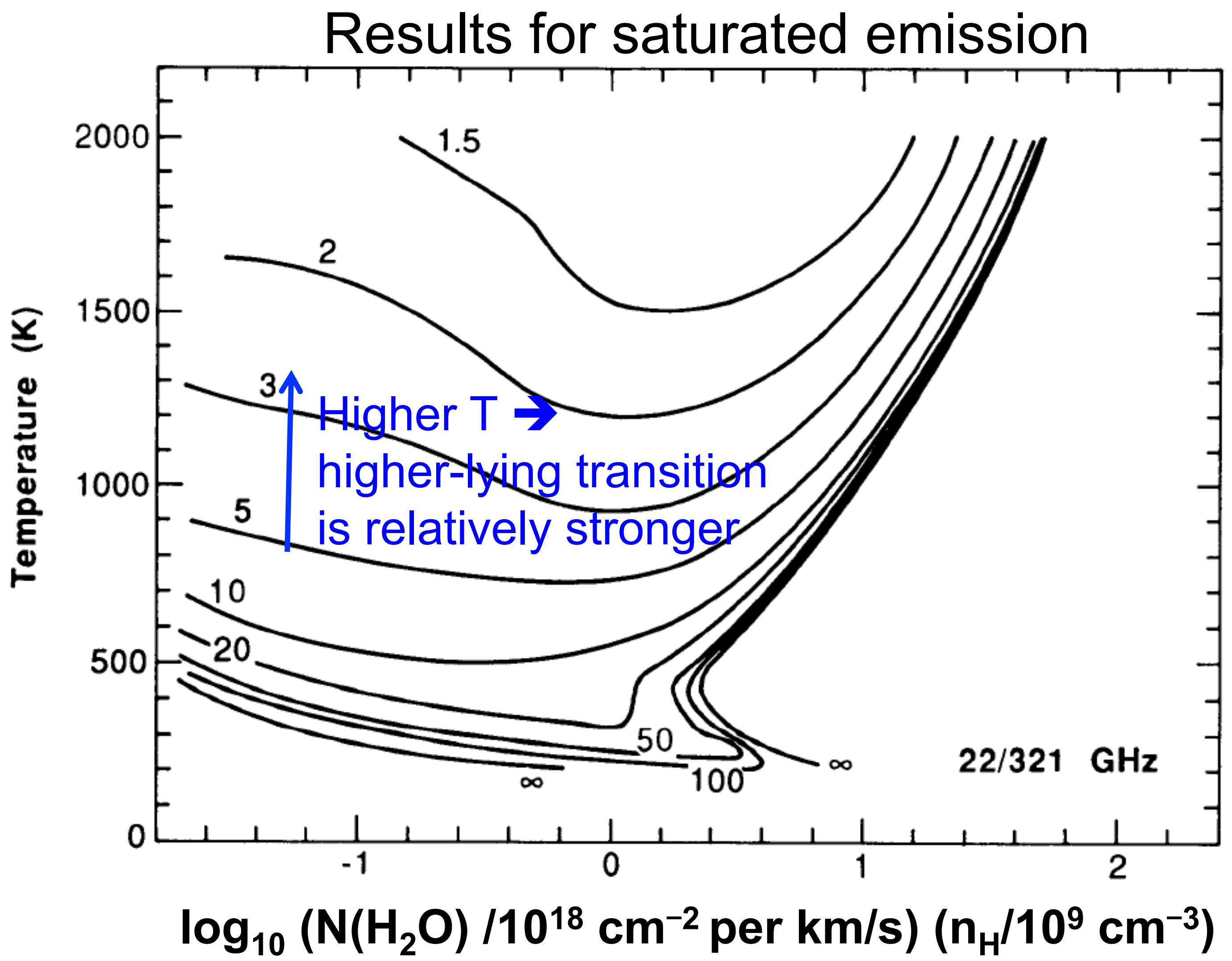
Results for saturated emission



Neufeld and Melnick 1990

Line ratios probe physical conditions

Neufeld and Melnick 1990



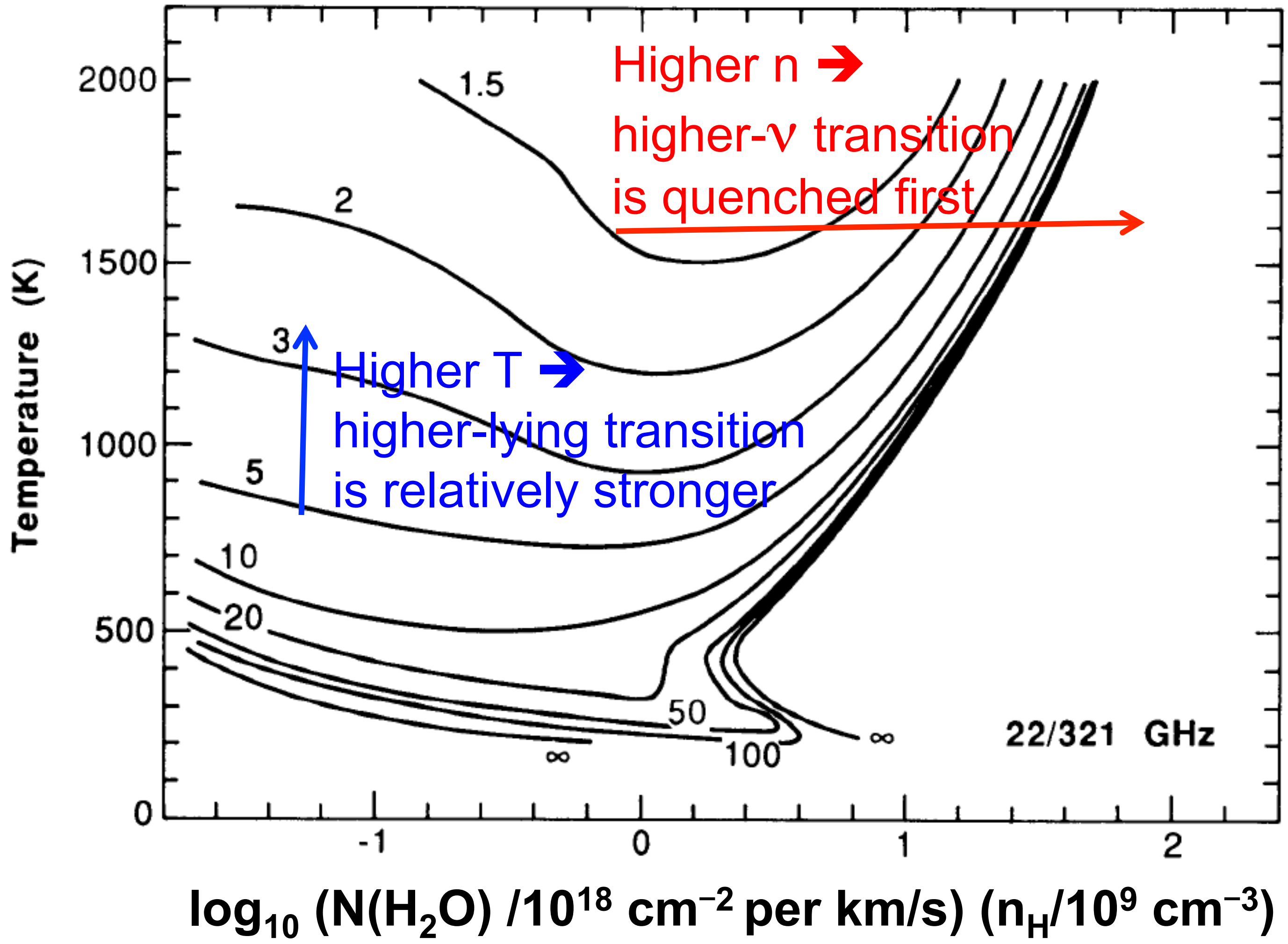
Results for saturated emission

Higher T → higher-lying transition is relatively stronger

Line ratios probe physical conditions

Neufeld and Melnick 1990

Results for saturated emission



$\log_{10}$ (N(H_2O) /10^{18} cm^{-2} per km/s) (n_H/10^9 cm^{-3})

Higher n ➔
higher-ν transition
is quenched first

Higher T ➔
higher-lying transition
is relatively stronger

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SOFIA/GREAT observations of O-rich evolved stars in Cycle 4

Search for two predicted maser transitions at THz frequencies

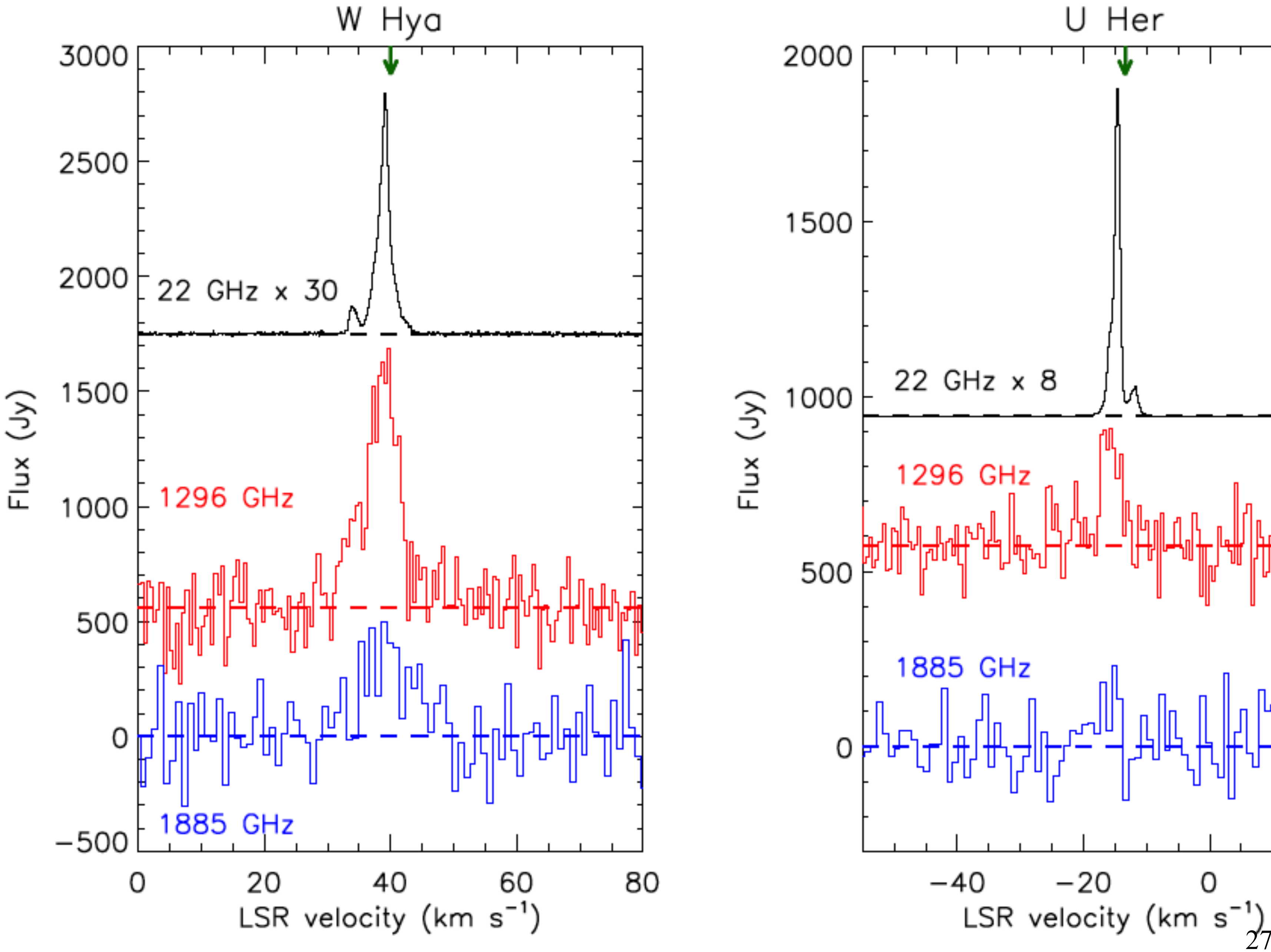
$8_{27} – 7_{34}$	1296 GHz (Band L1)
$8_{45} – 7_{52}$	1885 GHz (Band L2)

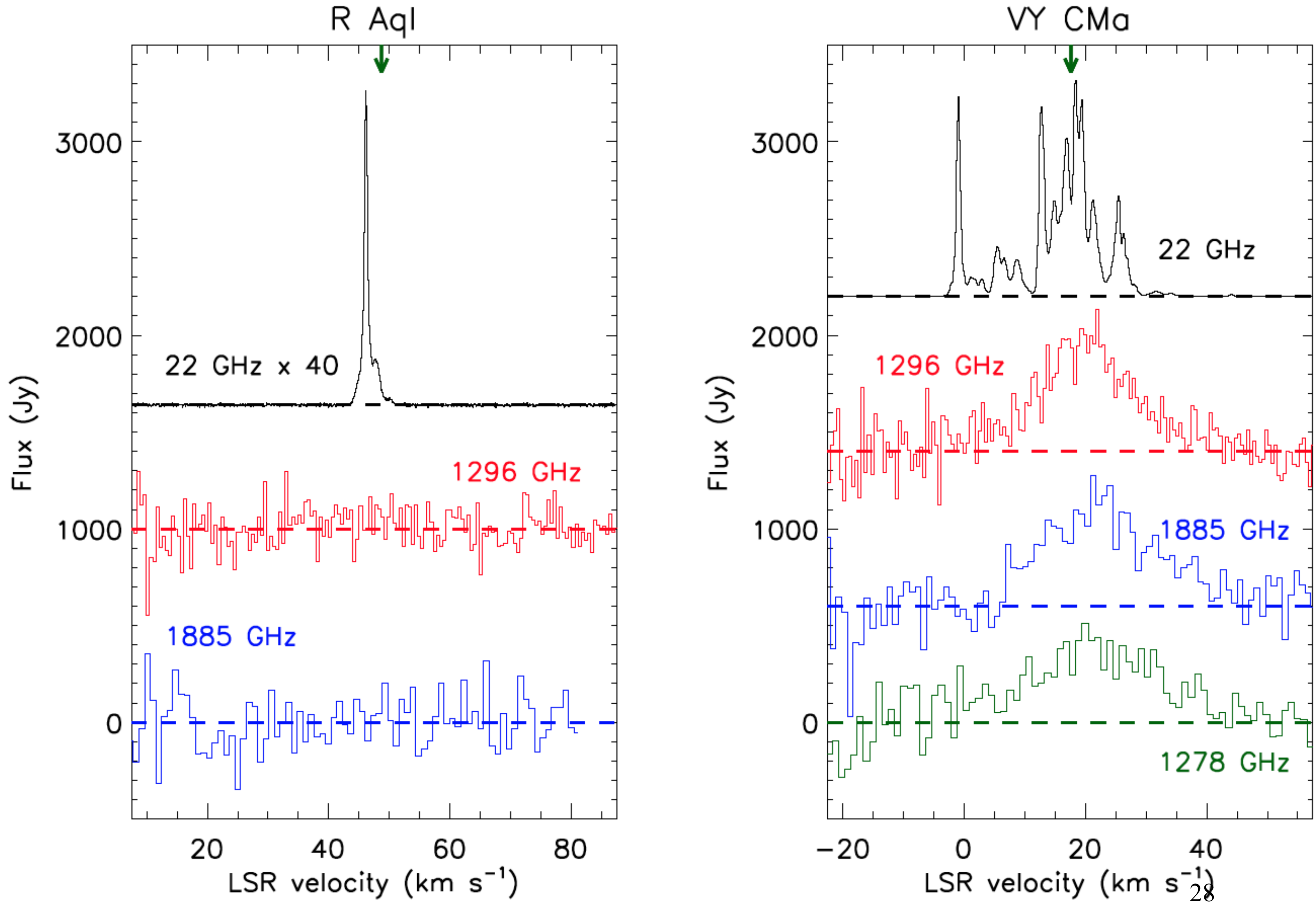
toward 4 oxygen-rich evolved stars with water masers in the 300 – 500 GHz range (and at 22 GHz)

W Hya, U Her, R Aql, VY CMa

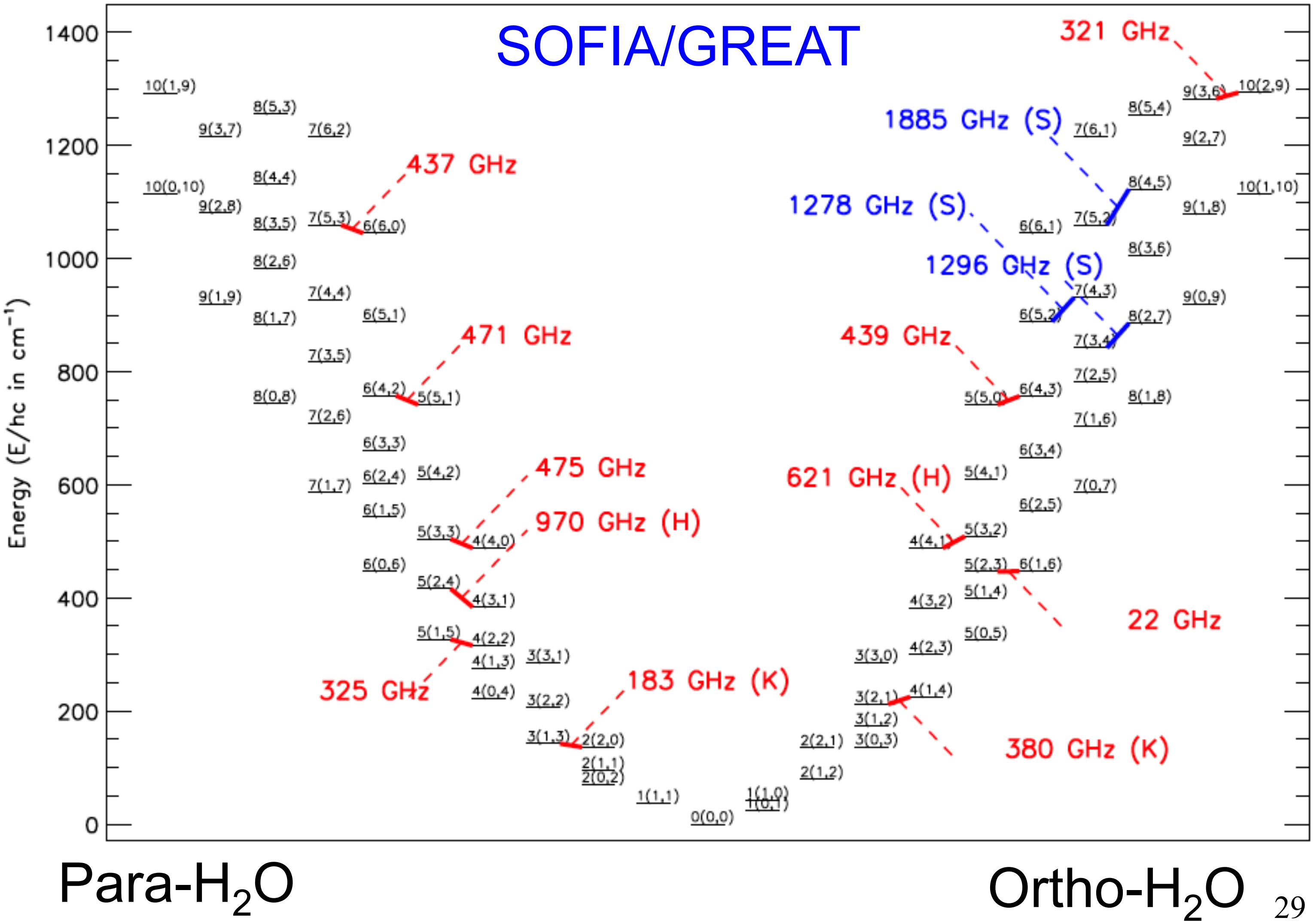
Near-simultaneous observations of 22 GHz transition from Effelsberg 100 m

Goal: test models for maser excitation and constrain physical conditions in the envelope


W Hya
U Her
Flux (Jy)
3000
2500
2000
1500
1000
500
0
−500
22 GHz x 30
1296 GHz
1885 GHz
0
20
40
60
80
LSR velocity (km s^{-1})
2000
1500
1000
500
0
22 GHz x 8
1296 GHz
1885 GHz
−40
−20
0
20
LSR velocity (km s^{-1})


R Aql
VY CMa
3000
2000
1000
0
Flux (Jy)
22 GHz x 40
1296 GHz
1885 GHz
22 GHz
1278 GHz
20
40
60
80
−20
LSR velocity (km s^{-1})

Water maser transitions observed (as of 2017)

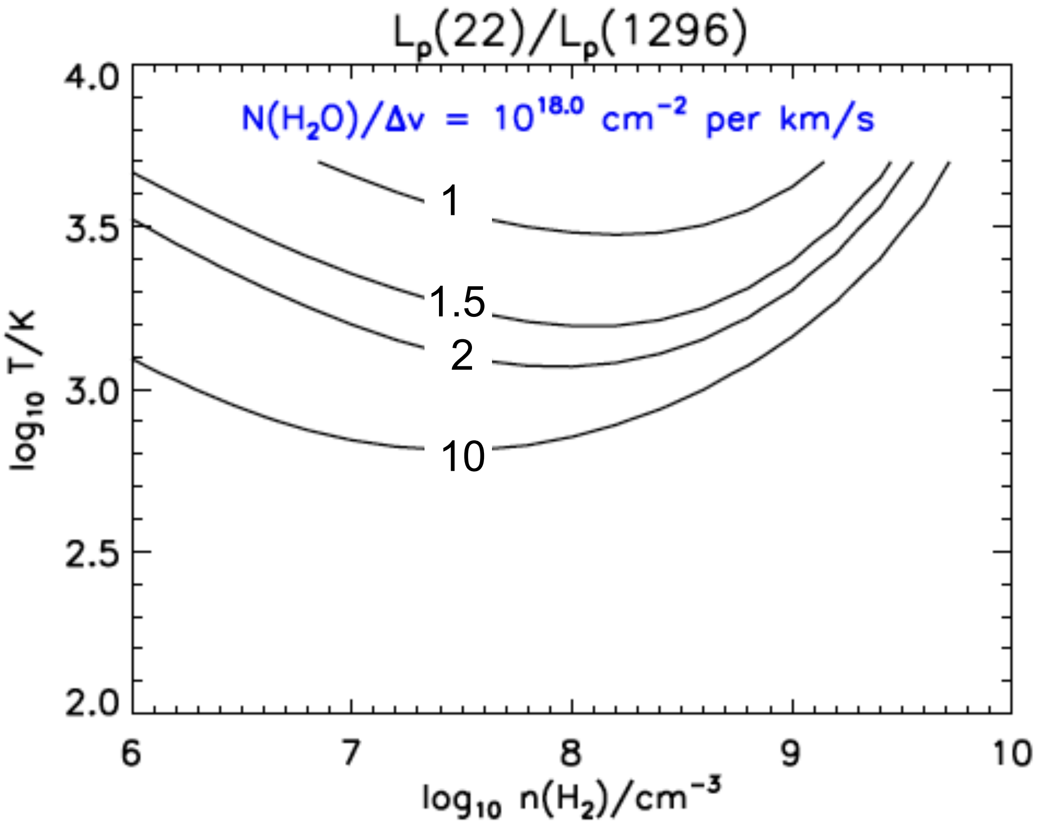


Observed line ratios

22 GHz / 1296 GHz photon luminosity ratios in W Hya and U Her (0.012 and 0.14) are much smaller than would be predicted for saturated masers

➔ confirms that 22 GHz transition is unsaturated (Menten & Melnick 1991) which would also explain the narrower line width

Results for saturated emission

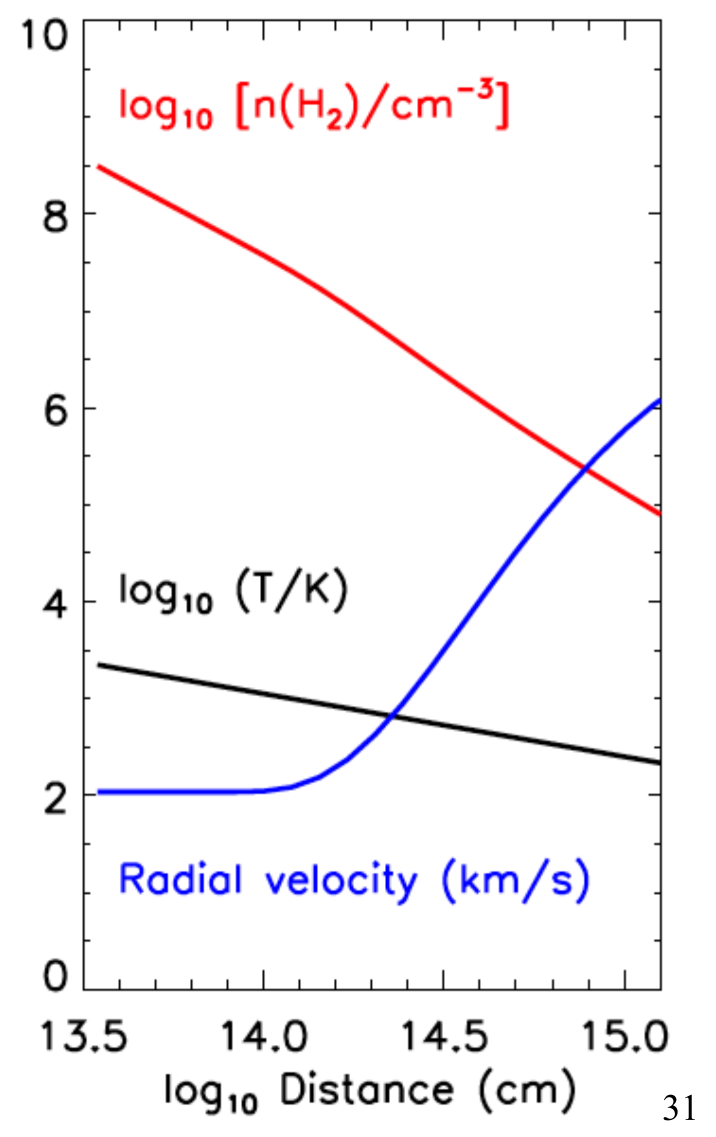


Preliminary model for W Hya

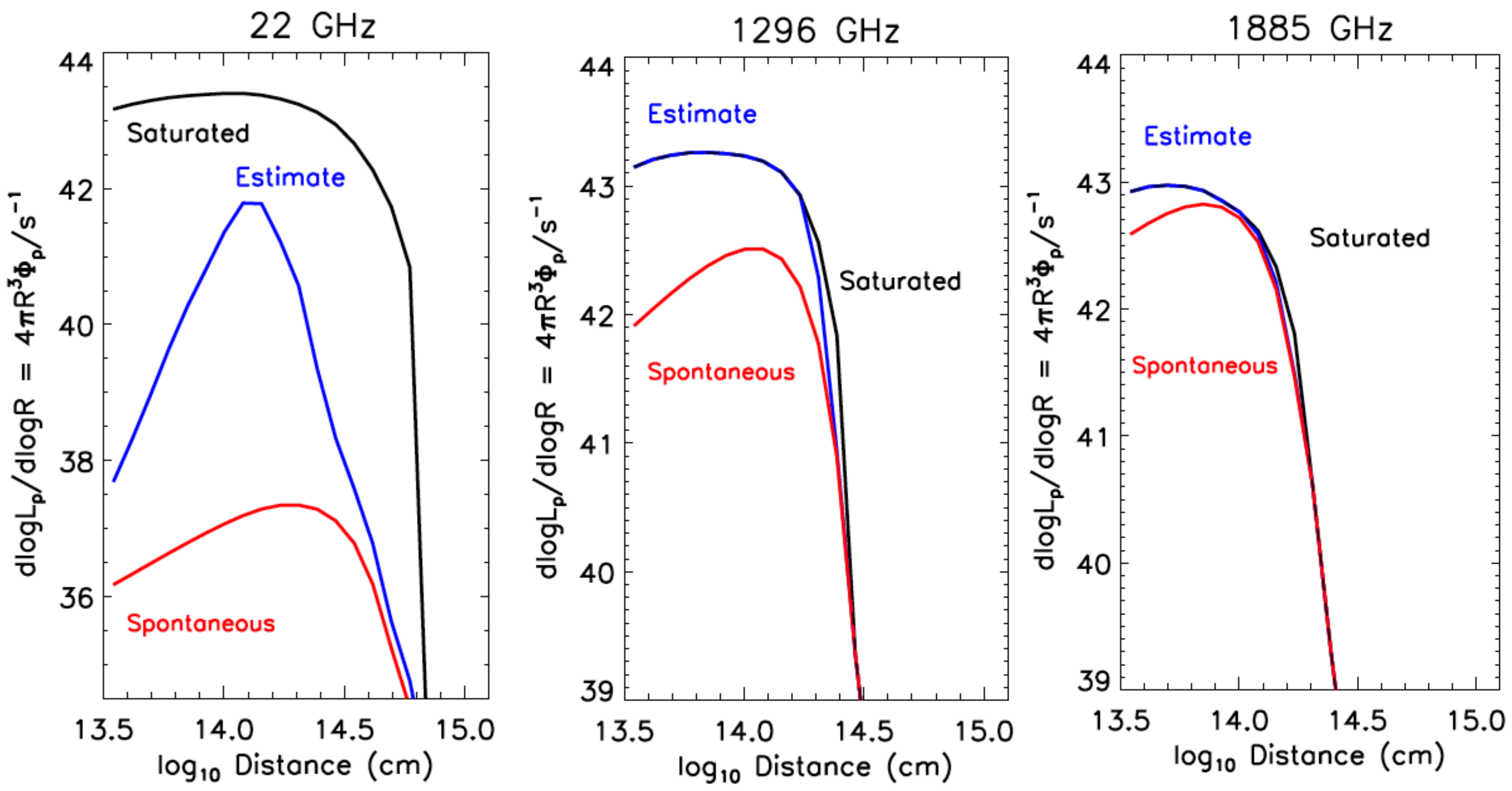
Based on velocity and temperature profiles from Khouri et al. (2014)

$\dot{M} = 7 \times 10^{-8}\ M_{\odot}\mathrm{yr}^{-1}$

$H_2O/H_2 = 4.1 \times 10^{-4}$

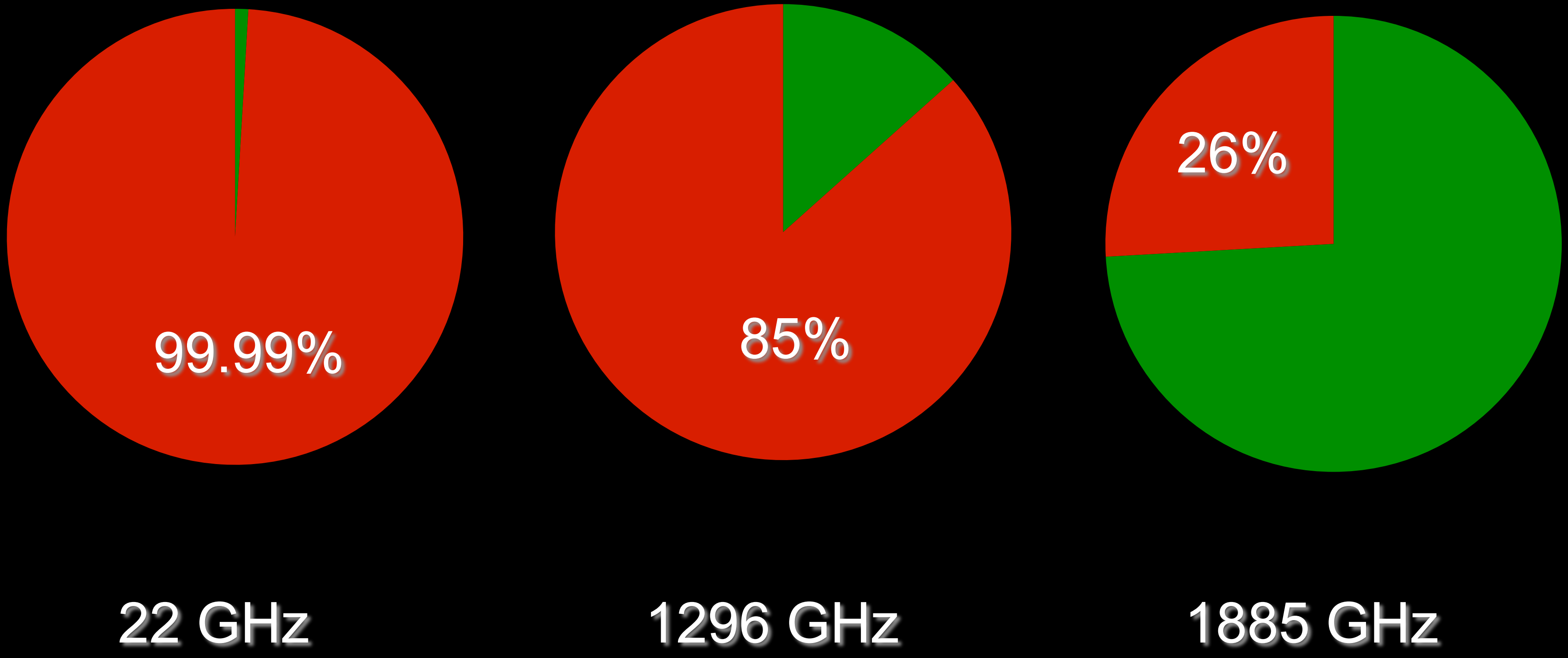


Preliminary model for W Hya



Fits 22, 1296 and 1885 GHz line fluxes to within 15%

Fractional contribution of stimulated emission, according to the preliminary model of W Hya



Summary and future directions

- We have detected 3 predicted maser transitions of water vapor at frequencies > 1 THz from the circumstellar envelopes of O-rich evolved stars
- The intensity of the 1296 GHz transition, in particular, suggests maser amplification. It may be the highest frequency transition with a luminosity dominated by stimulated emission.
- The relative intensity of the 22 GHz transition confirms it to be unsaturated in these sources: that behavior is consistent with preliminary models for W Hya
- Further modeling will include radiative pumping via rotational and vibrational transitions of water
- An approved Cycle 5 program will target 8 additional CSEs with a range of mass-loss rates