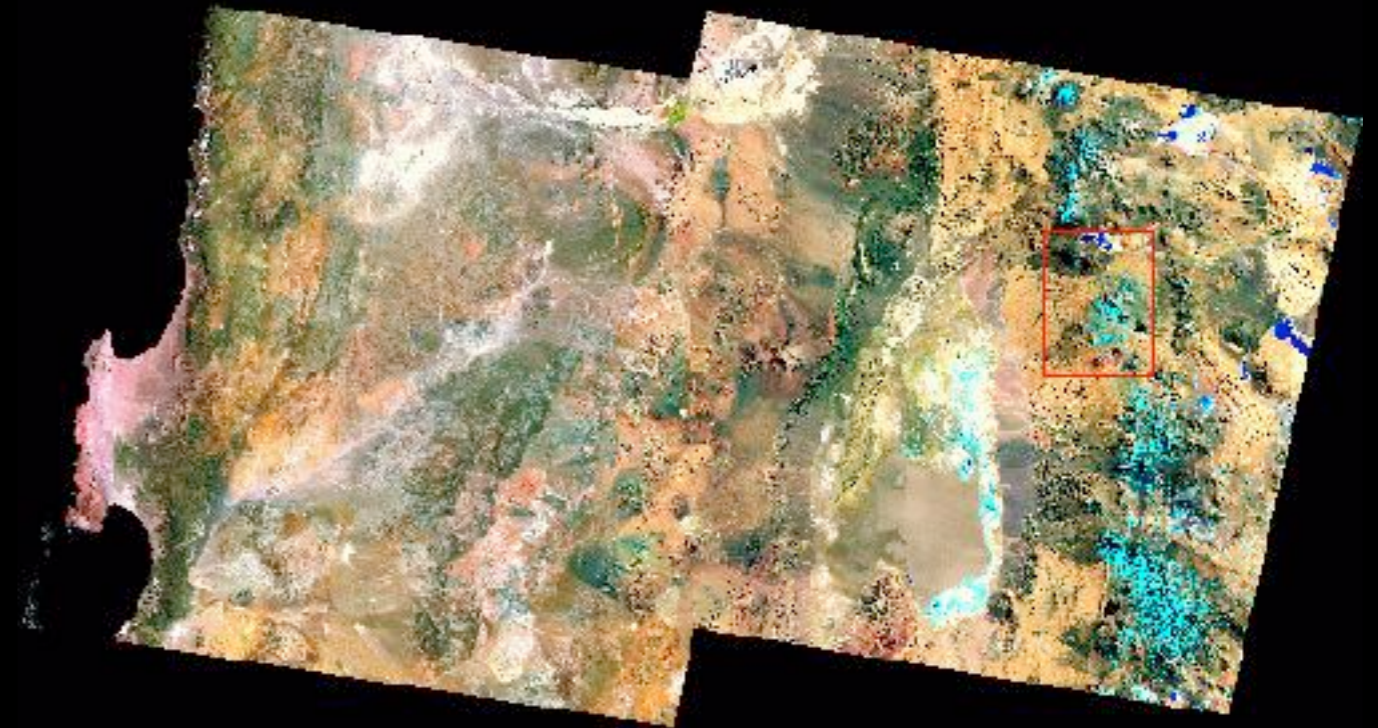


# Extragalactic Molecular Spectroscopy with C<sup>n</sup>CAT

Jeremy Darling  
Colorado



# Outline

The CCAT Niche

Beyond Butterfly  
Collecting

Spectral Surveys

Warm Gas

Cold Gas

Nonthermal Gas





# The CCAT Niche

- High(er) Frequency
- Instantaneous Coverage
- Field of View
- Transparency
- No Decorrelation



# Molecular Spectroscopy of Starburst Galaxies

## Gas Physics

- density
- temperature

## Timing

## Resolution

## Chemistry

## Abundances

- galaxy-scale metallicity
- IMFs

## Isotopic Abundances

## Deuterium

- enhancement/depletion/astration





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# Galaxy-Scale Measures of Gas Density

What is the “density” of a galaxy?

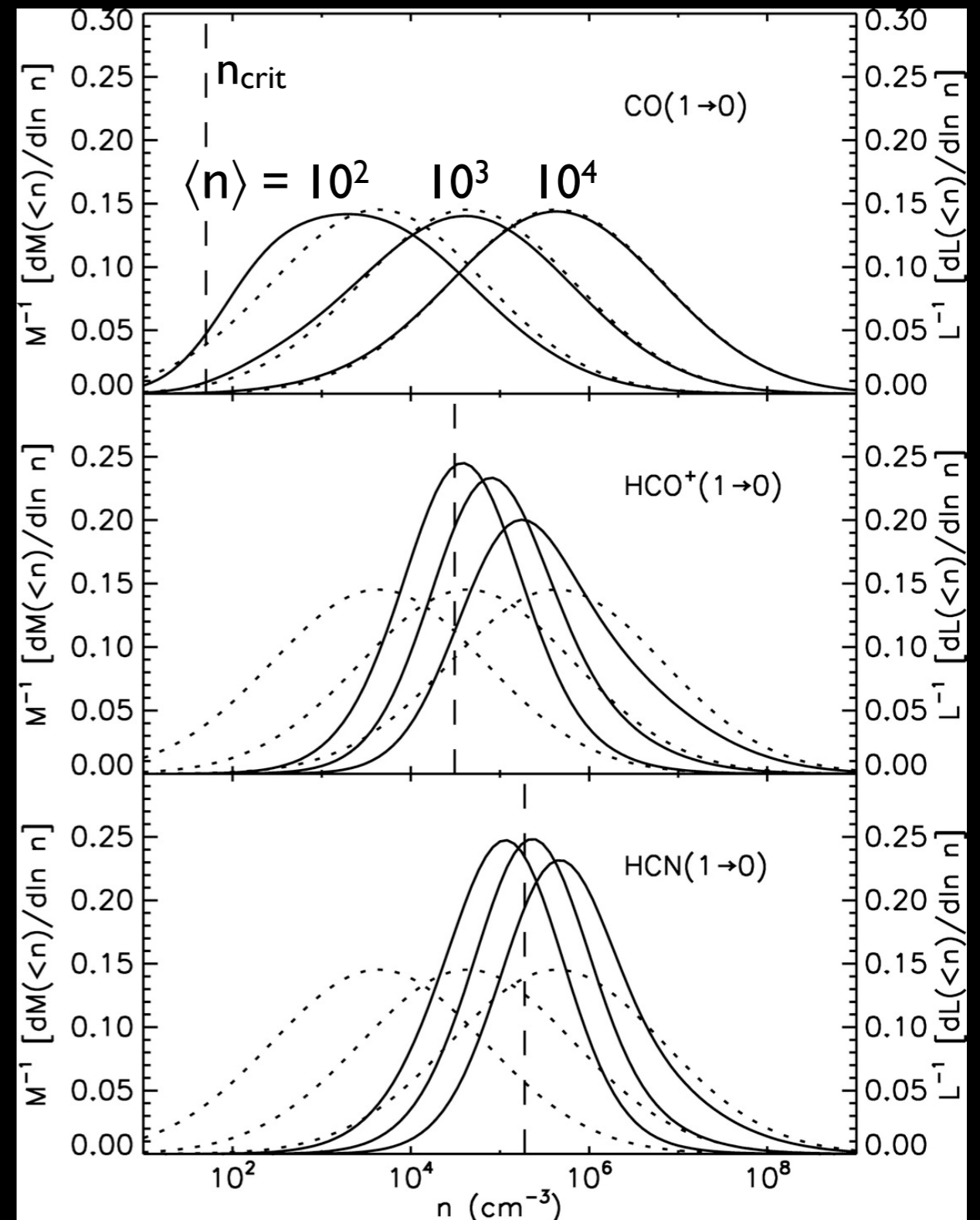
$n_{\text{crit}}$  is a poor guide to density, even for the “dense gas tracer” HCN

Different species *do* sample different density regimes (dipole moment, chemistry, depletion, etc)

The right probe can select regions of interest in an unresolved observation.

Supporting theory and models are key.

Krumholz & Thompson (2007)



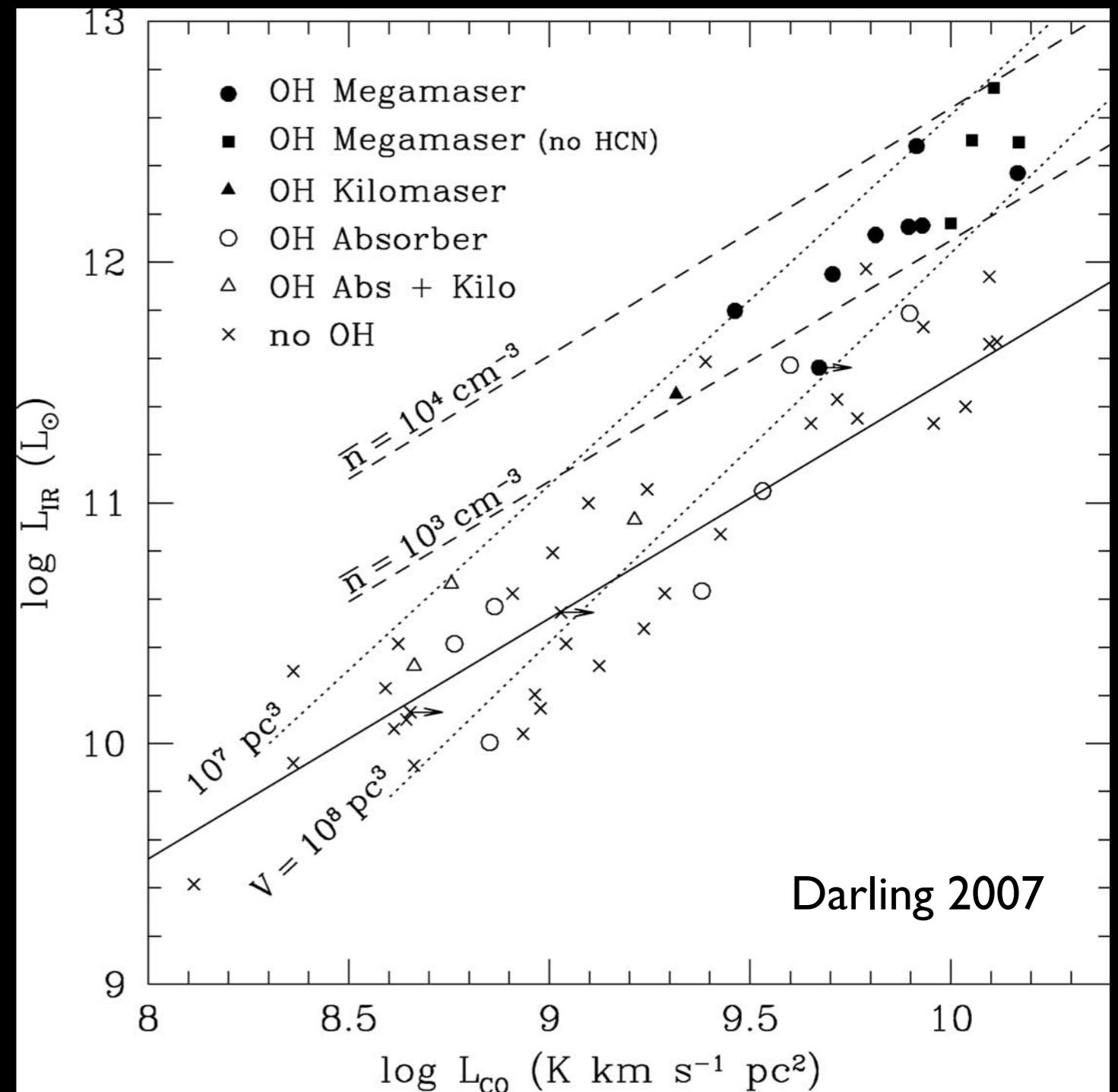
# Galaxy-Scale Measures of Gas Density

What is the “density” of a galaxy?

Density regimes are means

Models are required to assess volumes, densities

Necessary for various high  $\mu$  molecular probes or IR atomic fine structure lines...



# Galaxy-Scale Measures of Gas Density

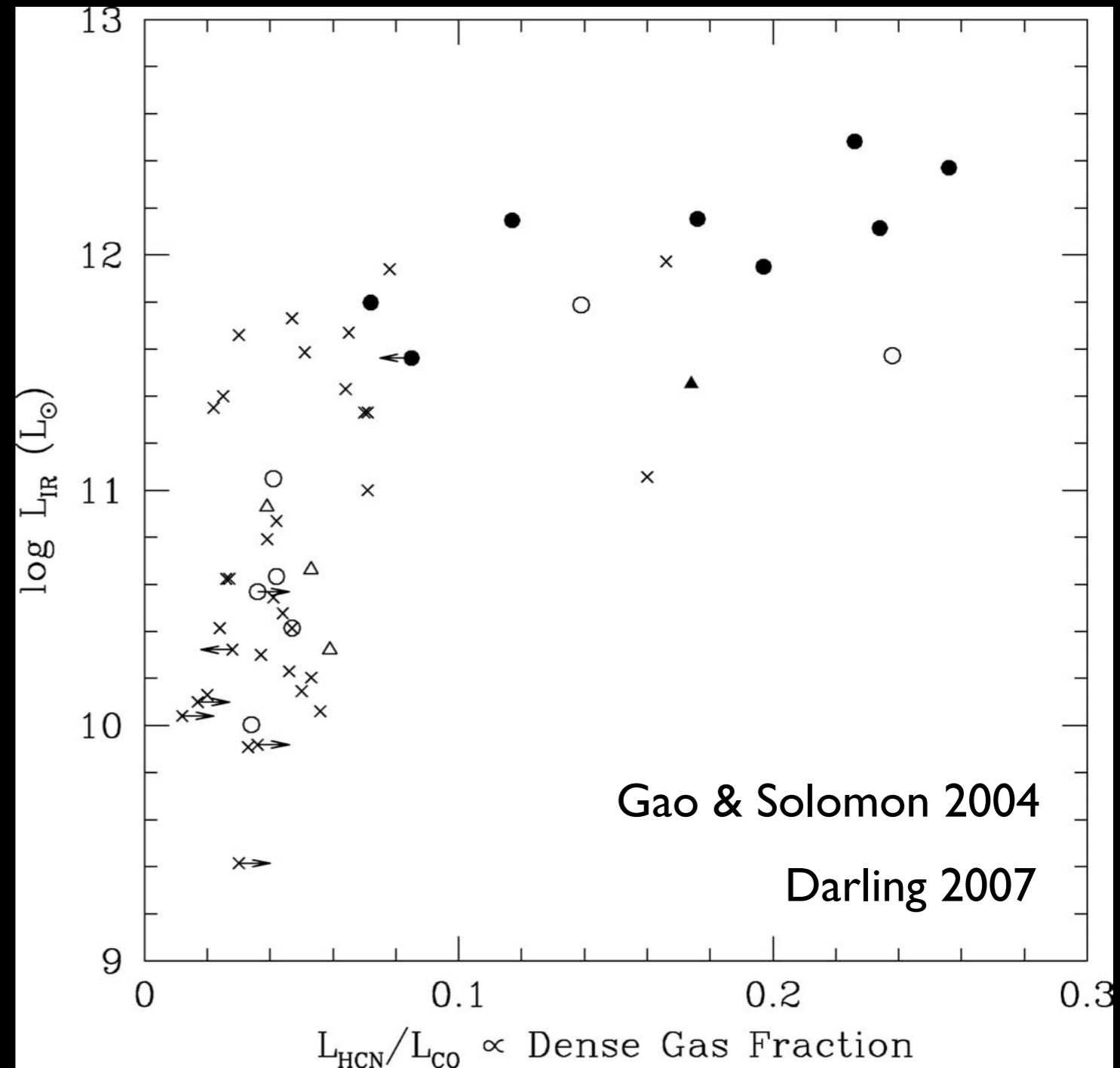
What is the “density” of a galaxy?

Density regimes are means

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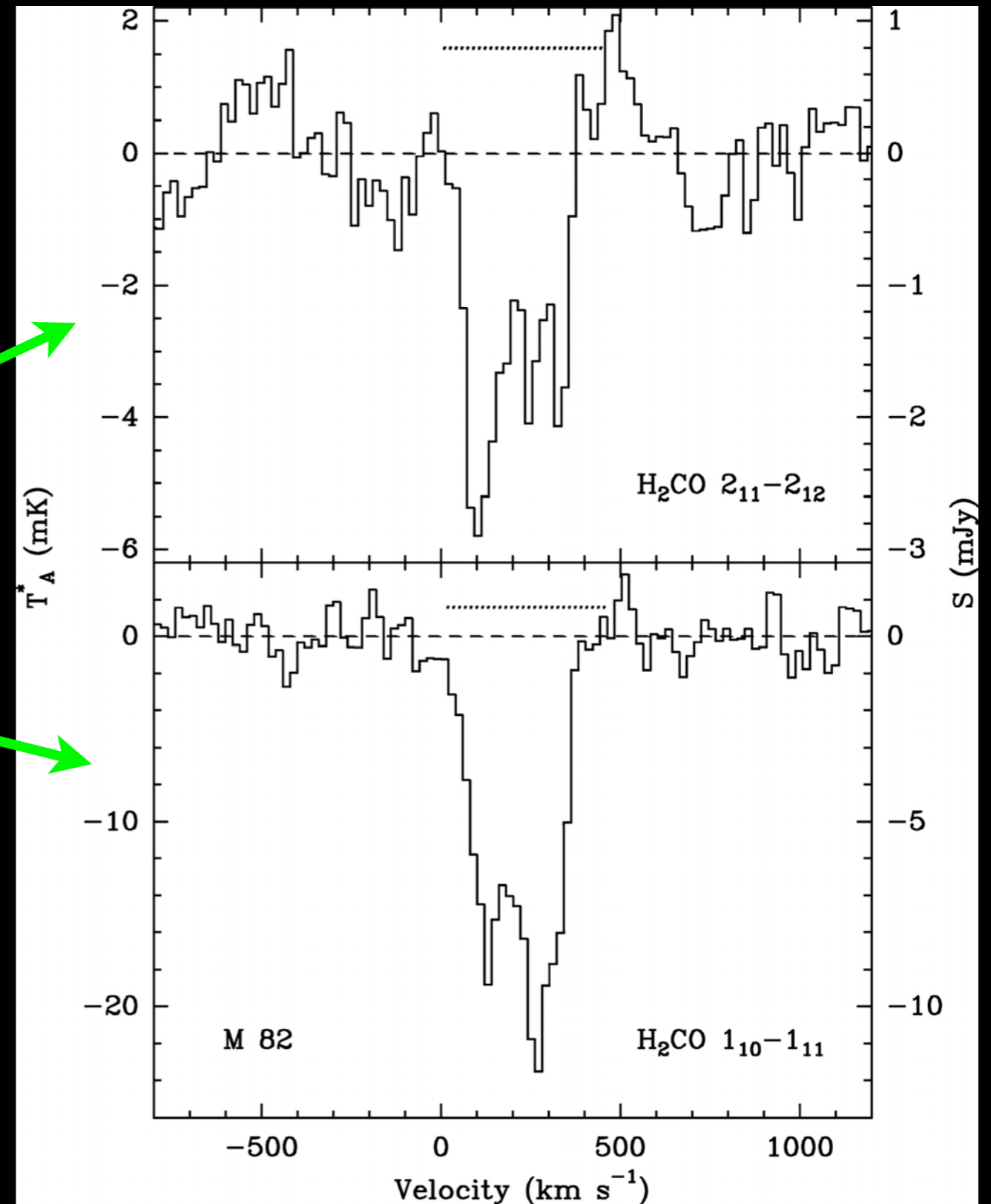
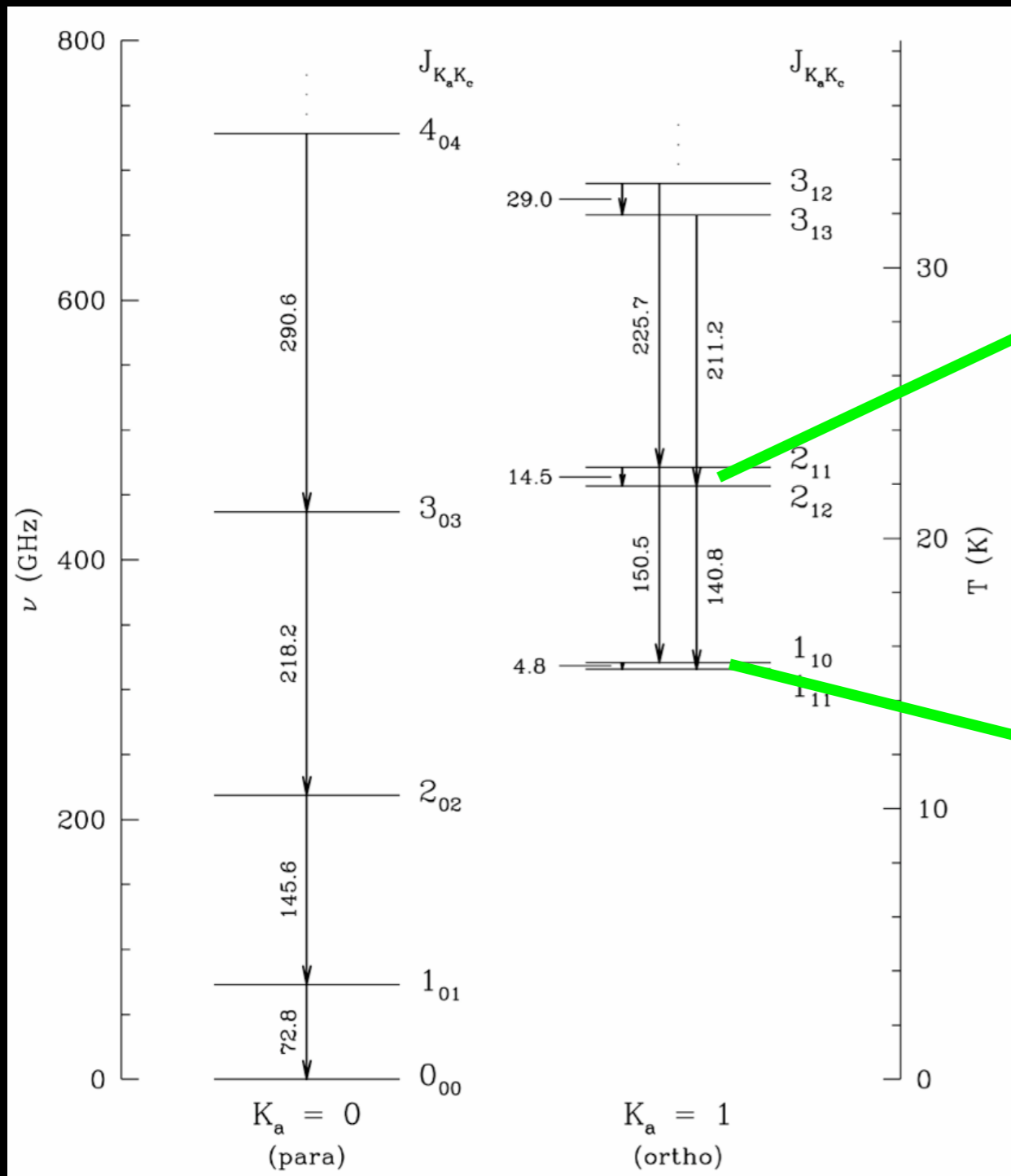
Necessary for various high  $\mu$  molecular probes or IR atomic fine structure lines...

Line ratios can discriminate

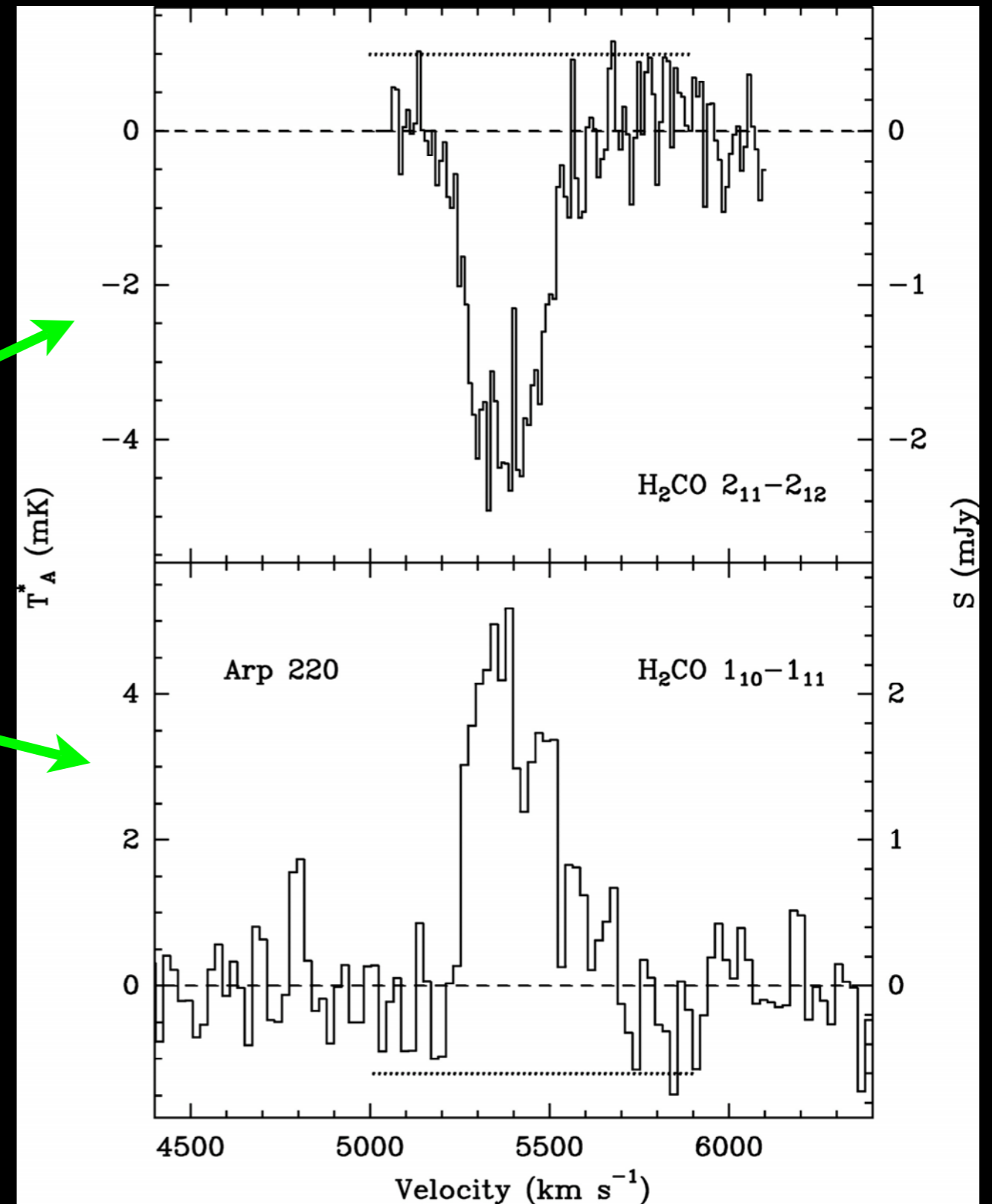
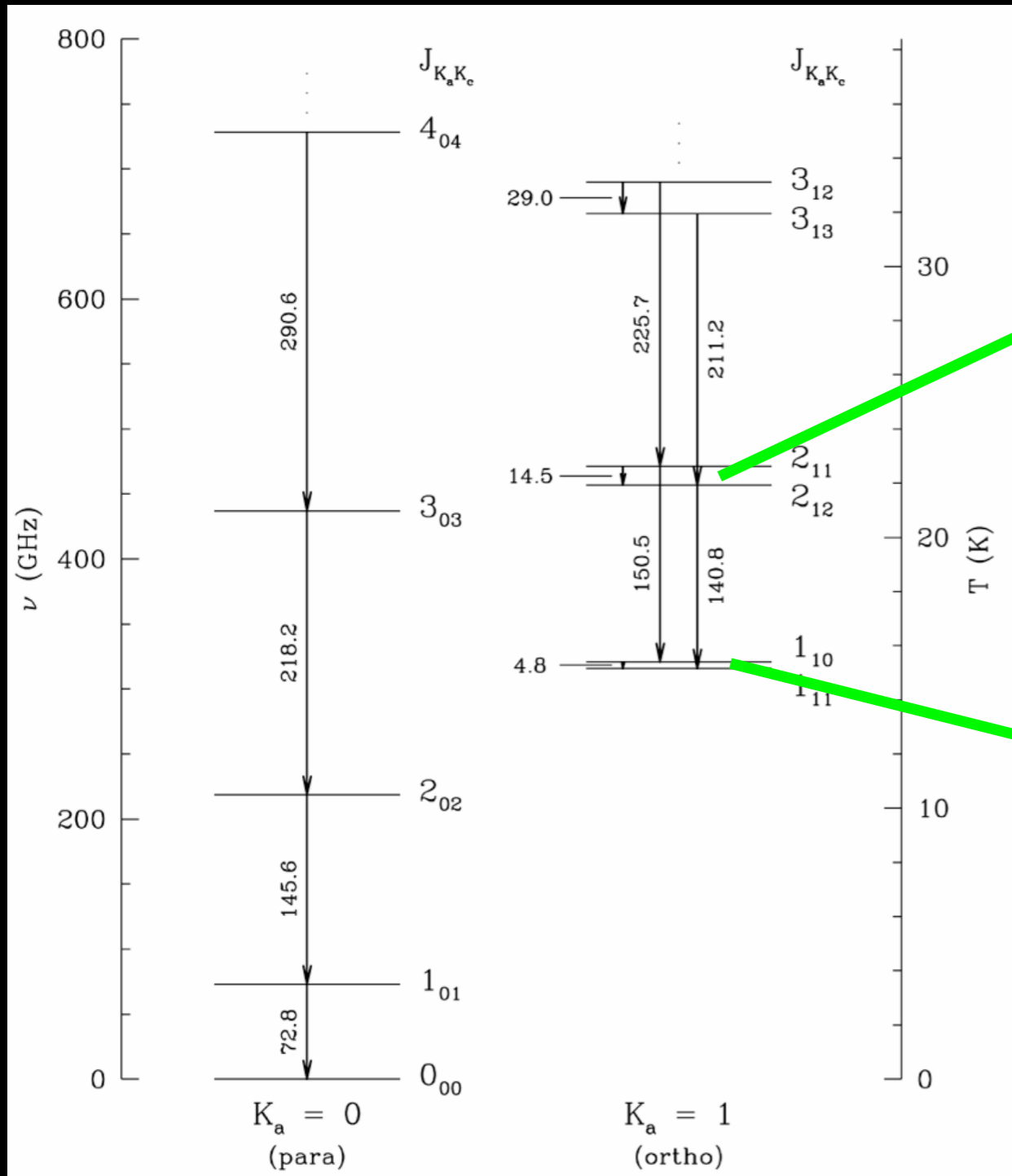




# Density Thresholds (true $n_{\text{crit}}$ )



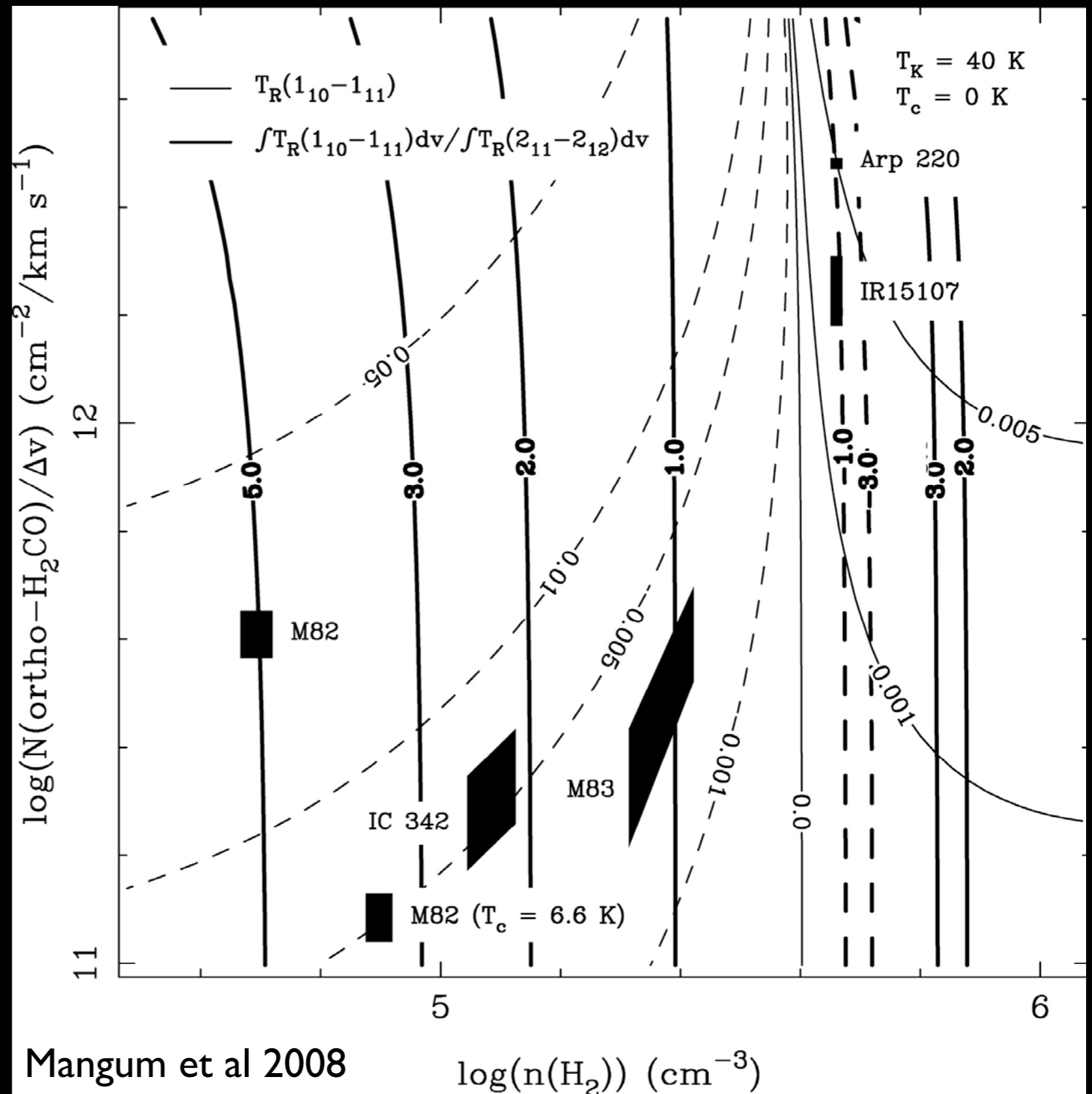
# Density Thresholds (true $n_{\text{crit}}$ )



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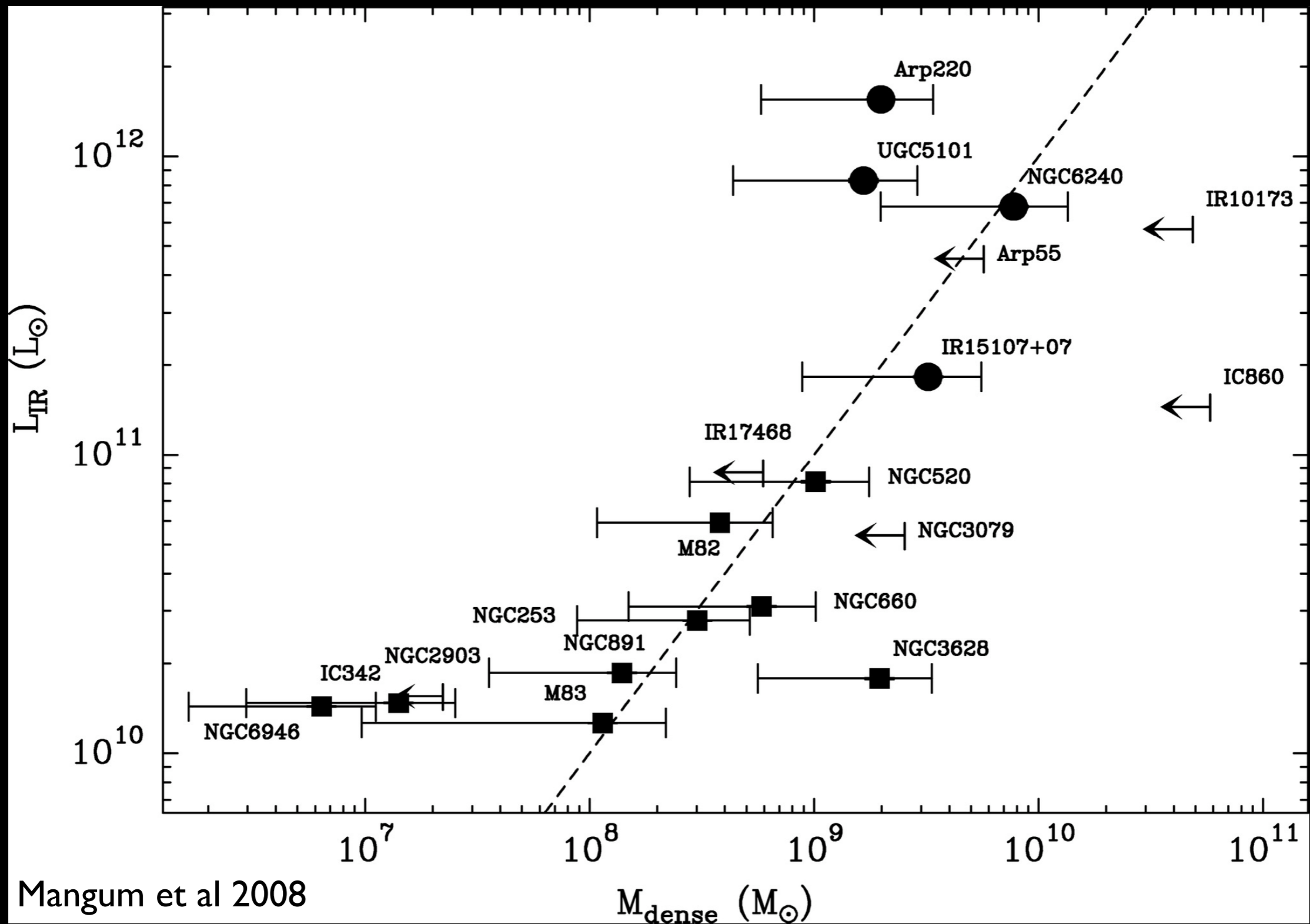
What is the “density” of a galaxy?

Density regimes measured by  $\text{H}_2\text{CO}$  are *in-situ!* (not means)





# Density Thresholds (true $n_{\text{crit}}$ )



Mangum et al 2008

# Spectral Surveys of Starburst Galaxies

NGC 253: 1 & 2 mm surveys

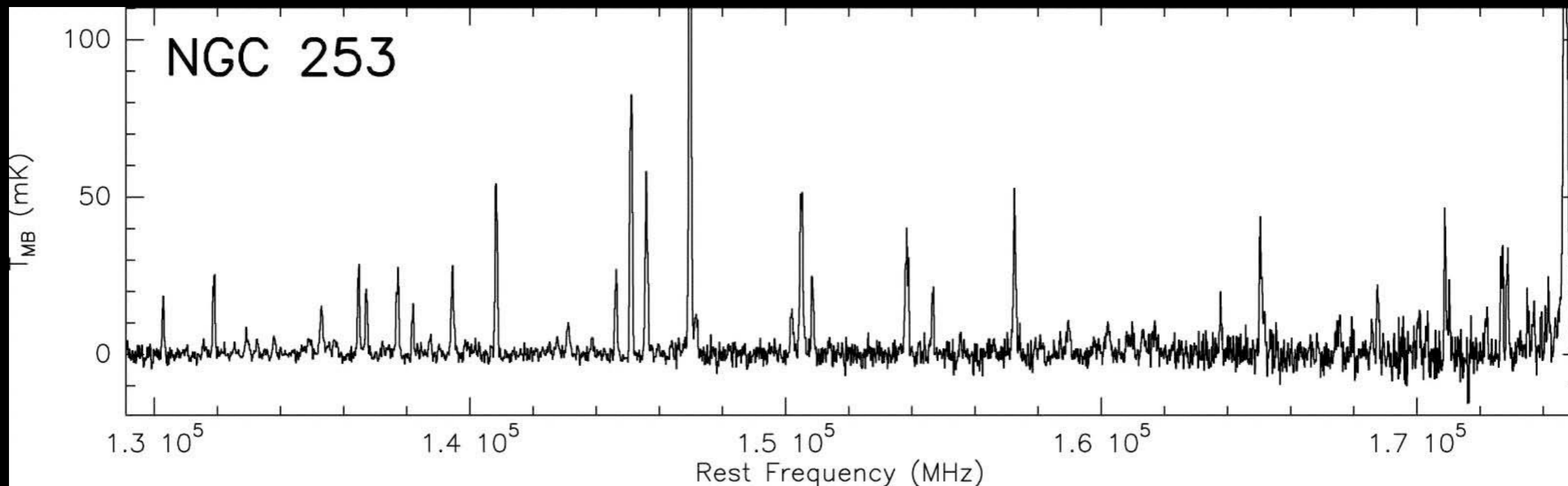
(Martin & Mauersberger 2006)

(Earle & Glenn)

Arp 220: 1-10 GHz @ Arecibo

(Momjian et al 2008)

# Spectral Surveys of Starburst Galaxies




## NGC 253

- 2 mm spectral scan
- 25 species (8 first-time exgal detections)
- Tentative detection of DNC and  $\text{N}_2\text{D}^+$

(Martin & Mauersberger 2006)



# Spectral Surveys of Starburst Galaxies



**NGC 253** \* Earle & Glenn \*

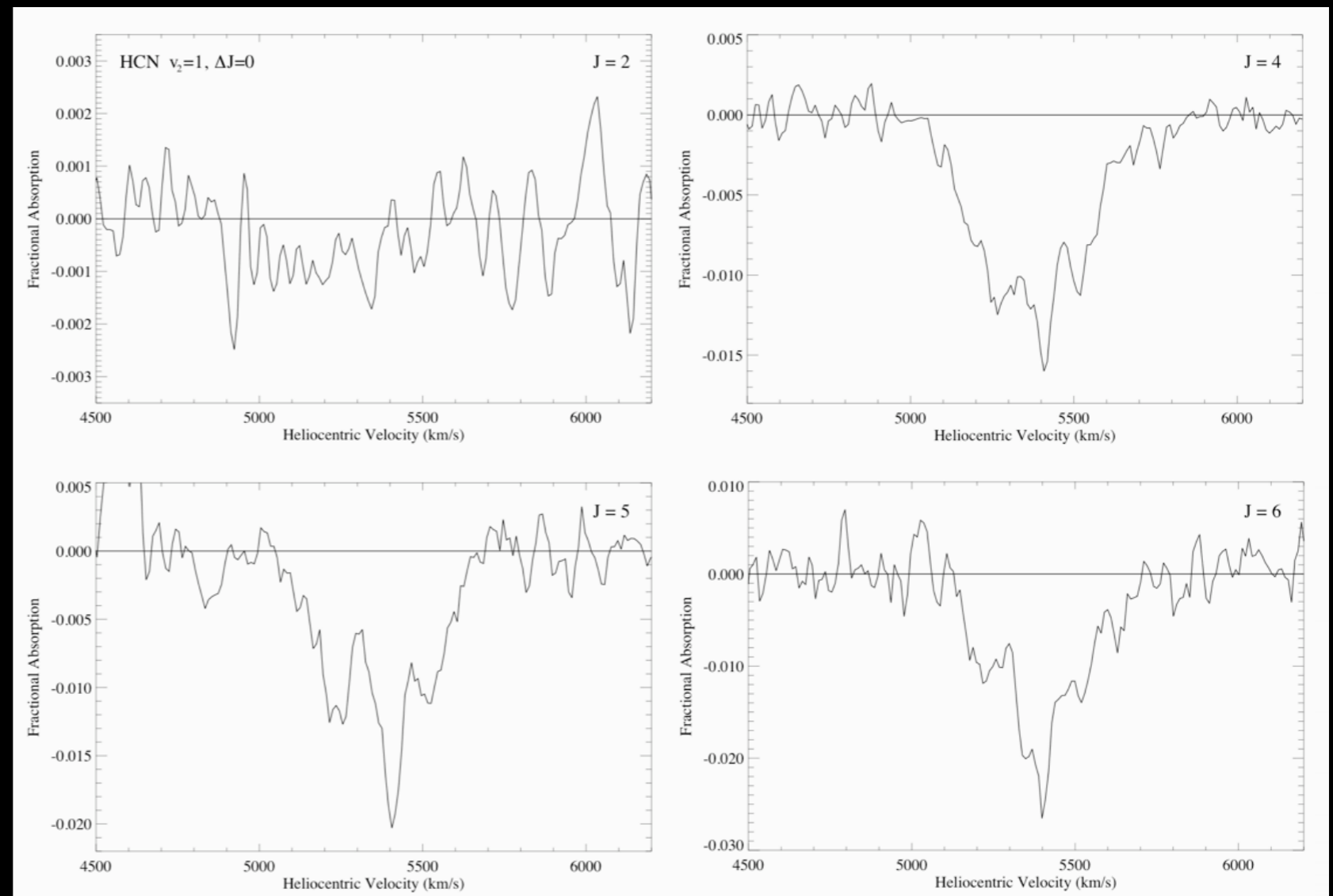
- 1 mm spectral scan with Zspec on CSO

# Spectral Surveys of Starburst Galaxies

## Arp 220: 1-10 GHz at Arecibo

- HCN bending modes
- First astronomical detection!

(Momjian et al 2008)

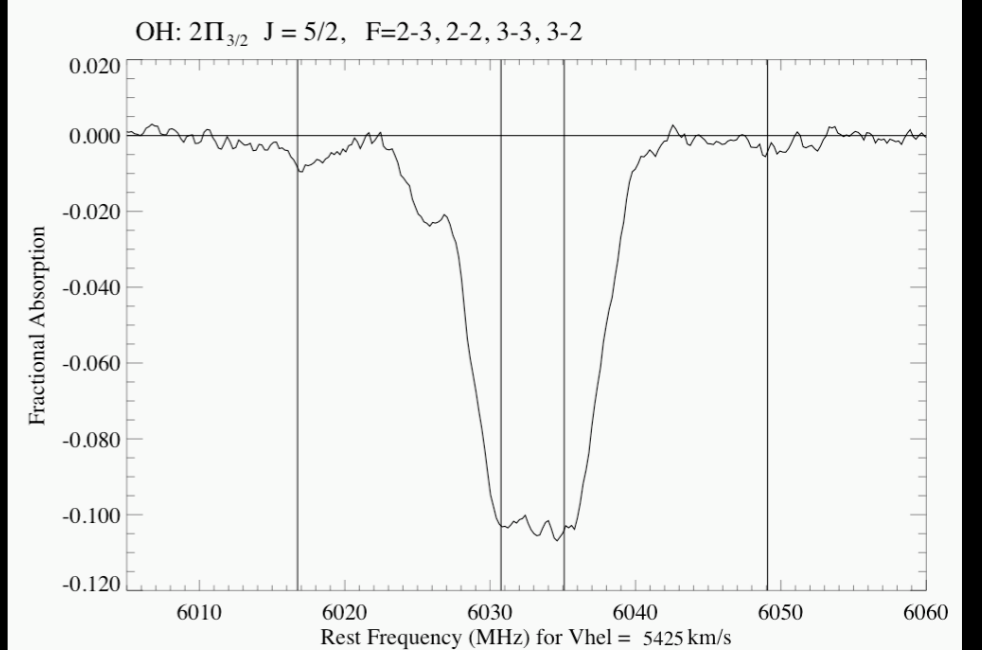
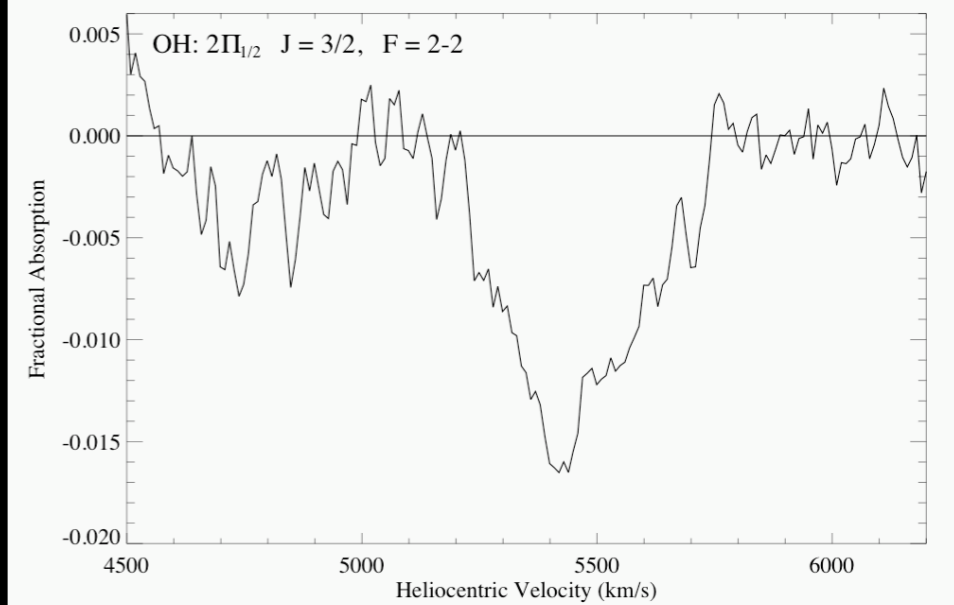
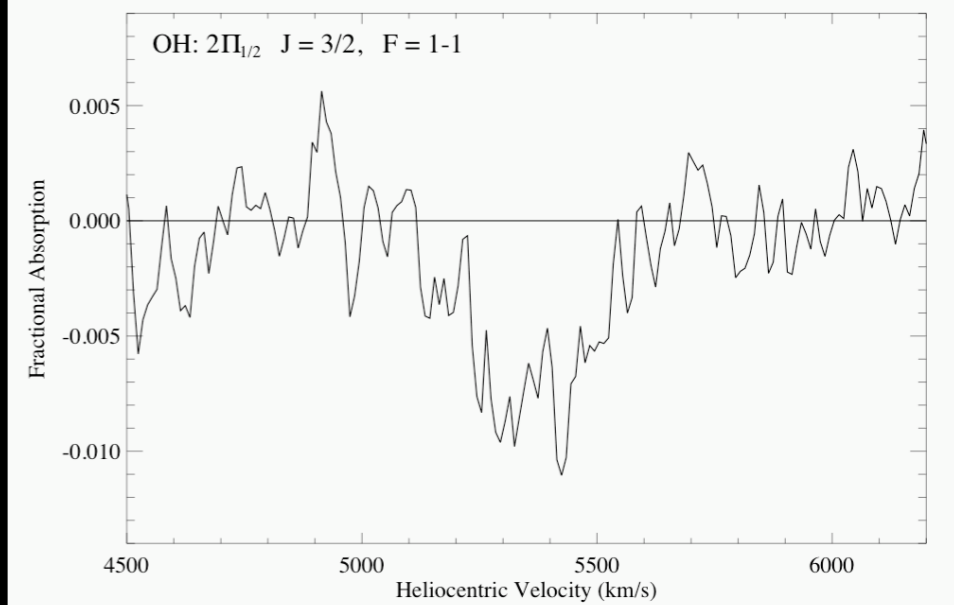
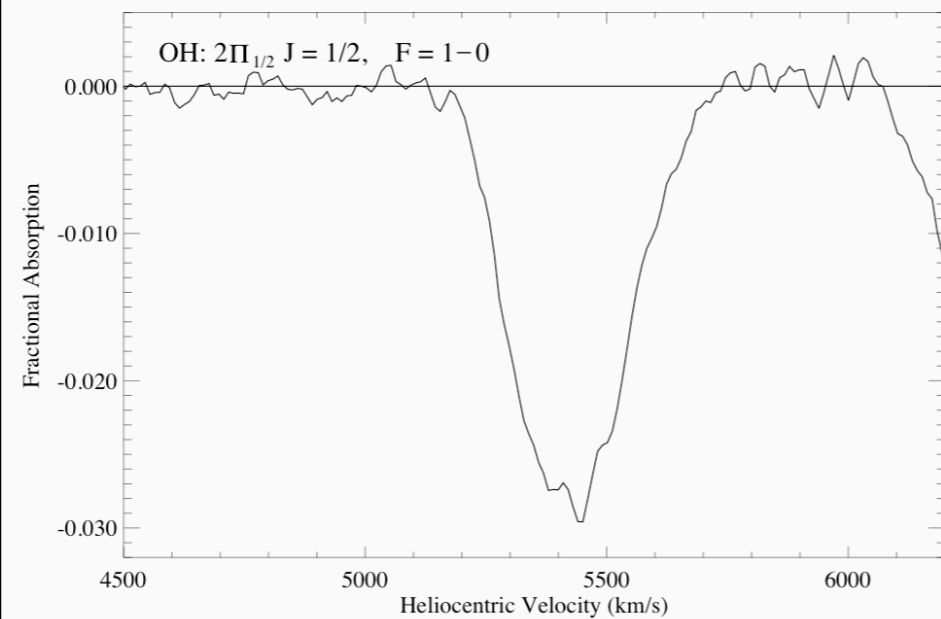
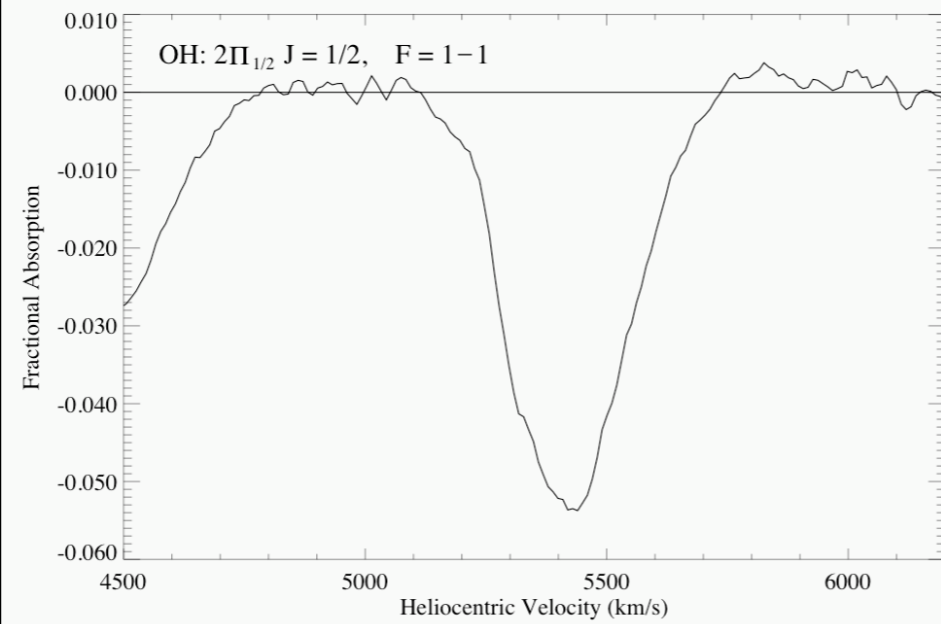
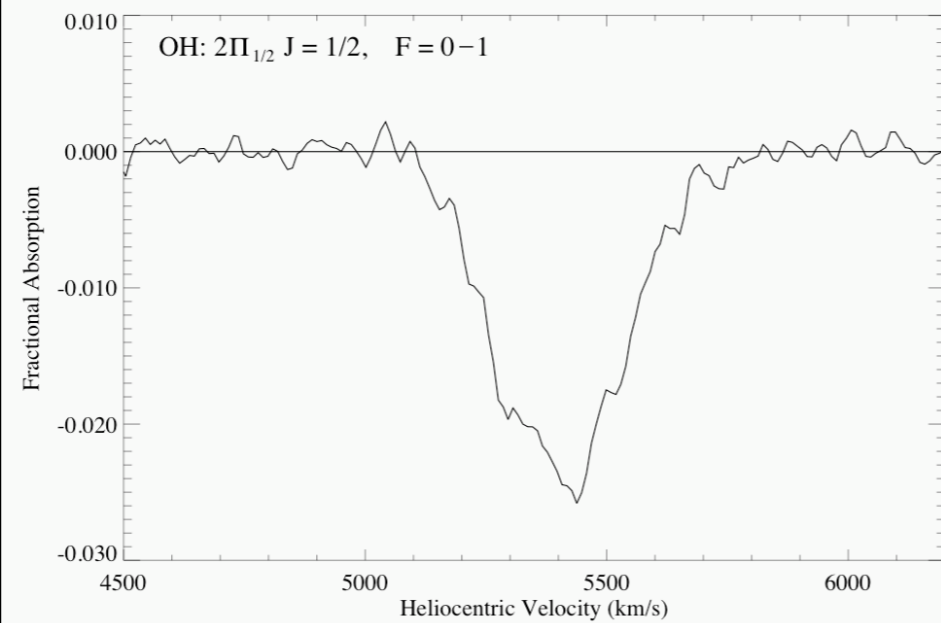


# Arp 220

## OH Lines

### Rotationally excited; probes IR field

(Momjian et al 2008)

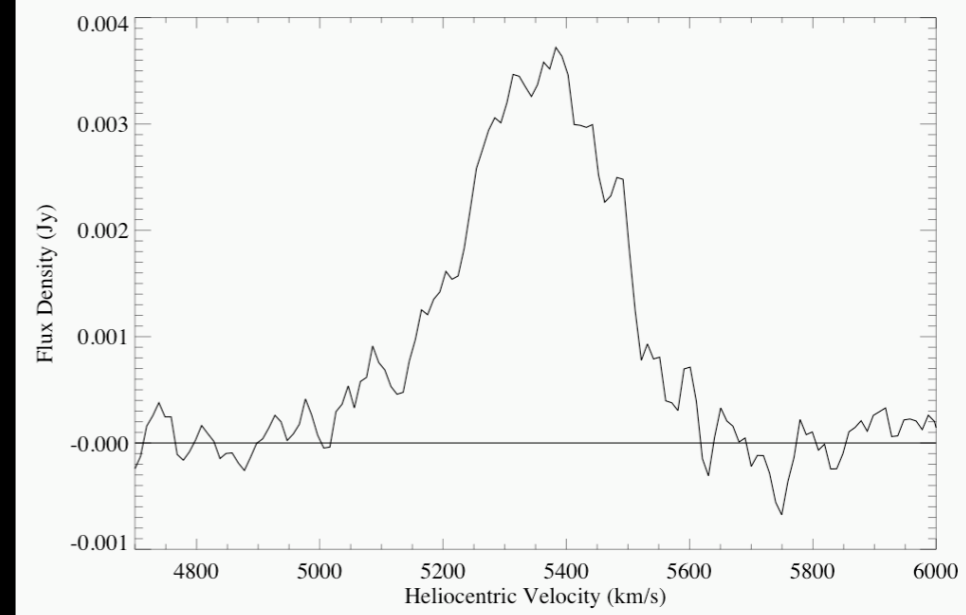
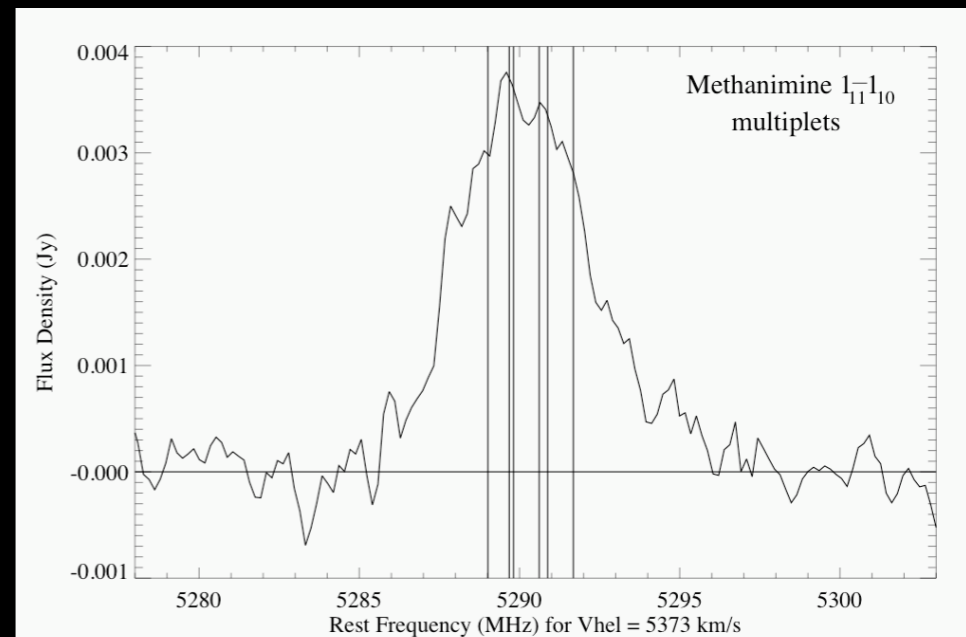
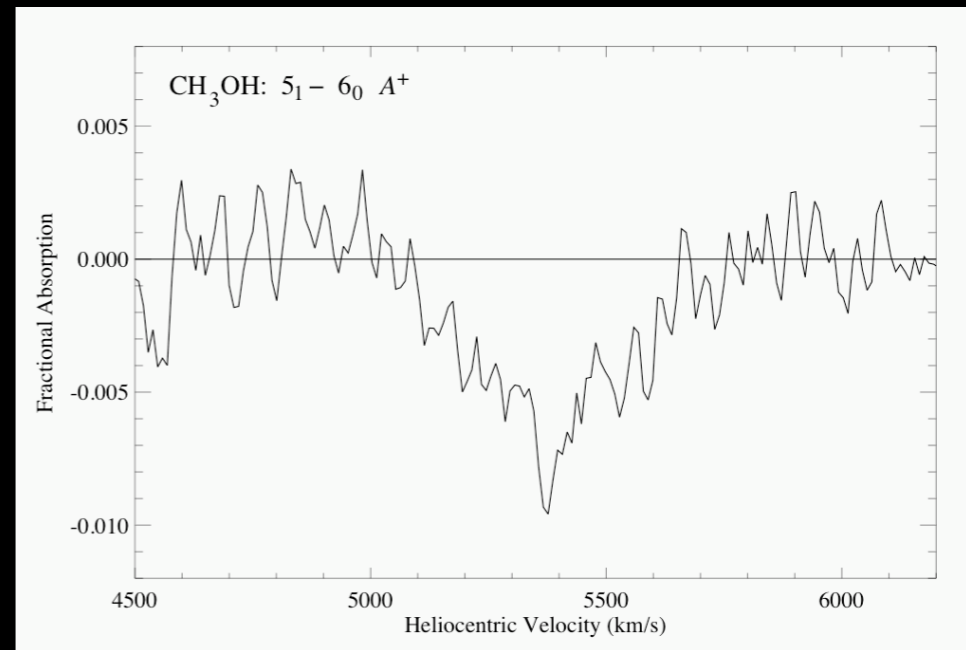




# Arp 220

- Methanol Absorption  
(first detection beyond Local Group)
- Methanimine ( $\text{CH}_2\text{NH}$ ) Emission
  - possible maser
  - amino acid precursor (glycine)

(Momjian et al 2008)



# Spectral Surveys of Starburst Galaxies

- Astrochemistry
- New Discovery Space
- Deuterium/Isotopes
- New Specific Probes (eg  $\text{N}_2\text{H}^+$ )



**Danger:** spectral confusion

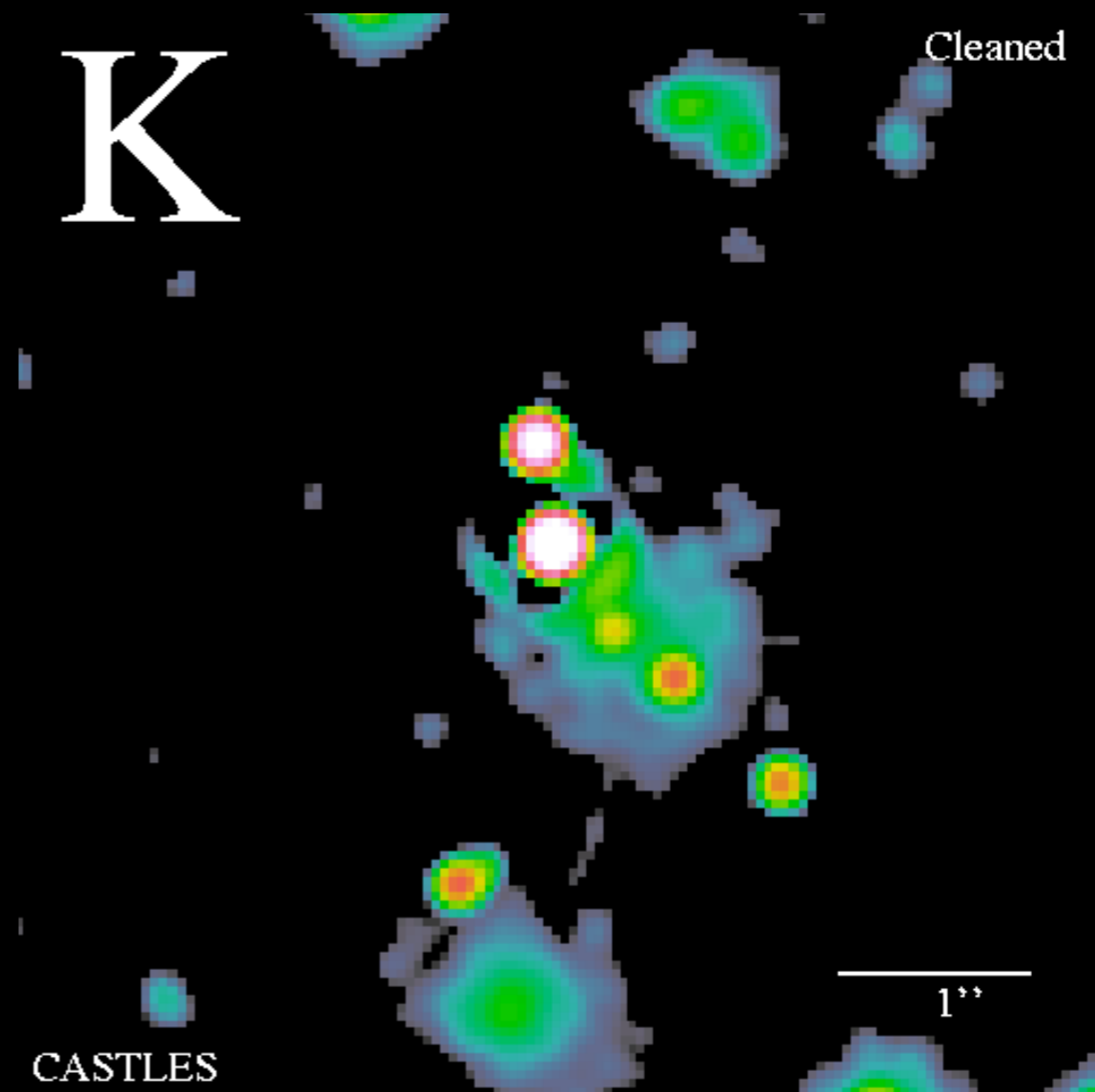
# Spectral Surveys of Molecular Absorbers

PKS 1830-211

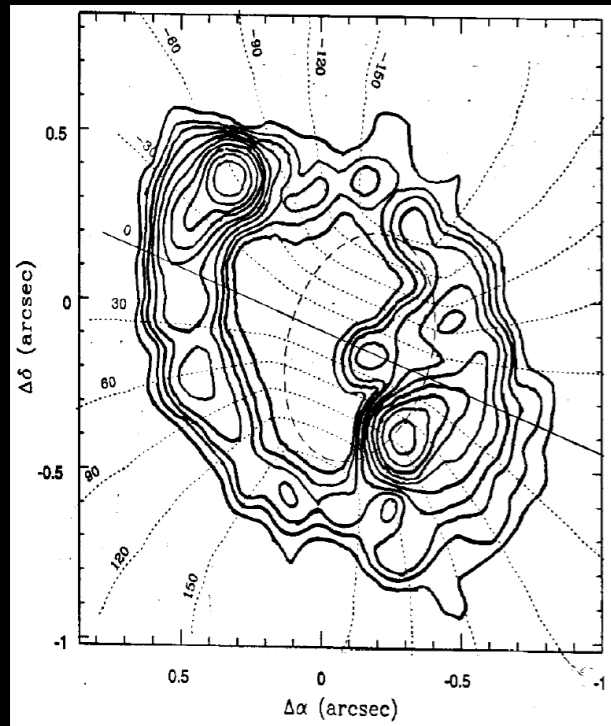
- Lens @  $z = 0.89$
- 2 Jy at 100 GHz
- 0.5 Jy at 1 THz

WMAP point sources

- \* The only means to study cold gas or individual clouds at high redshift



# Extended Illumination: PKS 1830-211



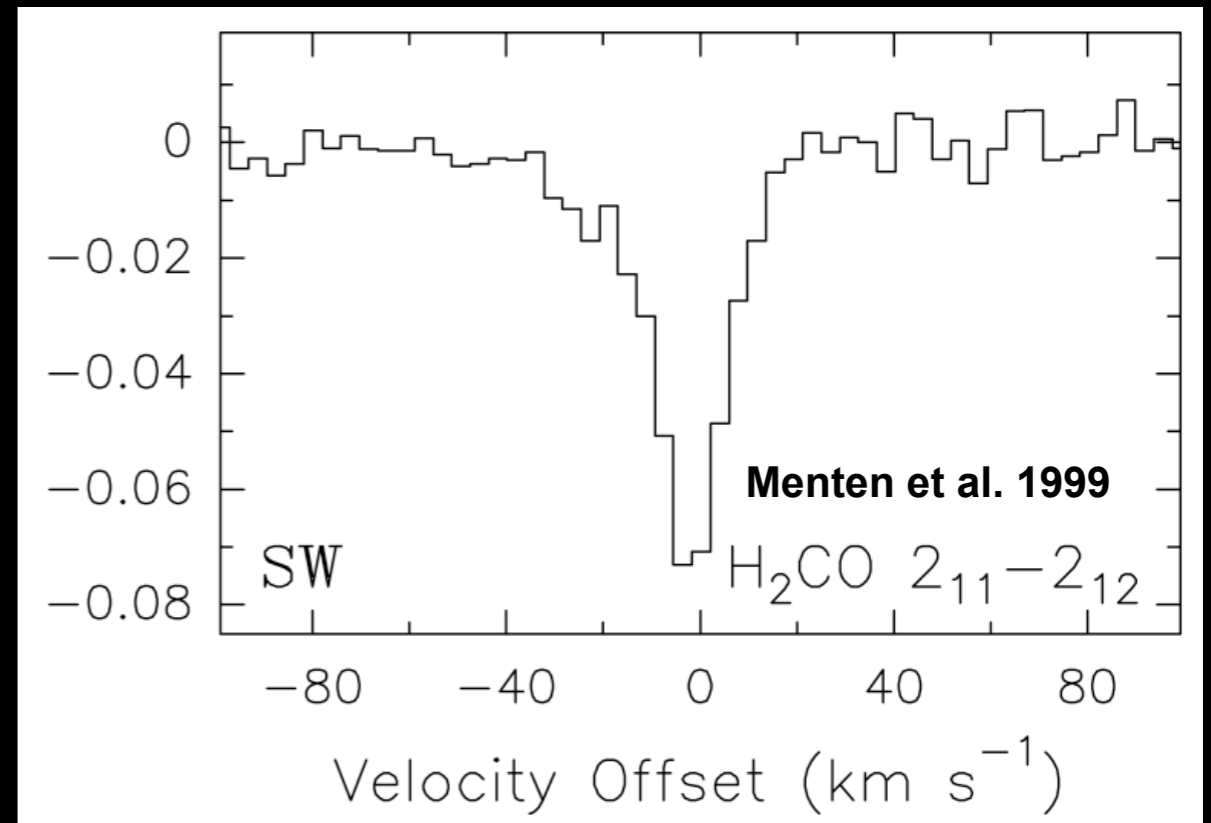
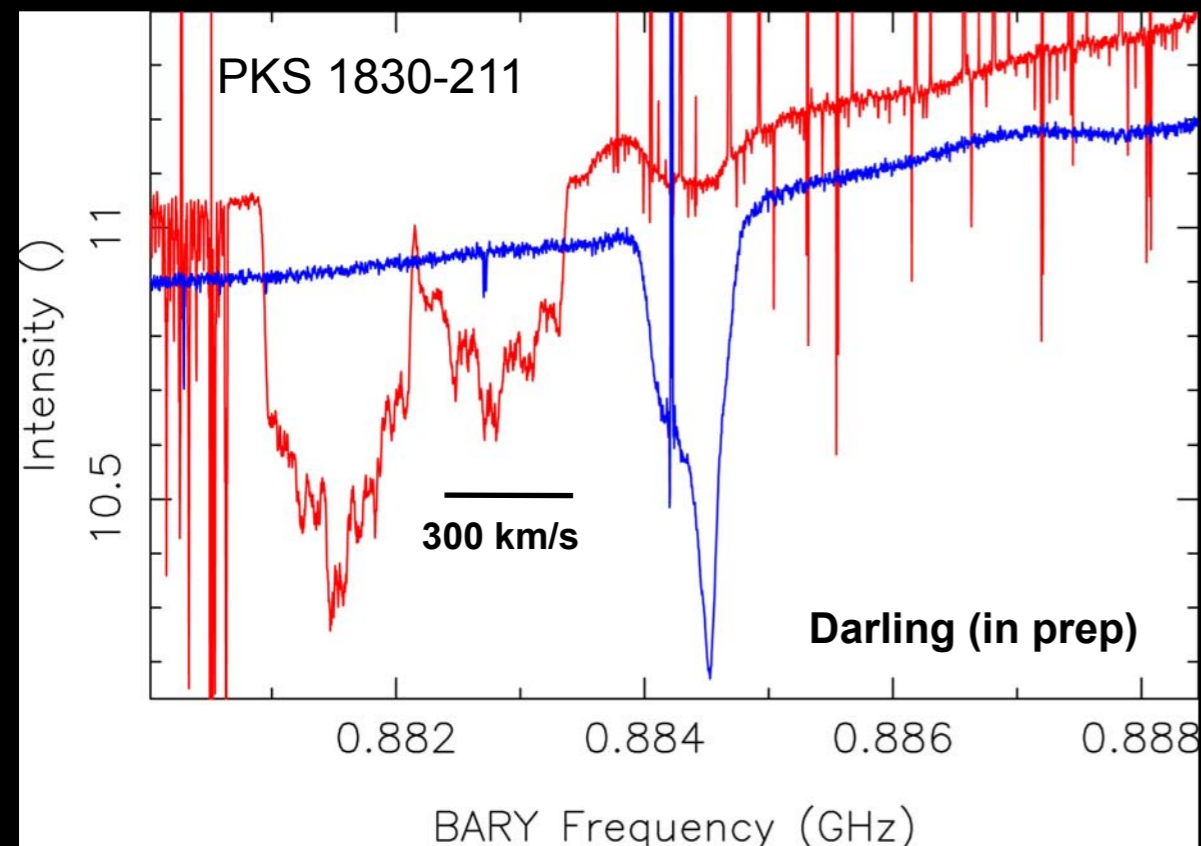
Chengalur, deBruyn, &  
Narasimha 1999

Patnaik et al. 1994

Nair et al. 1993

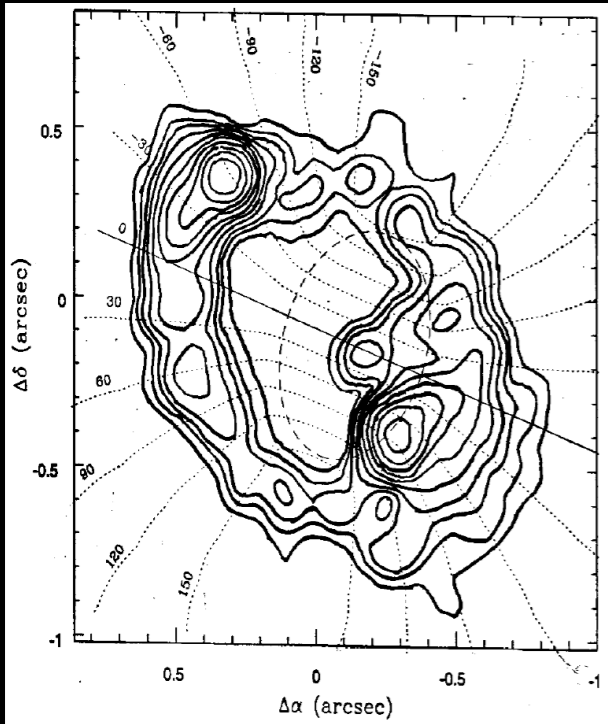
## PKS 1830-211:

- Einstein ring at  $z = 0.89$
- HI and OH absorption
- CO, HCN, HCO<sup>+</sup>, ... absorption
- Molecular isotope absorption
- H<sub>2</sub>CO absorption





# Extended Illumination: PKS 1830-211



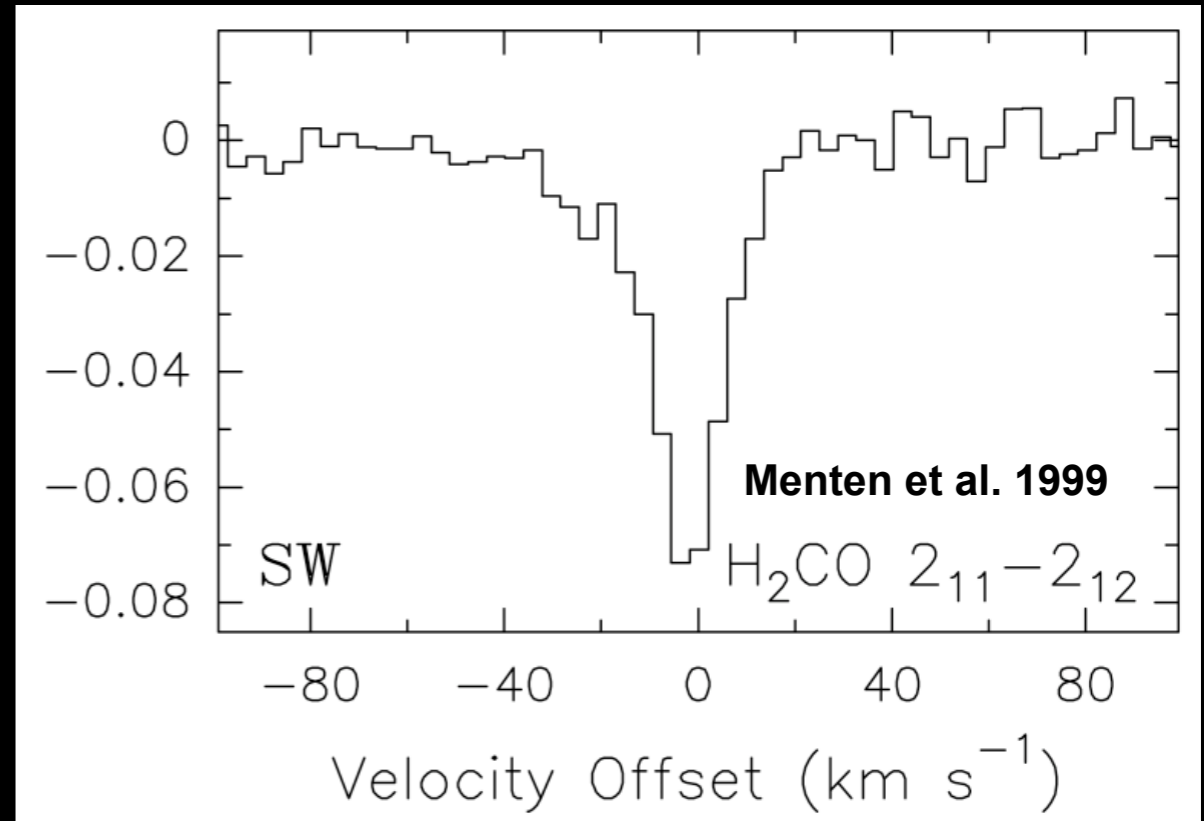
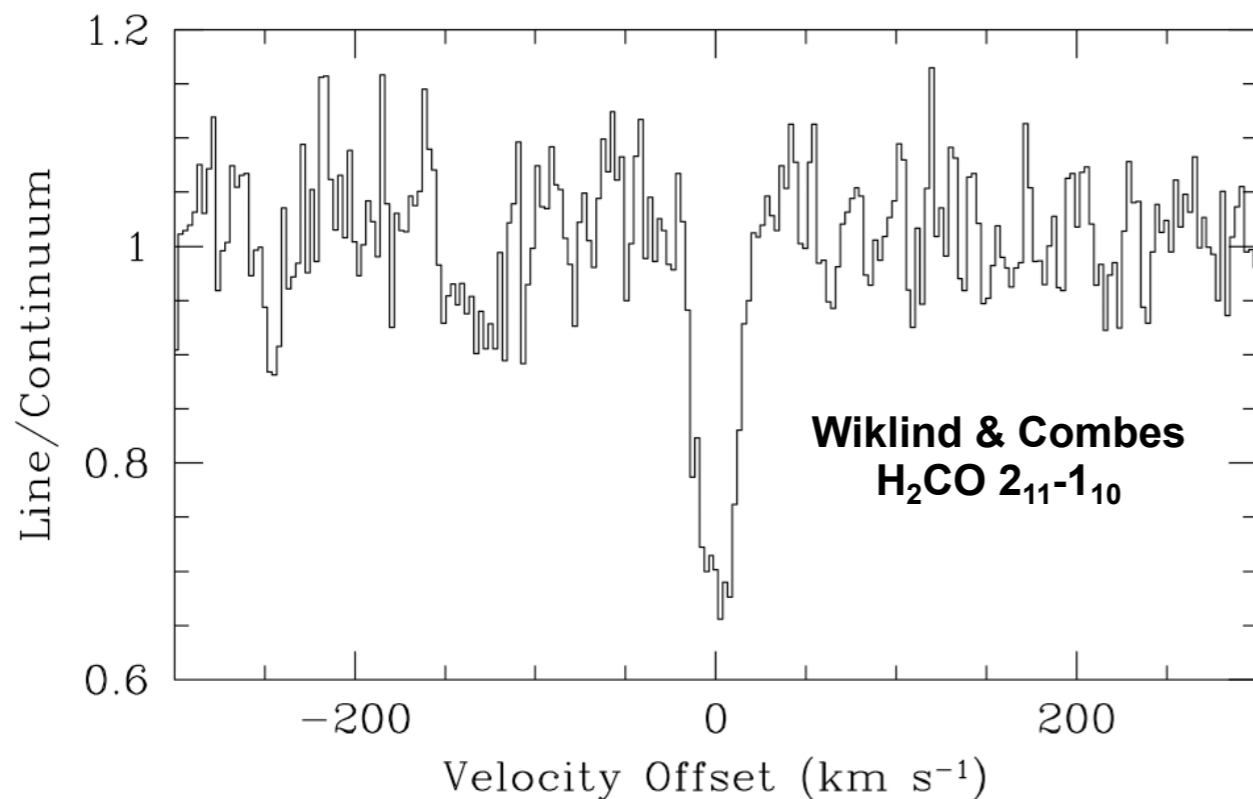
Chengalur, deBruyn, &  
Narasimha 1999

Patnaik et al. 1994

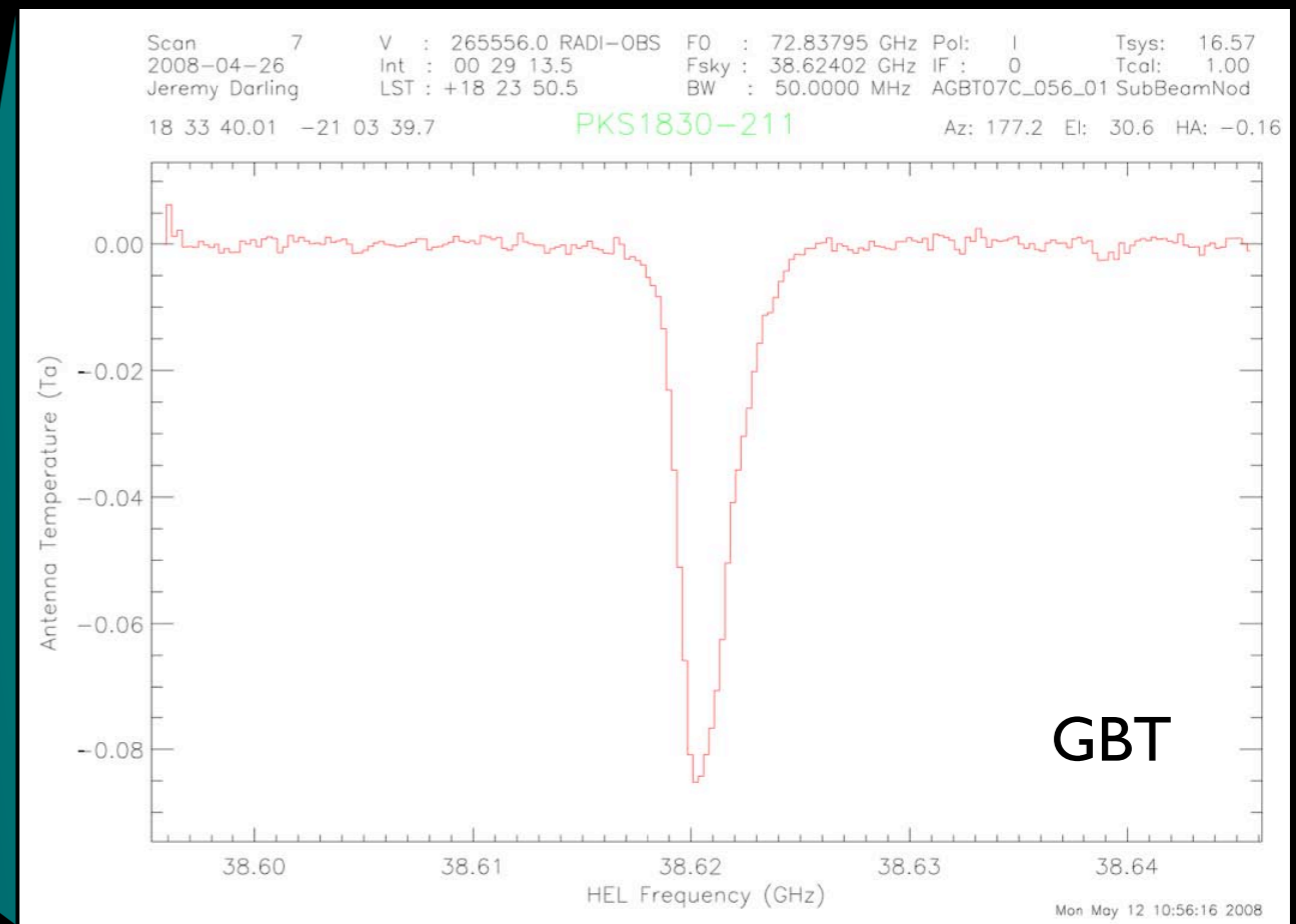
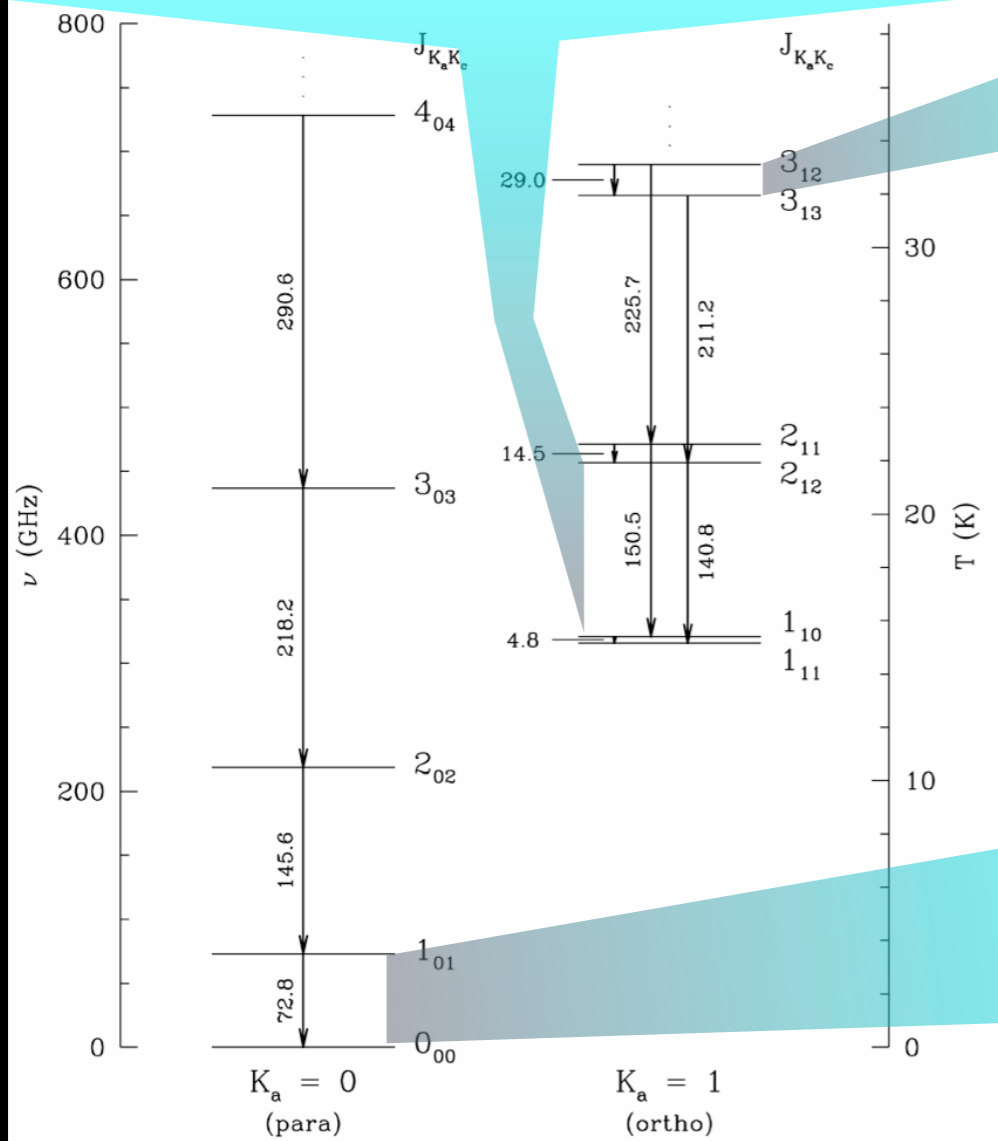
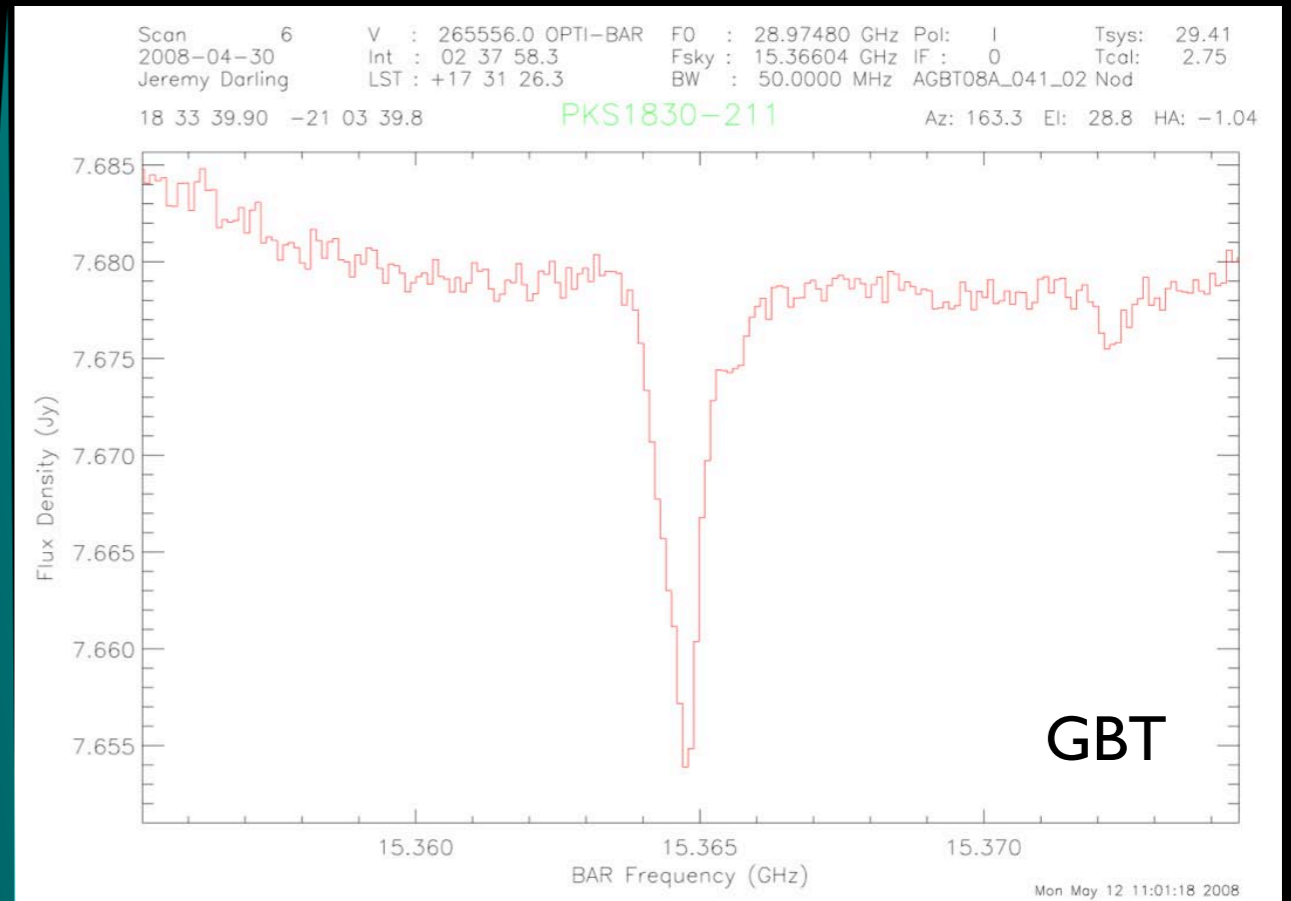
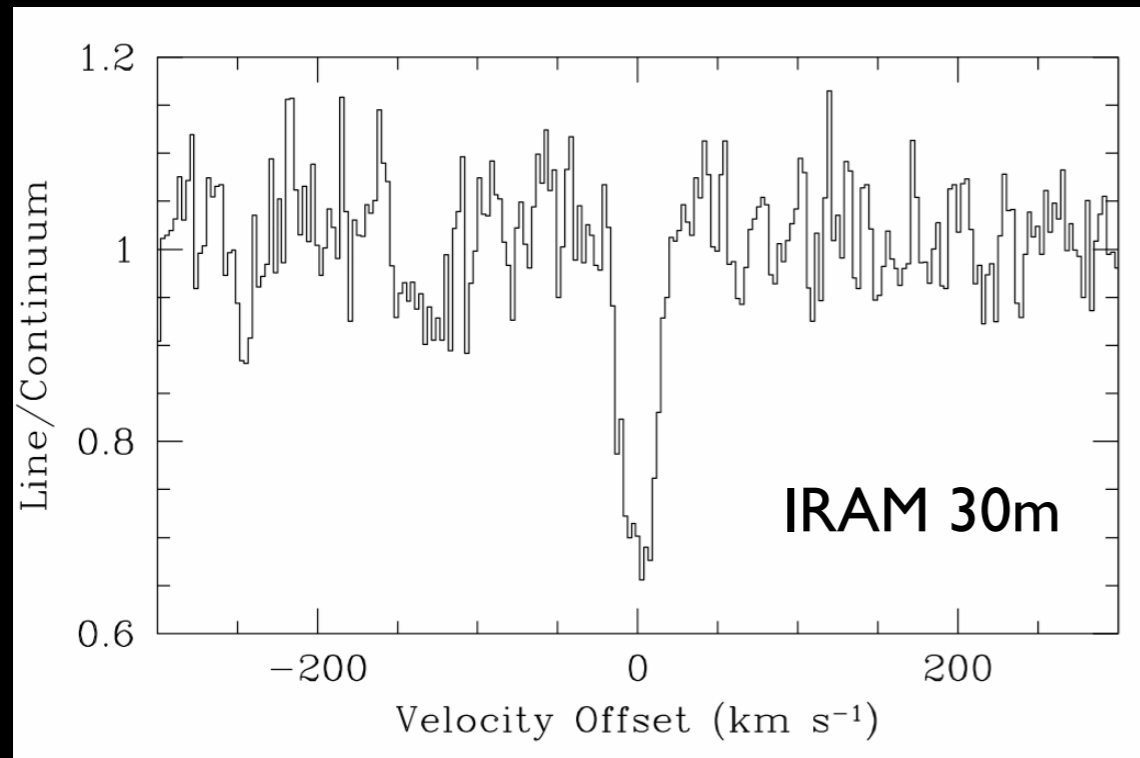
Nair et al. 1993

## PKS 1830-211:

- Einstein ring at  $z = 0.89$
- HI and OH absorption
- CO, HCN, HCO<sup>+</sup>, ... absorption
- Molecular isotope absorption
- H<sub>2</sub>CO absorption



# Formaldehyde in PKS 1830-211 at $z = 0.89$



# Spectral Surveys of Molecular Absorbers: PKS 1830-211 (gravitational lens at $z = 0.89$ )

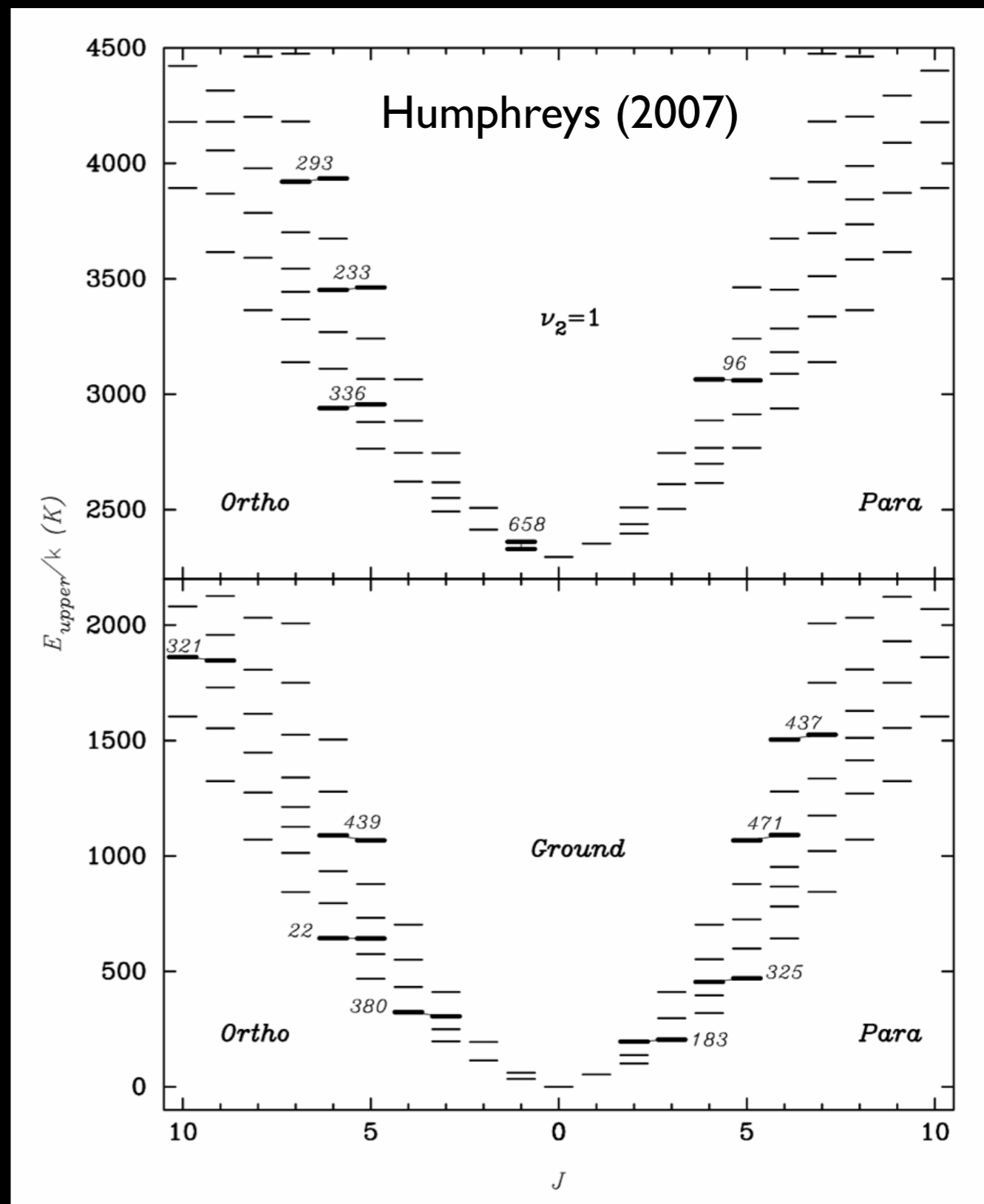
Molecules	Isotopes
CO	$^{13}\text{CO}$
$\text{HCO}^+$	$\text{H}^{13}\text{CO}^+$ , $\text{HC}^{18}\text{O}^+$ , $\text{HC}^{17}\text{O}^+$
HCN	$\text{H}^{13}\text{CN}$ , $\text{HC}^{15}\text{N}$
HNC	
$\text{H}_2\text{S}$	$\text{H}_2^{34}\text{S}$
$\text{N}_2\text{H}^+$	
OH	
$\text{HC}_3\text{N}$	
CS	$\text{C}^{34}\text{S}$
$\text{H}_2\text{CO}$	
$\text{NH}_3$	

# (sub)mm Masers

Many Species Known;  
Many More Likely

- H<sub>2</sub>O (~12 lines)
- SiO (+ isotopes)
- CH<sub>3</sub>OH (many predicted)
- HCN (~1 THz lines pred)
- SiS
- H Recombination Lines  
H2I-3I $\alpha$  (210-662 GHz)

\* see Humphreys 2007





# (sub)mm Masers

Extragalactic detections:

- H<sub>2</sub>O: 183 GHz (0.5 Jy!) in NGC 3079 @14 Mpc (Humphreys et al 2005)
- H Recombination Maser: H27 $\alpha$  (316 GHz) in M82 at 1.5 Jy! (Seaquist et al 1996)
- RRLs seen in starburst galaxies; submm lines should be produced as well

✦ CCAT should provide a bonanza of masers in the local Universe!

(and in the Galaxy...eg, 345 GHz H<sub>2</sub>O in W49N is 8000 Jy; Menten et al 1990)

# Extragalactic Molecular Astrophysics with CCAT

Tremendous opportunities  
to study galaxies (star-  
forming and quiescent, high  
and low  $z$ ) in great detail  
with very specific probes

Spectral Surveys:

Warm Gas

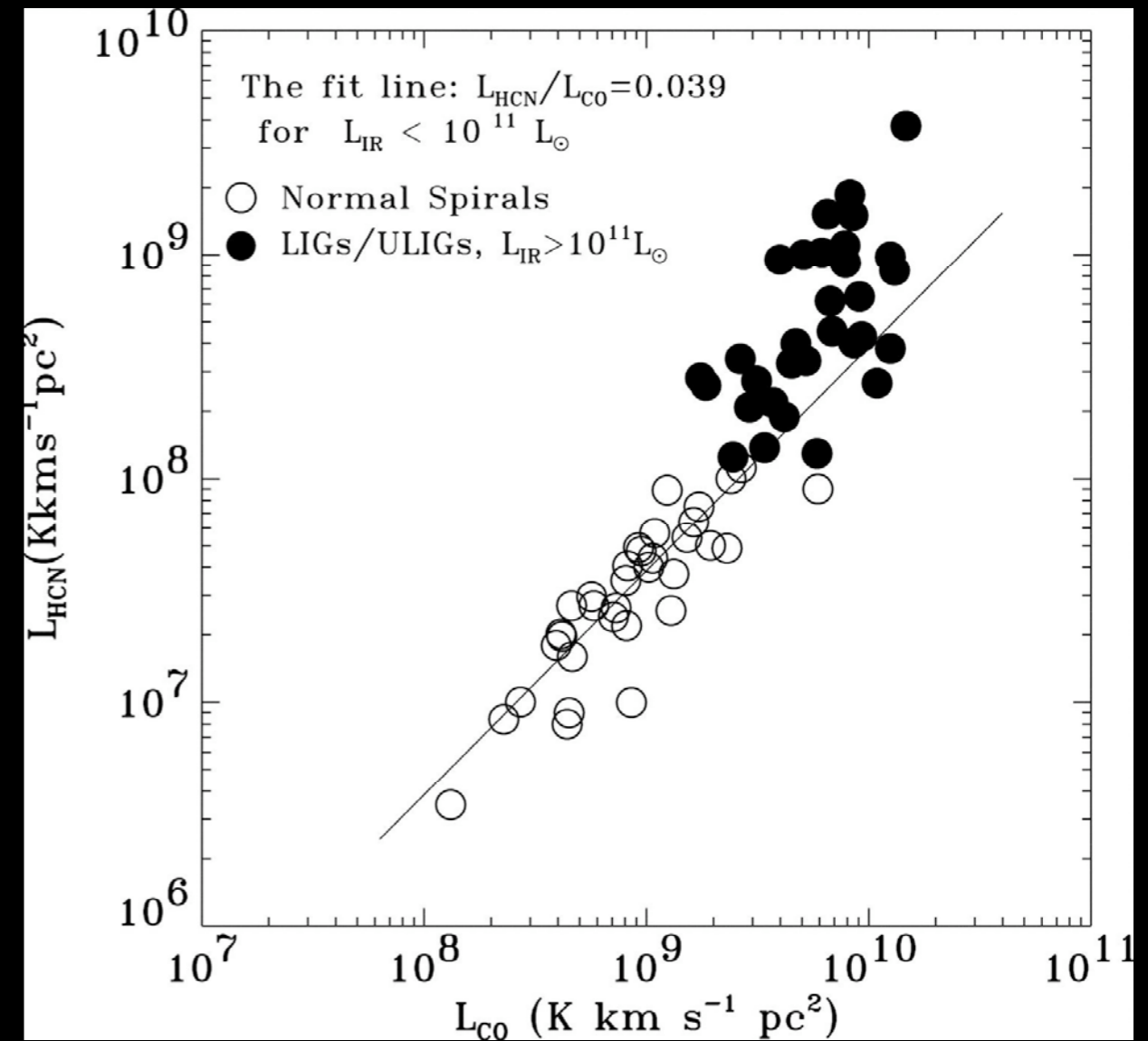
Cold Gas

Nonthermal Gas



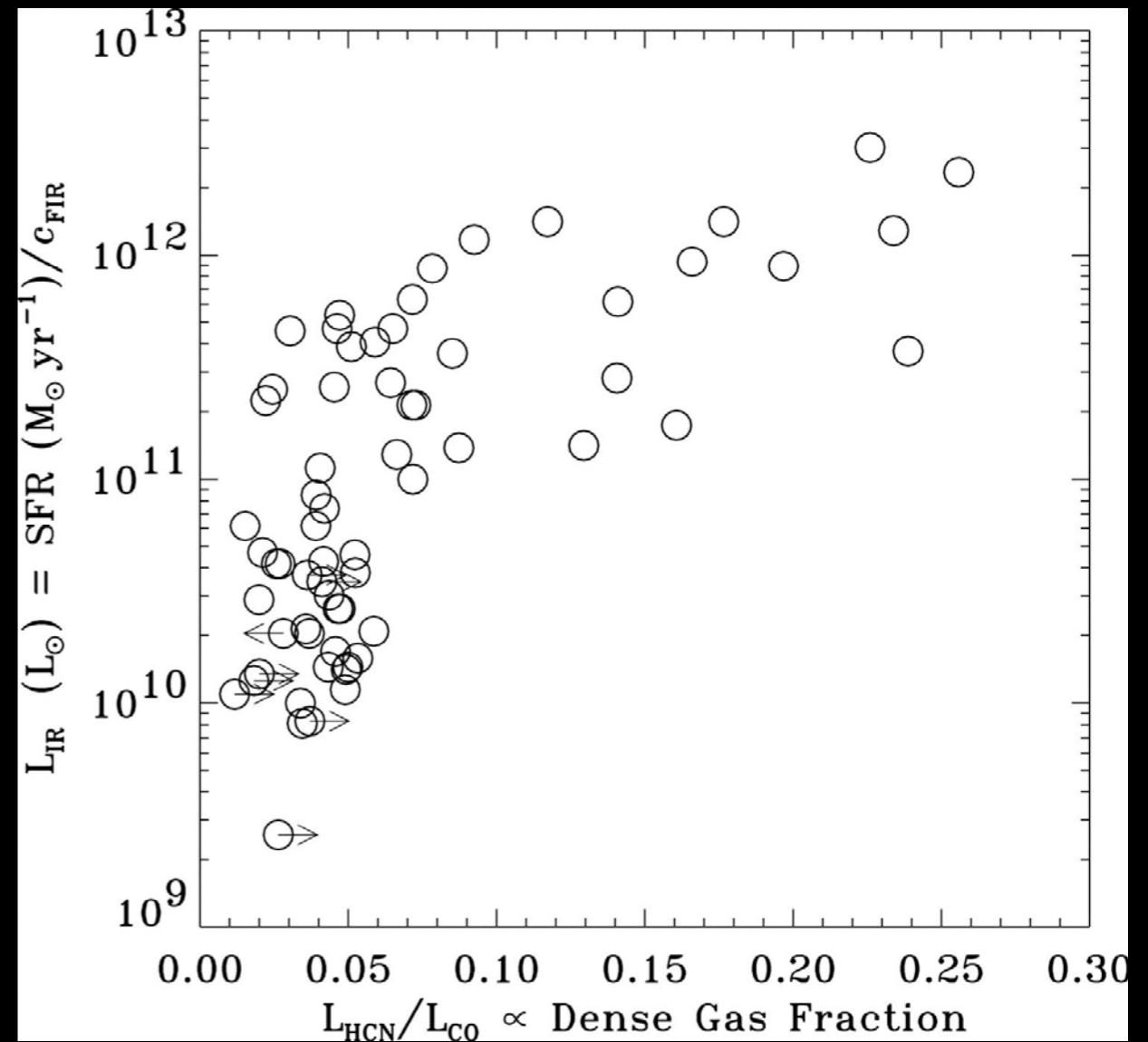


# Gao & Solomon (2004)+ OHM paper plot(s)





# Gao & Solomon + OHM paper plot(s)



# Conjugate lines in NGC 253

*Frayner, Seaquist & Frail (1998)*

Conjugate OH lines show changing structure along line of sight:

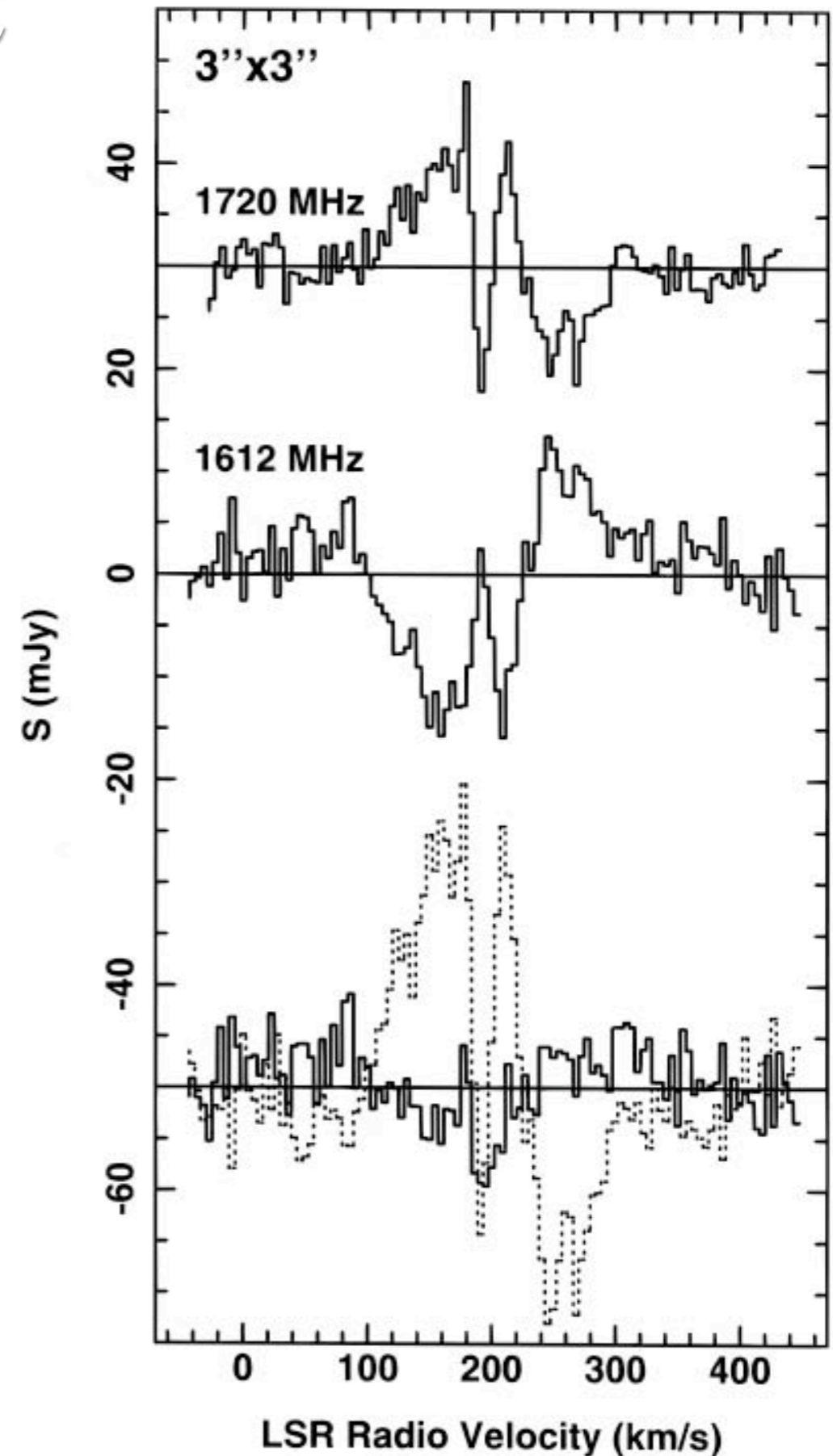
1720 emission  $\Rightarrow N(\text{OH})/\Delta V < 10^{15} \text{ cm}^{-2} \text{ km}^{-1} \text{ s}$   
 $\Rightarrow N(\text{H}_2) < 10^{22} \text{ cm}^{-2}$

1612 emission  $\Rightarrow N(\text{OH})/\Delta V > 10^{15} \text{ cm}^{-2} \text{ km}^{-1} \text{ s}$   
 $\Rightarrow N(\text{H}_2) > 10^{22} \text{ cm}^{-2}$

## Note:

Conjugate lines weakly amplify background continuum

$\Rightarrow$  Detectability follows rules of *absorption*, not emission



# (sub)mm Masers

Table 1. H<sub>2</sub>O Masers

Freq. (GHz)	Transition $J_{k_a, k_c} - J_{k_a, k_c}$	Vib. State	Species <sup>1</sup>	$E_u/k$ (K)	CSE <sup>2</sup>	SFR <sup>2</sup>	EXG <sup>2</sup>	Primary Reference
22.235	6 <sub>16</sub> - 5 <sub>23</sub>	G	O	644	Y	Y	Y	Cheung <i>et al.</i> (1969)
96.261	4 <sub>40</sub> - 5 <sub>33</sub>	$\nu_2=1$	P	3065	Y			Menten & Melnick (1989)
183.308	3 <sub>13</sub> - 2 <sub>20</sub>	G	P	205	Y	Y	Y	Waters <i>et al.</i> (1980)
232.687	5 <sub>50</sub> - 6 <sub>43</sub>	$\nu_2=1$	O	3463	Y			Menten & Melnick (1989)
293.439	6 <sub>61</sub> - 7 <sub>52</sub>	$\nu_2=1$	O	3935	Y			Menten <i>et al.</i> (2006)
321.226	10 <sub>29</sub> - 9 <sub>36</sub>	G	O	1862	Y	Y		Menten <i>et al.</i> (1990a)
325.153	5 <sub>15</sub> - 4 <sub>22</sub>	G	P	470	Y	Y		Menten <i>et al.</i> (1990b)
<sup>3</sup> 336.228	5 <sub>23</sub> - 6 <sub>16</sub>	$\nu_2=1$	O	2956	Y			Feldman <i>et al.</i> (1993)
354.885	17 <sub>412</sub> - 16 <sub>710</sub>	G	O	5782	Y			Feldman <i>et al.</i> (1991)
380.194	4 <sub>14</sub> - 3 <sub>21</sub>	G	O	324		Y		Phillips <i>et al.</i> (1980)
437.347	7 <sub>53</sub> - 6 <sub>60</sub>	G	P	1525	Y			Melnick <i>et al.</i> (1993)
439.151	6 <sub>43</sub> - 5 <sub>50</sub>	G	O	1089	Y	Y		Melnick <i>et al.</i> (1993)
470.889	6 <sub>42</sub> - 5 <sub>51</sub>	G	P	1091	Y	Y		Melnick <i>et al.</i> (1993)
658.007	1 <sub>10</sub> - 1 <sub>01</sub>	$\nu_2=1$	O	2361	Y			Menten & Young (1995)