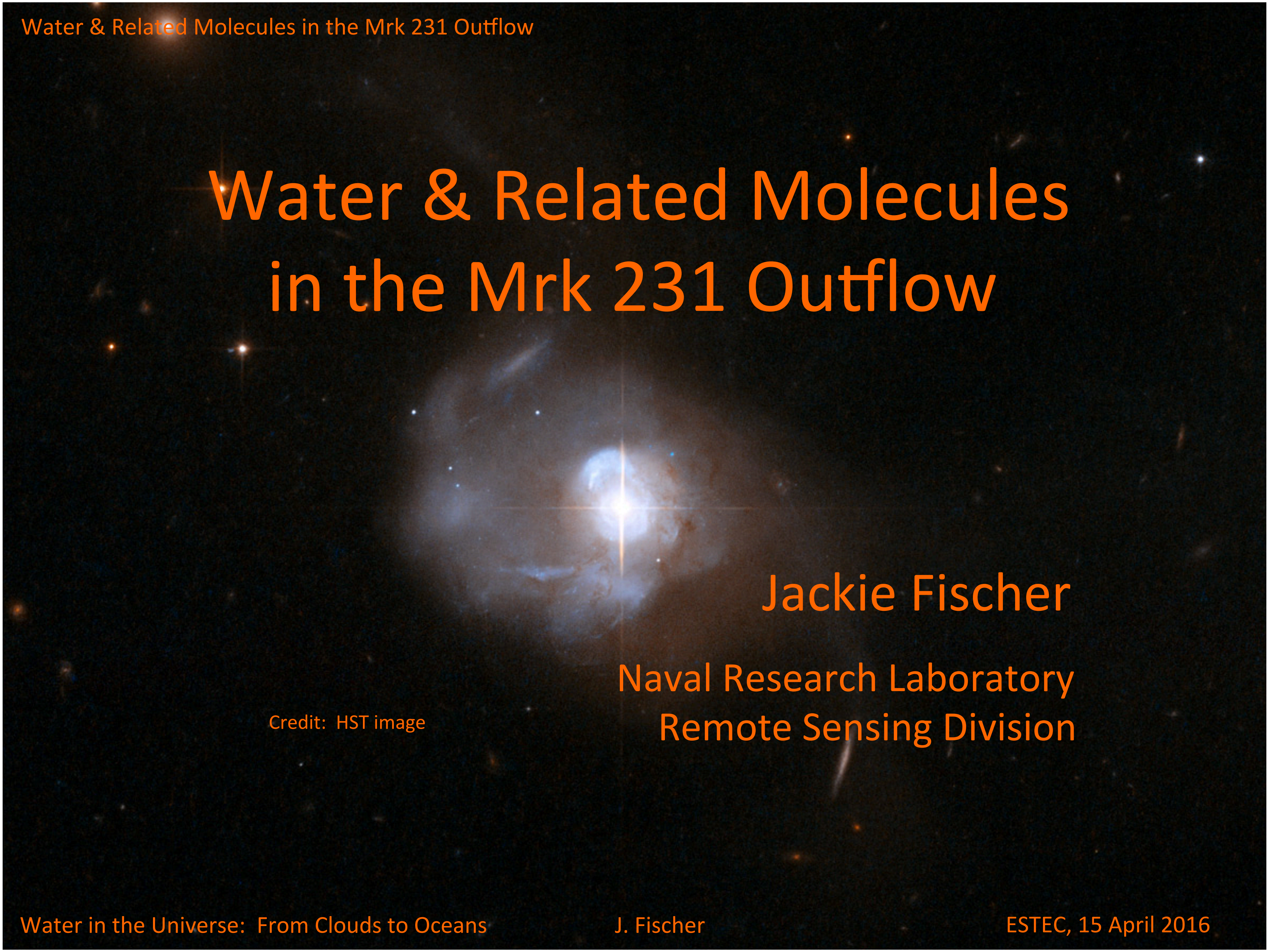
Water & Related Molecules in the Mrk 231 Outflow



Credit: HST image

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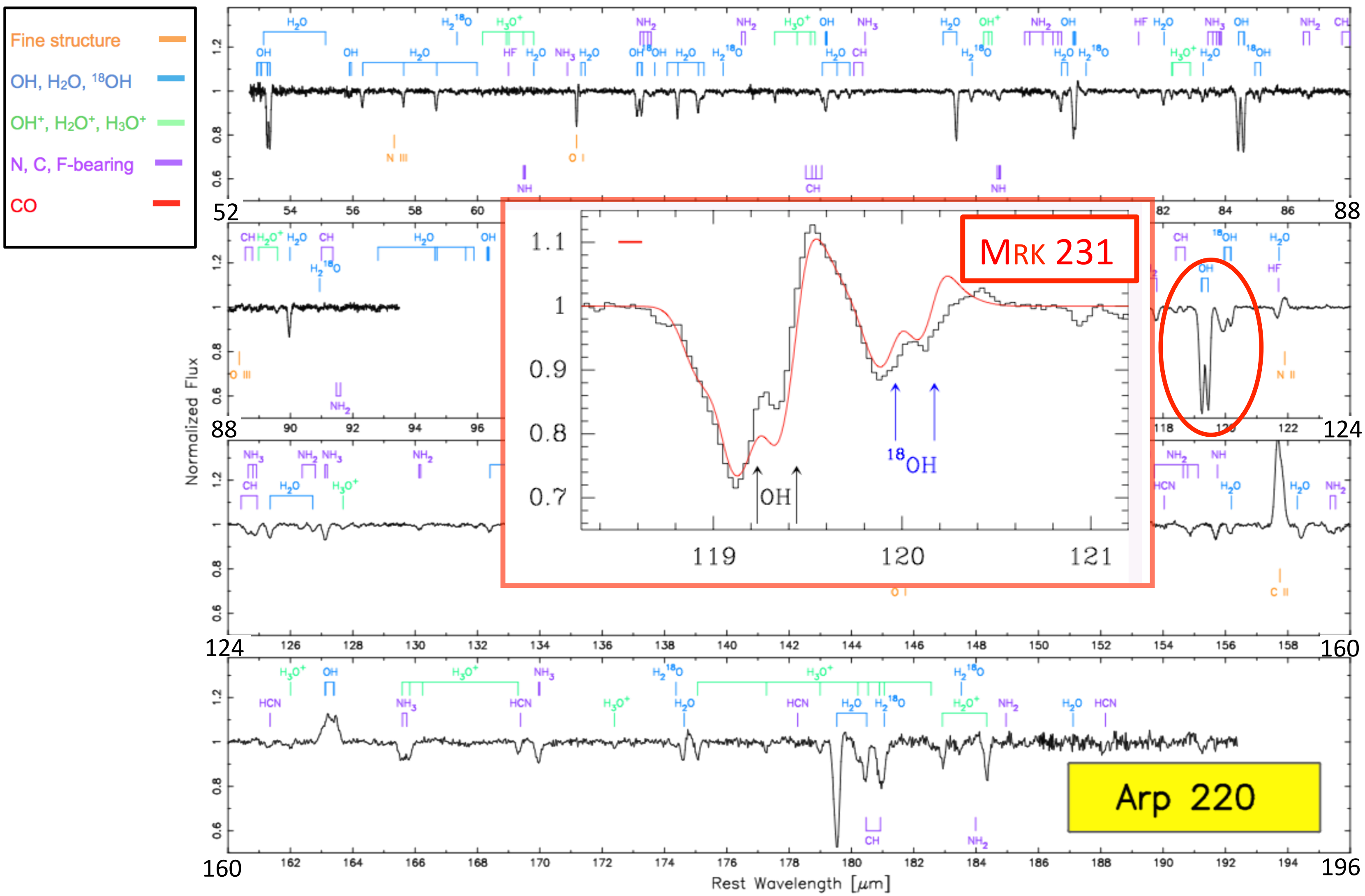
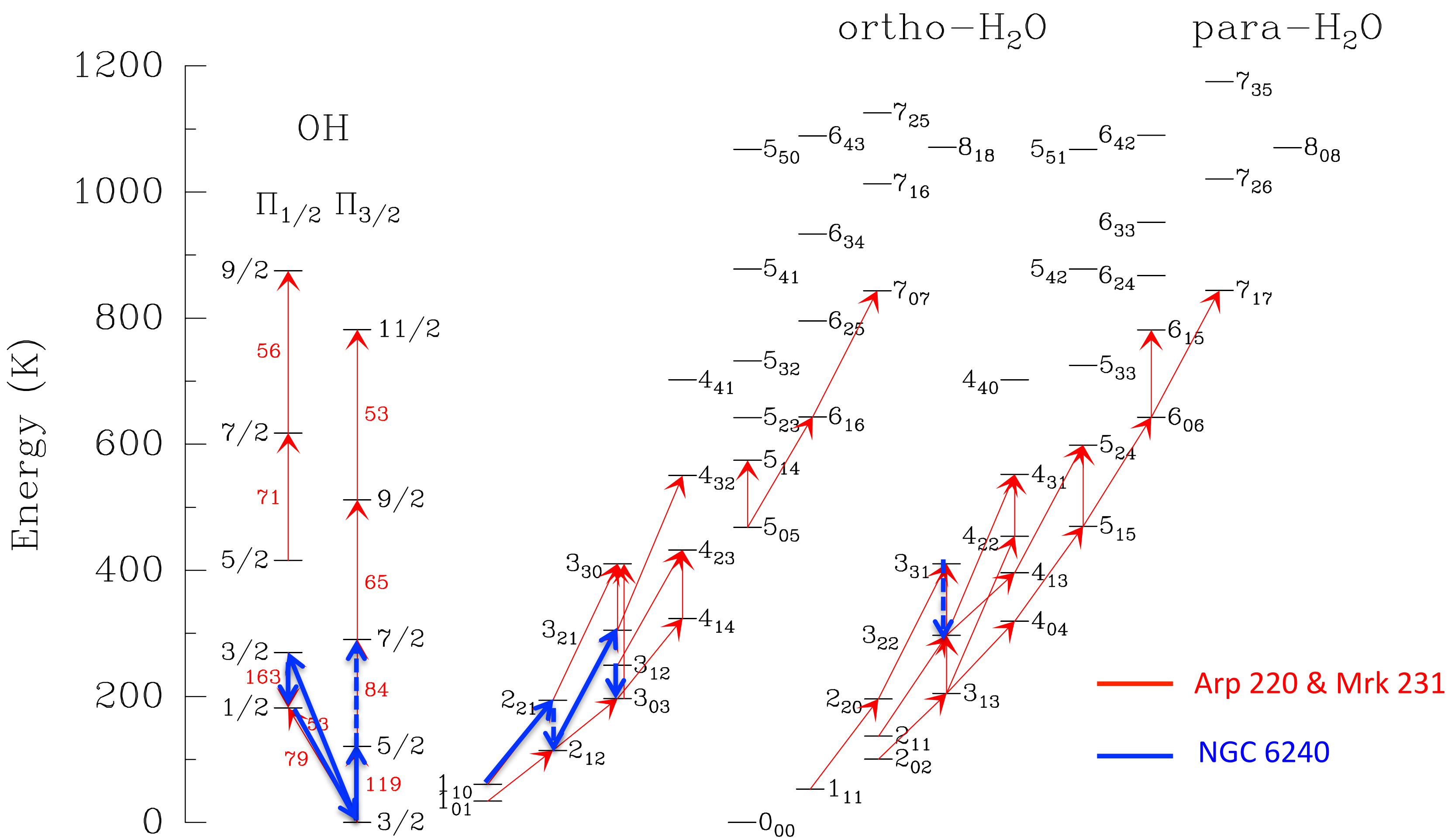
Full PACS Spectroscopic View of ULIRGs

For the nearest ULIRG – a "FIR, molecular photosphere", τ(FIR) >> 1

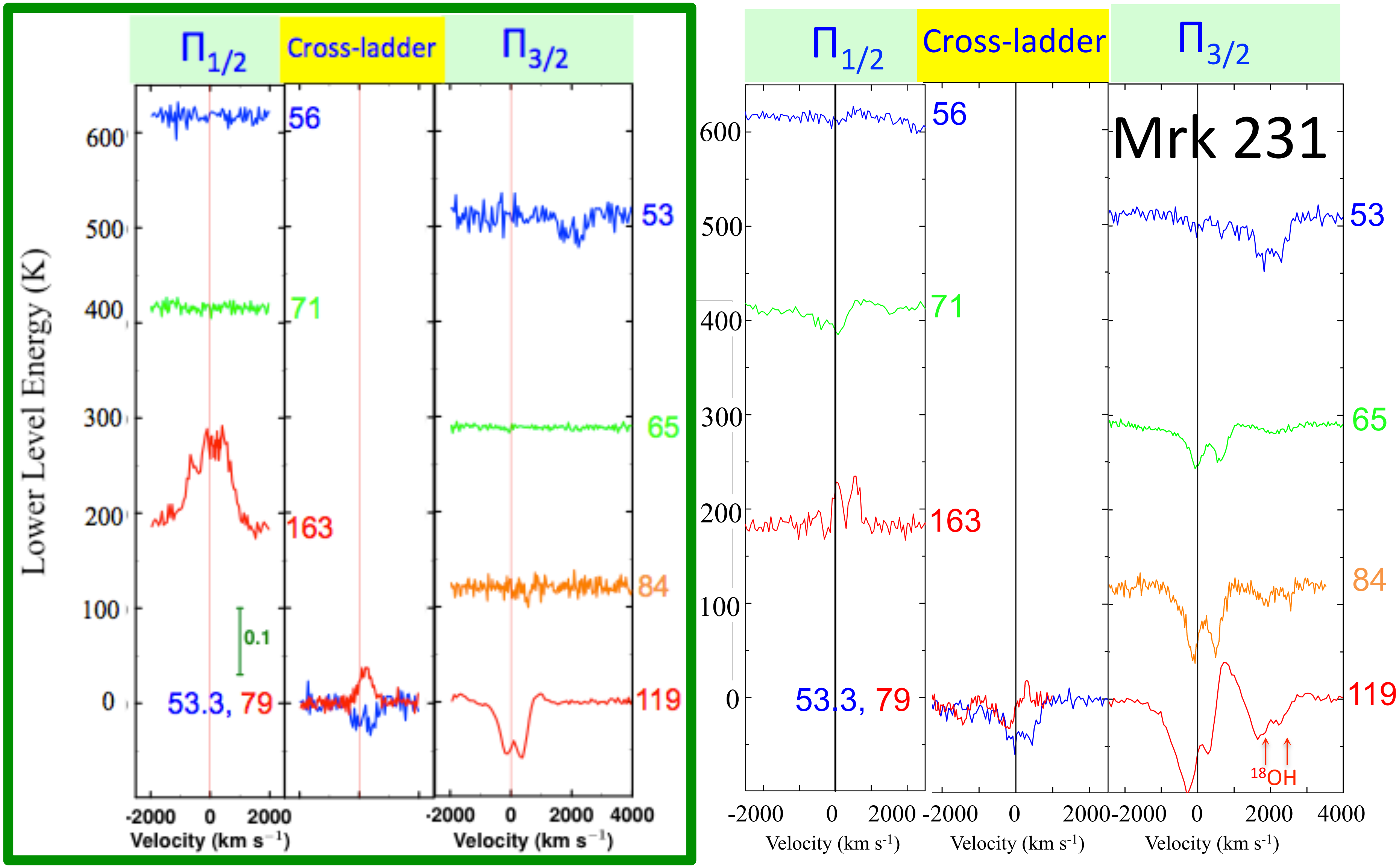


Arp 220 & Mrk 231: Absorption traces radiative pumping by high radiation field

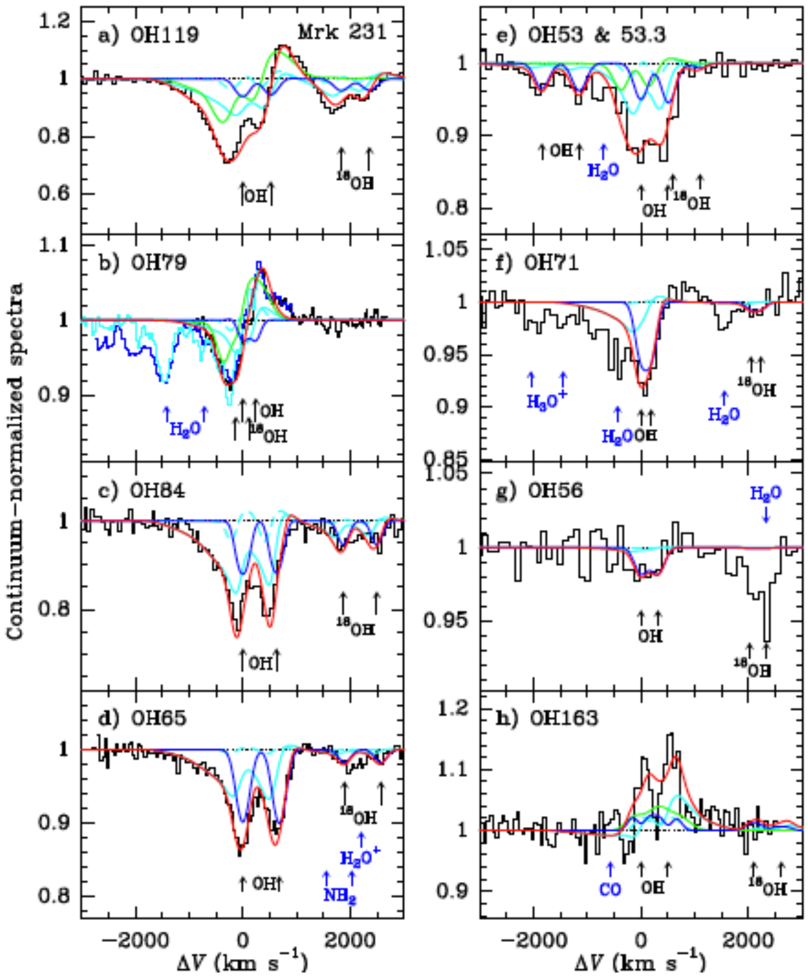


OH and ^{18}OH

NGC 6240 OH Line Profiles vs Lower Energy Level



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



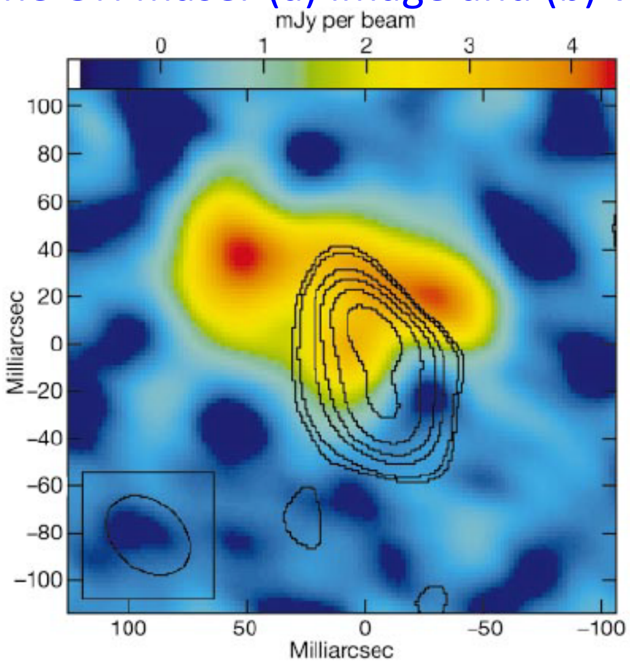
- T_{dust} ~ 90 - 120 K for HV and QC components
- The radius of the quiescent component (i.e. non-outflowing – thick disk, torus) is about
  R = 60 – 70 pc,
  log N(OH) ~ 18.6, & τ(100μm) ~ 1.5 - 2
- For the outflowing component
  R = 130 – 160 pc, with
  log N(OH) ~ 17.5, & τ(100μm) ~ 1.5 – 2
- The low excitation component has lower N(OH), τ(100μm) ≤ 1 and the size is less constrained
- Mass loss rate = 500 - 800 $M_{\odot}$ yr^{-1}
  Momentum flux ~ 10 L_{AGN}/c

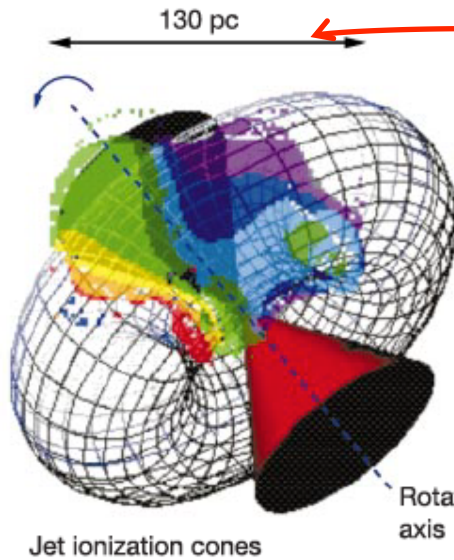
González-Alfonso et al 2014, 2016 - in prep.

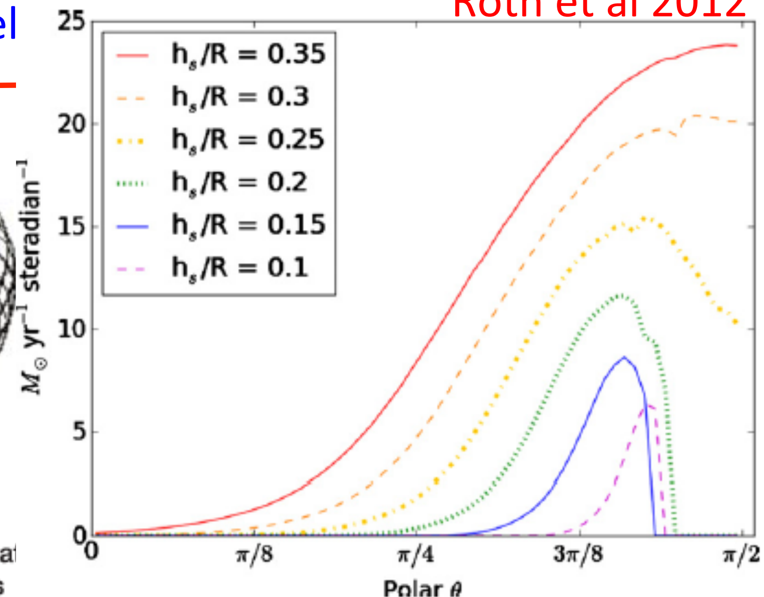
A thick disk/torus and an outflow

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

Roth et al 2012







Klöckner et al. 2003

Parameter	QC	HVC	LVC[b]
$R_{\rm int}$ (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

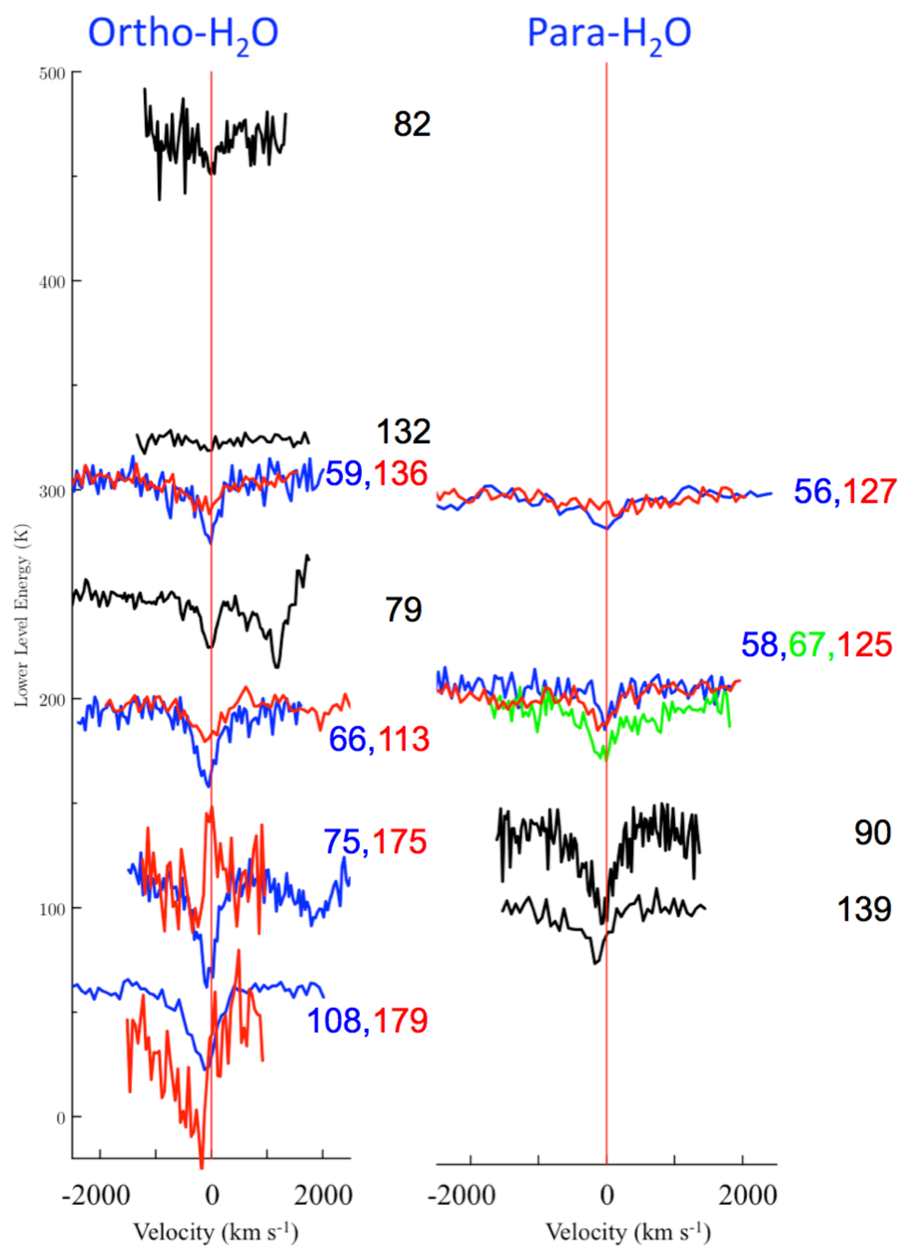
González-Alfonso+2014

H_2O and $H_2{}^{18}O$

H_2O profiles in Mrk 231

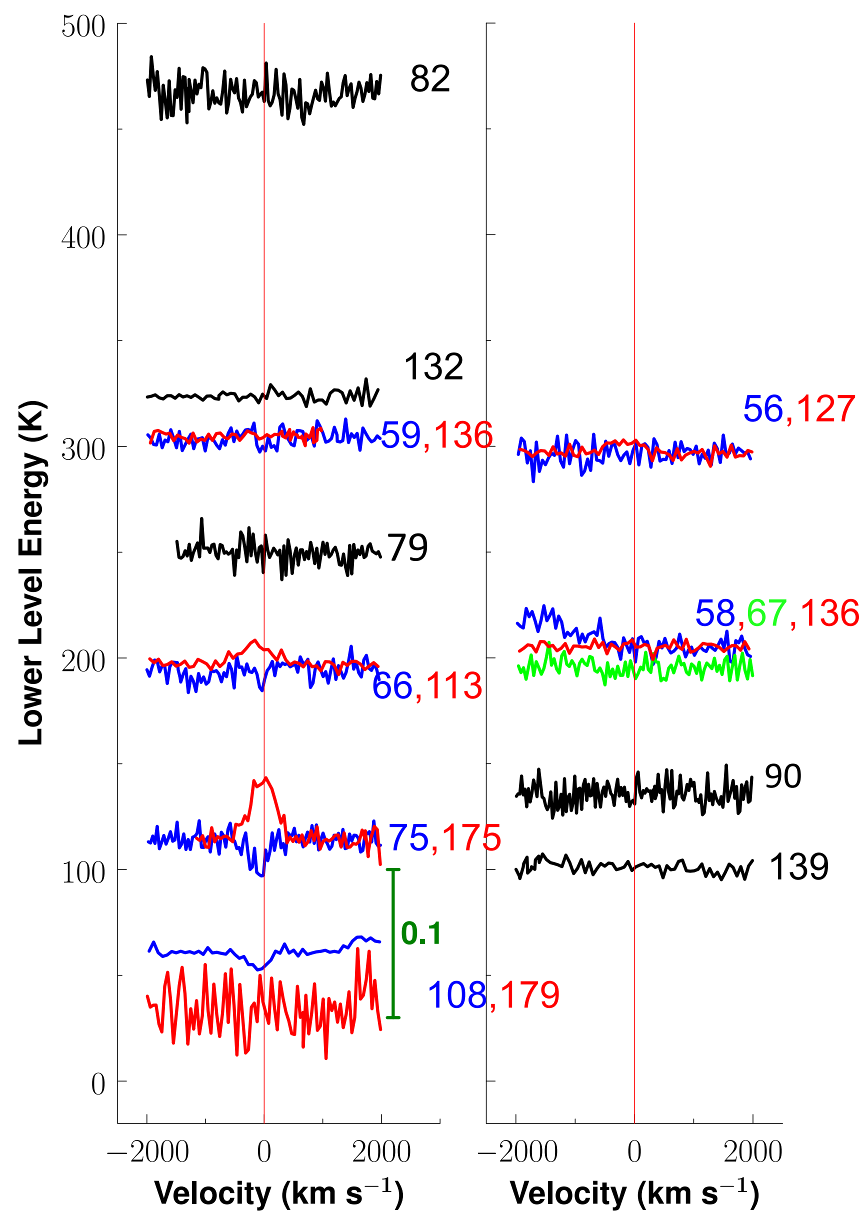
- Similar characteristics to OH profiles
- P-Cygni / blue –shifted peak absorption for lower level transitions
- Zero velocity centroids for higher excitation transitions
- Blue wings evident for most transitions
- $N(OH)/N(H_2O)_{QC}$ ~ 1.25

  $N(OH)/N(H_2O)_{HV}$ ~ 2.50



H_2O profiles in NGC 6240

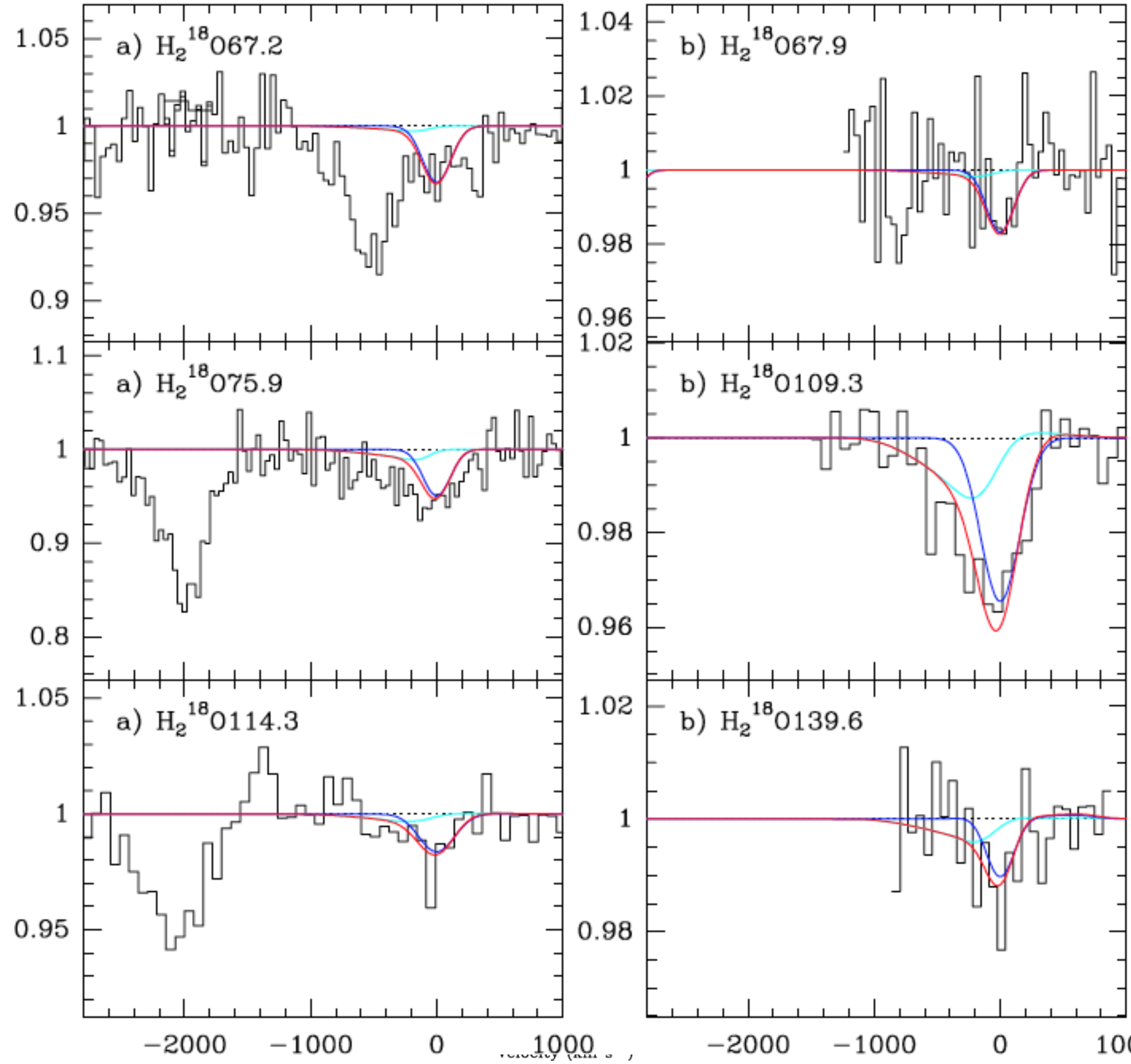
- Similar characteristics to OH profiles – lower excitation and stronger emission compared to Arp 220 and Mrk 231
- Zero velocity centroids for higher excitation transitions
- Blue wings evident for most transitions
- N(OH)/N(H_2O) ~ 1.2



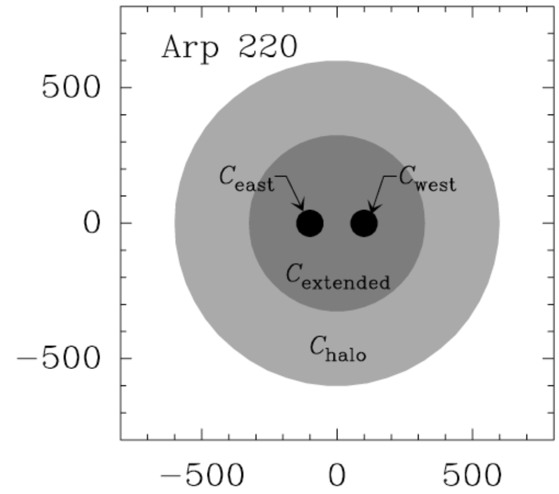
^{18}OH and $H_2{}^{18}O$ in Mrk 231: Model Line Fits

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

$H_2{}^{18}O$



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
- Importantly Arp 220 has higher optical depths with τ(200) ~ 6 – 12 ! (Gonzalez-Alfonso+2004; 2012; Sakamoto+2009)
- $^{16}O/^{18}O$ 70-90 for Arp 220

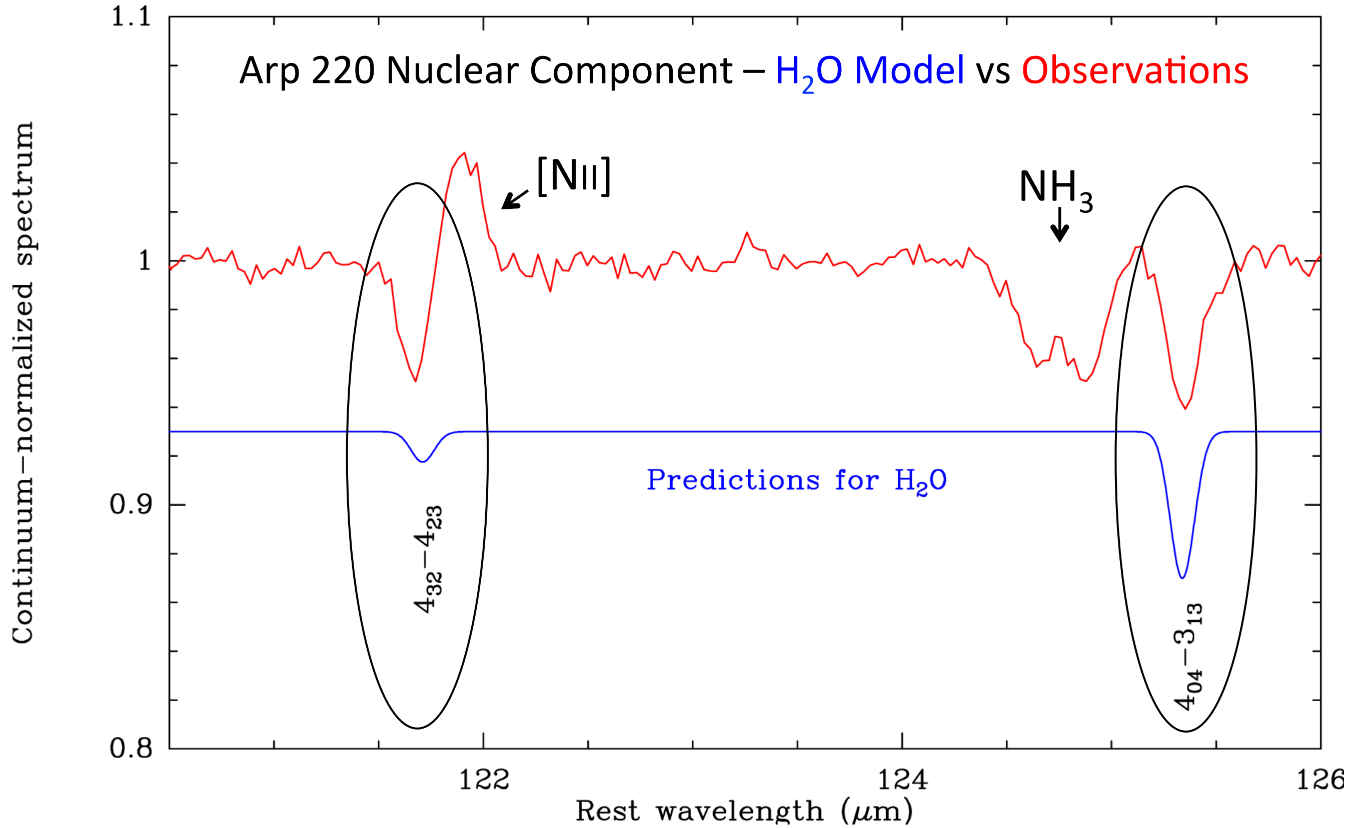
González-Alfonso+2012

HF

HF(2-1) Absorption in (U)LIRGs

The feature shortward of [NII]122 observed in many ULIRGs, is most likely the HF(2-1)121.7 line (E_{lower} ~ 60 K), not the H_2O 4_{32}-4_{23} line only +60 km s^{-1} away.

Both Arp 220 & NGC 4418 show this absorption as well one at the wavelength of HF(3-2).

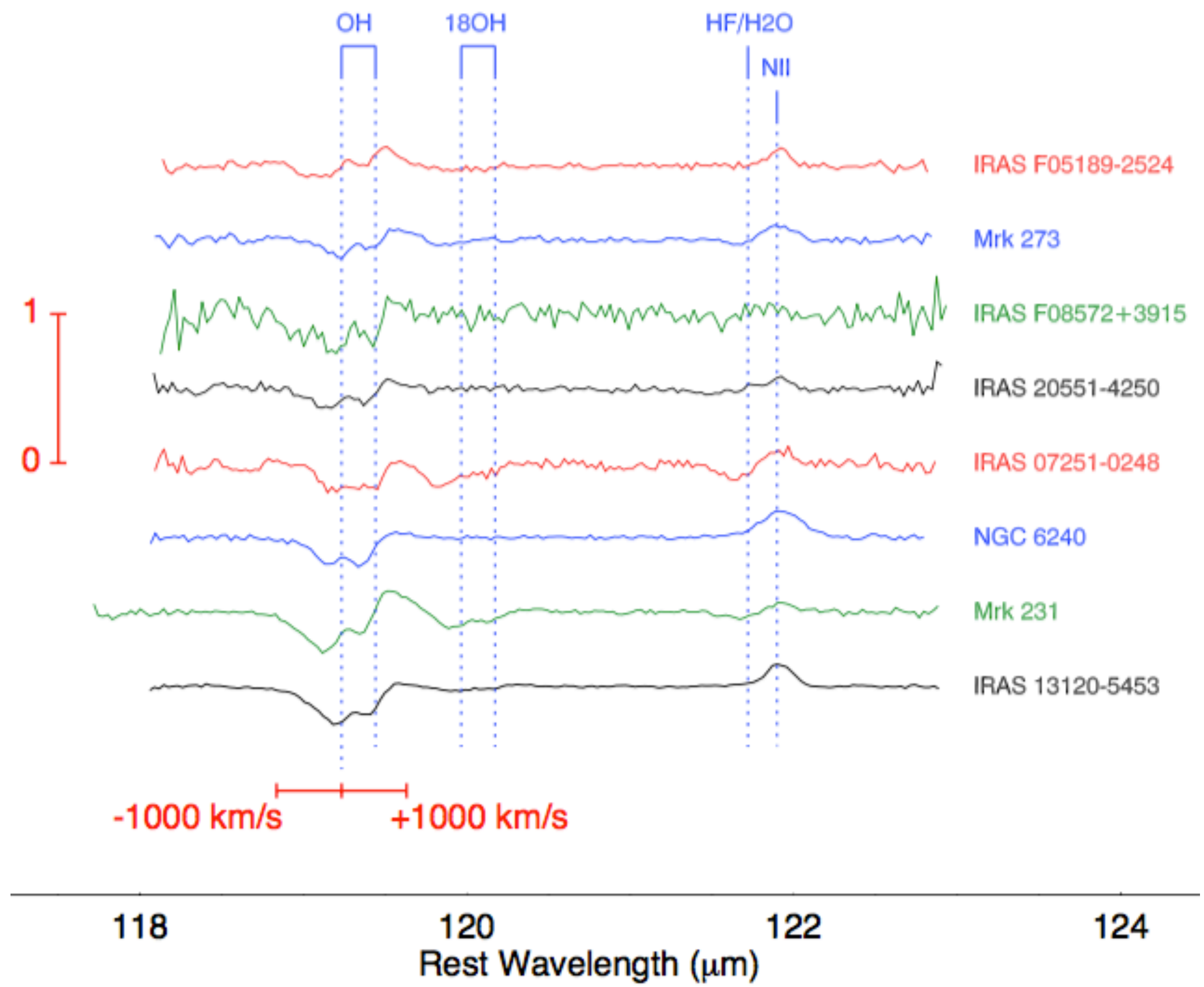


HF(2-1) High-Velocity Absorption

HF(2-1) is seen in absorption, and perhaps in emission, as in HF(1-0) and OH.

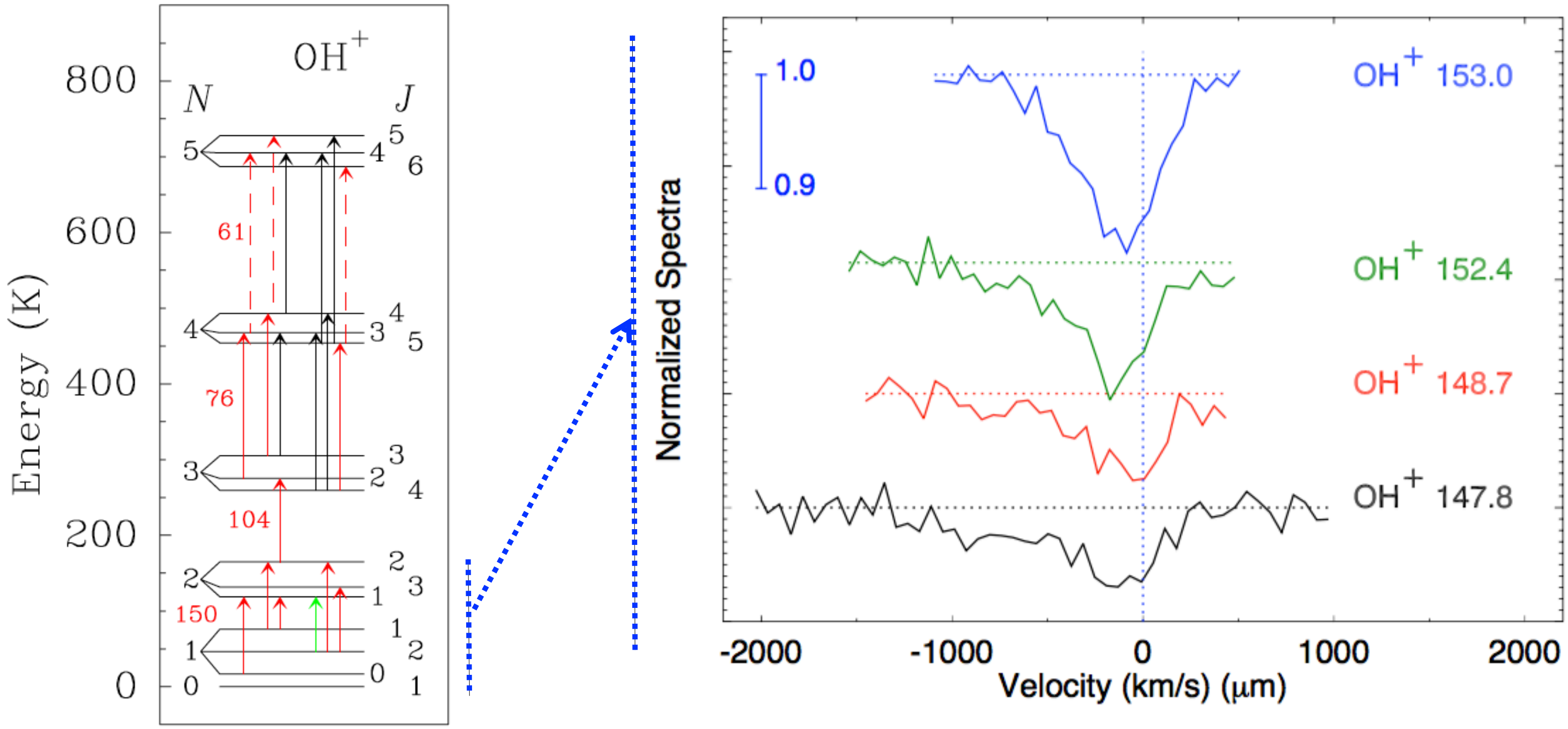
It often displays high velocity wings ~ 1000 km s^{-1}.

HF is present over a wide range of density and temperature in the interstellar medium and HF(2-1) is likely radiatively pumped by strong FIR though if in emission, it is probably a collisionally excited.



OH^+

OH^+ Lines in Mrk 231 Outflow



In González-Alfonso+2013, we reported on a plethora of OH^+ FIR absorption lines in Arp 220 and NGC 4418, and suggested that the OH^+ is produced in an interclump medium exposed to high fluxes of CRs and/or X-rays.

This is likely also in Mrk 231, where OH^+ is relatively stronger than other molecular ions. Blueshifted line profiles and high velocity blue absorption wings are observed in all detected (unblended) FIR OH^+ transitions in the Mrk 231 outflow, with the strongest lines at ~ 150 μm lines with lower level energies of 40-50 K.

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=5×10^{-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)

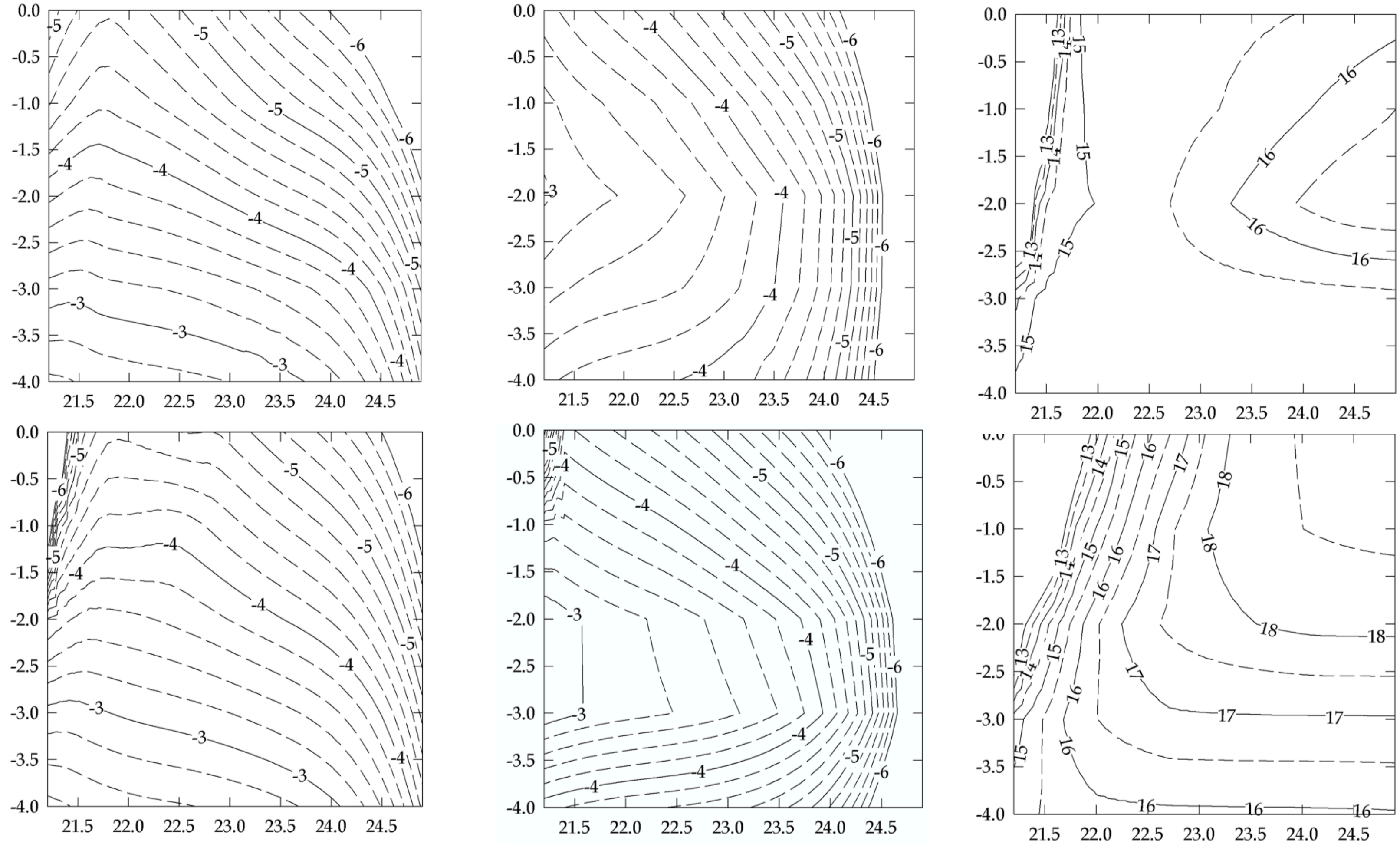
Model predictions versus U, $N_{H,}$ n_H= 3000

Log CII/FIR | Log OIII/FIR | Log N(OH)

SB

AGN

Log U



Log N(H)

Fischer+2014

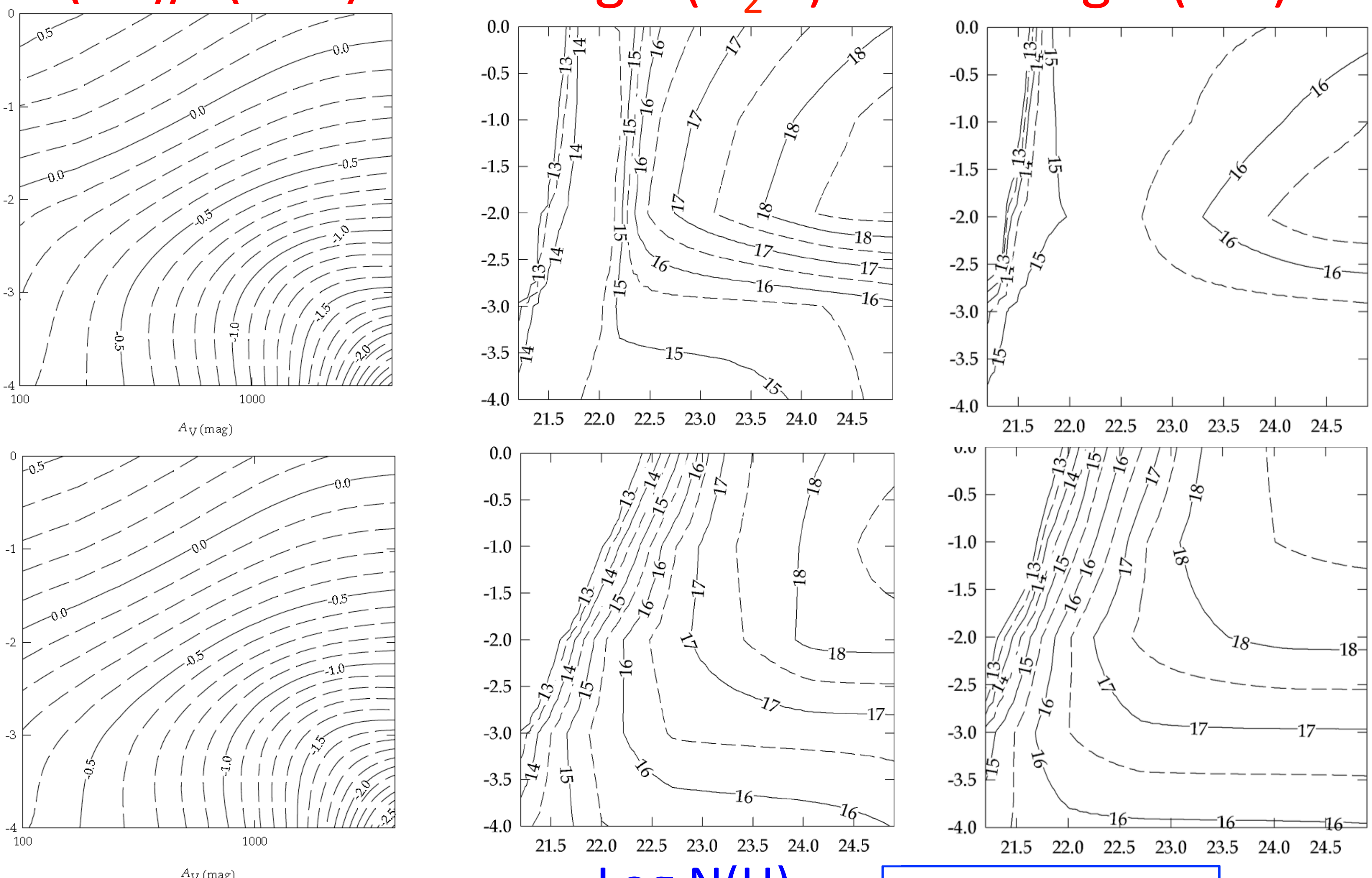
Model predictions versus U, $N_{H,}$ n_H= 3000

F(60)/F(100) | Log N(H_2O) | Log N(OH)

SB

AGN

Log U



Log N(H)

Fischer+2014

Summary

- The far-IR spectral range provides a plethora of probes of the molecular phase of the interstellar medium at high velocities as it is swept away from the active regions of galaxies. These strong, radiatively excited molecular lines of H_2O, $H_2{}^{18}O$, OH, ^{18}OH, OH^+, and HF appear primarily in absorption and thus provide strong constraints on the kinematics, abundances, and energetics of the flows. *Cloudy* models indicate that both high N(H) and high U are needed to explain the correlation between the excited molecular absorption and the deficits in the fine-structure lines.

- In viewing the complete far-IR spectra of three ULIRGs we are viewing three distinct stages of the clearing of the ISM. While in Arp 220, a quiescent component dominates the extremely thick FIR with hints of moderate velocity outflow, in Mrk 231 we see faint fine-structure lines and a massive warm molecular outflow indicating that the ISM is somewhat less thick but close to the excitation source, likely the AGN itself which has a direct line of sight to the observer. In NGC 6240, a high-velocity outflow is present with lower excitation and the fine-structure lines are bright, indicating that the molecular gas has lower column densities and is perhaps more distant from the X-ray bright AGNs.

- In order to quantitatively estimate the outflow rates involved, multiple transitions are needed, but well worth the effort. Observations of the FIR pumped lines together with modeling yield high spatial resolution independent of the distance to the source.

- Herschel has only scratched the surface in studying these outflows and while ALMA can of course reveal unique characteristics, including using H_2O as a probe, a future FIR observatory is sorely needed in order to further study the full set of diagnostics of this very exciting stage of galaxy transformation.