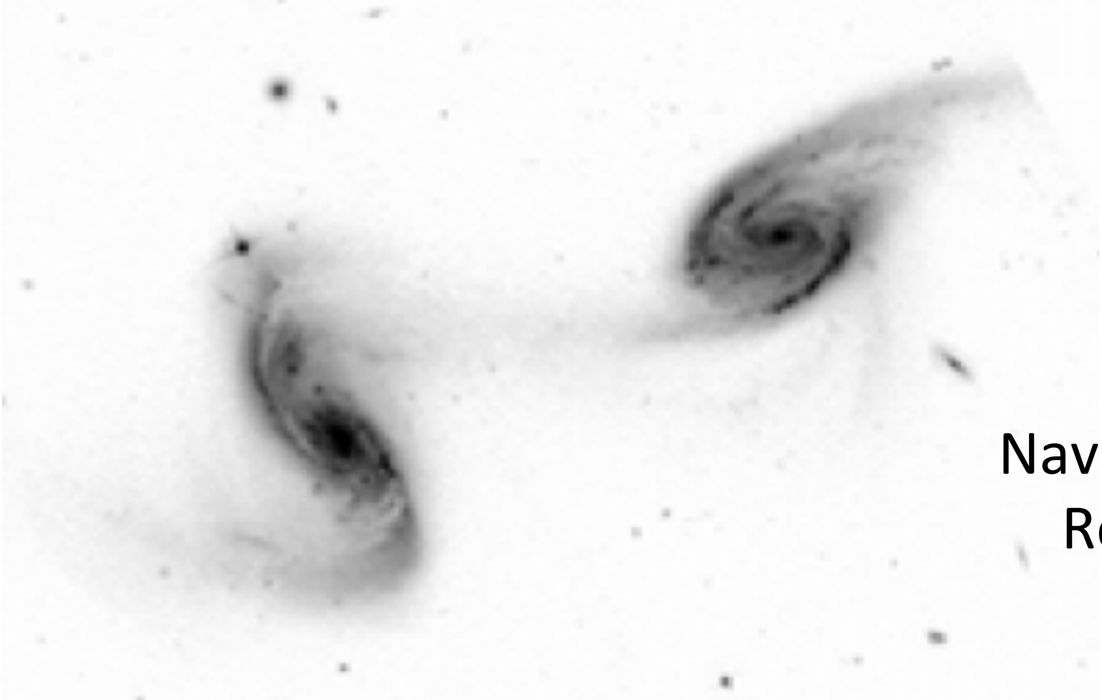
Water & OH in Mrk 231 as seen by Herschel:

Structure, excitation & feedback diagnostics



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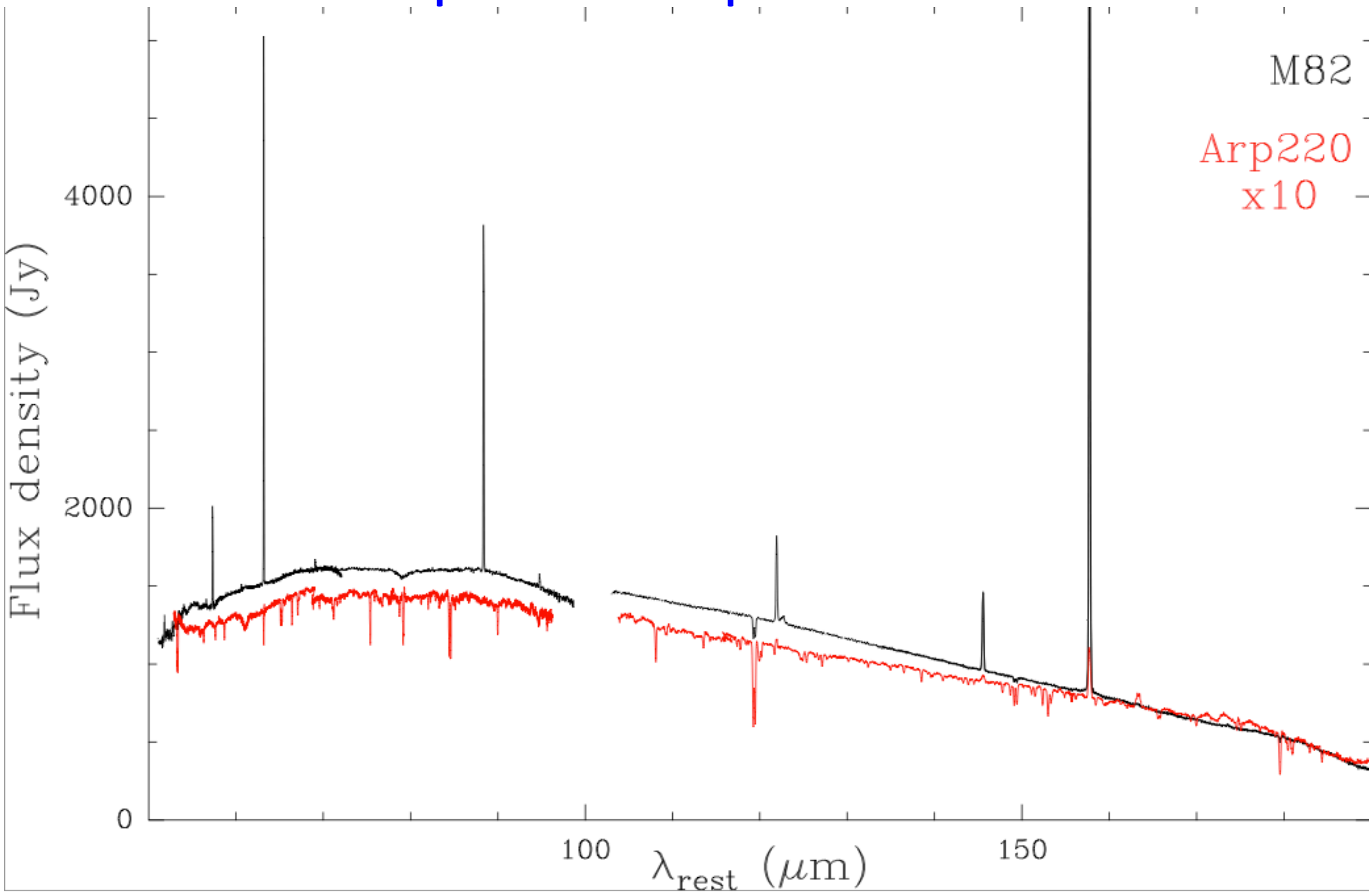
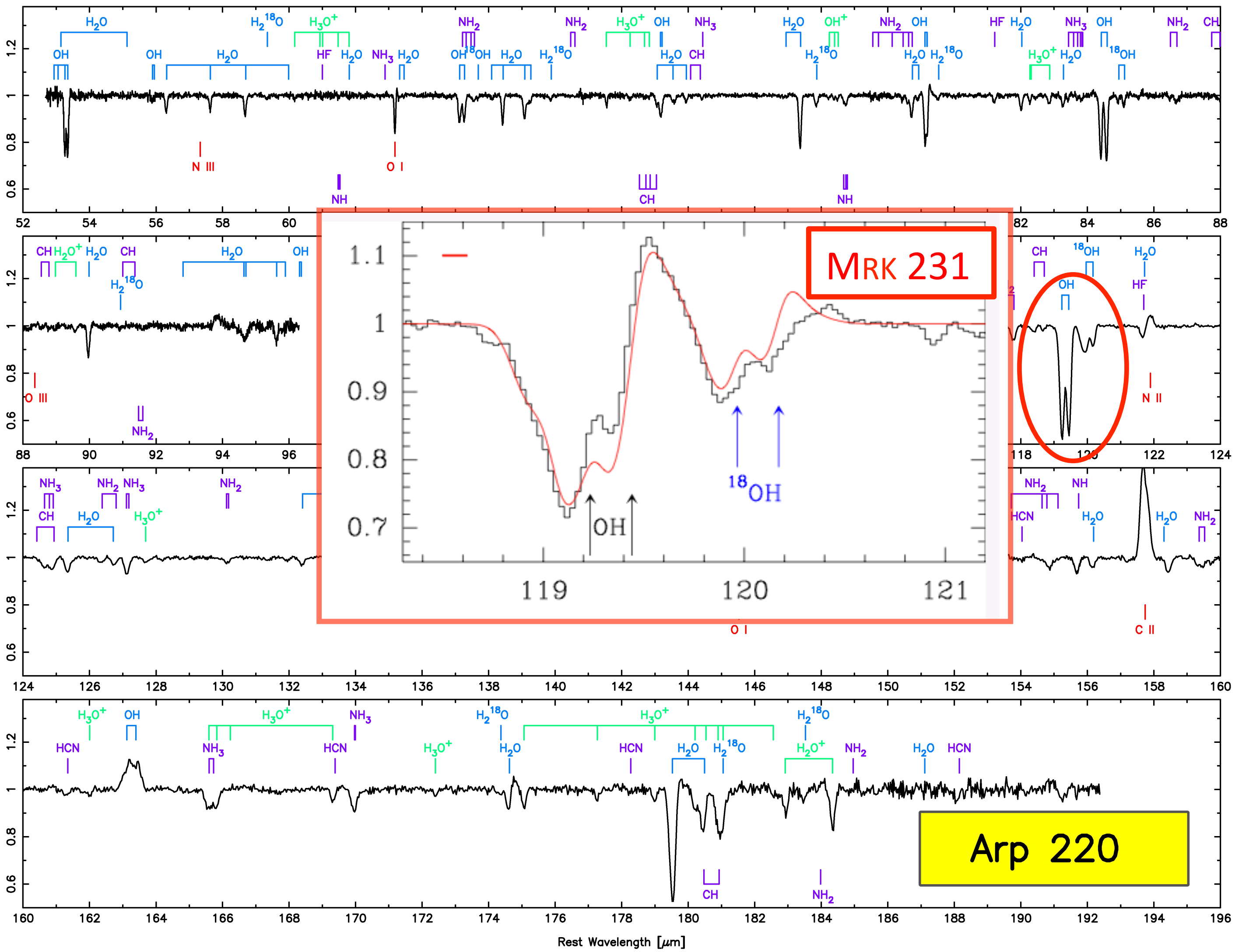
Full PACS Spectroscopic View of ULIRGs



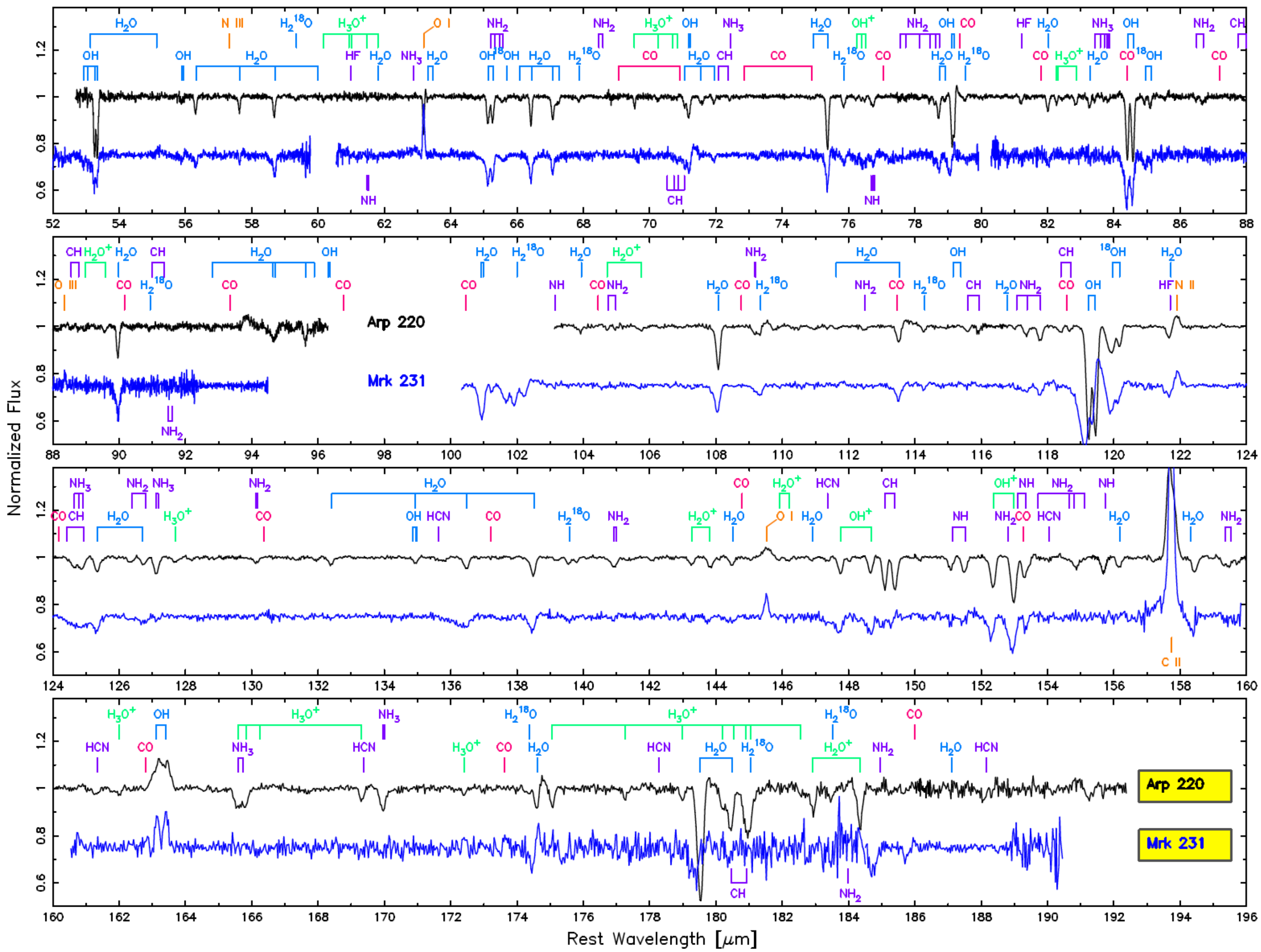
Full PACS Spectroscopic View of ULIRGs

For Arp 220 – a “FIR, molecular photosphere”, τ(FIR) >> 1

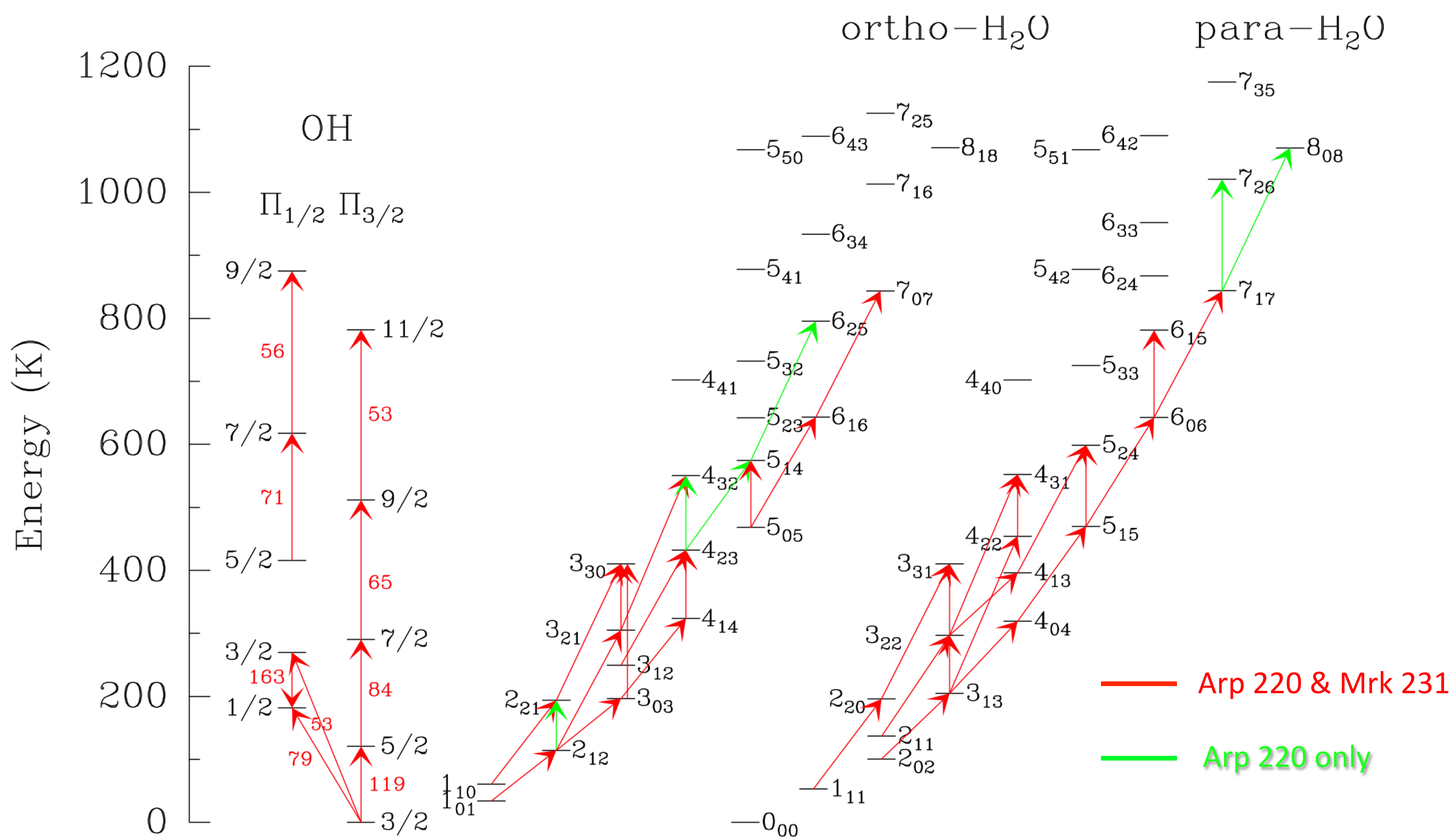


Full PACS Spectroscopic View of ULIRGs

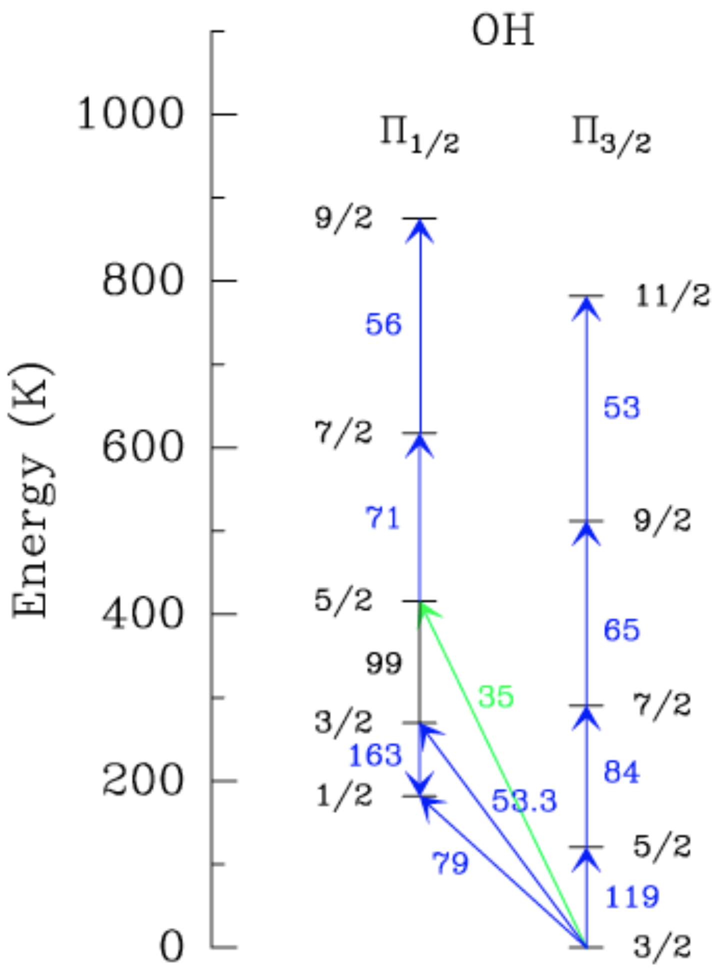
For the nearest Type 1 ULIRG – a “FIR, molecular photosphere”, τ(FIR) > 1

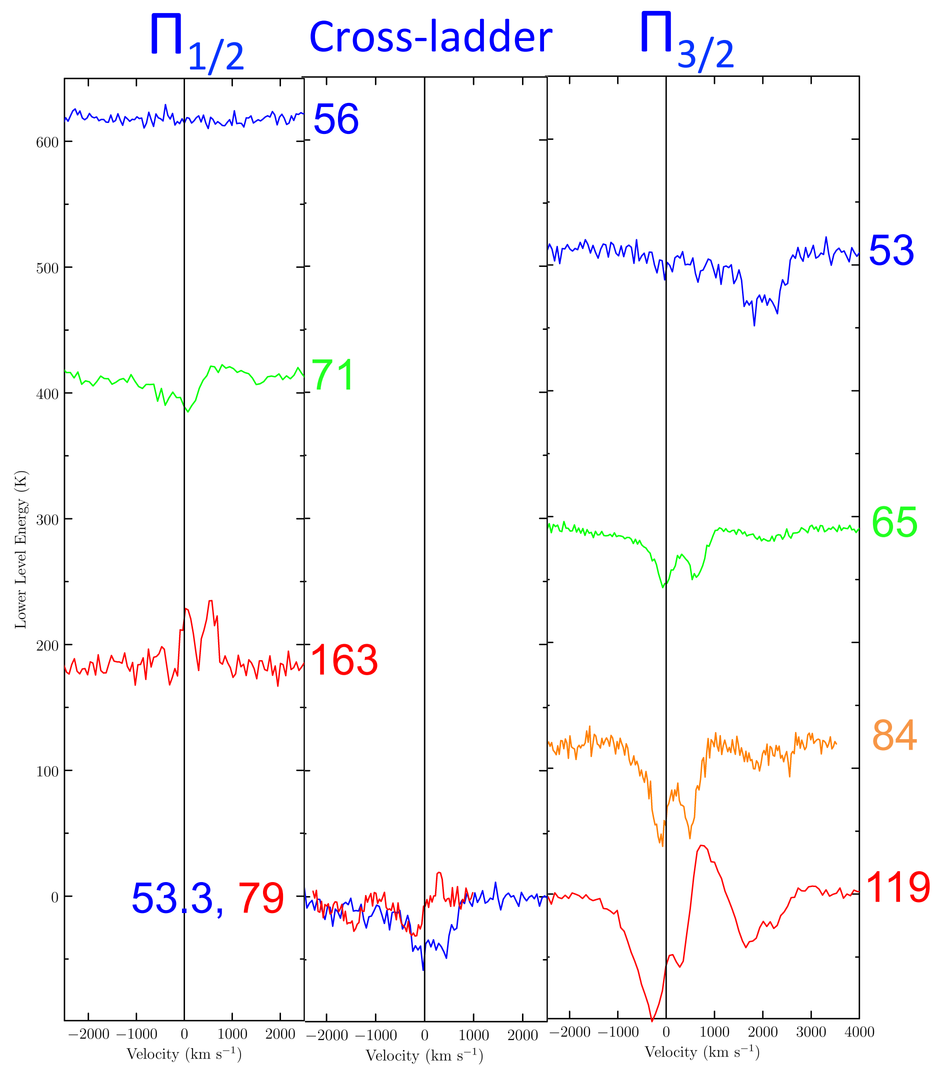


Arp 220 & Mrk 231: Absorption traces radiative pumping by high radiation field

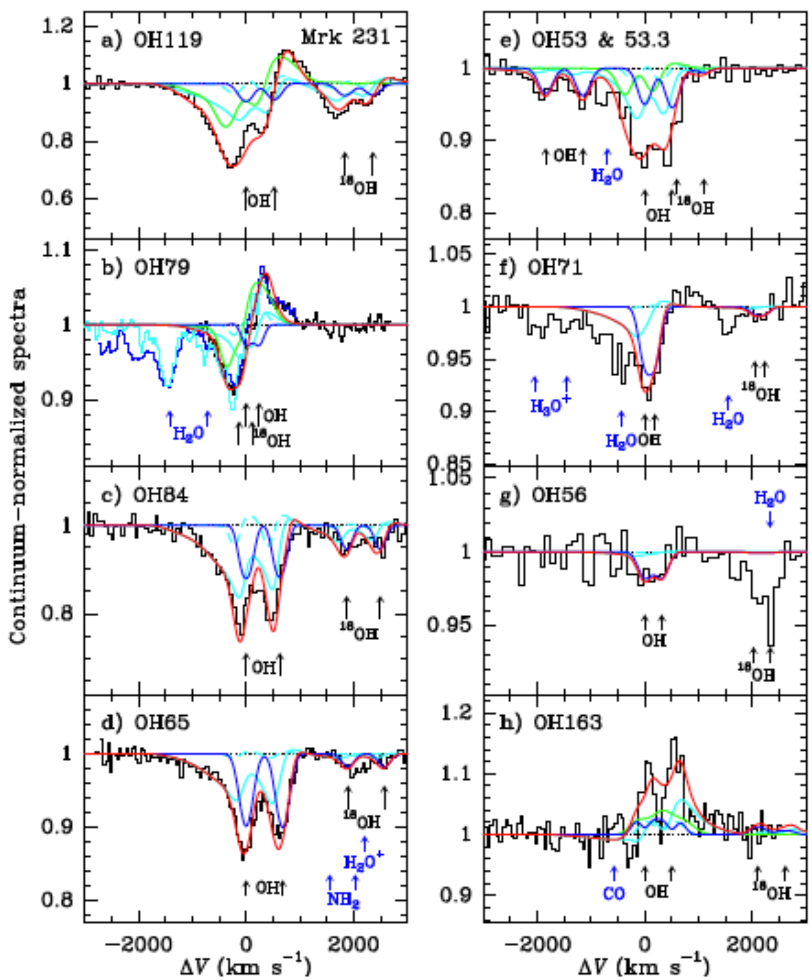


Mrk 231 OH Line Profiles vs Lower Energy Level





Mrk 231: Constraints on nuclear outflowing and quiescent, and low excitation components



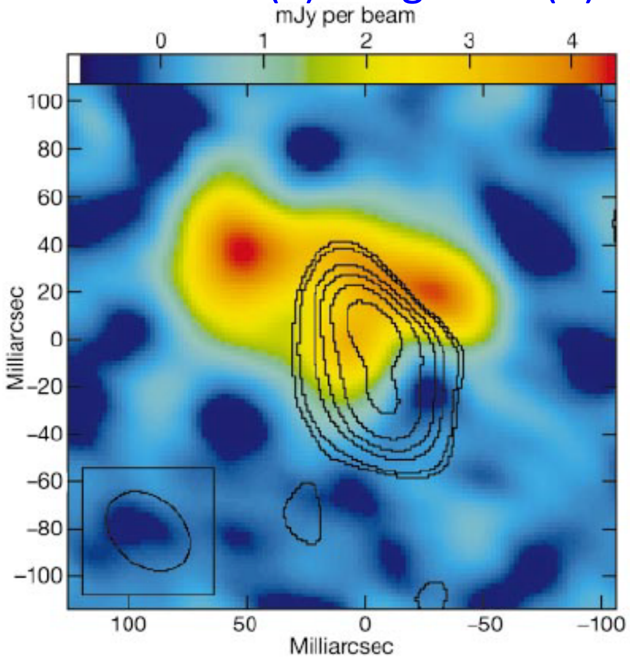
- T_{dust} ~ 90 - 120 K for all components
- The size of the quiescent component (i.e. non-outflowing – thick disk, torus) is about 120 – 140 pc, with
  log N(OH) ~ 18.6, & τ(100μm) ~ 1.5 - 2
- The outflowing component 130 – 160 pc, with log N(OH) ~ 17.4, & τ(100μm) ~ 1.5 – 2

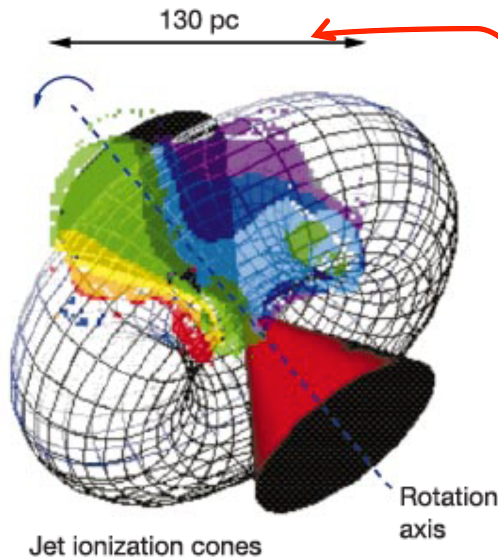
  Mass loss rate = 500 - 1200 $M_{\odot}$ yr^{-1}
  Momentum flux ~ 15 L_{AGN}/c
  Mechanical luminosity ~ 10^{11} $L_{\odot}$
- The low excitation component has lower N(OH), τ(100μm) ≤ 1 and the size is less constrained

González-Alfonso et al 2013, in press

A thick disk/torus and an outflow

The OH maser (a) image and (b) velocity gradient & model





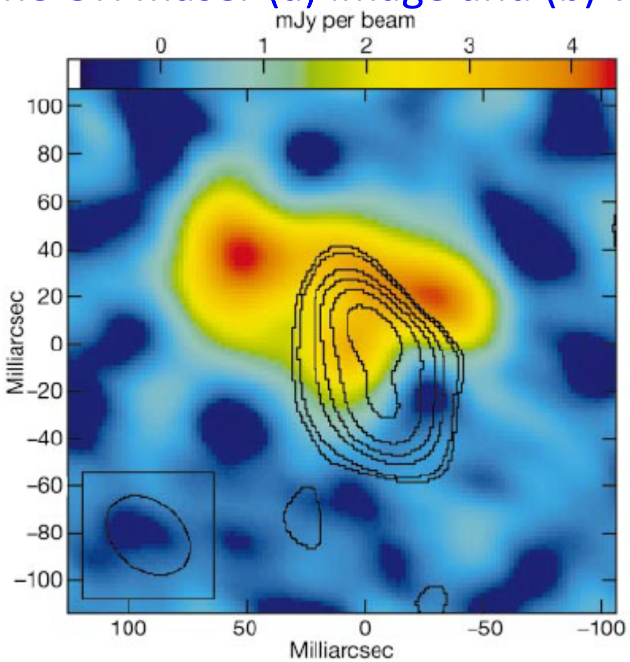
Klöckner et al. 2003

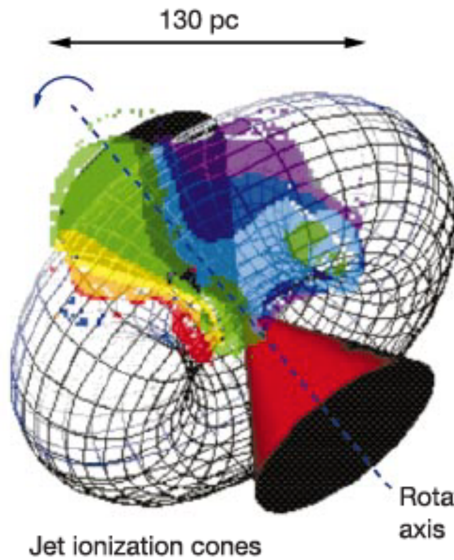
Parameter	QC	HVC	LVC[b]
$R_{\rm int}$ (pc)	60 – 70	65 – 80	65 – 80
$T_{\rm dust}$ (K)	∼ 110	90 – 105	∼ 90
τ_{100}	1.5 – 2.0	1.5 – 2.0	$\lesssim 1$
$R_{\rm out}/R_{\rm int}$	–	$\lesssim 1.5$	∼ 1.5 – 2
$v_{\rm int}$ (km s^{-1})	–	1700	∼ 300
$v_{\rm out}$ (km s^{-1})	–	100	∼ 200
$N_{\rm OH}$ (10^{17} cm^{-2})	40	1.5 – 3	∼ 0.3
$p_{\rm f}/R_{\rm int}$	1	∼ 1	∼ 1.5 – 2

González-Alfonso et al 2013, in press

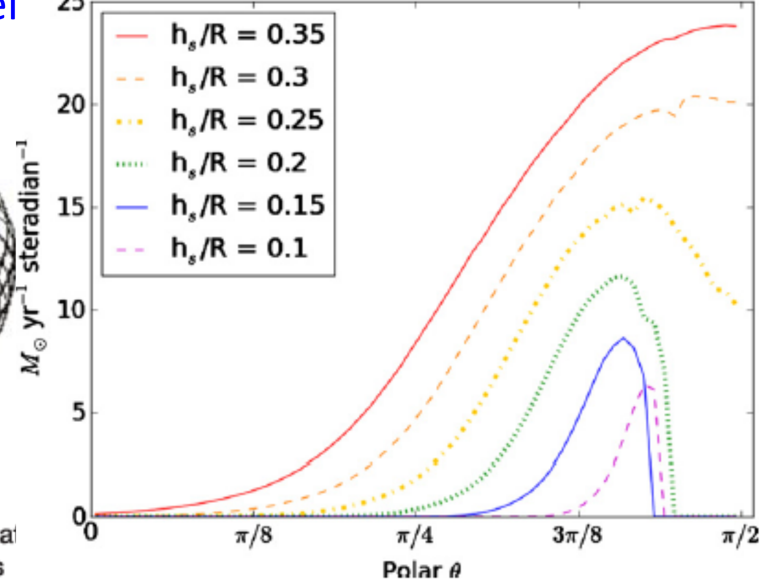
A thick disk/torus and an outflow

The OH maser (a) image and (b) velocity gradient & model





Roth et al 2012



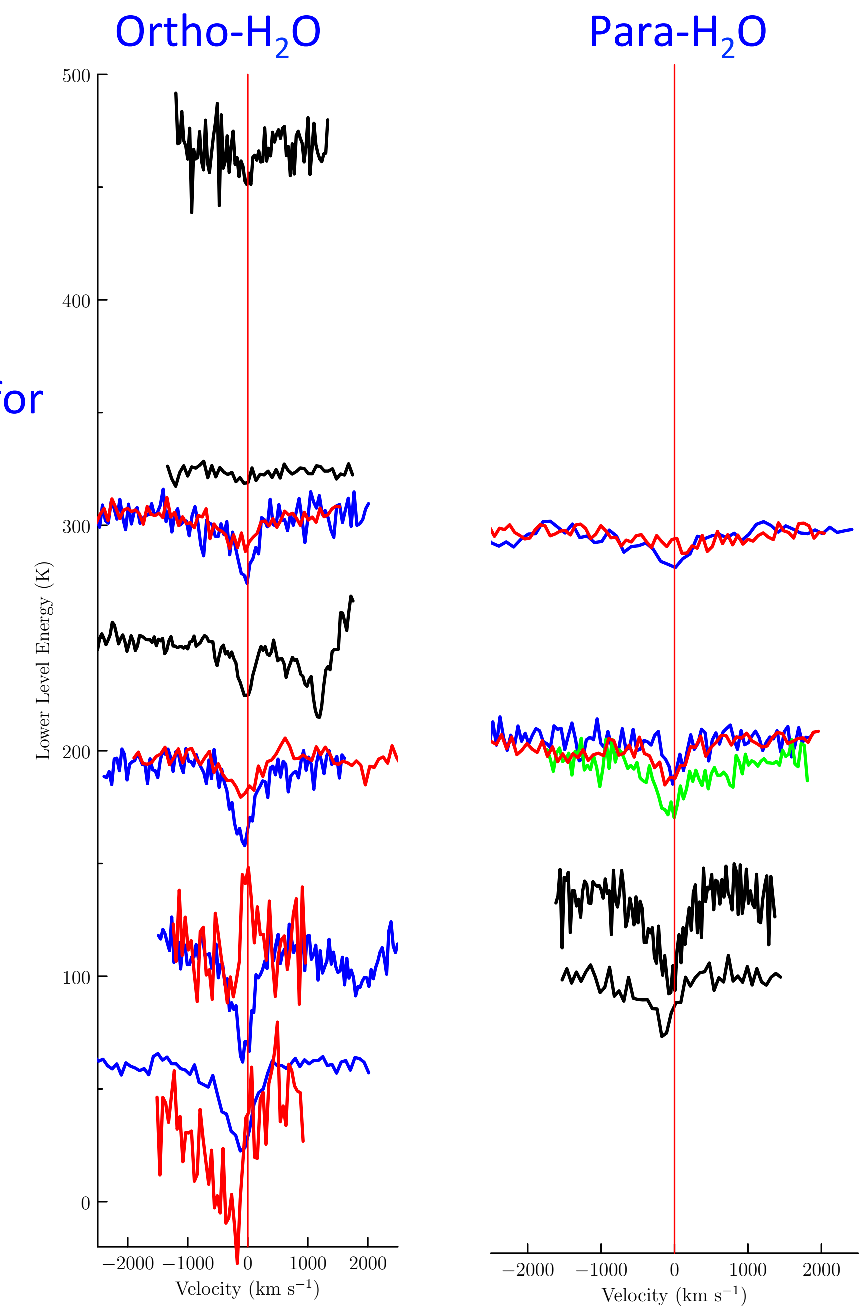
Klöckner et al. 2003

Parameter	QC	HVC	LVC[b]
R_{int} (pc)	60 – 70	65 – 80	65 – 80
T_{dust} (K)	$\sim$ 110	90 – 105	$\sim$ 90
τ_{100}	1.5 – 2.0	1.5 – 2.0	$\lesssim 1$
R_{out}/R_{int}	–	$\lesssim 1.5$	$\sim$ 1.5 – 2
v_{int} (km s^{-1})	–	1700	$\sim$ 300
v_{out} (km s^{-1})	–	100	$\sim$ 200
N_{OH} (10^{17} cm^{-2})	40	1.5 – 3	$\sim$ 0.3
p_f/R_{int}	1	$\sim$ 1	$\sim$ 1.5 – 2

González-Alfonso et al 2013, in press

H_2O profiles in Mrk 231

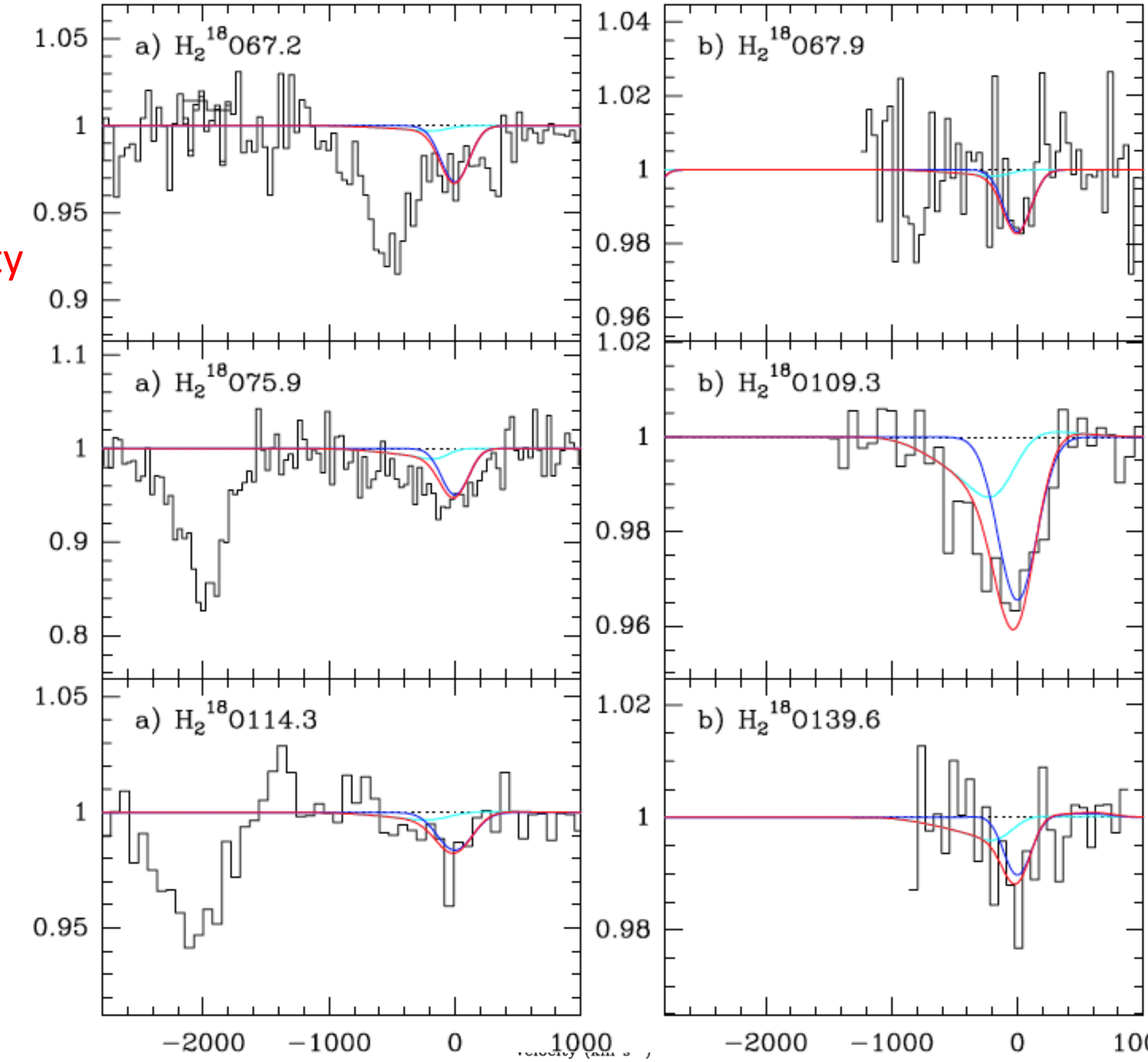
- Similar characteristics to OH profiles
- P-Cygni / blue –shifted peak absorption for ground-state and lower level transitions
- Zero velocity narrower absorptions for higher excitation transitions
- Blue wings present for all transitions



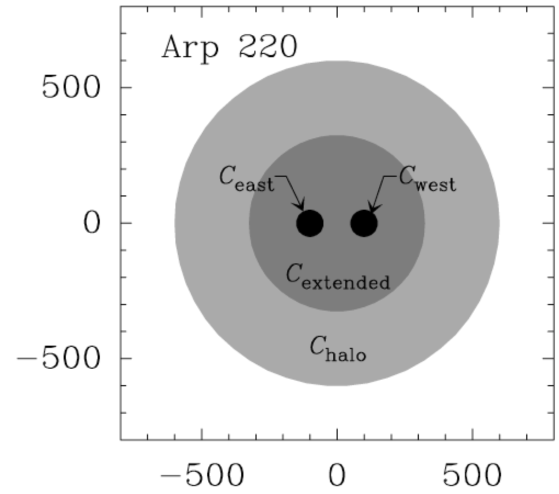
Water in Mrk 231: Model Line Fits

The H_2O line profiles can be fit fairly well just using the quiescent (QC) and high velocity (HV) components with $N(H_2O)$ about 20% and 60% lower than N(OH) for those components.

The implied $^{16}O/^{18}O$ ratio for both H_2O and OH is about 30, suggesting past and/or present stellar processing.



OH & H_2O in Arp220: Model Results



- The Arp 220 components have similar sizes and temperatures as Mrk 231
- In Arp 220, a quiescent component dominates the FIR with hints of moderate velocity outflow in the FIR (outflow is seen more clearly with high resolution submillimeter interferometry (has higher spatial resolution & probes deeper) by Sakamoto et al. (2009)
- Importantly Arp 220 has higher optical depths with τ(200) ~ 6 – 12 ! (Sakamoto et al.)
- $^{16}O/^{18}O$ 70-90 for Arp 220

González-Alfonso+2012

Cloudy Input Parameters

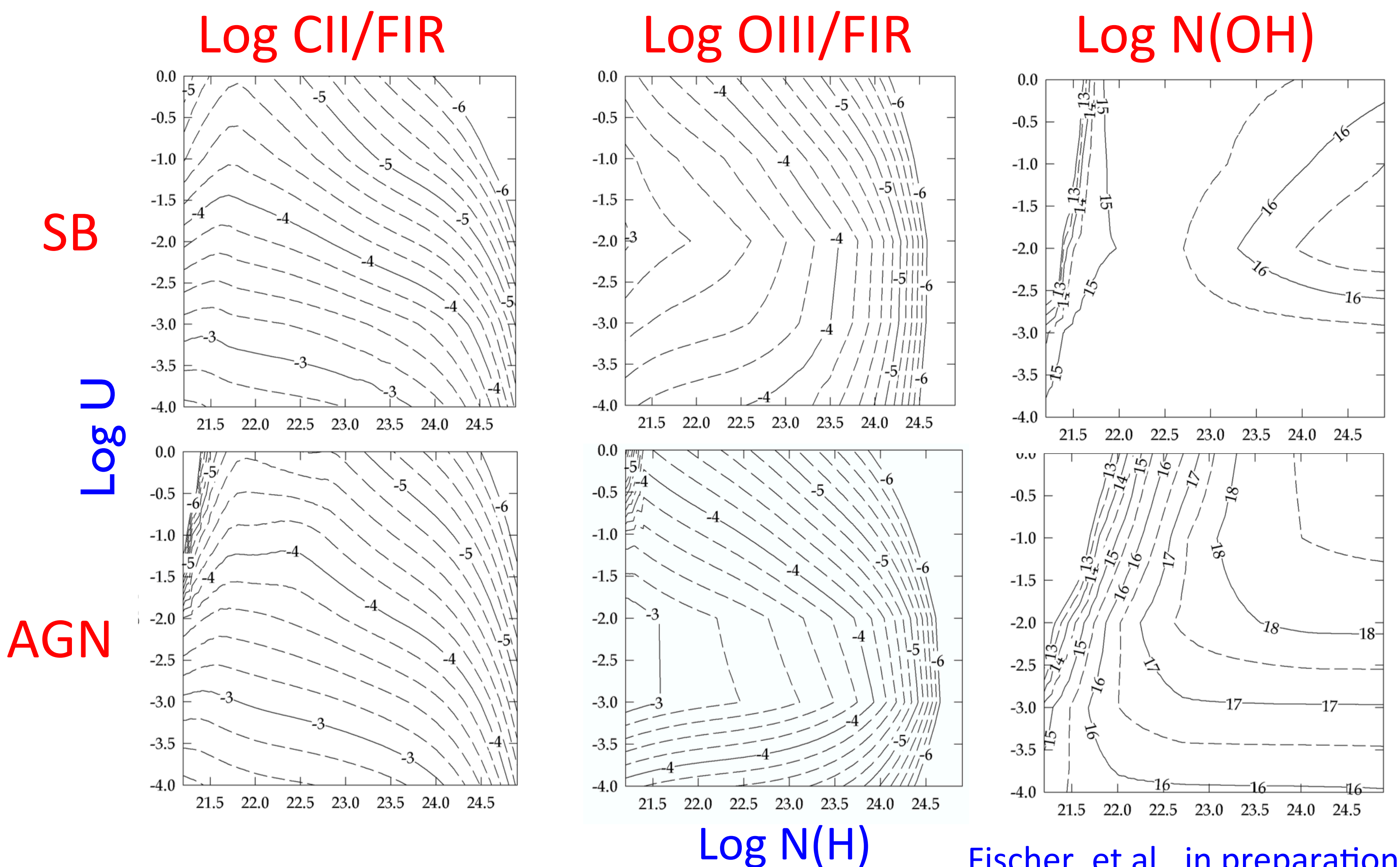
- SED: AGN ($T_{UV}=10^6$, $\alpha_{OX}=10^{-1.4}$, $\alpha_{uv}=10^{-0.5}$, $\alpha_x=10^{-1.0}$)
  SB (4 Myr continuous, Salpeter)
- n_H, density: at H^+ face = 30, 300, 3000 cm^{-3}
- Ionization param: $U = Q/4\pi r^2 nc$
- Stopping cond.: $N(H_{Total})=10^{21.3} - 10^{24.9}$
- B_o(at face), B(n): $B=B_o(n/n_o)^{2/3}$, B_o=100 μG
- Equation of state: eg. Isobaric (gas, magnetic, radiation)
- Abundances: Gas phase abundances
- Dust properties: including PAHs
- Cosmic rays: CR ionization rate=$5x10^{-17}$ s^{-1}

Cloudy code capabilities (esp. wrt XDR/PDRs)

- Photoelectric heating of grains
  - ➡ Grain temperature and charge (function of size & mat'l)
- 68 molecules including ~ 1000 reactions
- Size-resolved PAH distribution, where H is atomic
- H_2 formation on grains, temp. & material dependent
- Can extend calculation to a particular A_v or other condition
- Line intensities for CO and H_2
- Condensation of H_2O, CO, & OH onto grains for T<20 K
- Cosmic ray ionization processes and heating

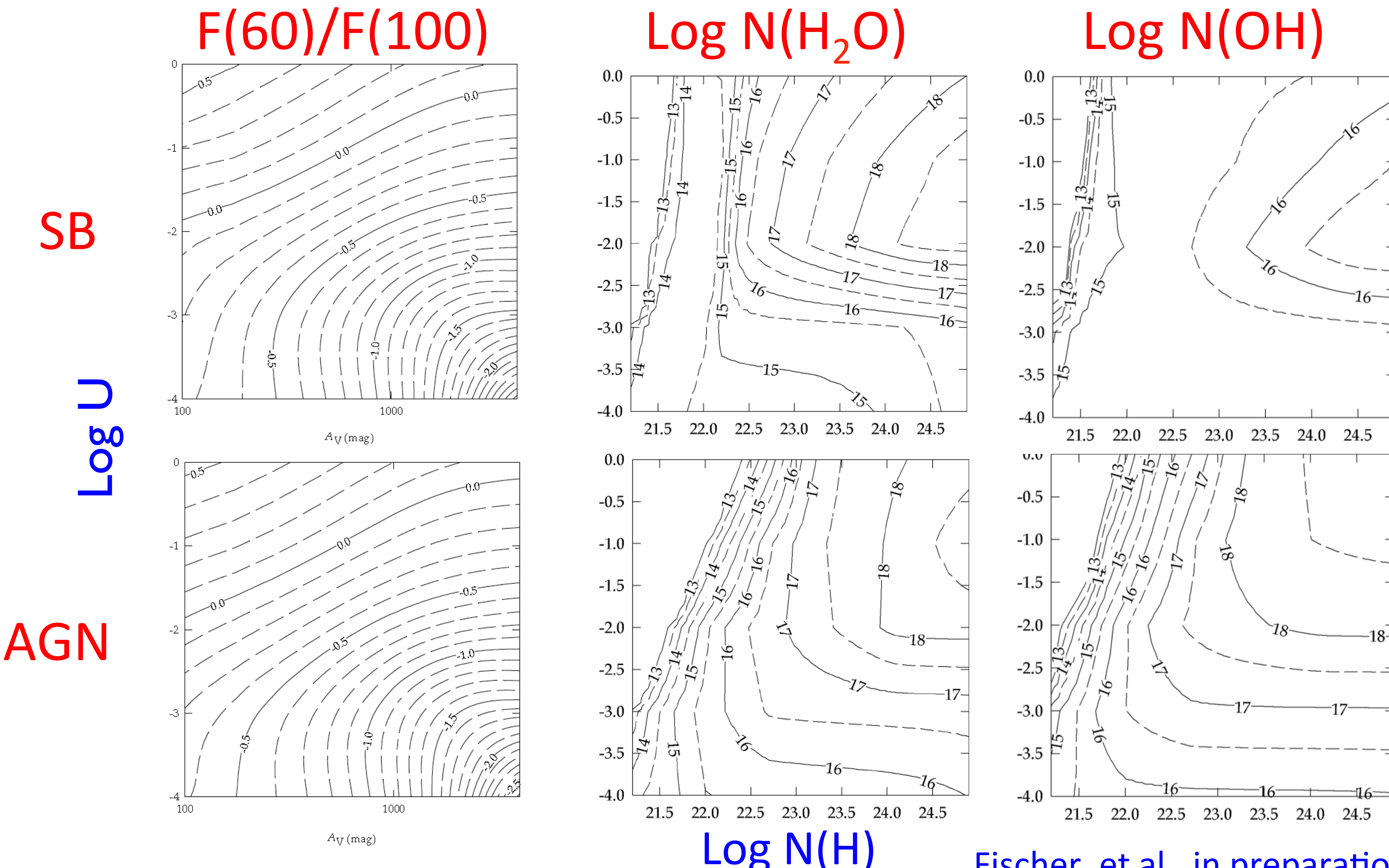
References:
Abel et al, 2004, '05, '08, '09 (molecular networks, microphysics)
van Hoof et al. 2004 (grain physics)
Shaw et al. 2005 (molecular hydrogen microphysics)
Rollig et al. 2007 (comparison of PDR models)

Model predictions versus U, $N_{H,}$ n_H= 3000



Fischer, et al., in preparation

Model predictions versus U, $N_{H,}$ n_H= 3000



Fischer, et al., in preparation

Summary

- A combination of high radiation density per particle density (ionization parameter, U), far-infrared extinction, geometry, and X-rays or cosmic rays play a role in the determining the far-IR spectroscopic signatures in ULIRGs – high OH, H_2O column densities, radiative pumping, and line deficits
- Both a thick molecular disk or torus and a massive molecular outflow show their strong signatures in Mrk 231, while in Arp 220, a quiescent component dominates the FIR with hints of moderate velocity outflow in the FIR (seen more clearly with submillimeter interferometry)
- Herschel has caught Mrk 231 and other ULIRGs in the act of clearing out the star forming molecular fuel and quenching star-formation !
- AGN illumination and feedback *appears* to play an important role as mergers pass from far-IR bright to gas-poor elliptical galaxies

Questions

- What role do projection effects and dust obscuration play? Are the different signatures really indicative of different kinematics and power sources?
- Is it possible to differentiate between the effects of cosmic rays and X-rays?