

# Molecular Oxygen in Mrk231

Junzhi Wang (王均智)

Shanghai Astronomical Observatory

Di Li (NAOC), Paul Goldsmith (JPL), Zhiyu Zhang (ESO), Yong Shi (NJU),  
Shanghuo Li (SHAO), Yu Gao (PMO), Min Fang (UA) .....

2016 Oct 29<sup>th</sup>, ASIAA

# Where is Oxygen?

- Oxygen is the third most abundant element, after H and He
- Oxygen was found in CO, H<sub>2</sub>O, OH, etc
- How about O<sub>2</sub>? Important coolant of molecular clouds? Abundance of O<sub>2</sub>?
- Chemistry?

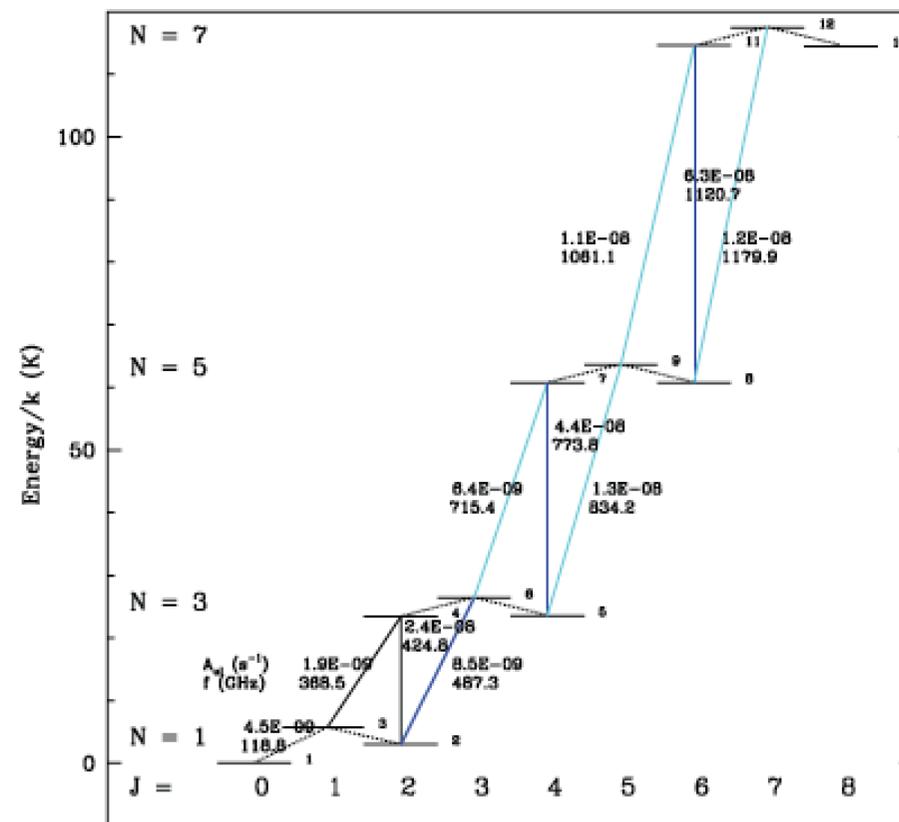
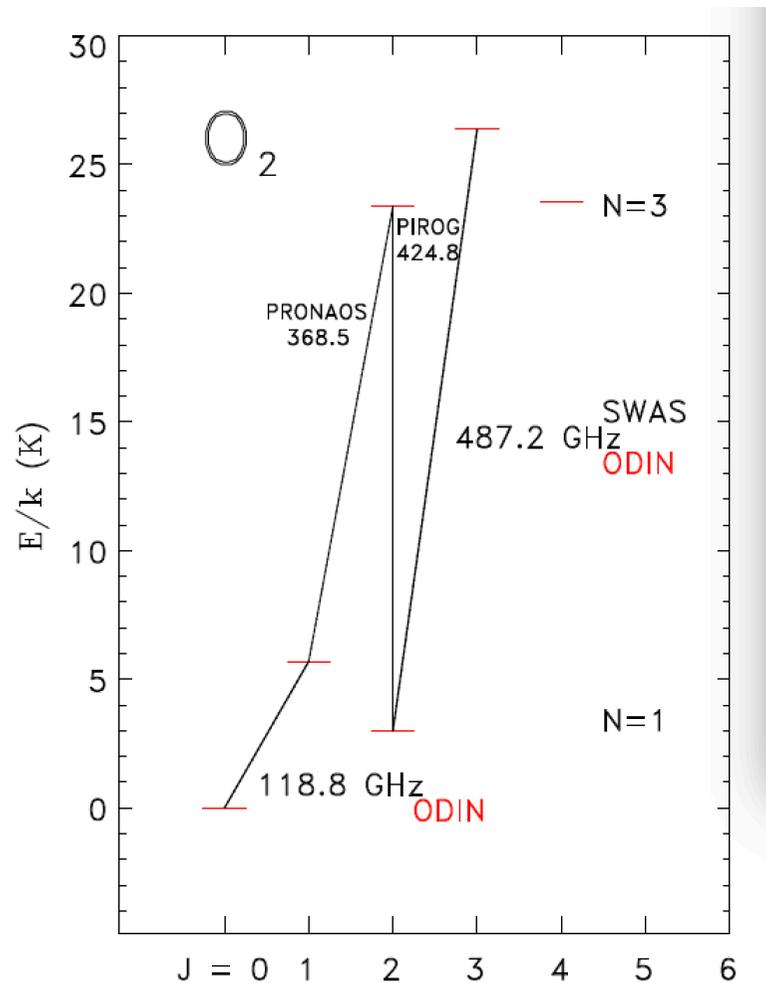
# Searching for O<sub>2</sub> emission

- O<sub>2</sub> emission can not be observed with ground based facilities due to the attenuation of Earth's atmosphere
- Galactic sources with Space missions: SWAS, odin, Herschel
- O<sup>18</sup>O line (non-detection)
- Red-shifted O<sub>2</sub> in galaxies with ground based facilities

# O<sub>2</sub> detections and abundances

- Theoretical predictions: comparable to CO (1980s)
- Marginal detection:  $\rho$  Oph with SWAS (Goldsmith et al. 2002)
- Detections:  $\rho$  Oph with Odin (Larsson et al. 2005), Orion with Herschel (Goldsmith et al. 2011)
- Not important as coolant in dense molecular gas

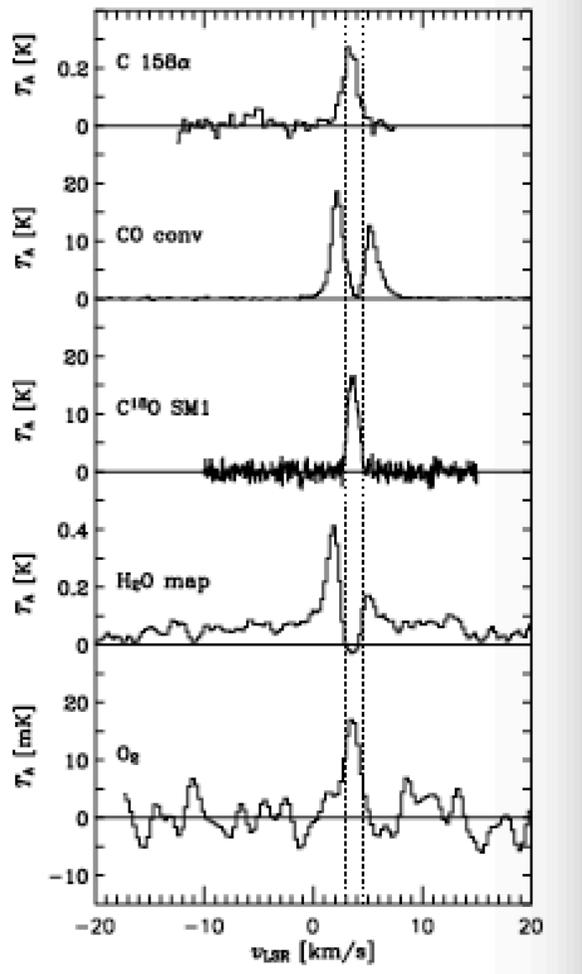
# Energy level diagram of O<sub>2</sub>



Goldsmith et al. 2011

Liseau et al. 2005

# O<sub>2</sub> in ρ Oph with Odin

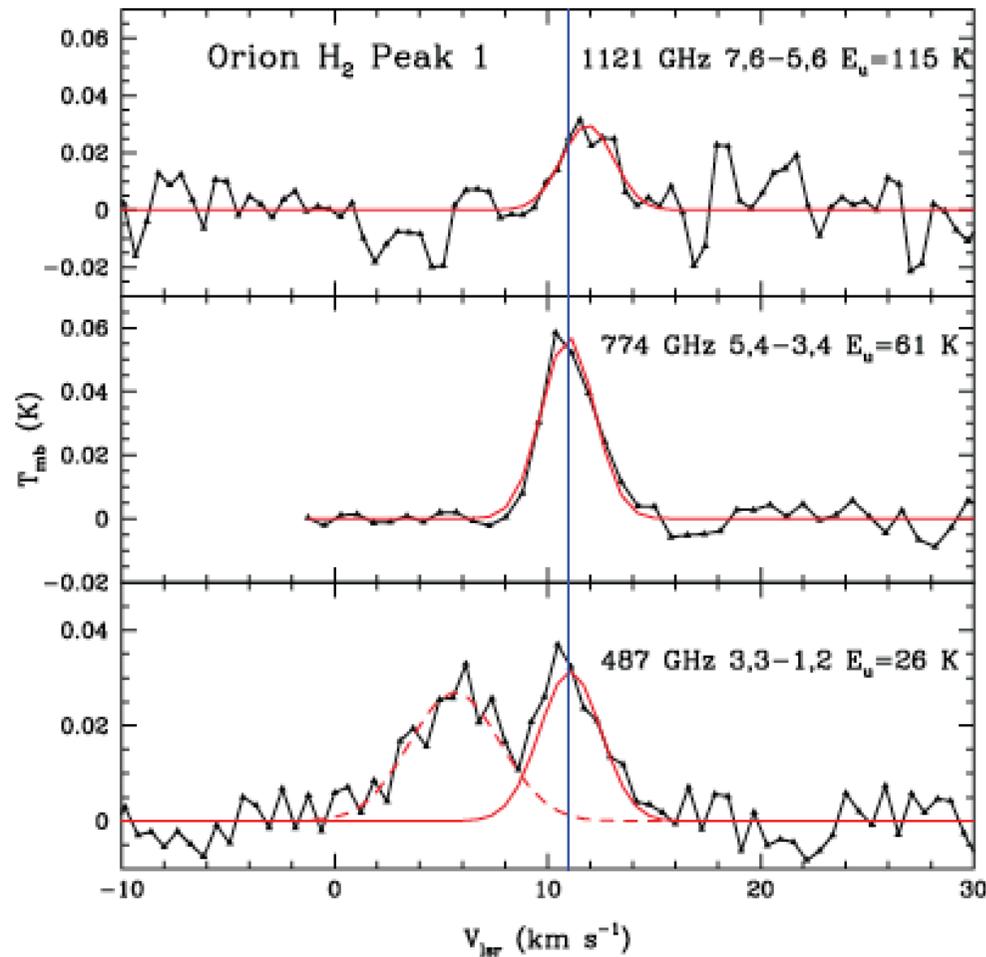


Transition: 118.75 GHz

Abundance(O<sub>2</sub> /H<sub>2</sub>):  $5 \times 10^{-8}$

Larsson et al. 2005

# O<sub>2</sub> in Orion with Herschel



Three transitions

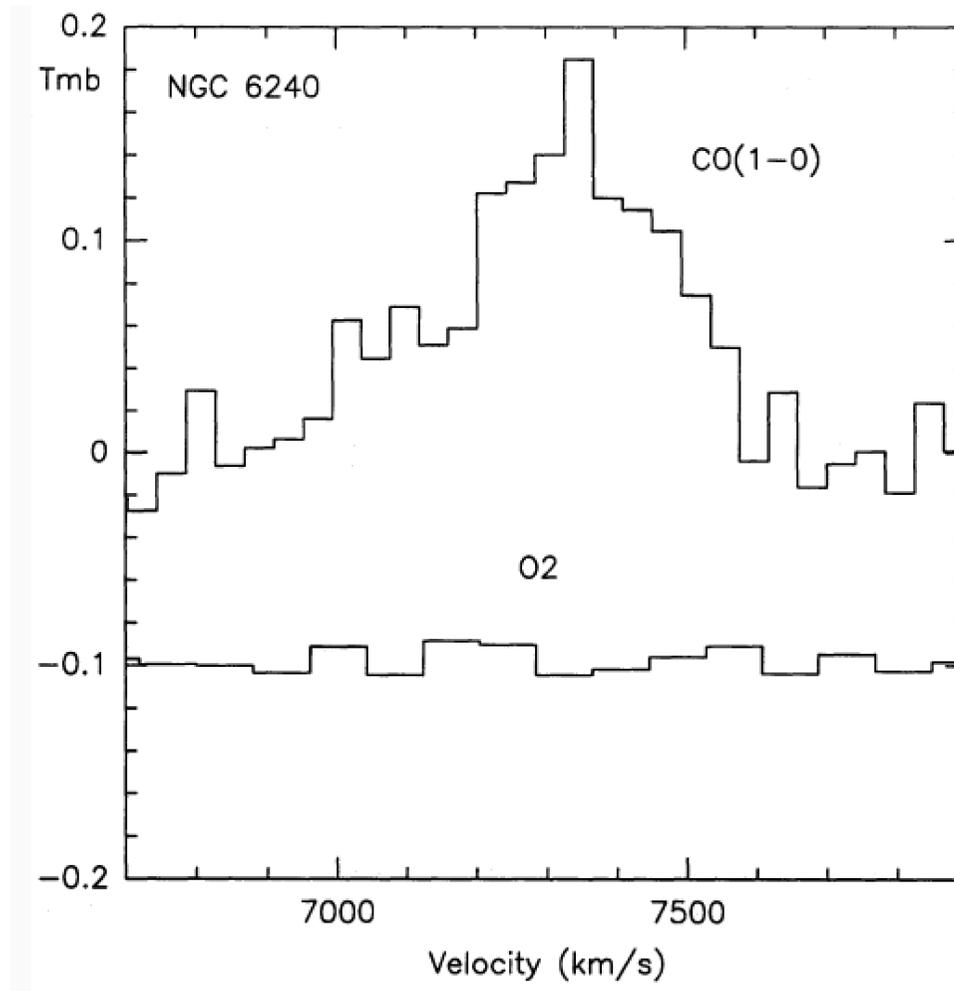
Abundance(O<sub>2</sub>/H<sub>2</sub>): 10<sup>-6</sup>

Shock?

# Non-detection of O<sub>2</sub> in galaxies

- Several sources were observed in past decades: NGC 7674 (Liszt 1985), VII ZW 31 (Goldsmith & Yong 1989, FCRAO), NGC 6240 (Combes et al. 1991, IRAM 30m) ....
- None of them had O<sub>2</sub> emission
- Best upper limit (3sigma) of O<sub>2</sub> /H<sub>2</sub> ratio: about 10<sup>-6</sup> in NGC 6240 with 3 hours integration time (CO 1-0/O<sub>2</sub> 118.75GHz line ratio >82)

# O<sub>2</sub> upper limit in NGC 6240

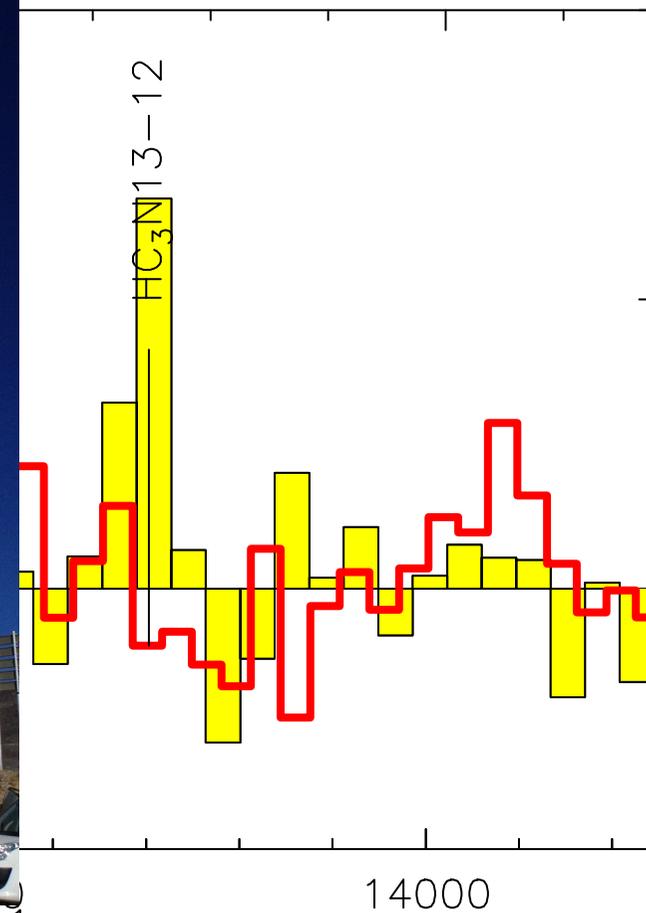


Combes et al. 1991

# Observations

- Telescope: IRAM 30 meter (PI: Junzhi Wang, 26 hours scheduled)
- Time: 2015 Aug, about 10 hours observing time for this source
- Transition: 118.75 GHz (rest frequency)
- Source: Mrk 231, the nearest QSO

# O<sub>2</sub> emission detected



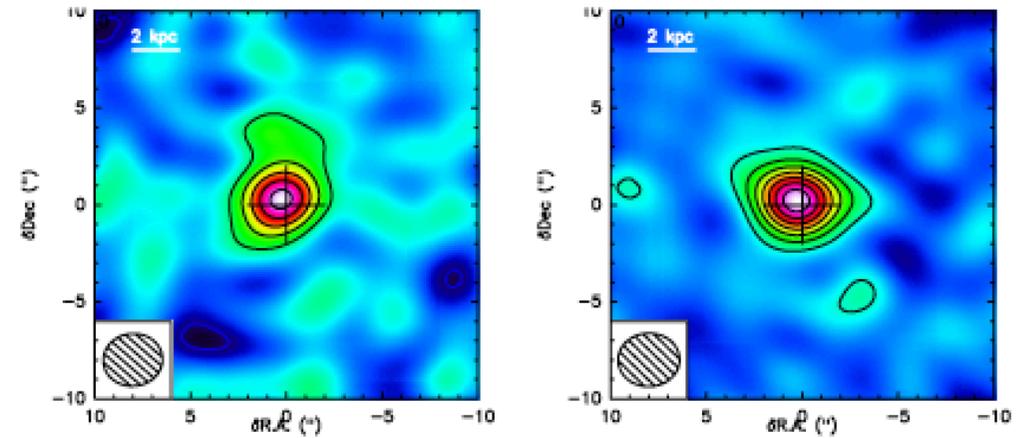
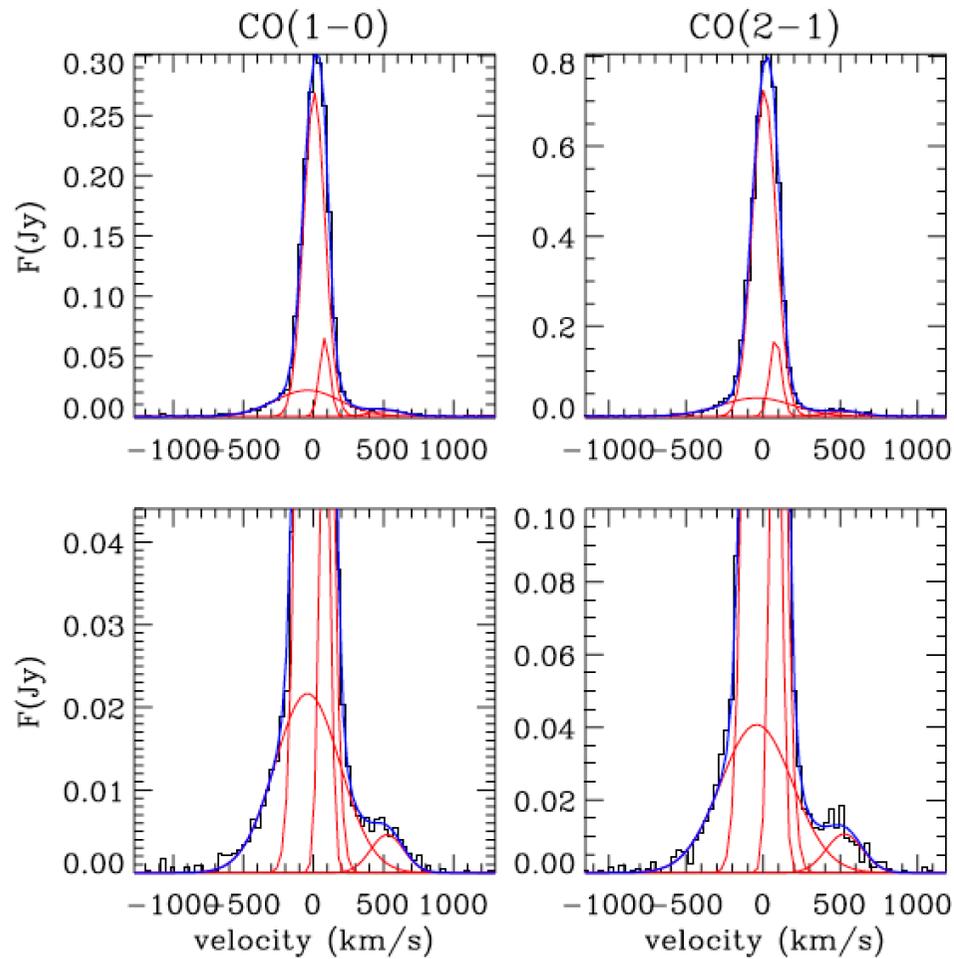
Velocity (km s<sup>-1</sup>)

First detection of extra-galactic O<sub>2</sub> emission

# Where is O<sub>2</sub> emission from?

- Single dish data, without spatial information
- Velocity: associated with the red wing of CO emission
- AGN molecular outflow?

# Molecular outflow in Mrk231



Blue wing

Red wing

Cicone et al. 2012

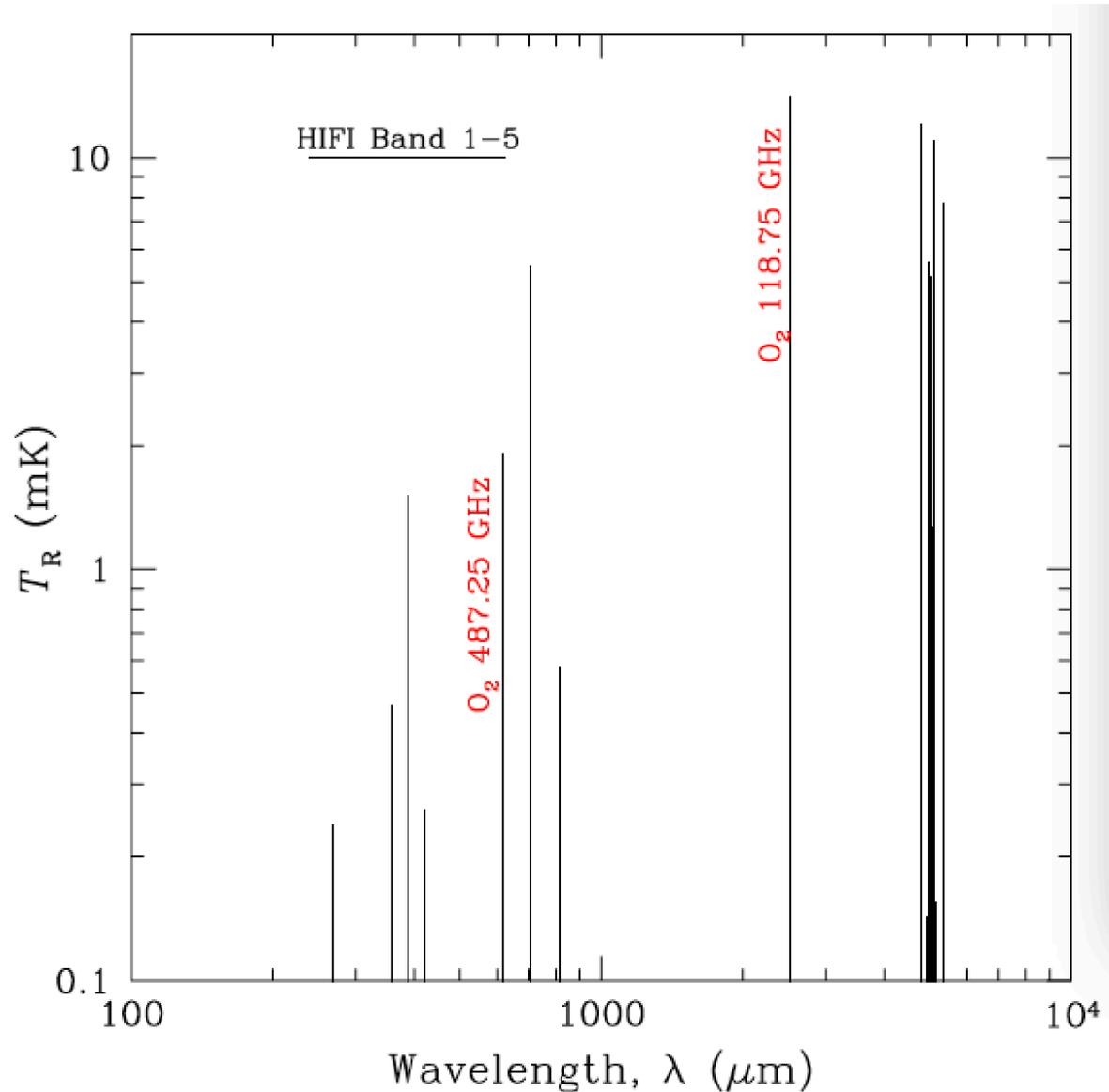
# O<sub>2</sub> abundance in Mrk 231

- Host galaxy: CO 1-0/O<sub>2</sub> >140 (1 sigma)
- Best upper limit of extra-galactic O<sub>2</sub> (~82 in NGC 6240, Combes et al. 1991), O<sub>2</sub>/H<sub>2</sub> abundance ratio should be less than 10<sup>-6</sup>
- Detected O<sub>2</sub> in red wing (outflow?), comparable to CO 1-0
- O<sub>2</sub>/H<sub>2</sub> abundance ratio: ~10<sup>-4</sup>

# Shock enhanced O<sub>2</sub>?

- Red wing v.s. blue wing: O<sub>2</sub> only in red wing
- Excitation condition in blue wing is similar to that of the host galaxy (Cicone) with CO 2-1 and 1-0 observations
- Red wing: higher excitation, might be affected by shocks
- CO 3-2 imaging with the SMA for molecular outflow in Mrk231 and maybe more sources?

# O<sub>2</sub> emission as an important coolant in such molecular AGN outflow?



Liseau et al. 2005

Comments are welcome!

*Thanks*