Water in the Universe: from clouds to oceans
Estec, 15 April 2016

WATER VAPOR ABSORPTION AND EMISSION FROM EXTRAGALACTIC SOURCES

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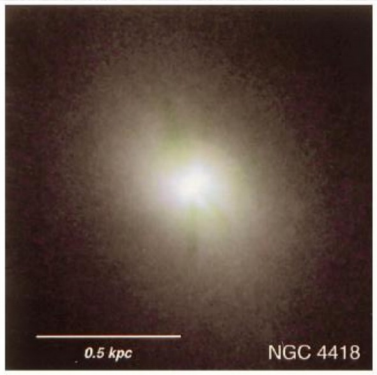
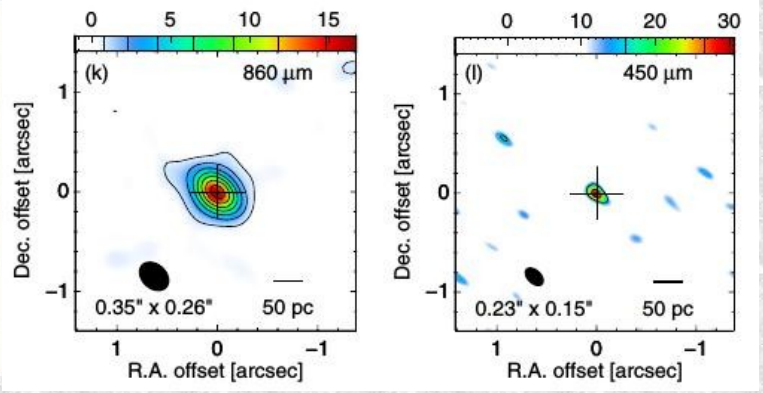
Based on Herschel/PACS & SPIRE observations

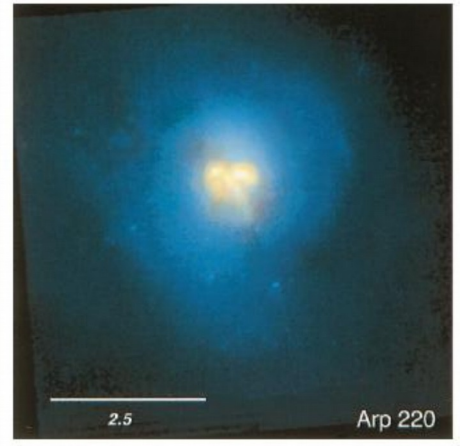
NEAR-IR IMAGES (Scoville+2000, Evans+2002)

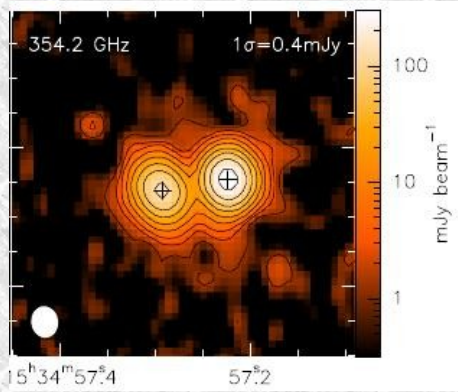




NGC 4418
Sakamoto+2013
LIR=1x10^{11} Lsun
Submm size: ~30 pc
SB, AGN?

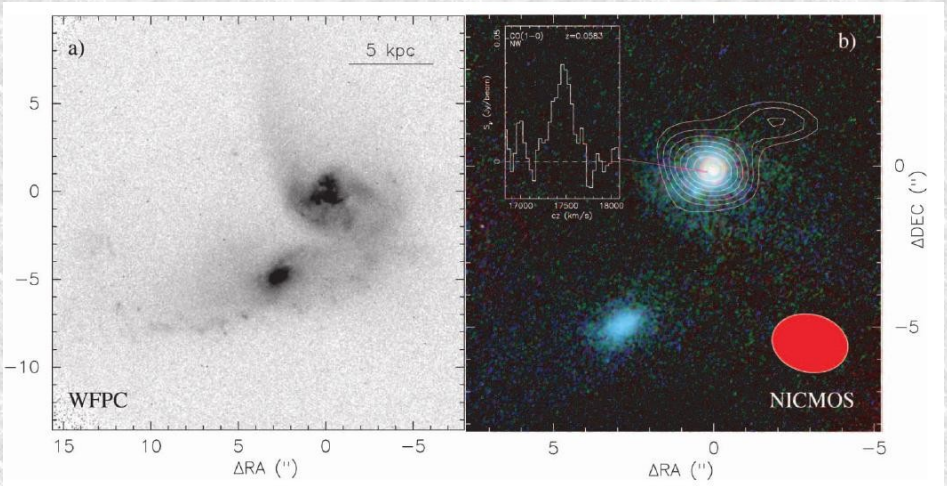
Milky Way:
LIR(MW)=1.5x10^{10} Lsun
Size CMZ~400 pc





Arp 220
Martín+2016
LIR=1.5x10^{12} Lsun
Nuclei sep: 350pc
SB, AGN?

Mrk 231
LIR=3x10^{12} Lsun
QSO & SB

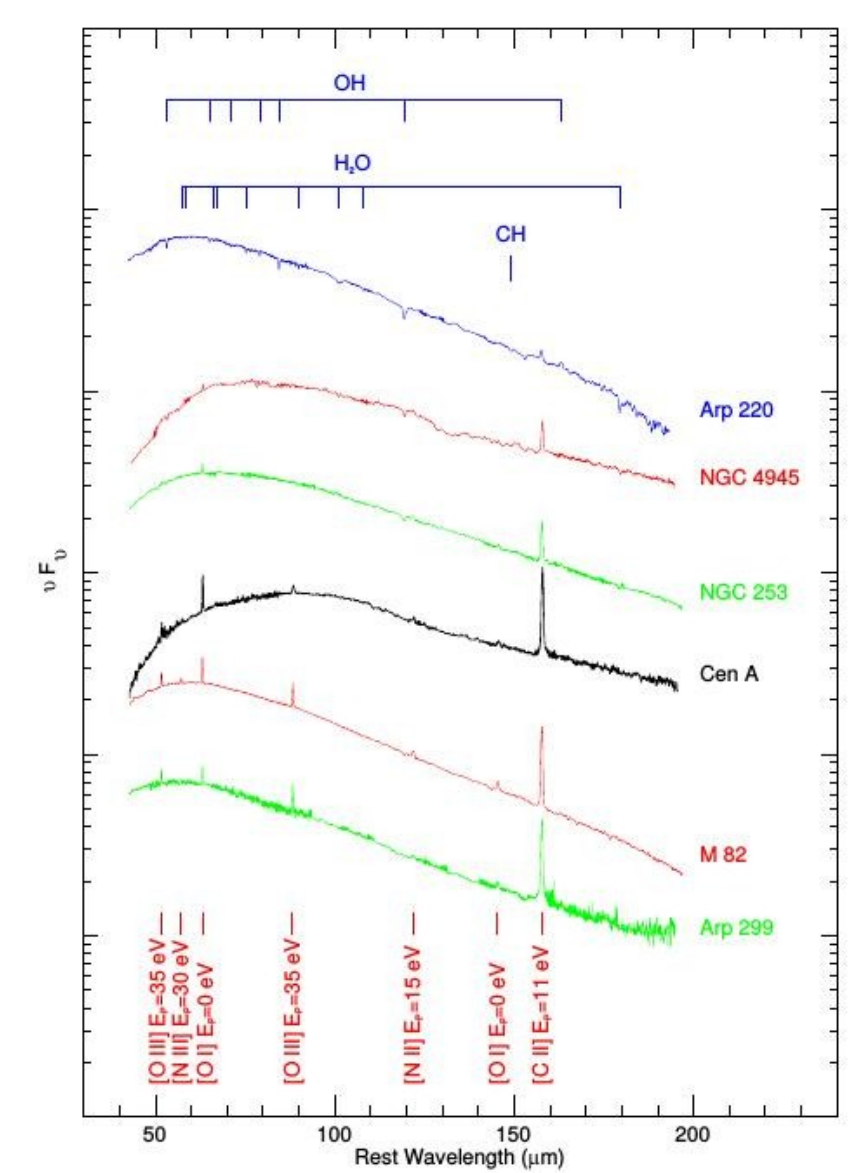


IRAS 08572+3915
Evans+2002
LIR>1.5x10^{12} Lsun
Nuclei sep: 5kpc
QSO

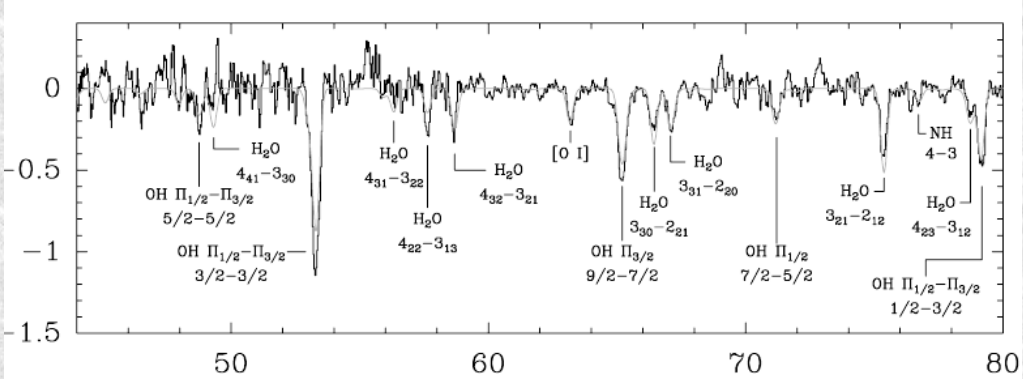
Infrared Space Observatory (ISO)

(U)LIRGs with high far-IR radiation densities have far-IR spectra (50-200 μm) dominated by absorption in molecular lines

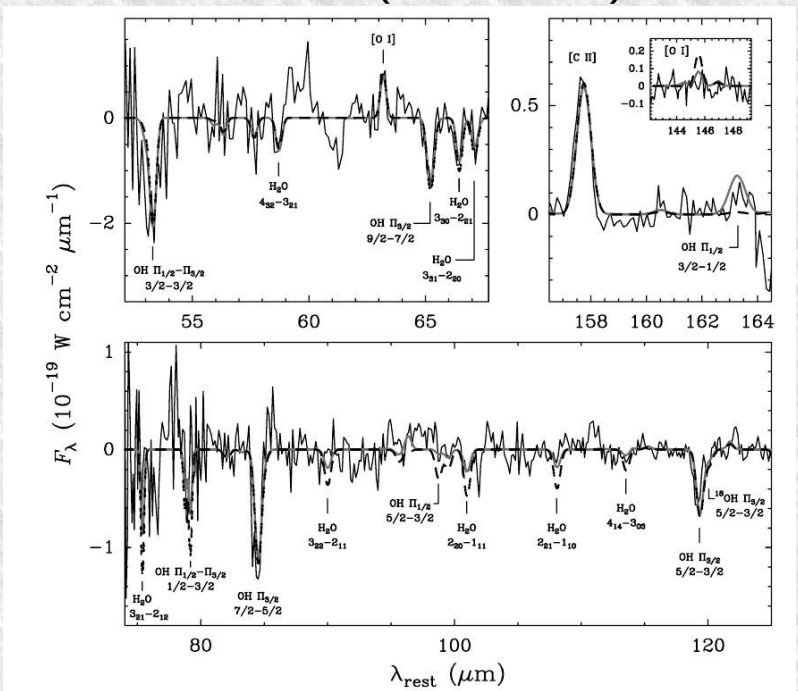
Fischer+1999



Arp 220 (G-A+2004)

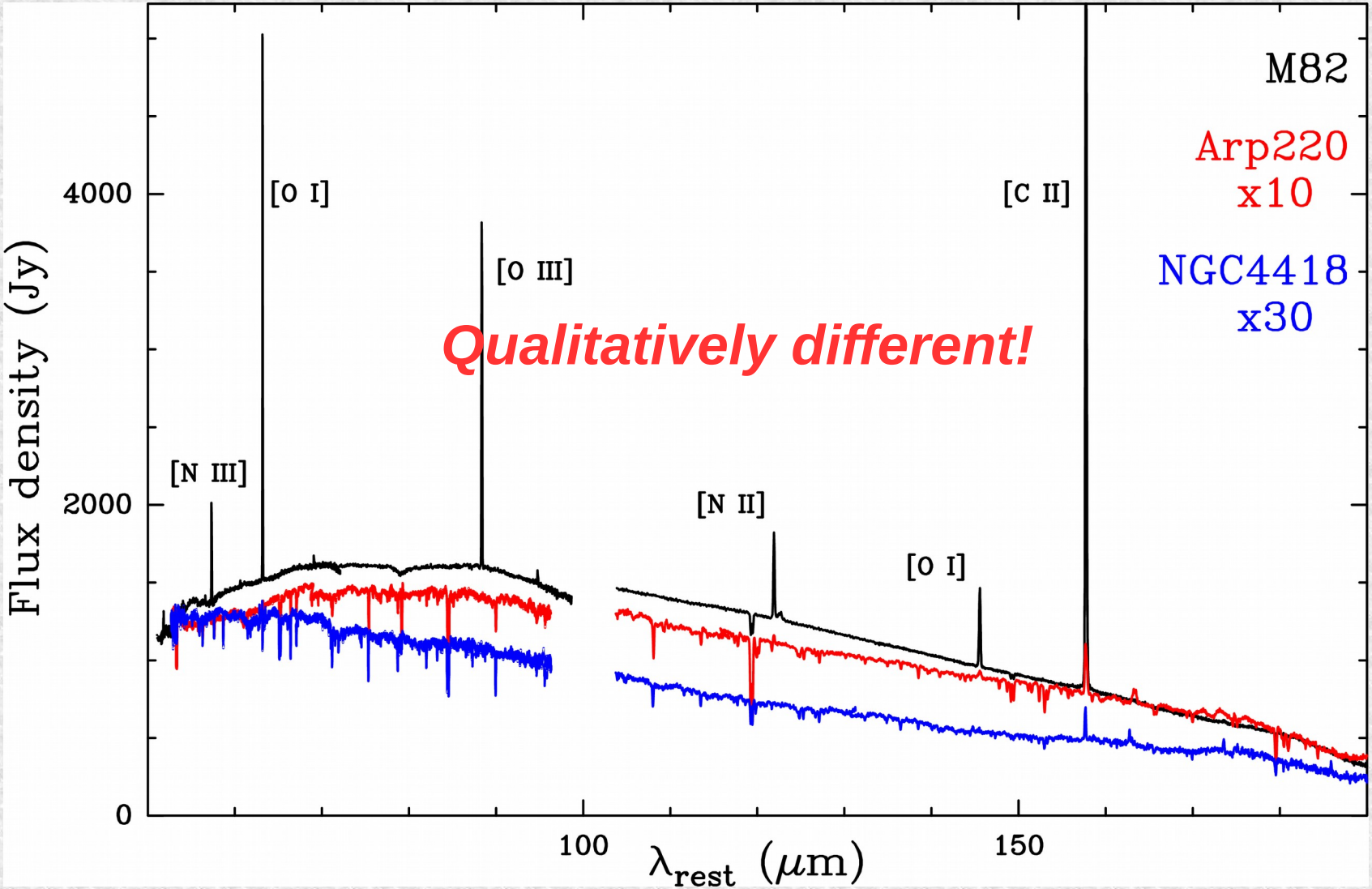


Mrk 231 (G-A+2008)



ABSORPTION LINES: Herschel/PACS

(U)LIRGs with high far-IR radiation densities have far-IR spectra (50-200 μm) dominated by absorption in molecular lines

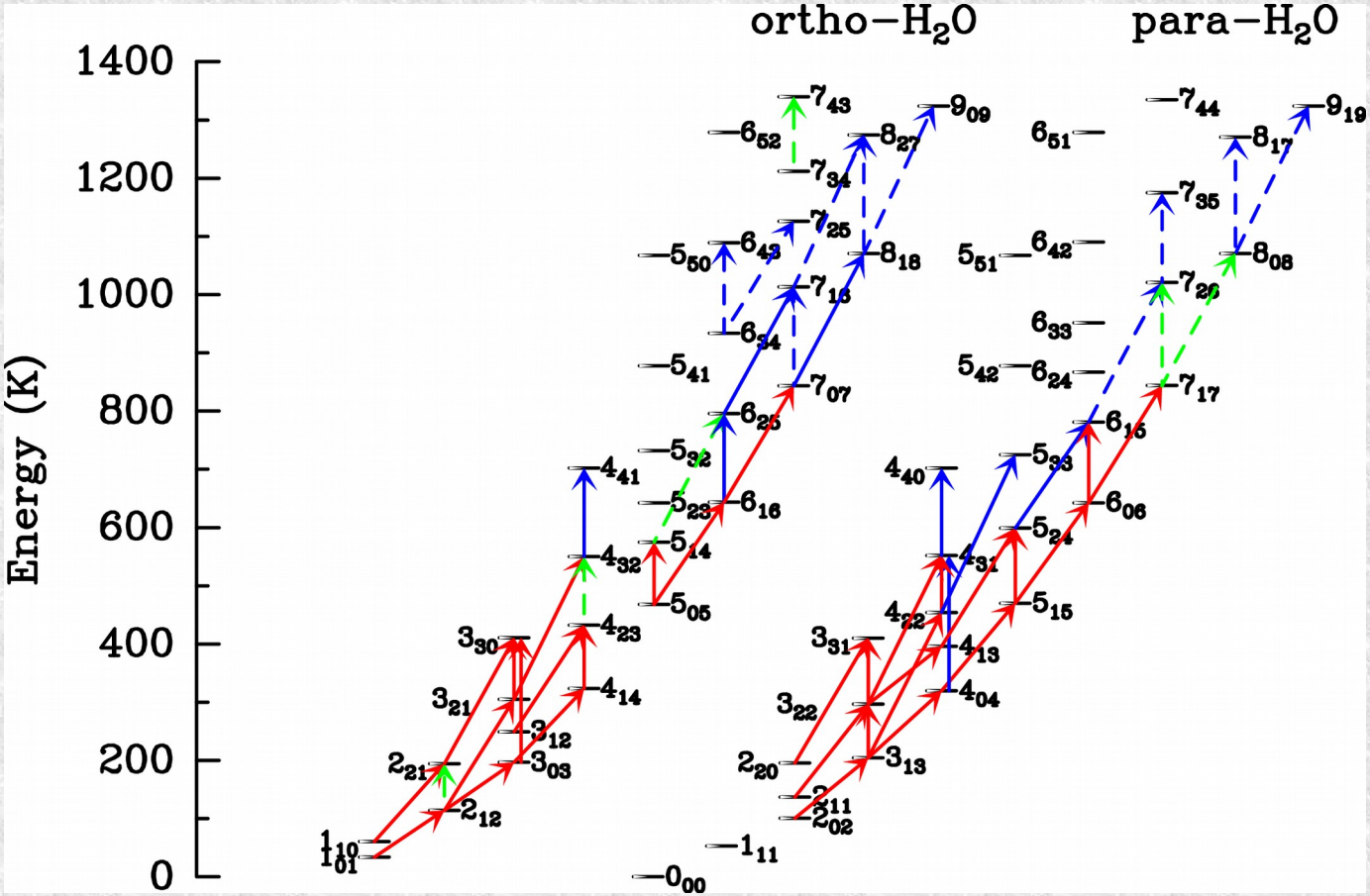


ABSORPTION LINES

Many hydrides contribute to the far-IR absorptions (OH, OH+, H2O+, H3O+, CH, CH+, NH, NH2, NH3, etc), but H_2O dominates in both absorption strength and number of lines

NGC 4418: 38 H_2O absorption lines

Arp 220: 28 H_2O absorption lines



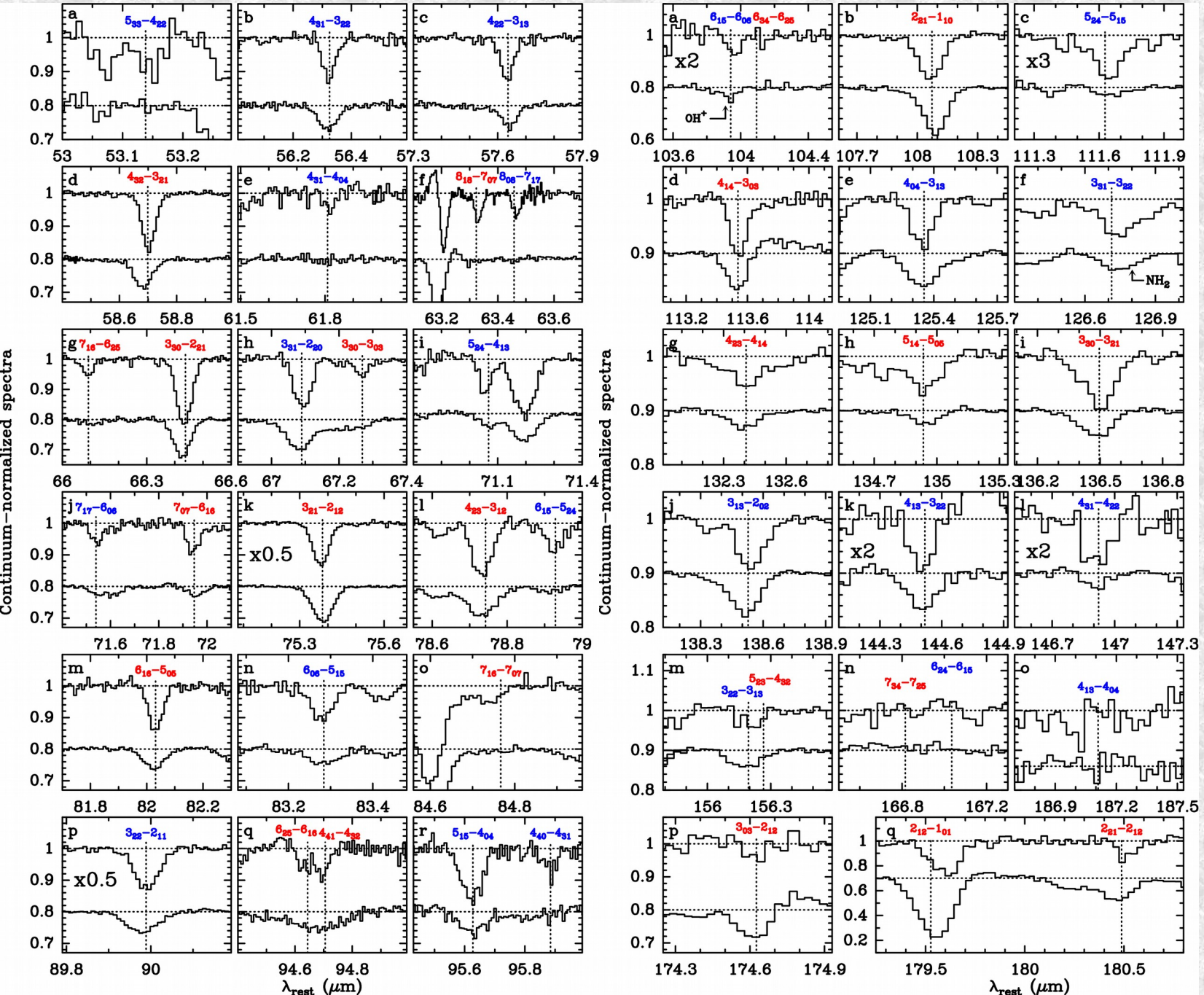
H2O: asymmetric rotor
Red: detected in both NGC 4418 & Arp 220
Blue: detected in NGC 4418
Dashed blue: marginal
Green: contaminated

González-Alfonso+2012

ABSORPTION LINES

H_2O lines in NGC 4418 & Arp 220 (G-A+2012)

Upper spectra:NGC 4418
Lower spectra: Arp 220

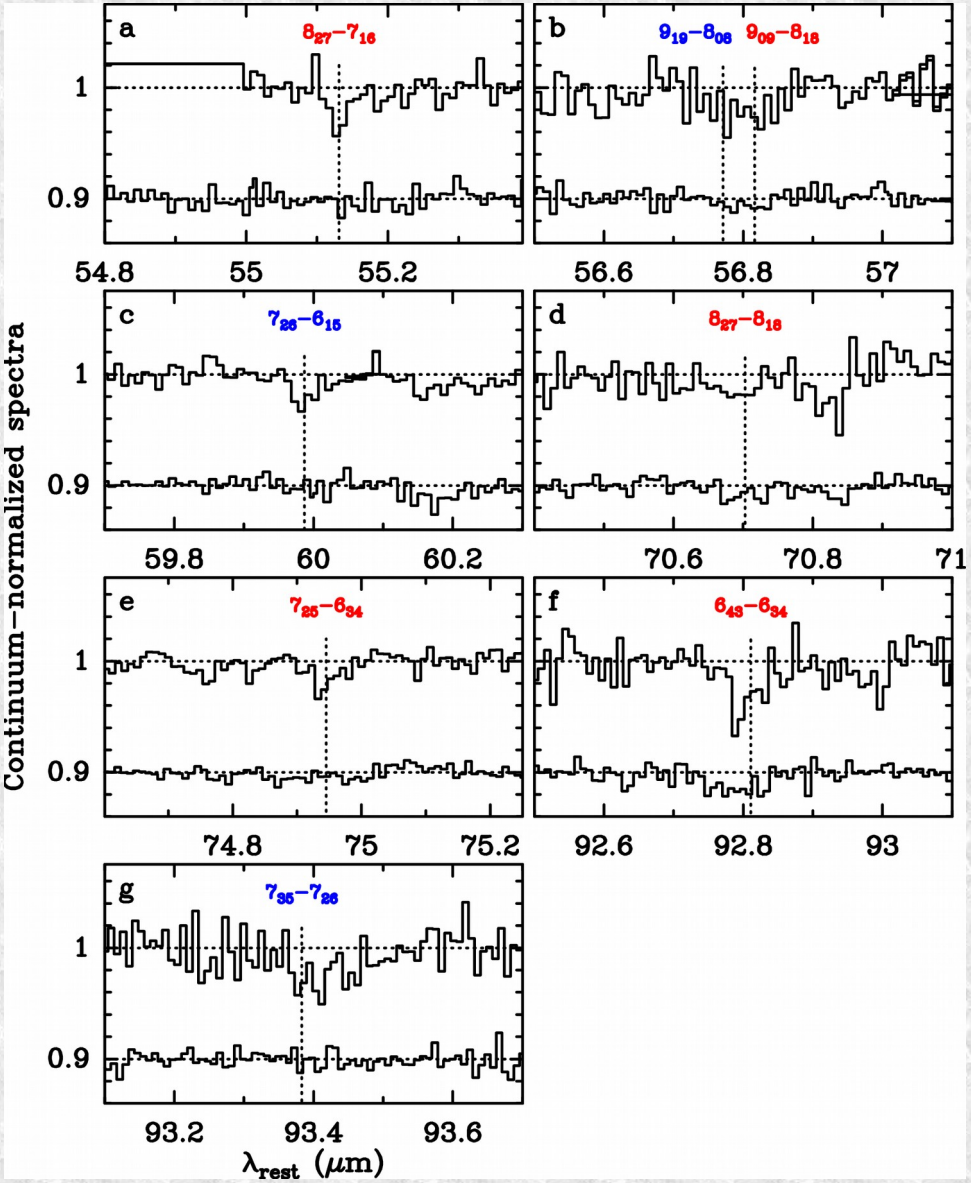


Red: ortho
Blue: para

ABSORPTION LINES

Upper spectra:NGC 4418
Lower spectra: Arp 220

Very high-lying (tentative) absorption lines of H_2O in NGC 4418



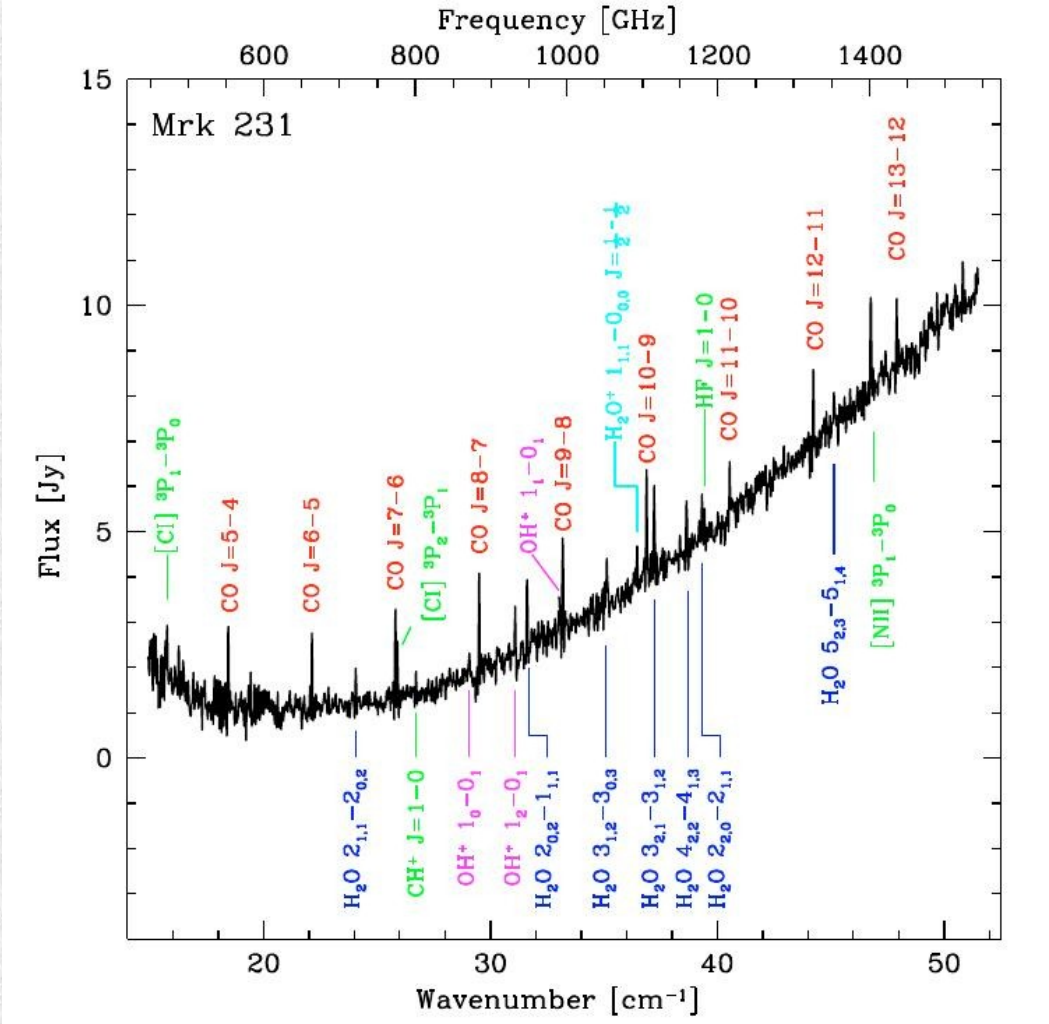
Red: ortho
Blue: para

Elower=800-1100 K

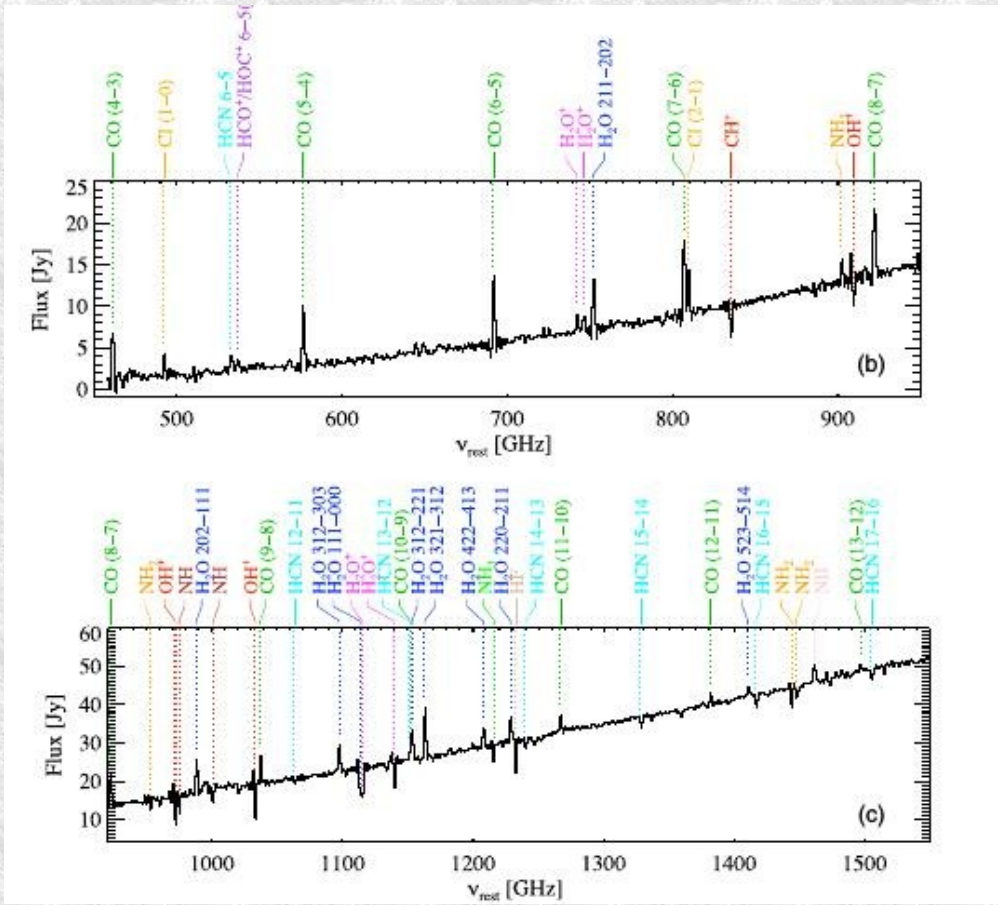
EMISSION LINES

Galaxies also show H2O *emission* lines in the submm (>200 μm), with upper level energies up to 640 K

Van der Werf+2010: Mrk 231



Rangwala+2011: Arp 220



...with strengths comparable to the CO lines!

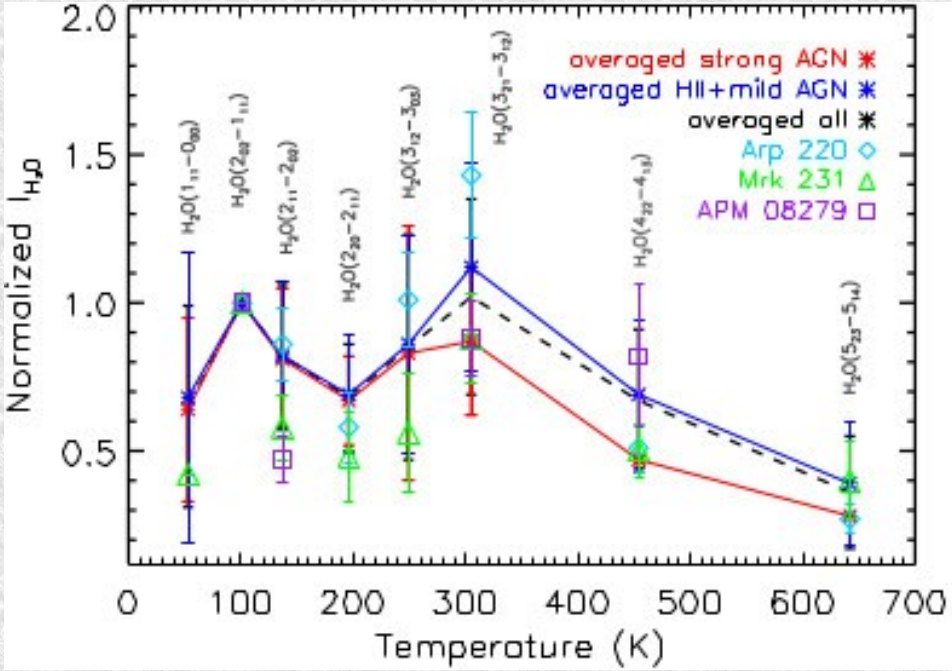
Note: the ortho-H2O ground-state 110-101 at 557 GHz is not detected

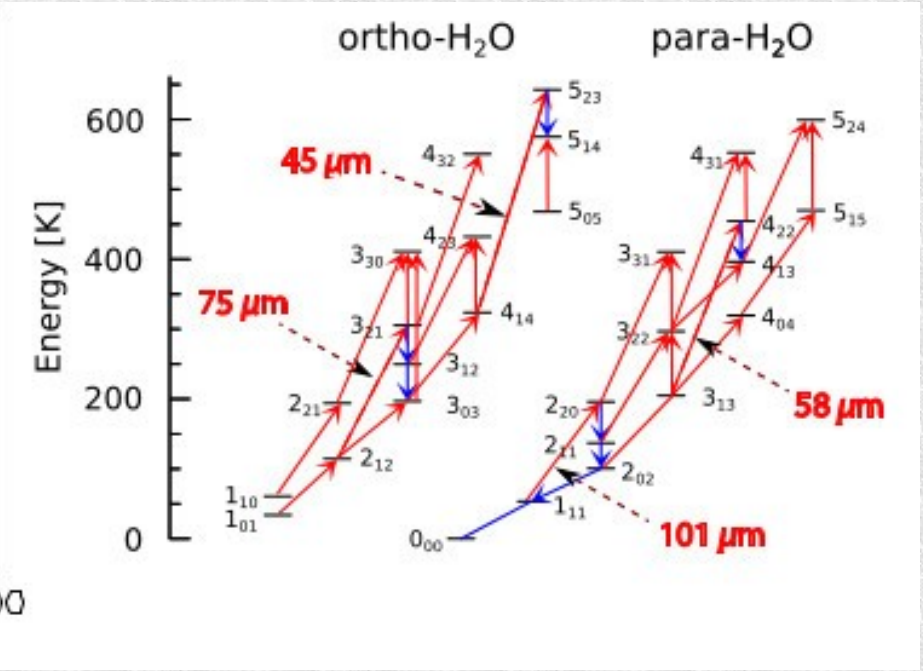
EMISSION LINES

Many local Galaxies show H2O *emission* lines in the submm

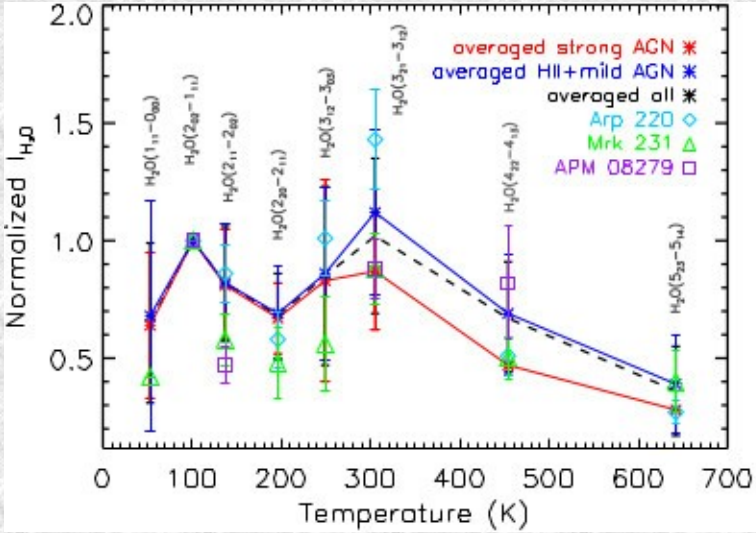
Yang+2013: 45 sources with at least 1 H2O line detected

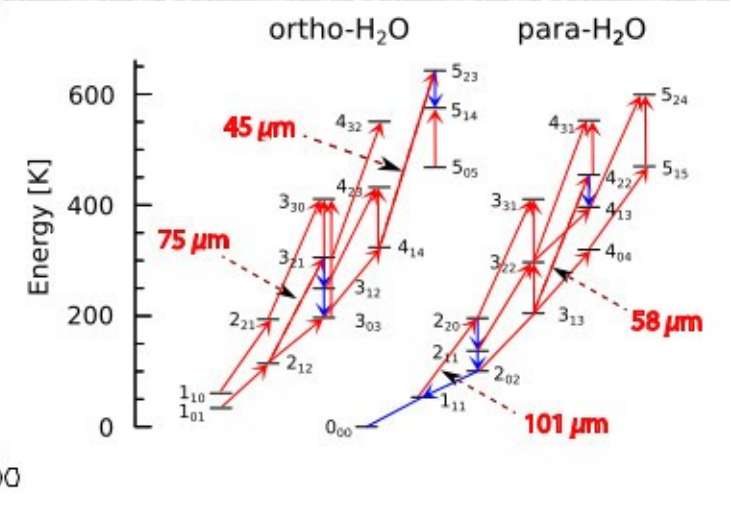
→ ***Talk by Chentao Yang at 14:50***





ABSORPTION & EMISSION LINES

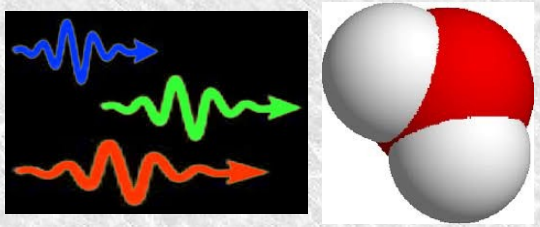




H2O is thus a great tool to study the ISM of galaxies! But…

*** How are these lines excited?**
*** What kind of information is providing?**

CO:
-Tgas, n(H2)
-M(H2)

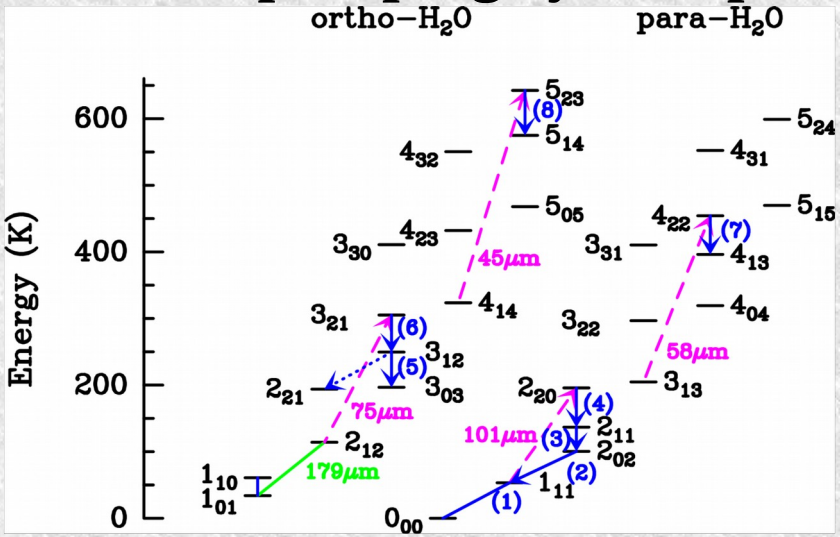


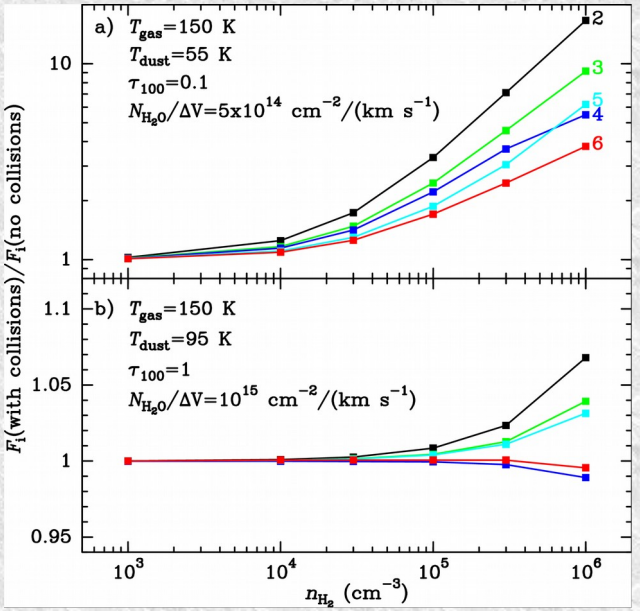
H2O:
-Tdust, τ(100)
-M(H2), N(H2)

- A complementary view of the ISM
-Absorption and emission lines are the 2 faces of the same coin
-H2O traces the far-IR continuum emission, with an obvious observable: SED
-Goal: fiting the H2O absorption/emission and the SED simultaneously
-Advantage: Einstein coefficients are much better known than collisional rates

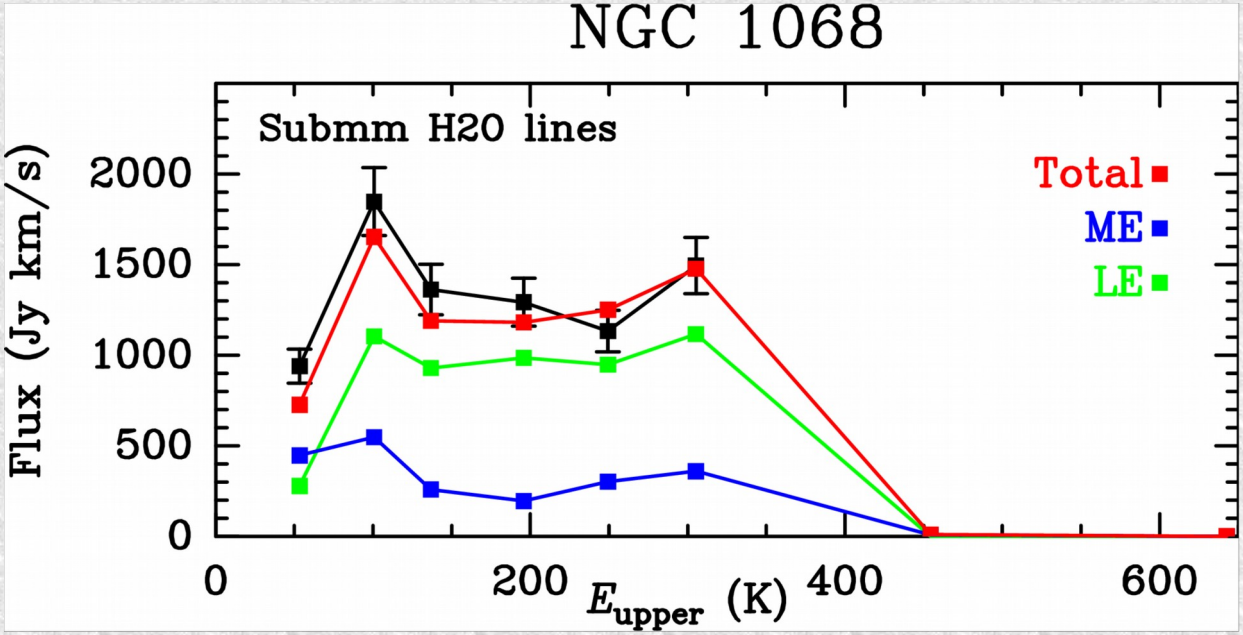
COLLISIONAL EXCITATION MAY STILL HAVE AN EFFECT!

In far-IR optically thin sources, as the 1(11) and 2(12) are the base-levels from which the pumping cycles operate (G-A+2014)





And how do we know observationally that collisions play a role?
The 1(11)-0(00) at 269 microns will be seen in *emission*

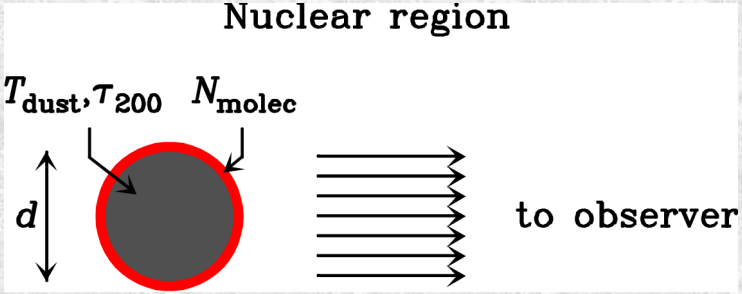


Observations from Spinoglio+2012
Model from G-A+2014

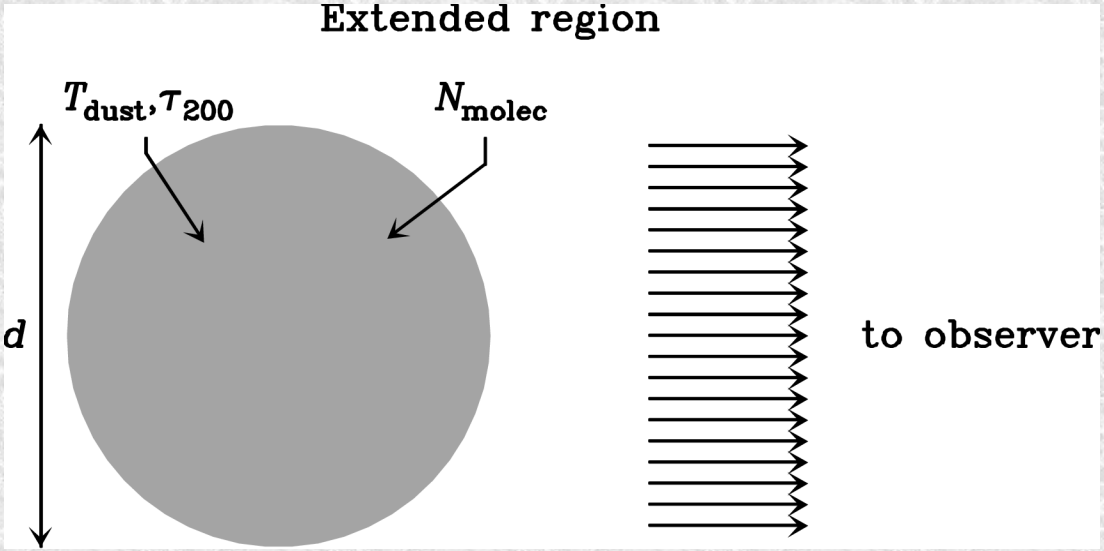
***Lines 7-8 not detected: optically thin far-IR**

How models work...

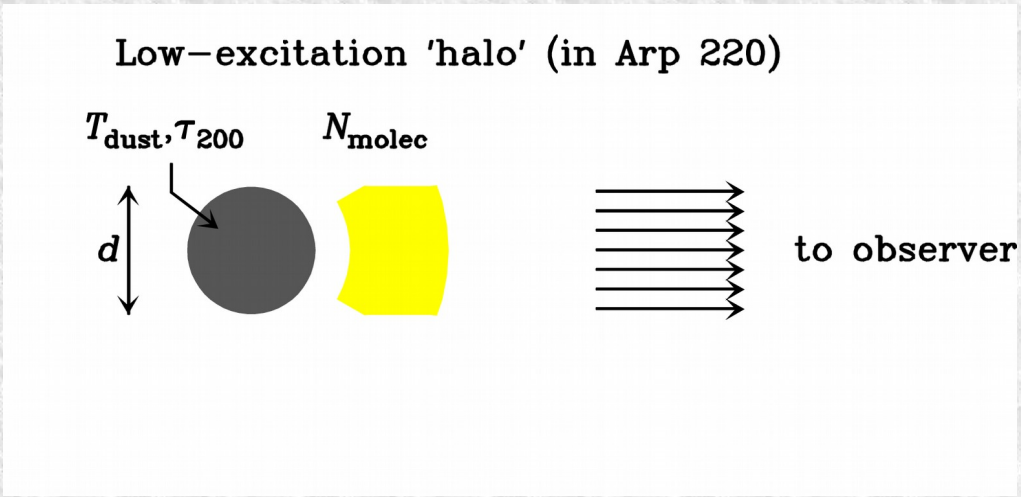
González-Alfonso et al (2012, 2013, 2014)



Nuclear regions: required to fit the high-lying absorption lines, and the emission lines with Eupper>400 K"

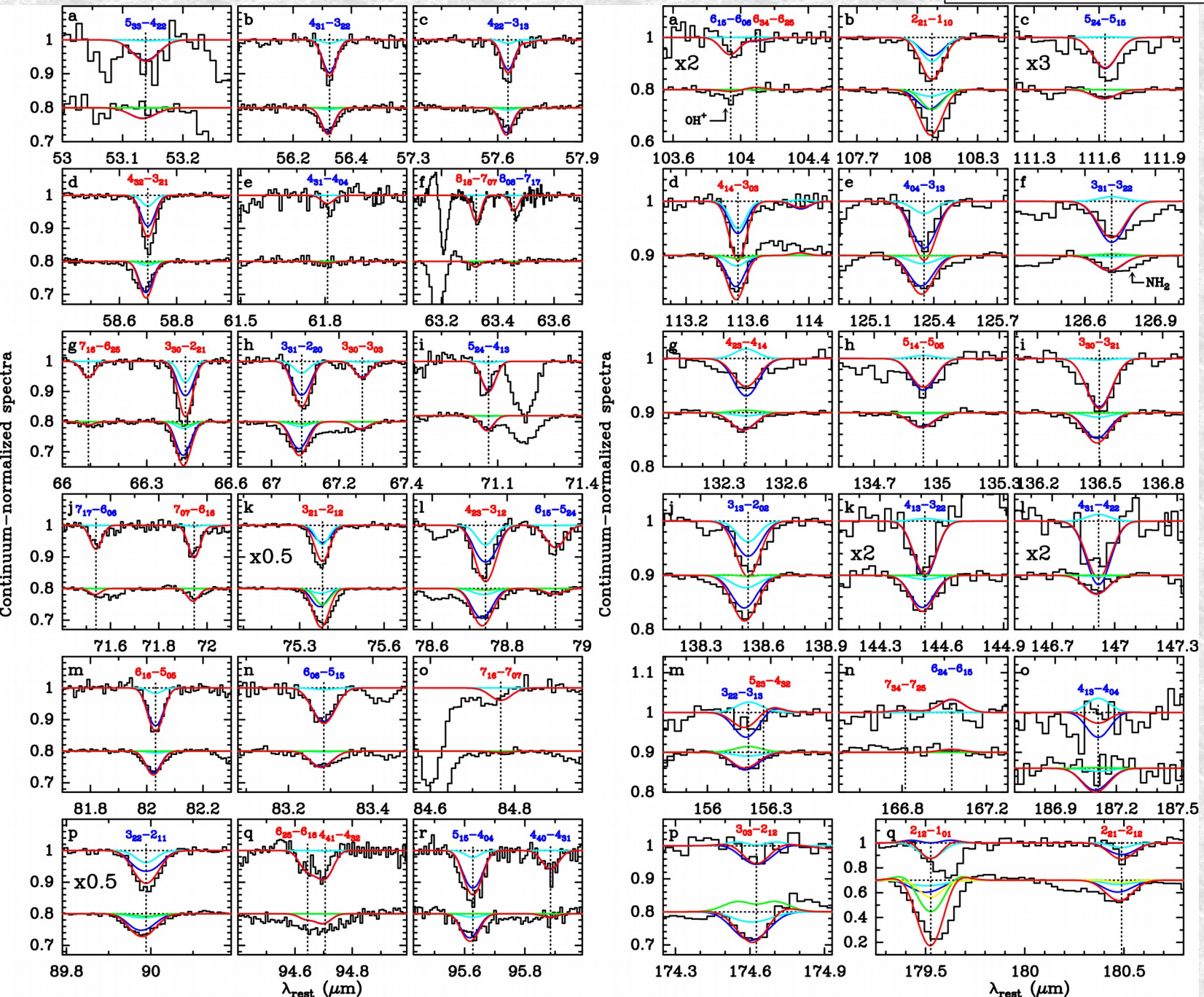


Extended regions: required to fit the low-lying absorption lines, and the emission lines with Eupper<400 K



Halo: the ground-state lines in some sources are strong and require foreground absorption

Models for the absorption H_2O lines: ortho/para=3



Red: ortho
Blue: para

Nuclear regions:

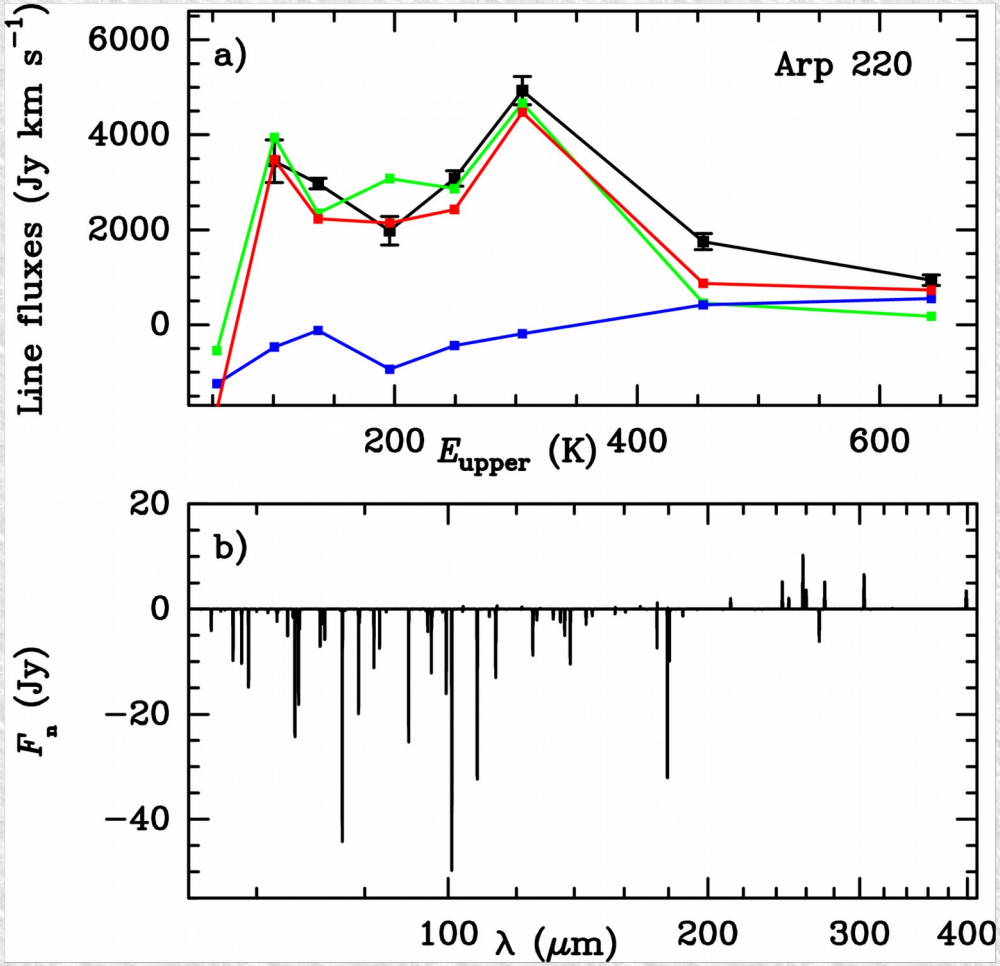
NGC 4418:
Tdust~130-150 K
$N(H_2O)/\tau_{50}$~
(2-6)x10^{18} cm^{-2}

Arp 220:
Tdust~90-110 K
$N(H_2O)/\tau_{50}$~
(0.8-6)x10^{18} cm^{-2}

mantle-free dust grains

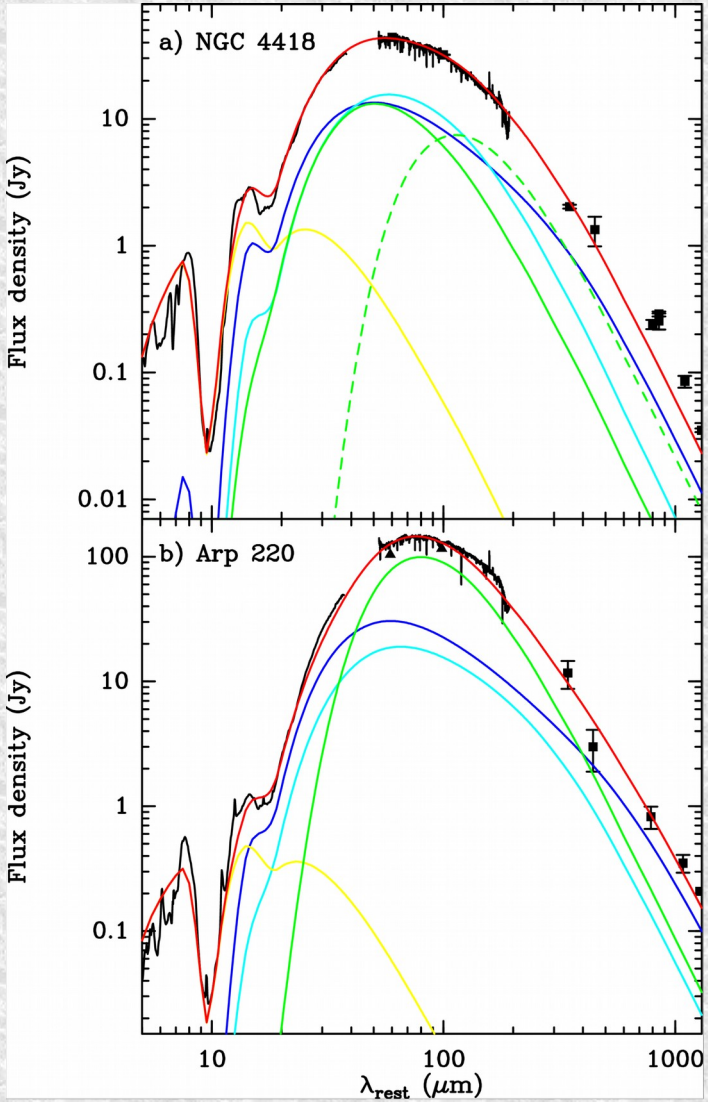
or "undepleted chemistry"

Models for the emission H_2O lines: ortho/para=3 (G-A+14)



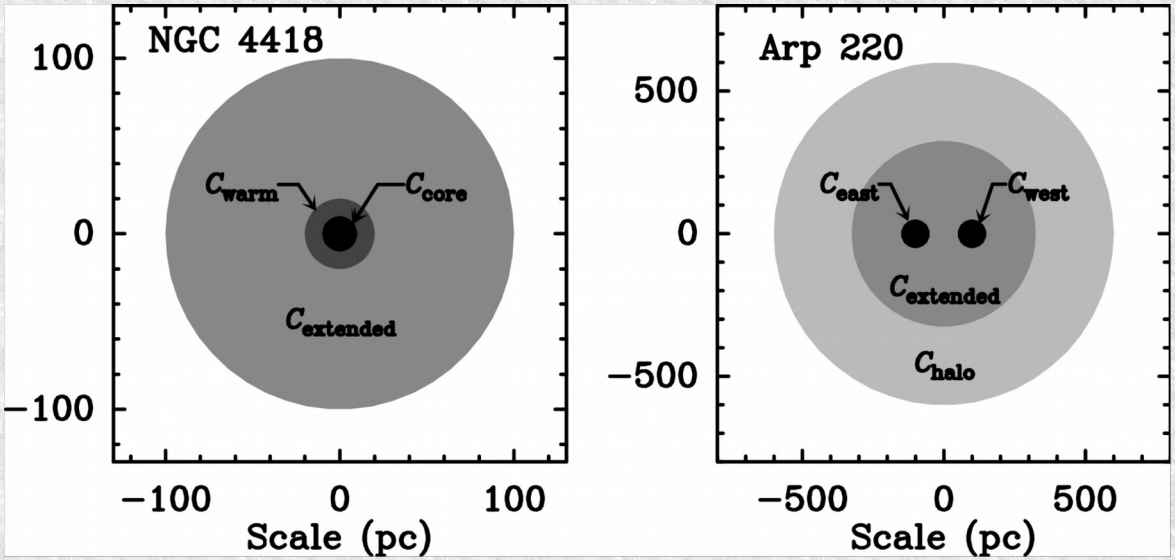
The emission lines with E<400 K require a more extended region (and less thick) than the absorption lines

The far-IR continuum (G-A12)



The nuclear regions probe the transition from the mid- to the far-IR

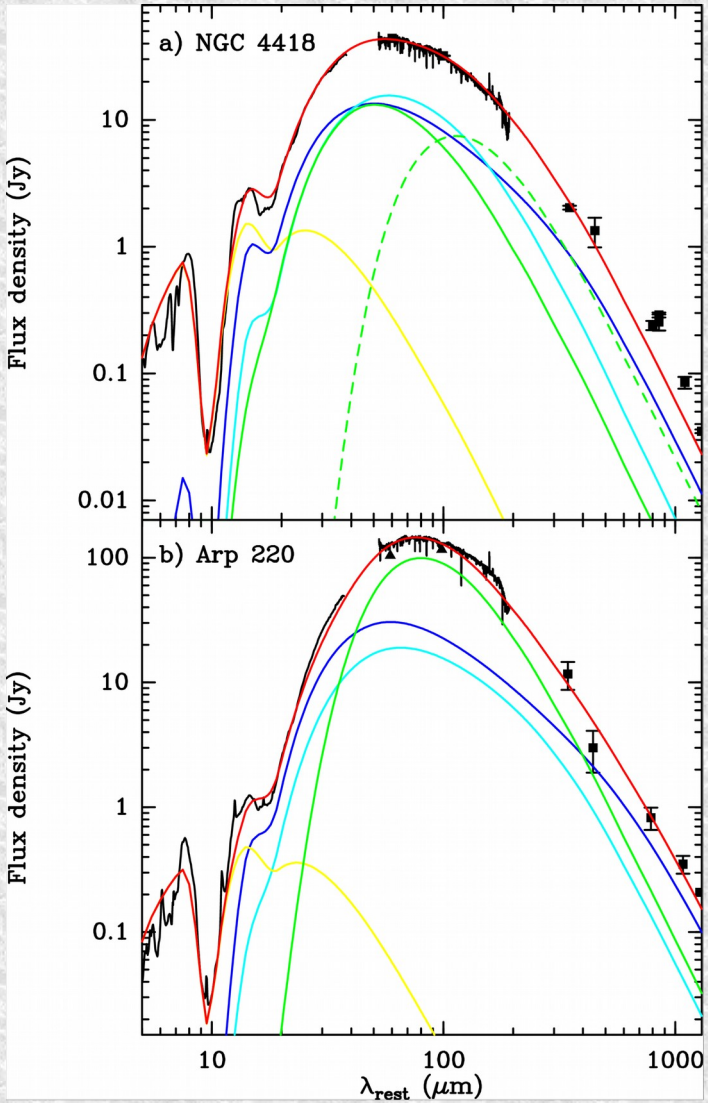
H2O emission/absorption probes the source structure (G-A+12)



**The optically thick and compact nuclei are responsible for the high-lying H2O absorption lines.*
**The more optically thin, more extended Cextended dominate the emission in the submm H2O emission lines*

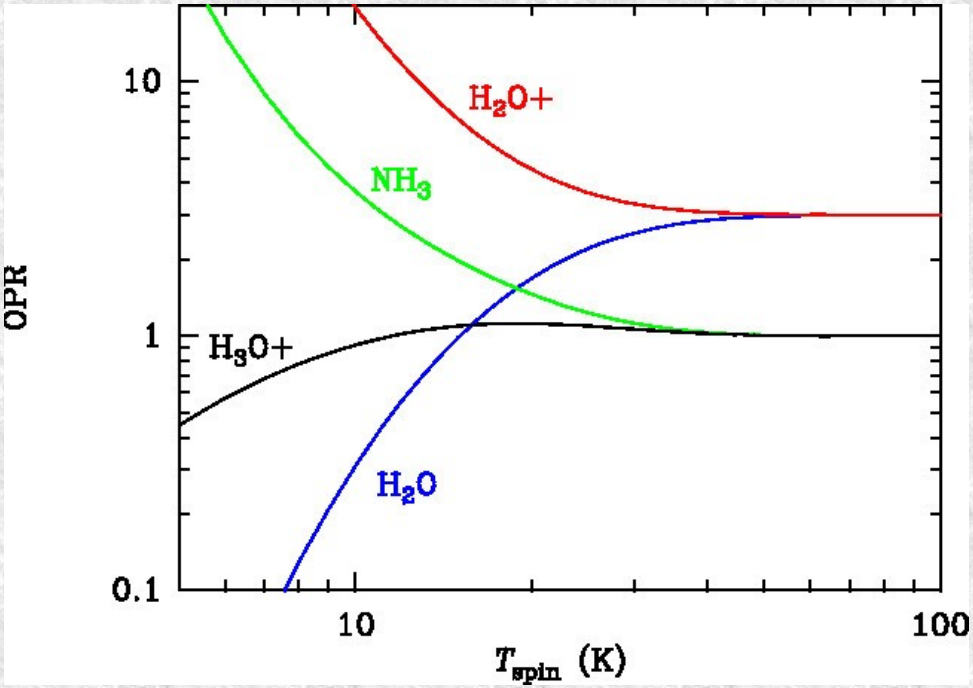
We understand better the SEDs… from the lines!

The far-IR continuum (G-A+12)



The nuclear and extended regions may have different SEDs

Expected ortho-to-para ratios OPRs



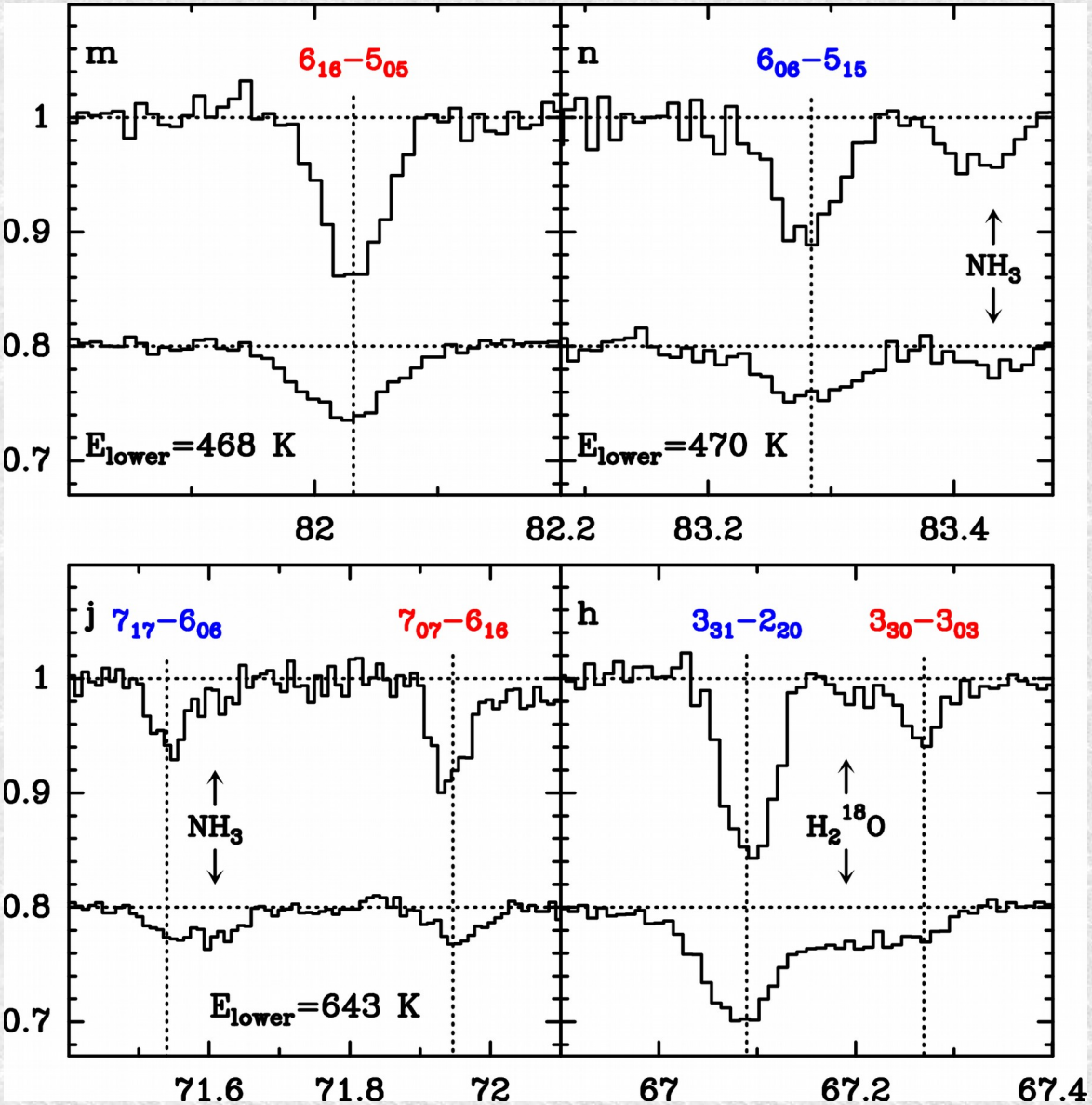
Caveats:

1) Line opacity effects
2) Line excitation
3) Several components contributing to the absorption
4) Line blending
5) Baseline uncertainty

We investigate whether the observed H2O line ratios are consistent with the high Tspin OPR value of 3, or whether there is evidence for departure from this value.

High-lying H_2O lines

Upper spectra:NGC 4418
Lower spectra: Arp 220



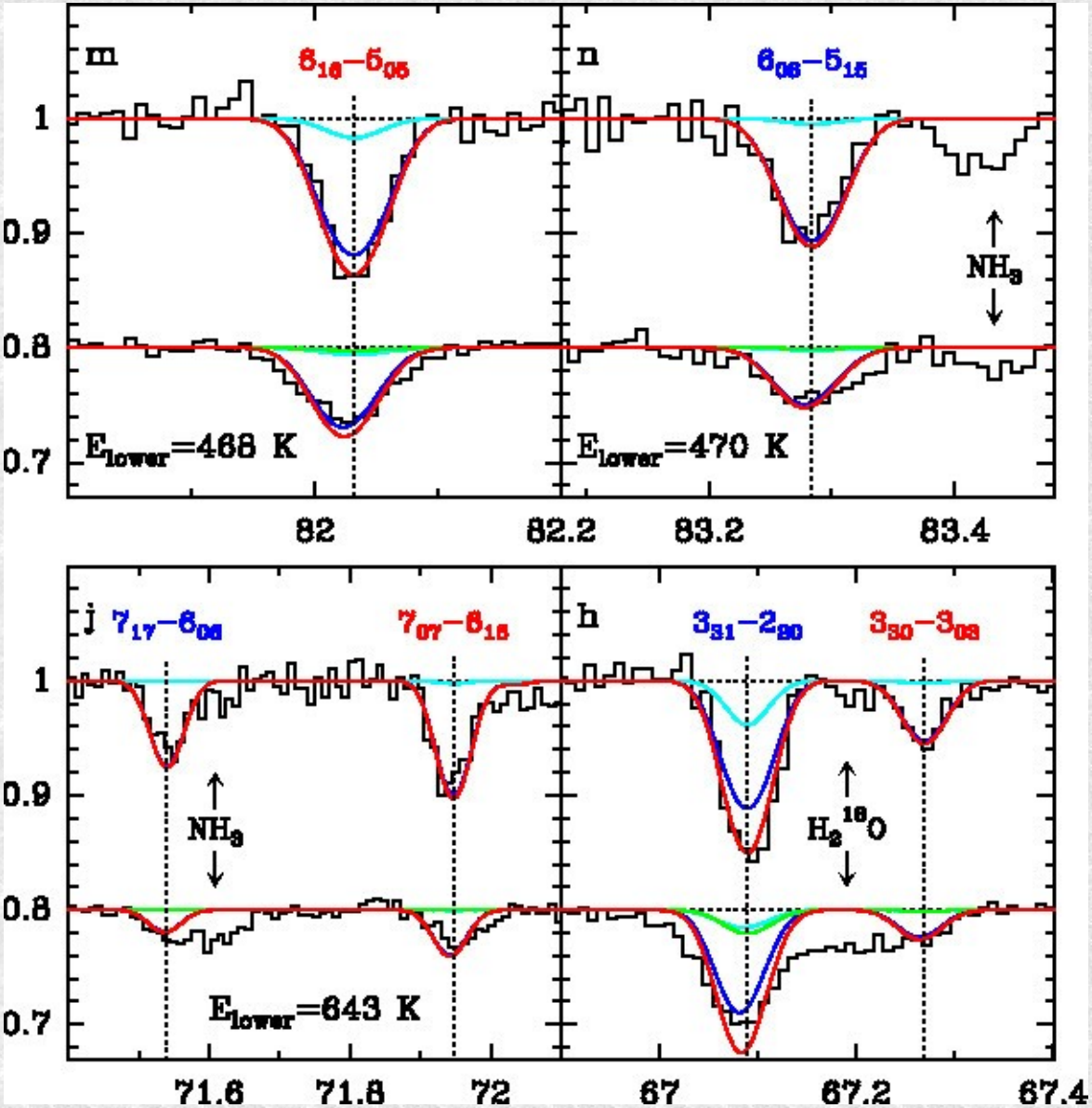
Labels
Red: ortho
Blue: para

The *observed* OPR is not 3, but...

(G-A+12)

Models for H_2O: ortho/para=3

Upper spectra:NGC 4418
Lower spectra: Arp 220

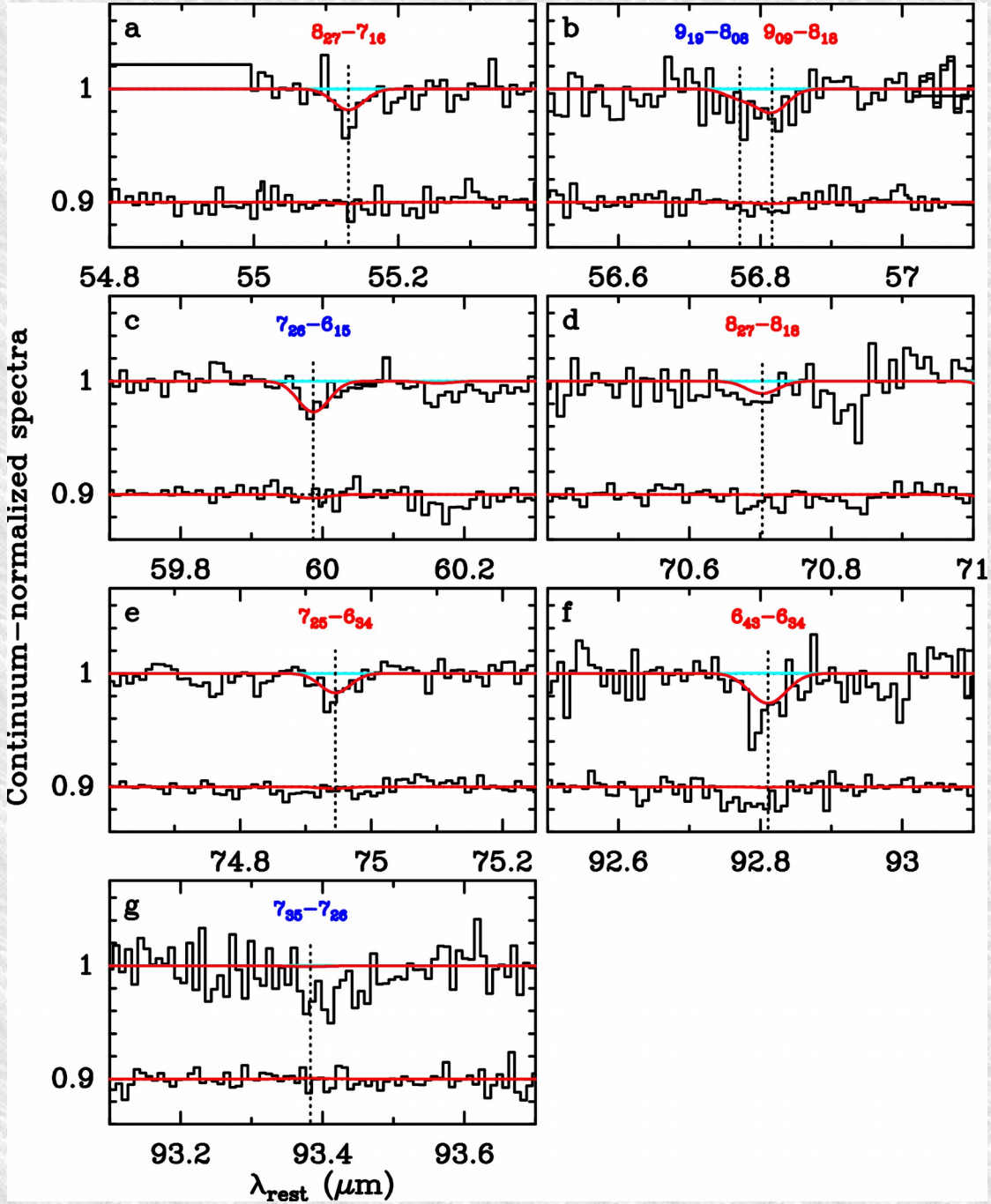


Labels
Red: ortho
Blue: para

...this is attributable to very high H2O columns: consistent with OPR=3

(G-A+12)

Models for H_2O: ortho/para=3



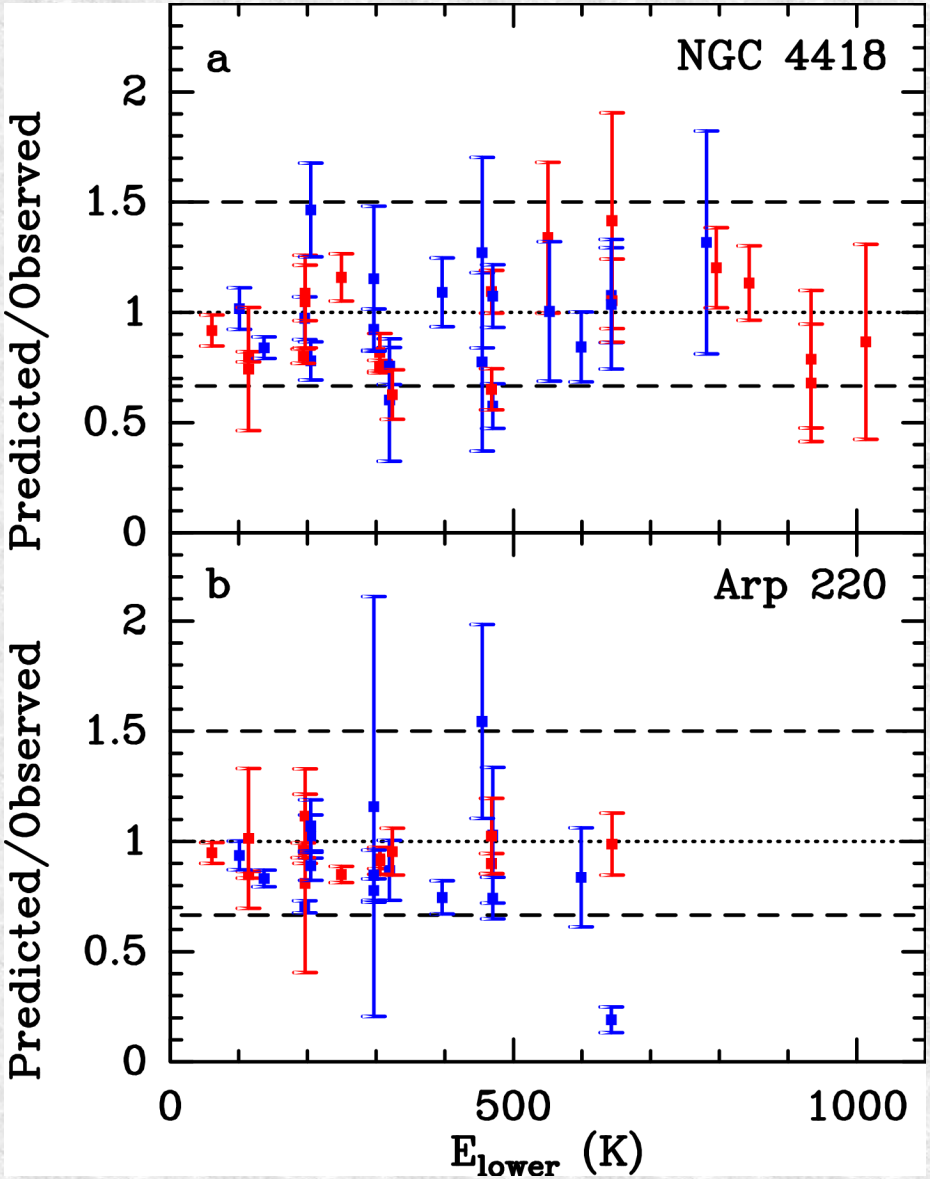
Upper spectra:NGC 4418
Lower spectra: Arp 220

Labels
Red: ortho
Blue: para

Elower=800-1100 K

(G-A+12)

No significant departure from an ortho-to-para H_2O ratio of 3 (high-temperature limit) is found



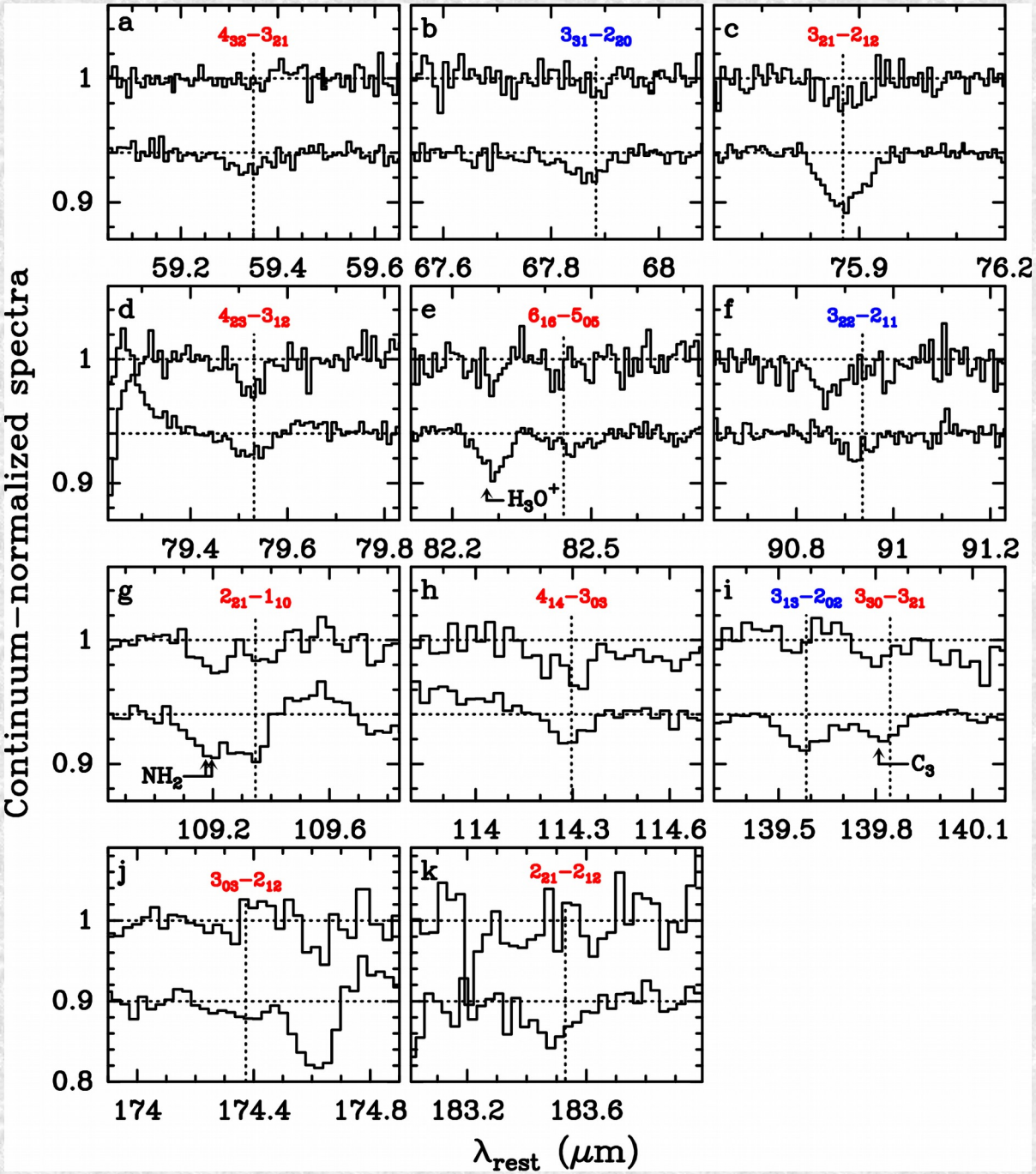
Red: ortho
Blue: para

NGC 4418 (nuclear):
Tdust~130-150 K
$N(H_2O)/\tau_{50}$~(2-6)x10^{18} cm^{-2}

Arp 220 (nuclear):
Tdust~90-110 K
$N(H_2O)/\tau_{50}$~(0.8-6)x10^{18} cm^{-2}

(G-A+12)

$H_2{}^{18}O$ lines also detected

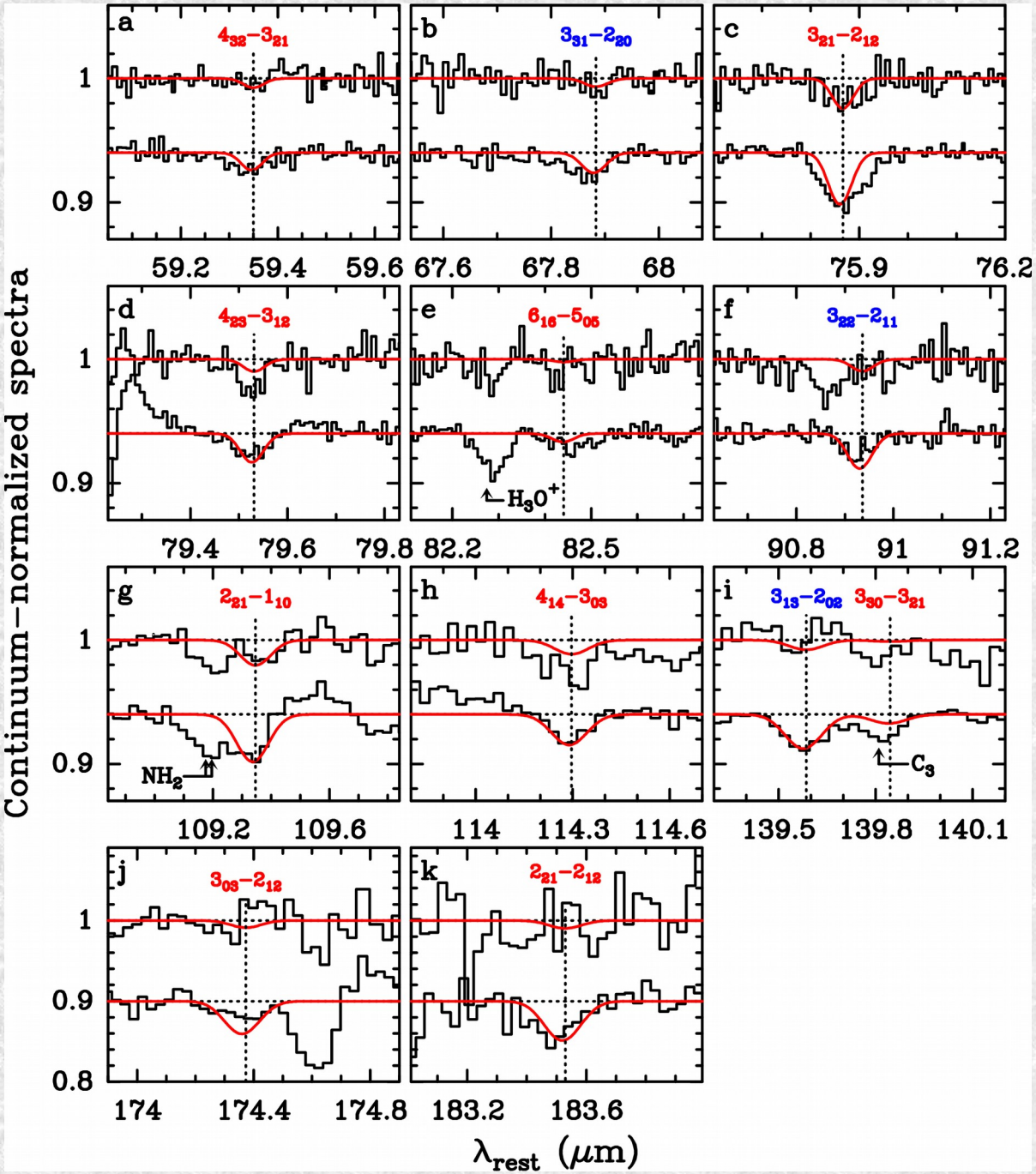


Upper spectra:NGC 4418
Lower spectra: Arp 220

Labels
Red: ortho
Blue: para

(G-A+12)

$H_2{}^{18}O$ lines: ortho/para=3



Upper spectra:NGC 4418
Lower spectra: Arp 220

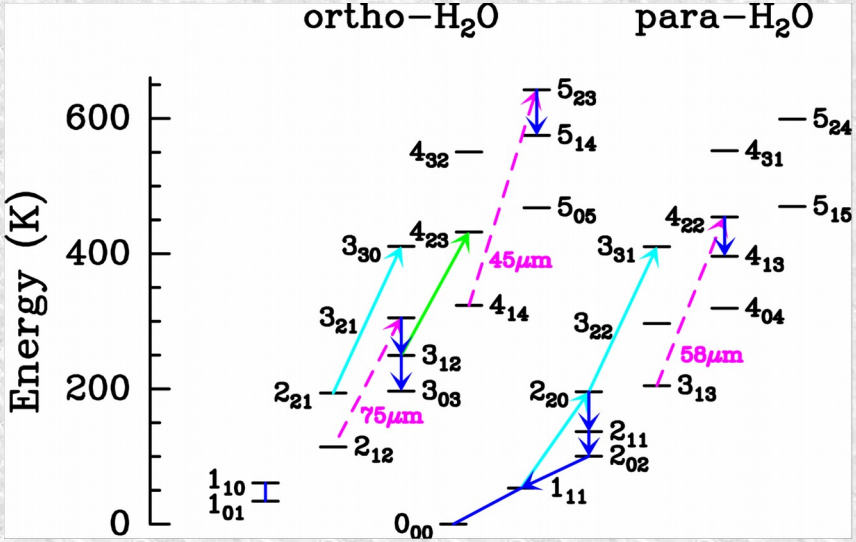
Labels
Red: ortho
Blue: para

NGC 4418: 16O/18O=250-500
Arp 220: 16O/18O=70-130

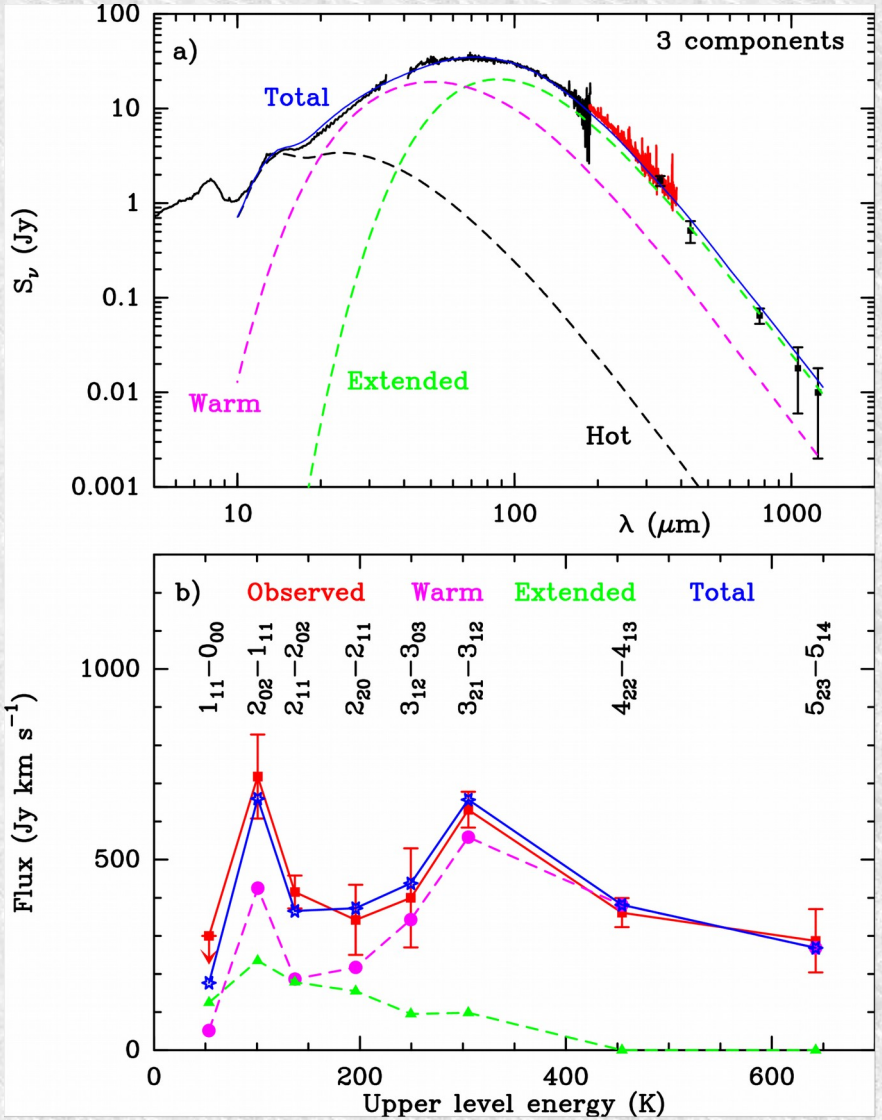
(G-A+12)

Emission lines in Mrk 231 (G-A+10)

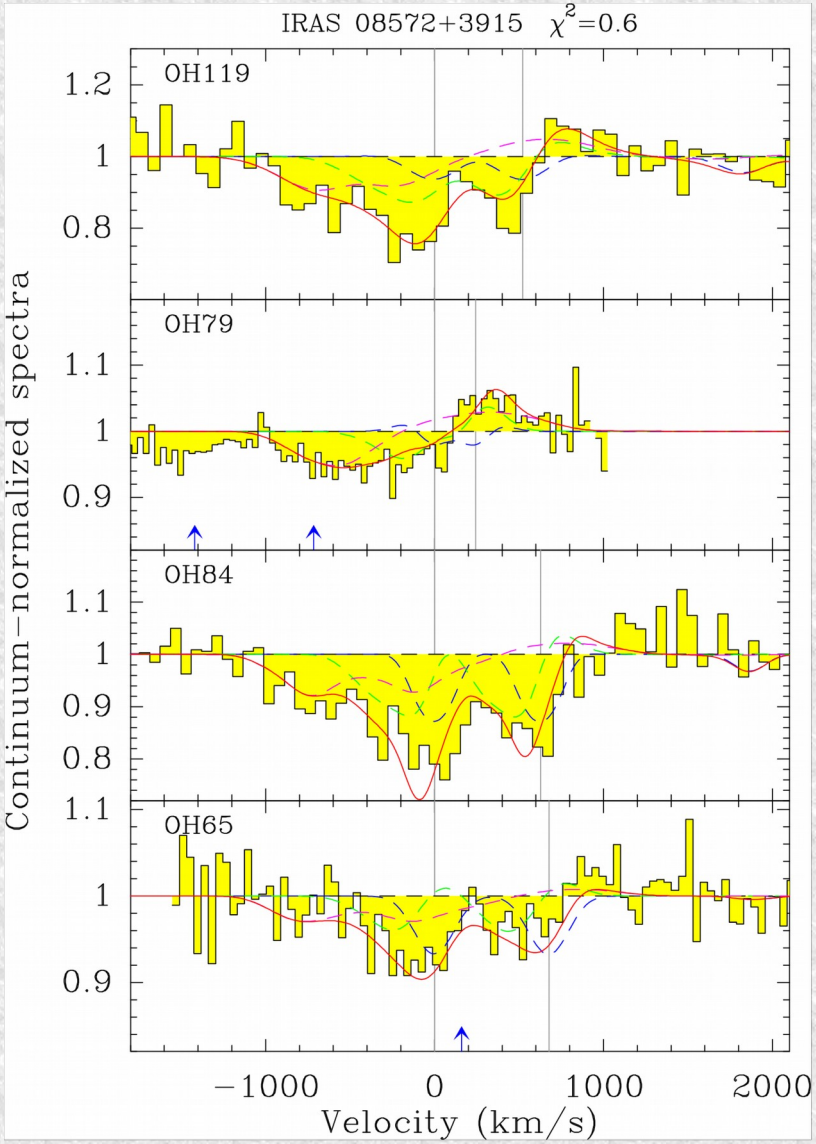
PACS: Talk by Jackie Fischer at 14:30

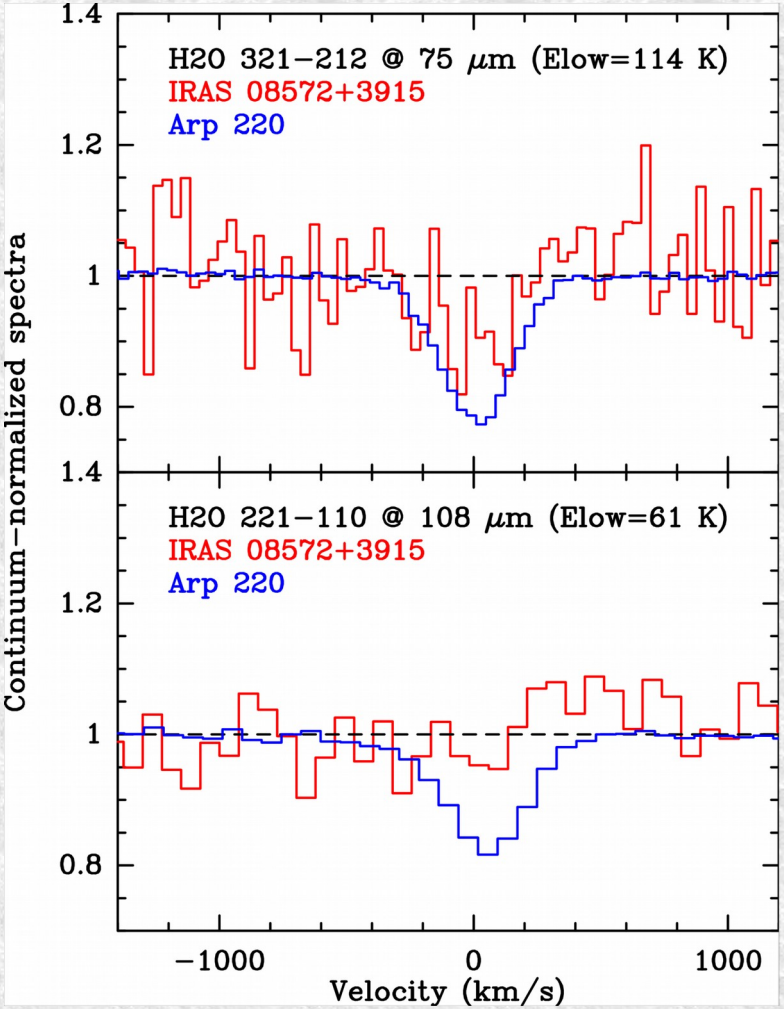


Component→	Hot[a] (H$_C$)	Warm (W_C)	Extended (E_C)
Radius (pc)	23	120	610
T_{dust} (K)	400–150	95	41
$\tau_{100\ \mu m}$	0.4	1.0	0.5
L ($L_\odot$)	7.5×10^{11}	1.9×10^{12}	9.6×10^{11}
Gas Mass[b] ($M_\odot$)	1.9×10^{6}	5.9×10^{8}	7.7×10^{9}
$N(H_2O)$ (cm^{-2})	–	5.2×10^{17}	2.0×10^{16}
V_{turb} (km s^{-1})	–	60[d]	40
$n(H_2)$[c] (cm^{-3})	–	1.5×10^{6}	5×10^{5}
T_{gas}[c] (K)	–	150	100



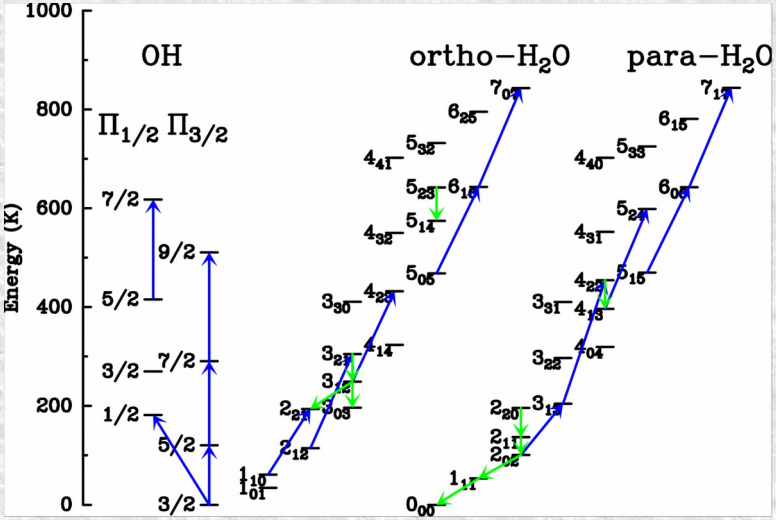
OH and H2O in IRAS 08572+3915, G-A+in prep

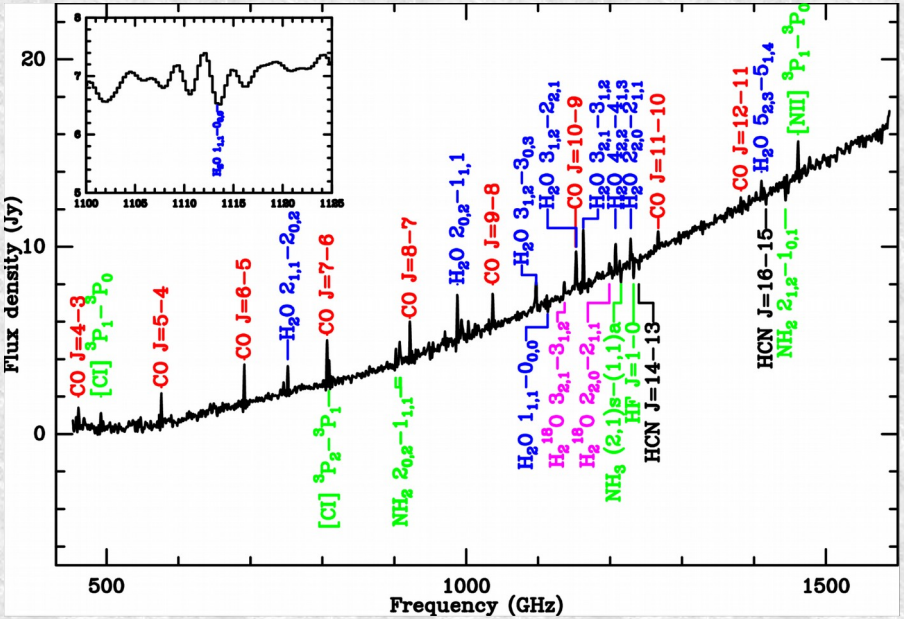


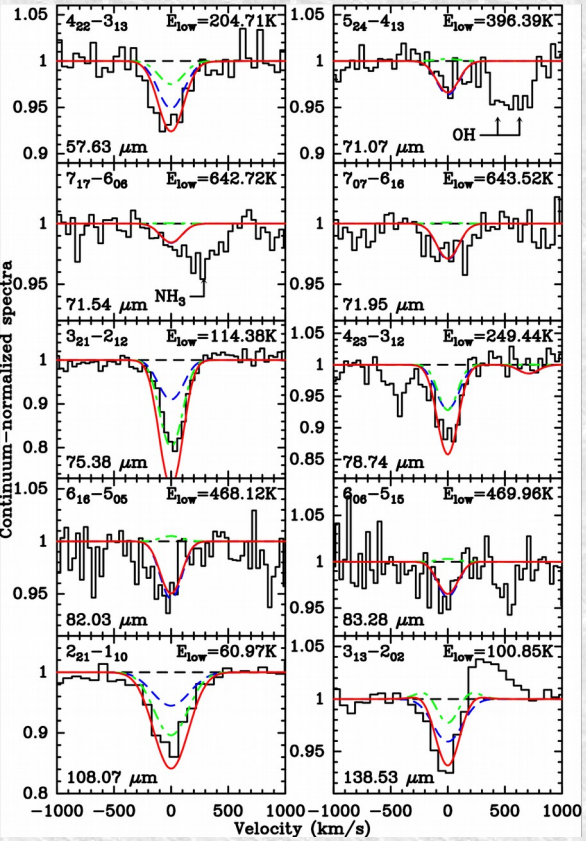


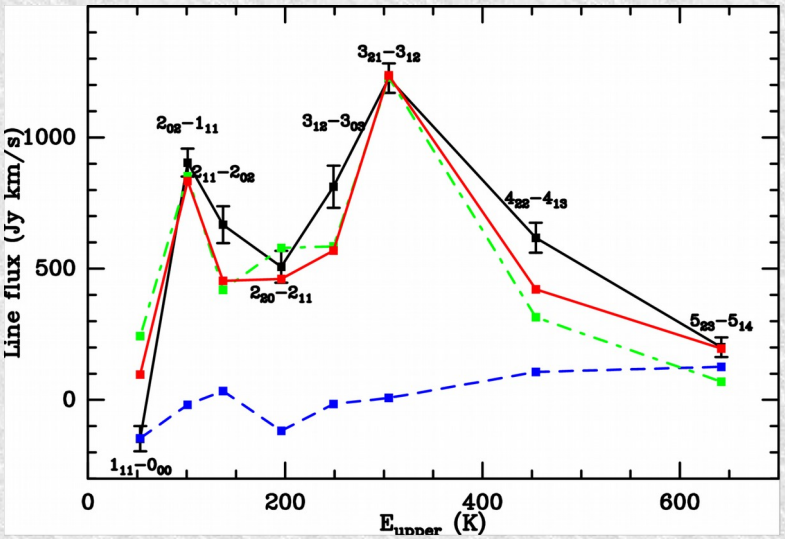
H2O/OH decreases in strong AGNs → H2O formed in surrounding SB?

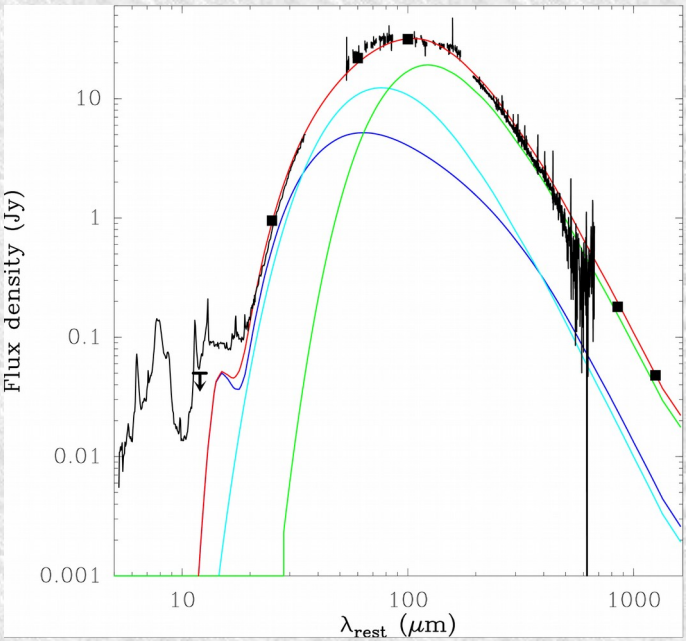
Emission & absorption lines in Zw049 (Falstad+15) *Poster by Niklas Falstad (P10)*





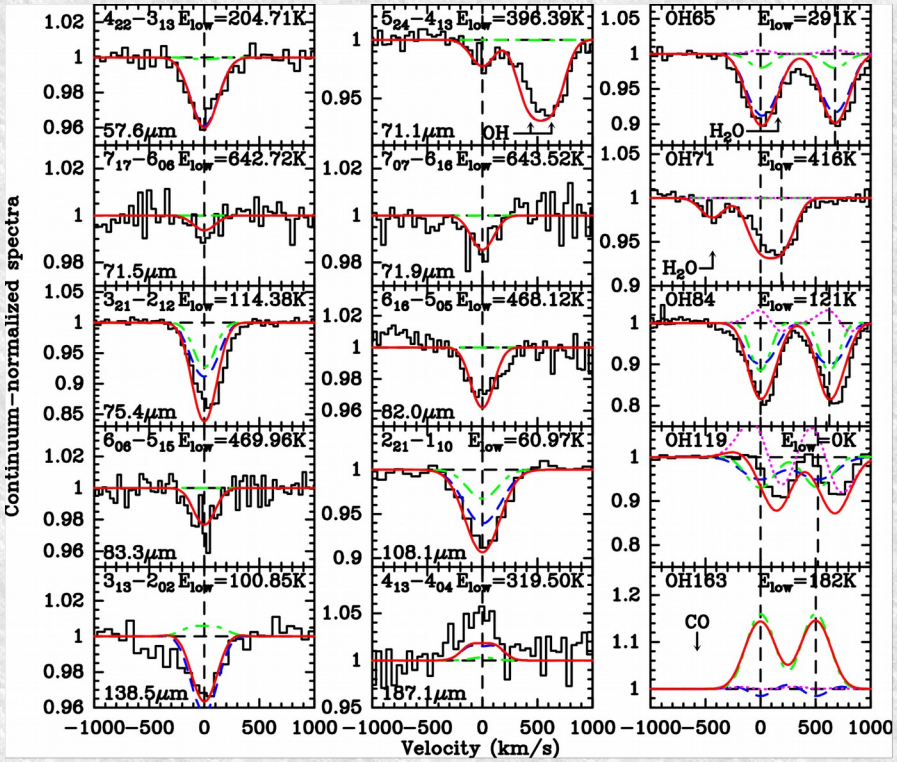


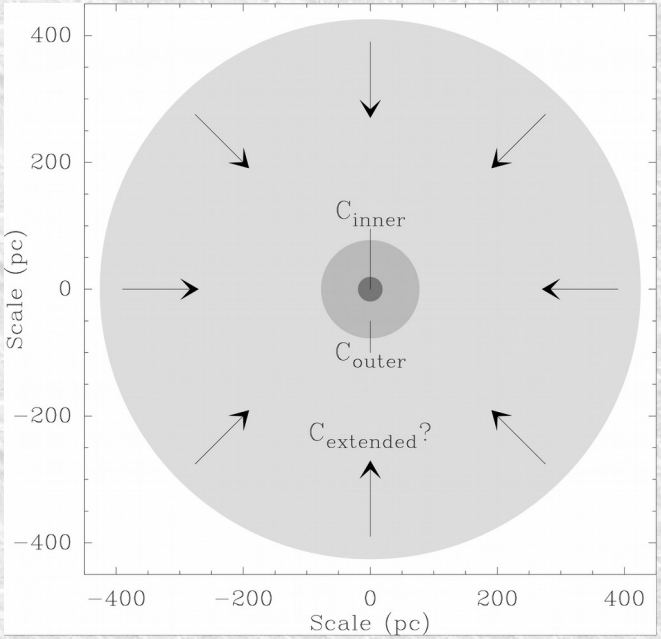


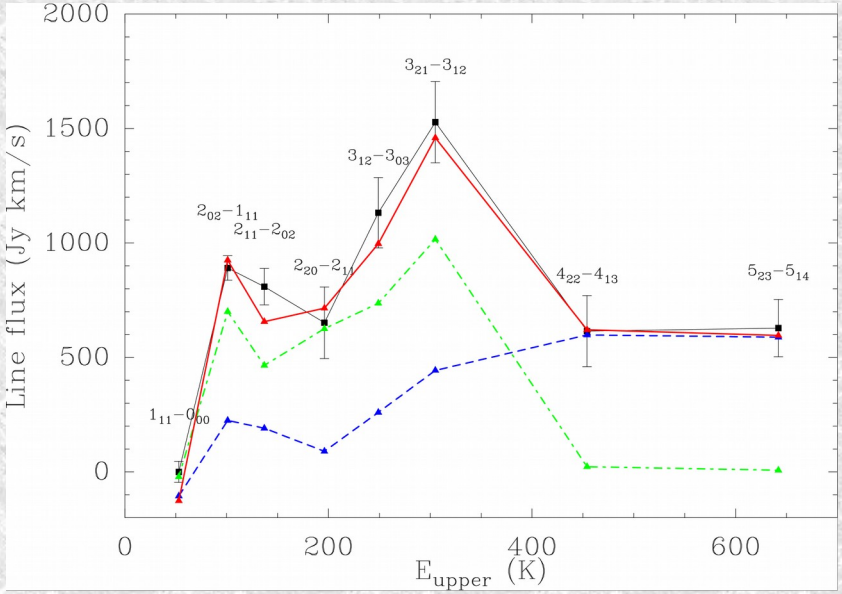


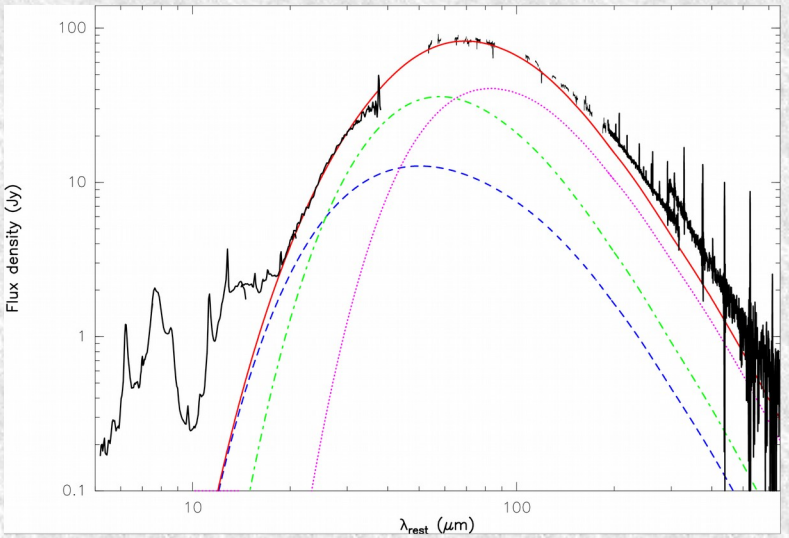
H2O lines in Arp299a (Falstad+16, submitted)

Poster by Niklas Falstad (P10)

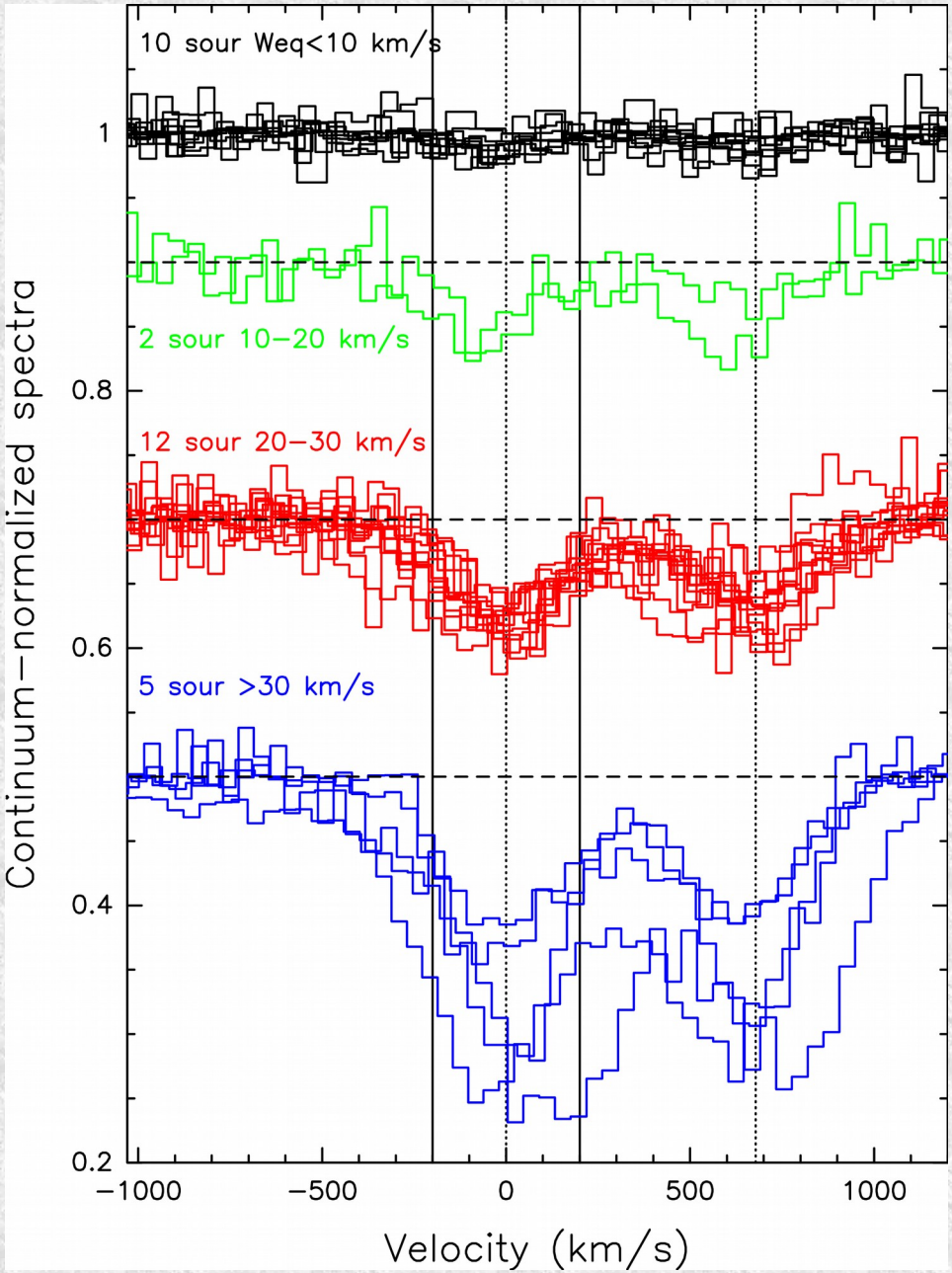




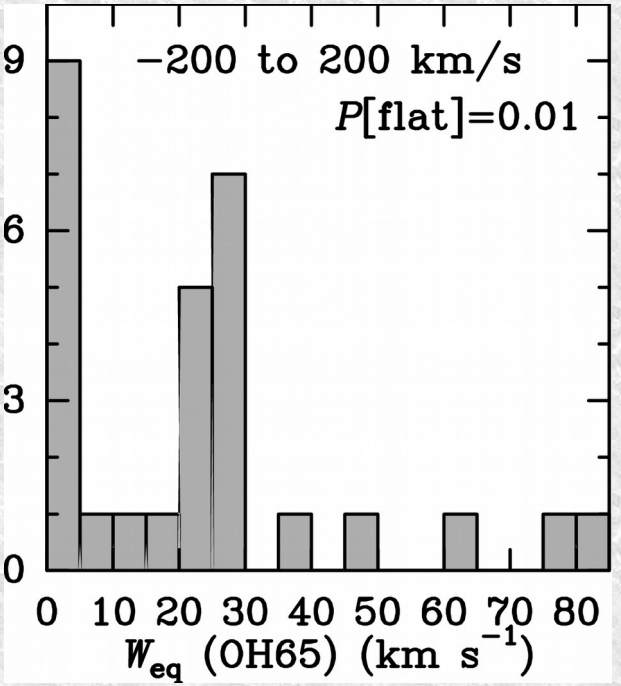




THE OH 65μm *HERSCHEL*/PACS SPECTRA



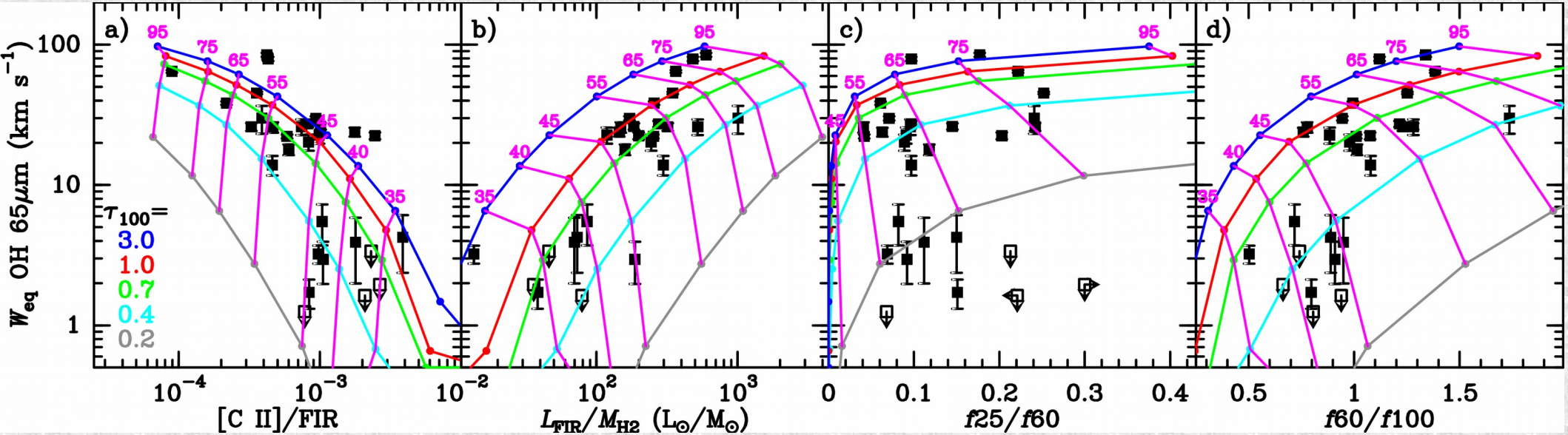
Bimodality in OH65



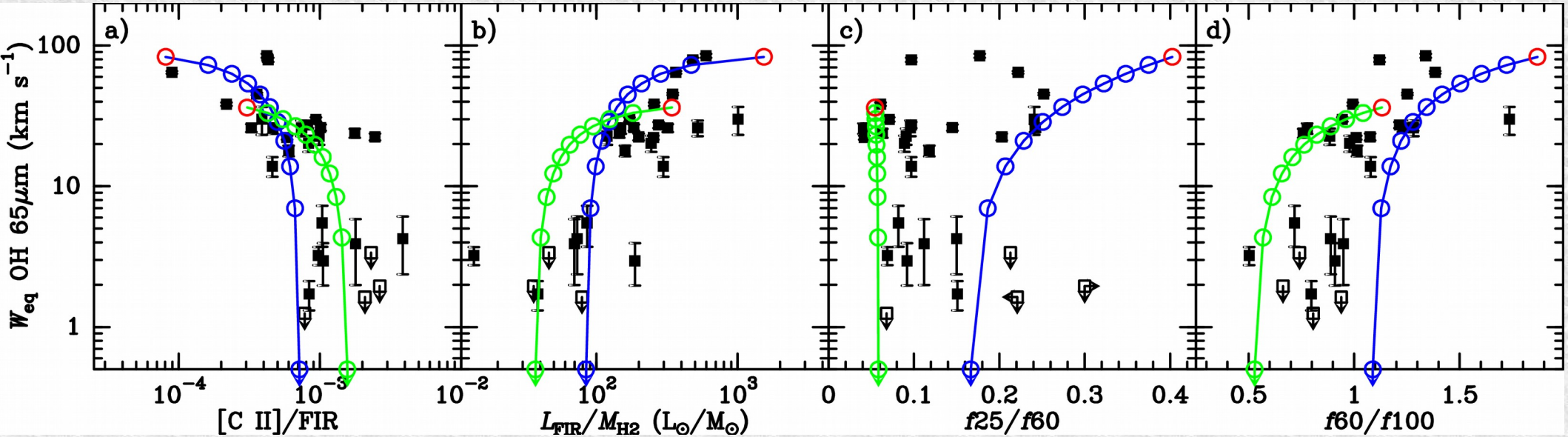
*** Coherent structures**
*** Short-living structures**

(G-A+15)

Single component models: assuming coexistent OH65 and [CII]

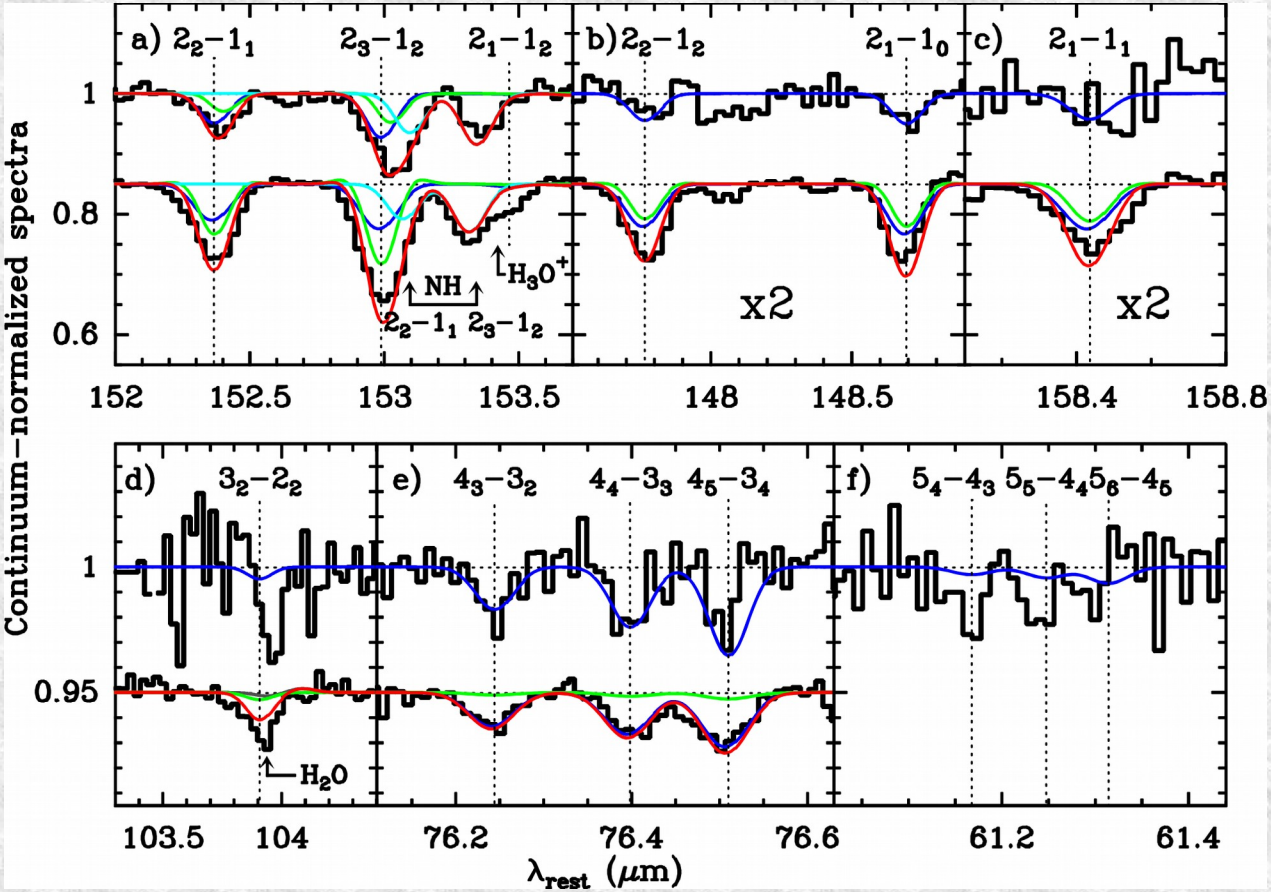


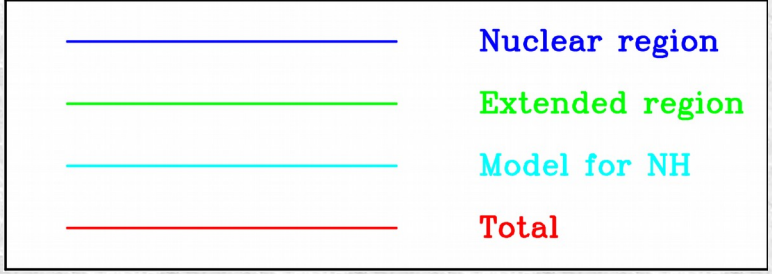
Composite models: optically thick (OH65) and thin [CII]

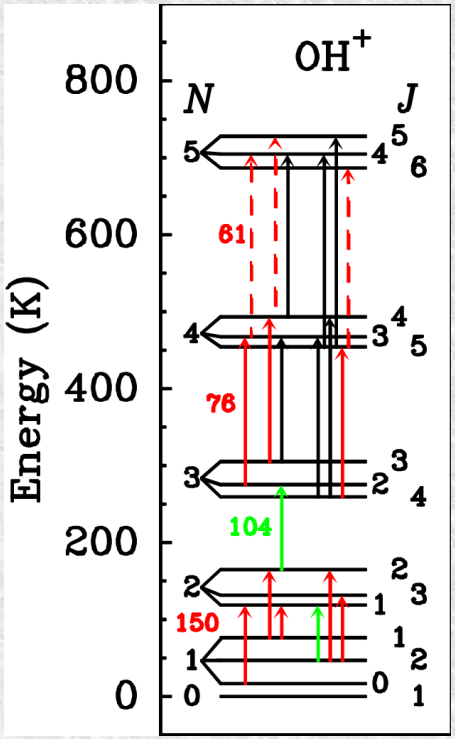


(G-A+15)

Models for OH+ in NGC4418 & Arp220 (G-A13)







NGC 4418

T_{dust}=110−150 K, d=20−35 pc, $N(OH^+)$=(6−10)x10^{15} cm^{-2}

T_{dust}=100−50 K, d~100 pc, $N(OH^+)$~3x10^{15} cm^{-2} ?

Arp 220

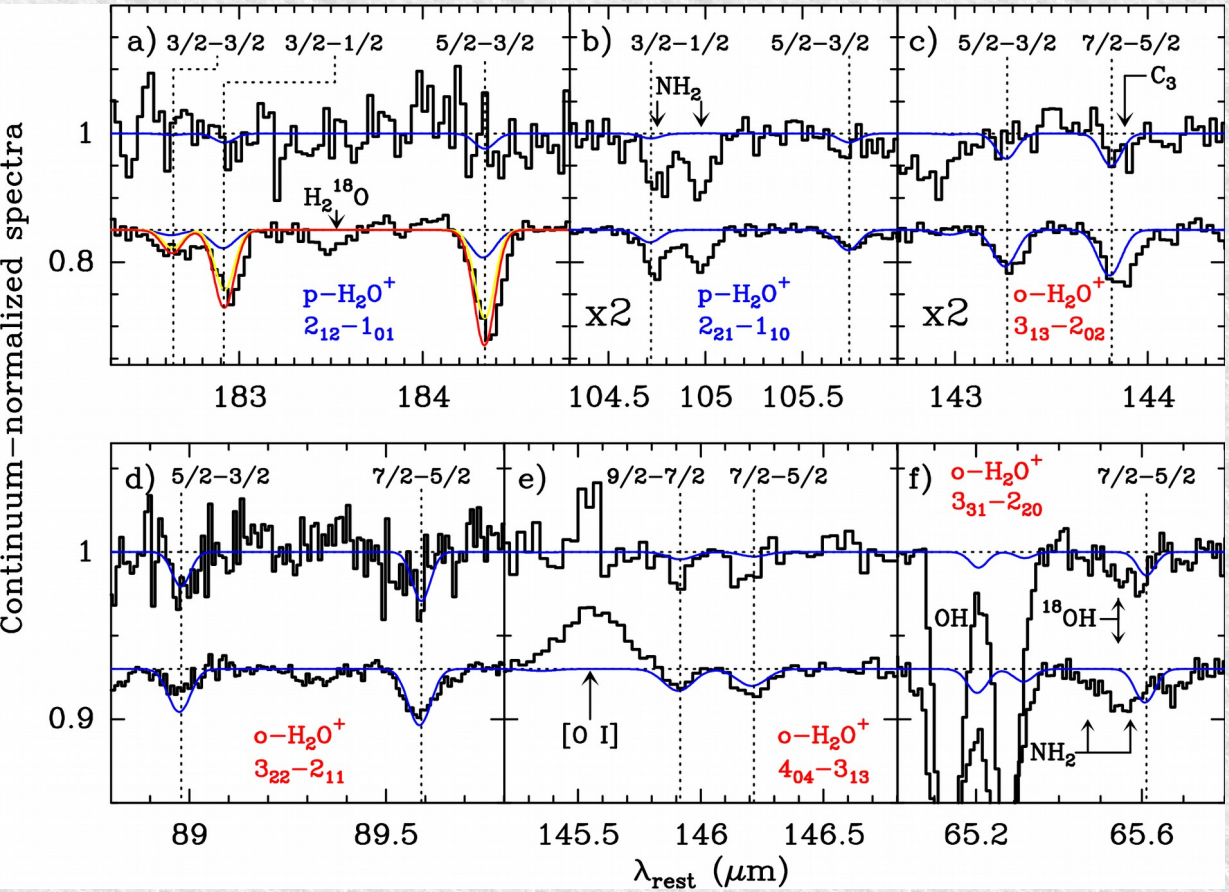
T_{dust}=90−110 K, d=160−90 pc, $N(OH^+)$=(5−11)x10^{15} cm^{-2}

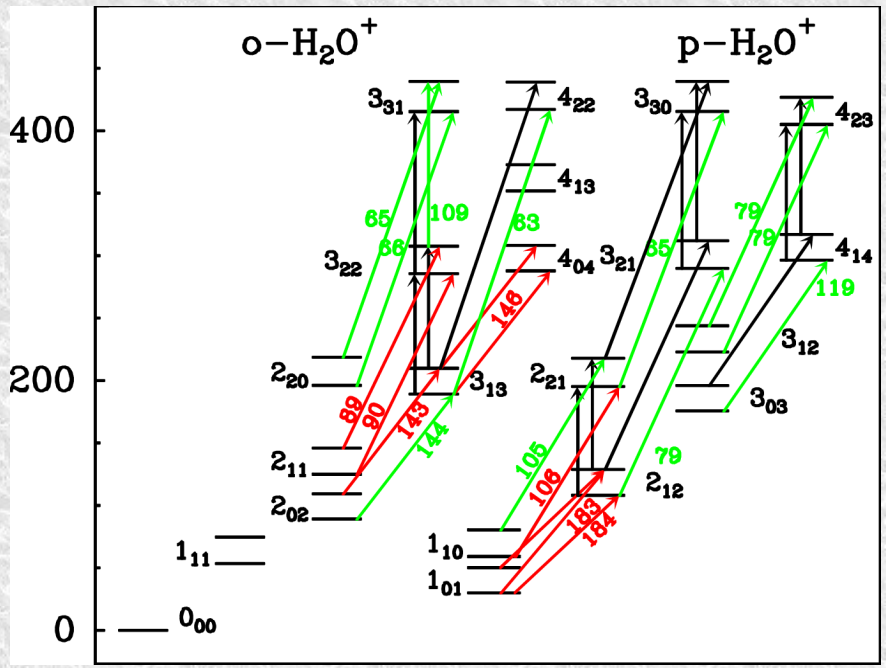
T_{dust}=90−40 K, d~600 pc, $N(OH^+)$~(20−40)x10^{15} cm^{-2} ?

Red: ortho
Blue: para

Models for H_2O^+ in NGC4418 & Arp220 ortho/para=3

Nuclear region
Halo
Total

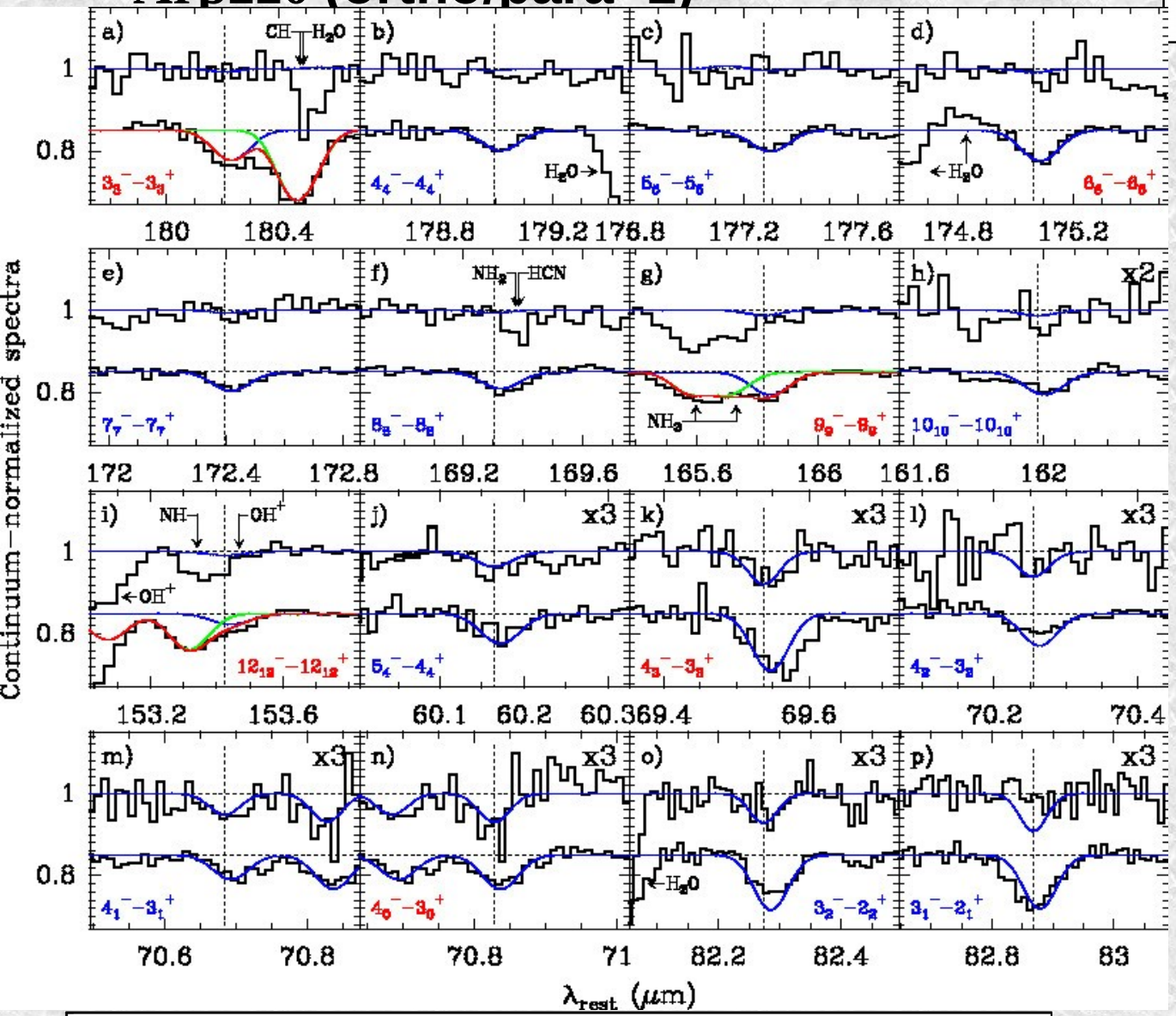


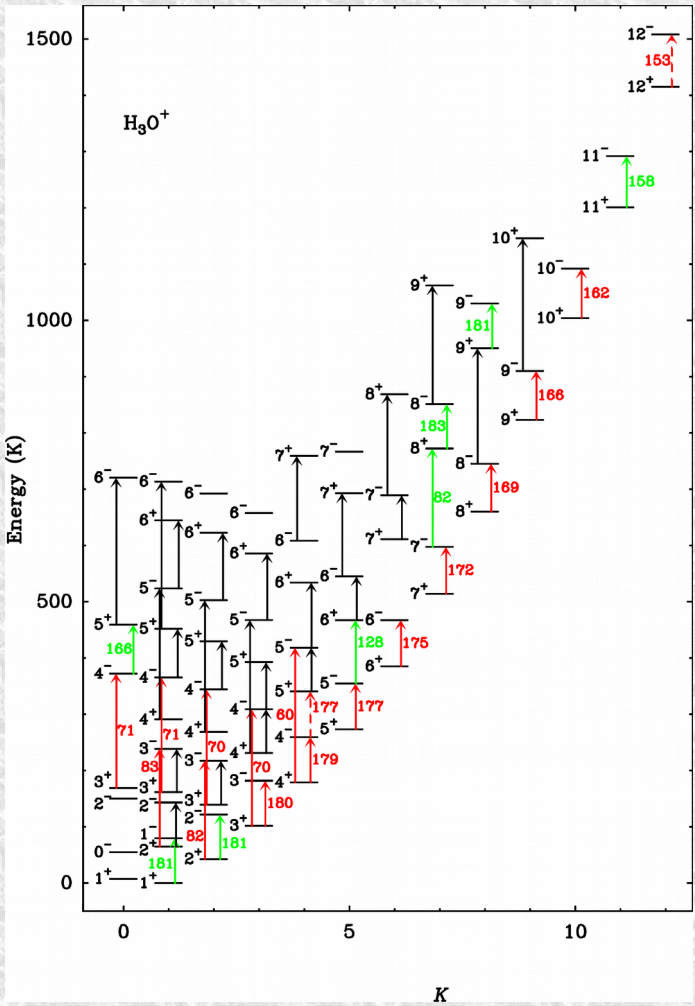


NGC 4418
T_{dust}=110–150 K, d=20–35 pc, $N(H_2O^+)$=(3–4)x10^{15} cm^{-2}
Arp 220
T_{dust}=90–110 K, d=160–90 pc, $N(H_2O^+)$=(3–9)x10^{15} cm^{-2}
T_{dust}=90–40 K, d~600 pc, $N(H_2O^+)$~5x10^{15} cm^{-2} ?
T_{dust}=90–110 K, $N(H_2O^+)$~3x10^{15} cm^{-2} ?

(G-A+13)

Models for H_3O^+ in NGC4418 & Arp220 (ortho/para=1)



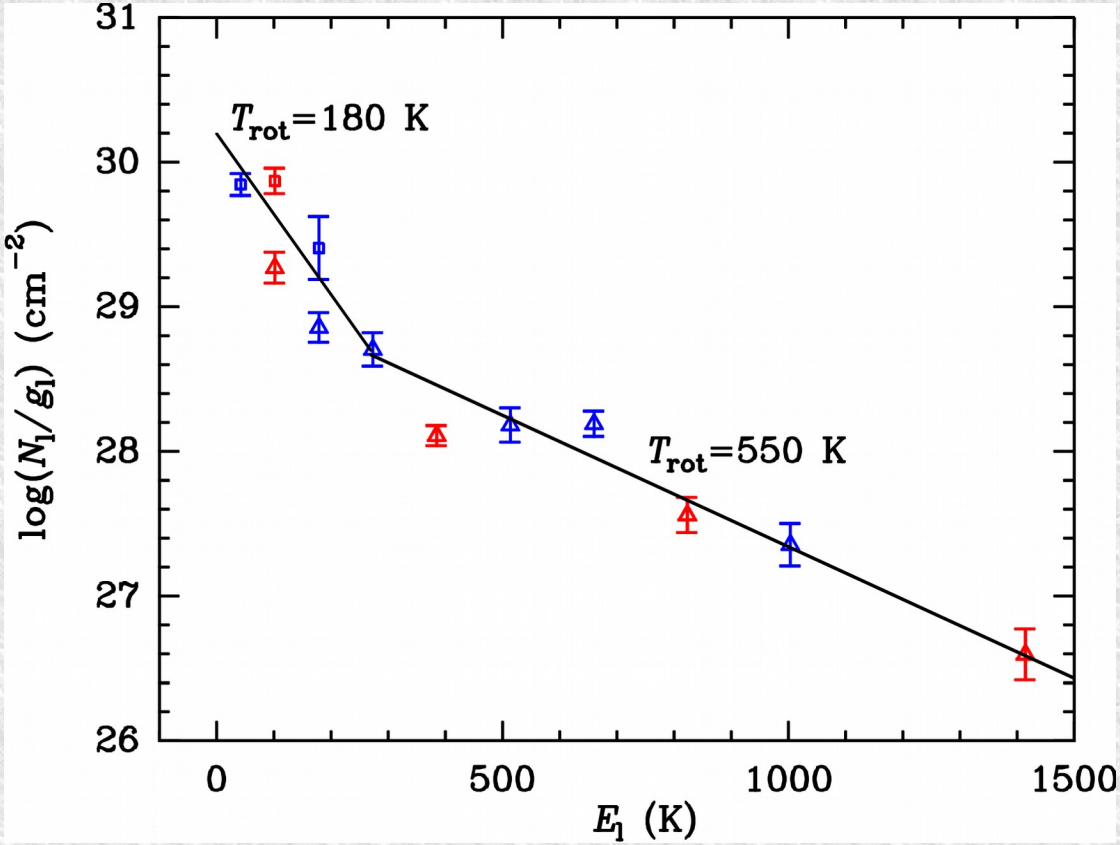


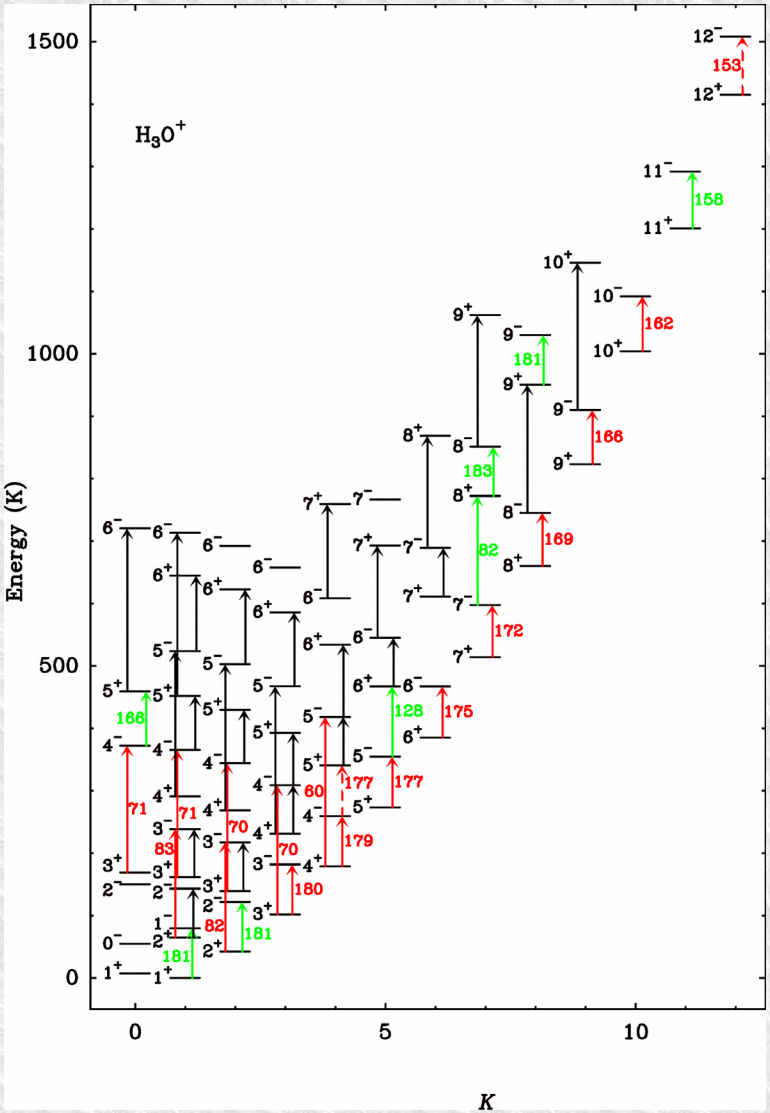
NGC 4418
T_{dust}=110−150 K, d=20−35 pc, $N(H_3O^+)$=(5−8)x10^{15} cm^{-2}
Arp 220
T_{dust}=90 K, d=160−110 pc, $N(H_3O^+)$=(9−25)x10^{15} cm^{-2}

T_{rot}=170 K up to K=5, 500 K for K>5

(G-A+13)

Population diagram of H_3O^+ (metastable levels) in Arp 220





Similar to Sgr B2 (Lis+2012)
Formation pumping?

(G-A+13)

Chemical models by Simon Bruderer (G-A13)

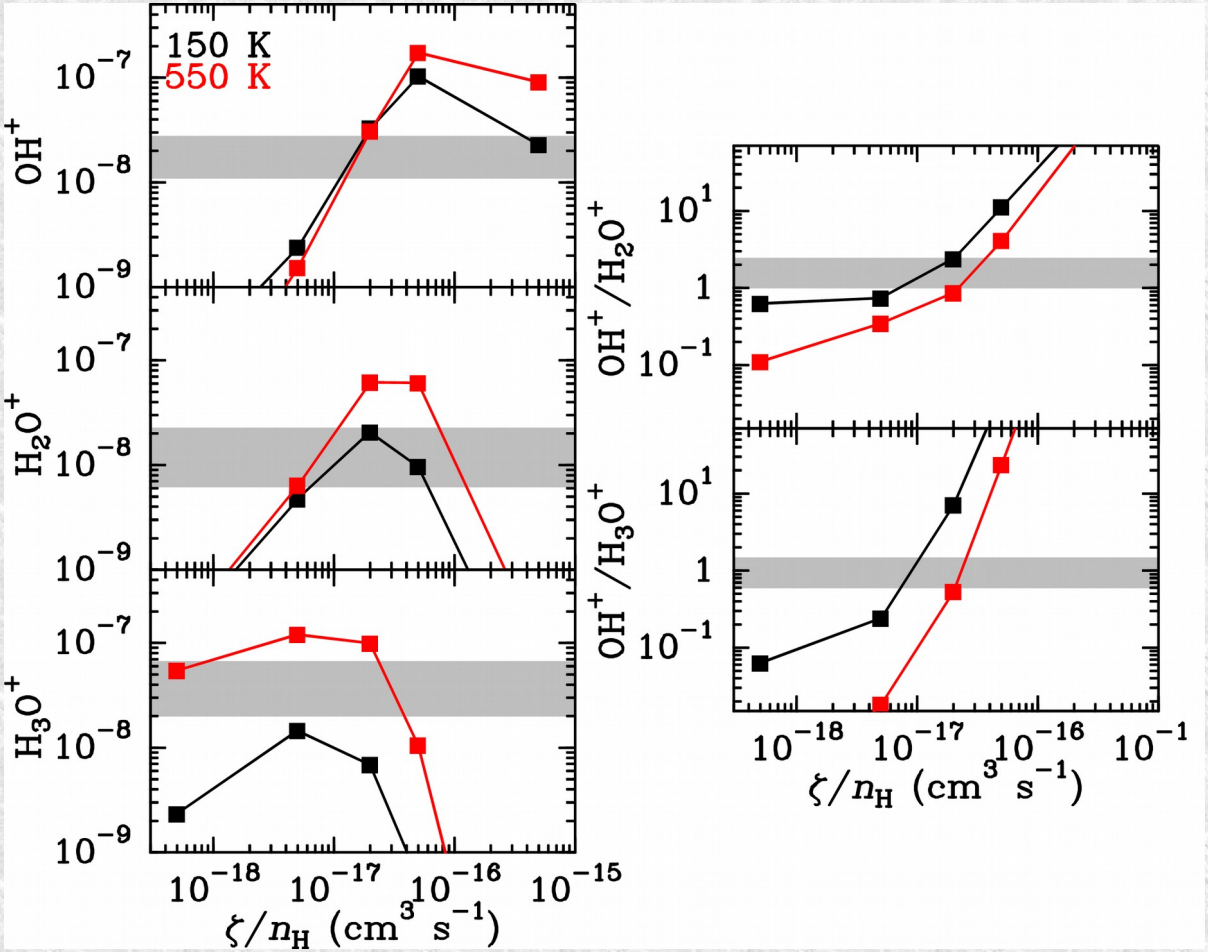
Results for the nuclear regions of NGC 4418 and Arp 220 are consistent with

$\zeta/n_H = (1-2)\times10^{-17}$ cm^3 s^{-1}

Density n_H of at least 10^4 cm^{-3}

$\zeta > (1-2)\times10^{-13}$ s^{-1}

(~1000 times the value in Galactic diffuse clouds)



Conclusions

*** Dozens of H2O absorption lines, and up to 8 H2O emission lines, are observed in the far-IR and submillimeter spectra of bright infrared galaxies with buried nuclei.**

*** H2O absorption/emission probes the structure and properties of the source: absorption lines are produced towards very warm (Tdust~>100 K), optically thick (tau100>~1) compact (R~10-100 pc) cores, and emission lines (Eupper<400 K) are generated towards more extended (R~a few x 100 pc) surrounding regions.**

*** H2O absorption/emission probes the SEDs at far-IR wavelengths, where the bulk of the galaxy luminosity is generated. H2O (and other hydrides) absorption trace the transition from mid- to far-IR.**

*** Very high columns and abundances of H2O are inferred in the nuclear regions of buried galactic nuclei, with $X(H_2O)\sim10^{-6}$-10^{-5}.**

*** The OPR of H2O is consistent with the high-temperature limit of 3, or Tspin>~35 K.**

*** Nuclear regions are very optically thick and dusty, so UV photons are absorbed in small volumes around the heating sources while these regions are warm: high molecular abundances.**

*** 2 modes of star formation in galaxies have been proposed: "disk-like" and "starburst". High-lying H2O absorption represents the most extreme mode of starburst, with $\Sigma_{IR}\sim(10^{13}$ -$10^{14})$ Lsun/kpc^2**

*** How is H2O formed? Hot molecular chemistry:**
-Mechanical heating (shocks, dissipation of turbulence)
-X/Cosmic rays (high columns of excited OH+, H2O+, and H3O+ are found)? Disfavoured.
-Undepleted chemistry, with high abundance of Oxygen in the gas phase (Tdust is high). In some sources, complex molecules are found, similar to hot cores (NGC 4418).

*** How is H2O destroyed?**
-X/Cosmic rays

*** In "four" words: Giant Shock-Hot-Cosmic-Rays Dominated Regions**