J. Fischer

Herschel PACS Spectroscopy of ULIRGs

I describe our Herschel PACS survey of local Ultraluminous Infrared Galaxies (ULIRGs), which is part of the SHINING Guaranteed Time survey of local galaxies. In particular, I discuss far-infrared spectroscopy of Mrk 231, the most luminous of the local ULIRGs, and a type 1 broad absorption line AGN. For the first time in a ULIRG, all observed far-infrared fine-structure lines in the PACS range were detected and all were found to be deficient relative to the far infrared luminosity by 1 – 2 orders of magnitude compared with lower luminosity galaxies. The deficits are similar to those for the mid-infrared lines, with the most deficient lines showing high ionization potentials. Aged starbursts may account for part of the deficits, but partial covering of the highest excitation AGN powered regions may explain the remaining line deficiencies. A massive molecular outflow, discovered in OH and ^{18}OH, showing outflow velocities out to at least 1400 km s^{-1}, is a unique signature of the clearing out of the molecular disk that formed by dissipative collapse during the merger. The outflow is characterized by extremely high ratios of ^{18}O / ^{16}O suggestive of interstellar medium processing by advanced starbursts

Herschel PACS Spectroscopic Diagnostics of Local ULIRGs

Conditions and Kinematics

Jackie Fischer

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with *SHINING* team

(see also our A&A 2010 Special Issue paper, Fischer et al. 2010)

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- Alessandra Contursi

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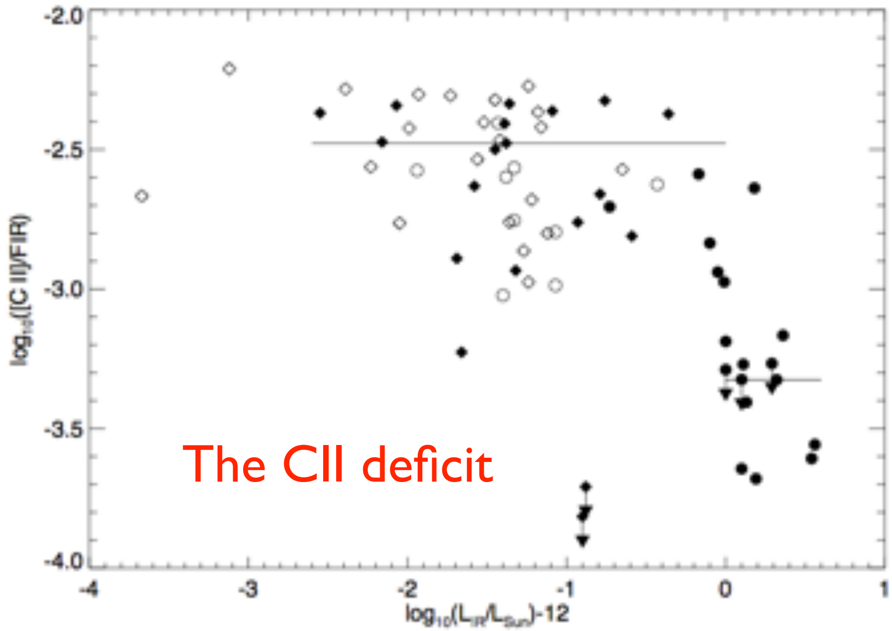
Linda Tacconi

Why study local ULIRGs?

- In the local Universe, ULIRGs signal the merging and morphological transformation of gas rich galaxies: what are their evolutionary precursors, products and how do they reach them?
- They're a major contributor to the IR background.
- ULIRGs: often the first galaxies we'll learn about at high z.
- In what ways and which high-z ULIRGs are like local ones and at what z, if any, is there a change?
- Unique ISM: warm, high far-infrared radiation density, molecular and possibly opaque, so our task is not easy, but we have a great

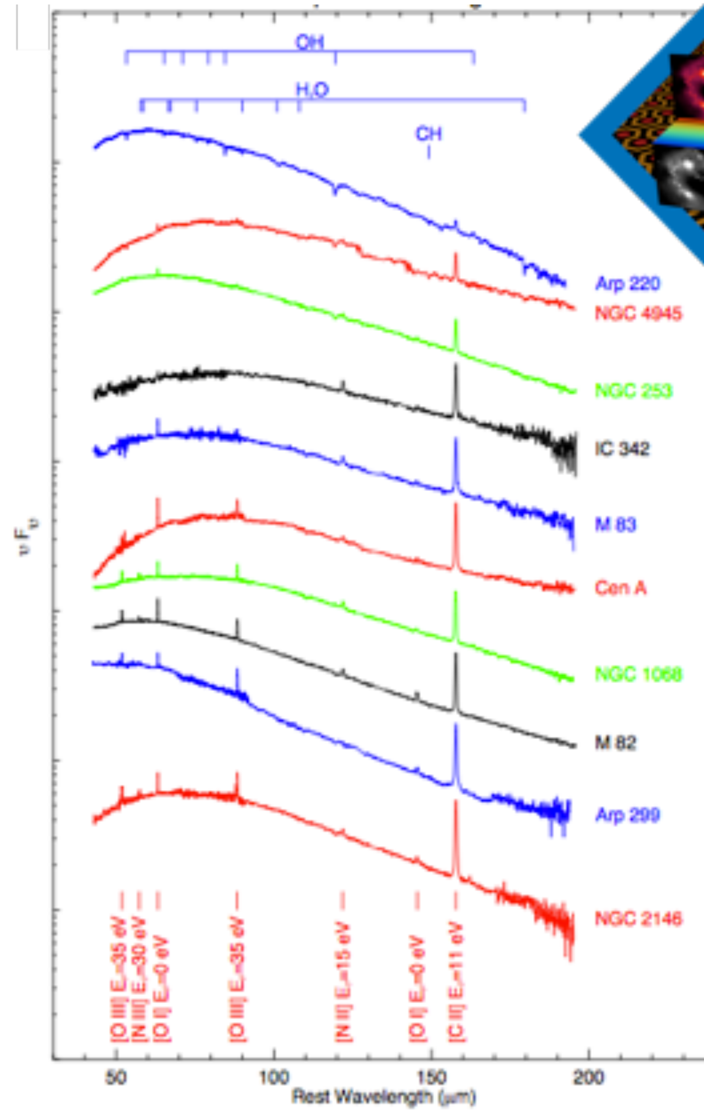
Dust-Bounded ULIRGs?



What is responsible for the line deficits in ULIRGs?

- A high ionization parameter, U?
  (Luhman et al. 2003, Abel et al. 2009)

U, the ratio of ionizing radiation density to particle density



10 BGS galaxies with L> 10^{10} $L_{\odot}$ and $F_{IRAS60} \geq F_{ARP\ 220}$

SHINING ULIRG Observations

- About 80 hrs is devoted to PACS IF spectroscopy of ULIRGs
- Full PACS highly sampled scan of Arp 220
- Range scans ≥ (±1000 km s^{-1}) of IRAS RGBS galaxies with
- $L \geq 10^{12} L_{\odot}$ plus NGC 6240 and UGC 5101 (23 galaxies):
  - Fine-structure lines tracing atomic and ionized gas, [CII]158, [OI]145,63, [NII]122, [OIII]88, [NIII]57
  - ^{16}OH 119, 79, 65 µm, ^{18}OH 120 µm, lines
  - H_2O 78.7 µm, 121.7 (HF 2-1) lines
  - CO (20-19)

Mrk 231, a type I LoBAL ULIRG

- Most luminous of the local ULIRGs in the RBGS, $L_{IR} = 3.2 \times 10^{12}\ L_{\odot}$ for adopted distance, 172 Mpc (z=0.04217)
- Central quasar is covered by a semi-transparent dusty shroud producing about 3.1 magnitudes of extinction at 4400 Å (Reynolds et al. 2009)
- Low ionization broad absorption is observed, eg. in Na I D, at both high velocities (up to ~ 8000 km/s) and lower velocities (up to ~ 2000 km/s)
- Mid-IR/Spitzer: Veilleux et al. (2009) the AGN contribution to L_{bol} is ~ 70% by most of 6 estimation techniques (vs 35 – 40% for all ULIRGs)
- Contribution of an advanced 120 – 250 Myr nuclear starburst is ~ 25 – 40% (near-IR, Davies et al. 2007)
- Dominated by molecular absorption in the far-IR (Gonzalez-Alfonso et al 2008)
- Nuclear rotating, nearly face-on molecular disk (Downes & Solomon 1998)

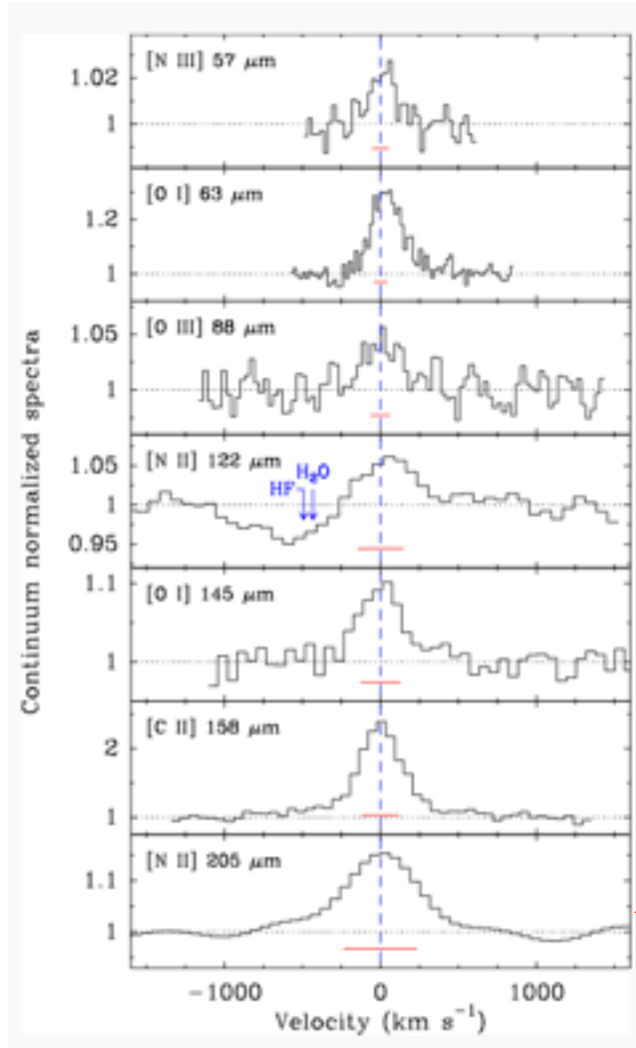
Fine Structure Lines & Kinematics

All searched for fine-structure lines were detected in a ULIRG for the first time! They are faint!

Inferred FWHMs are in the range 180 - 290 km/s, Δv_{avg} = 235 km/s

This early in the mission the best calibration is on the continuum of Mrk 231 itself, ≤ 25%

Blue wing (out to -1000 km/s) is evident in [CII], [NII], and possibly the HF/H2O line



Fine-structure FWHMs similar to those of CO(1-0) and stellar disk 170 & 270 km/s

The blue wings have similar velocities as "low" velocity, kpc scale outflow components (v> -2100 km/s, Rupke et al. 2005)

[N II] 205 µm
HerCULES SPIRE FTS
(HerCULES KP)
van der Werf et al. 2010

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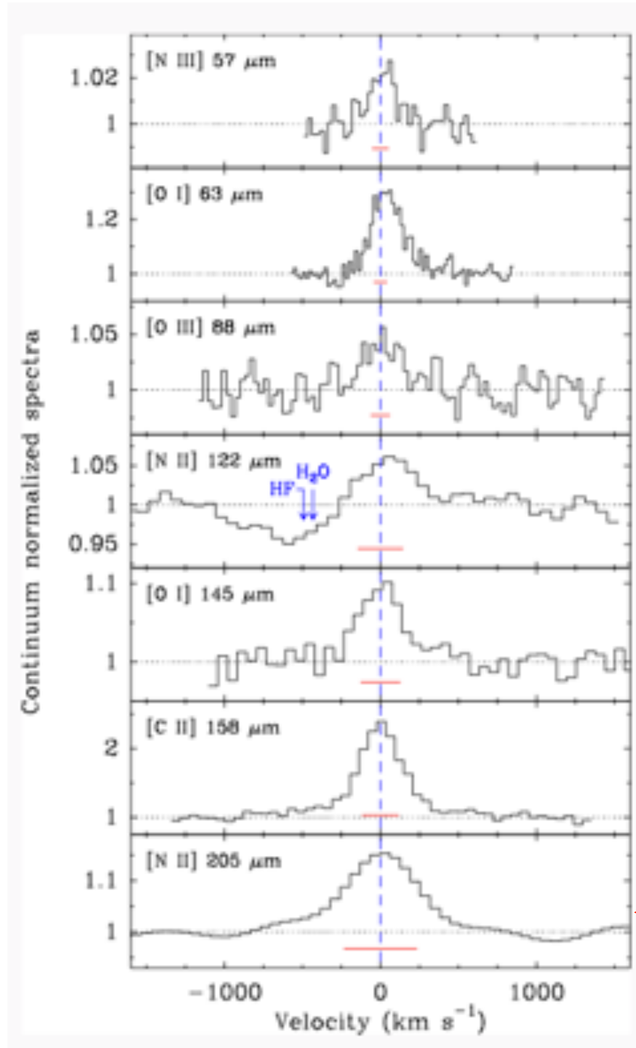

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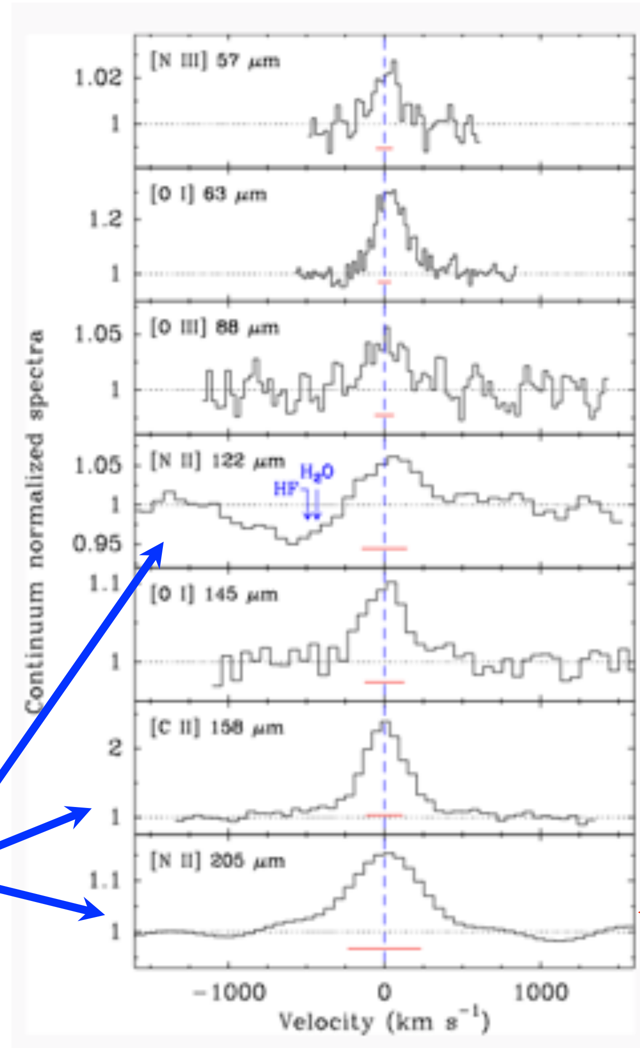

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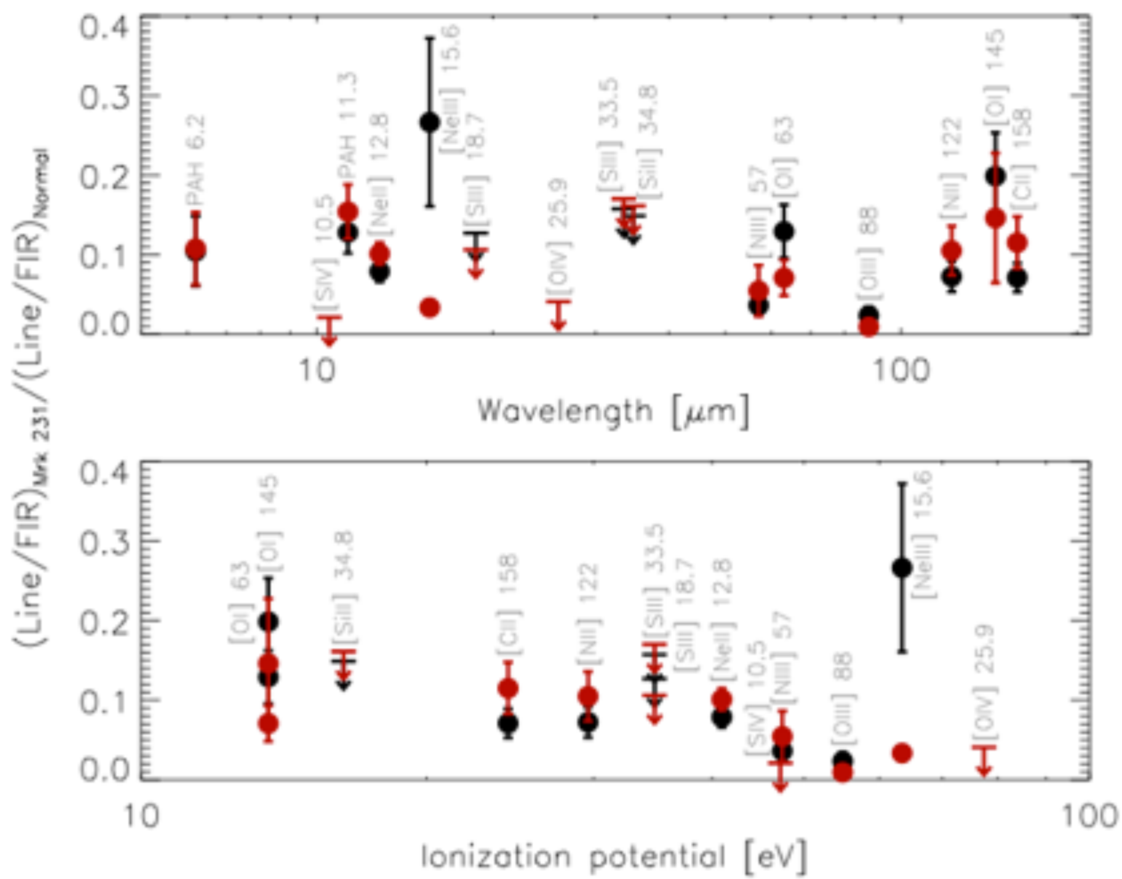
Fine-structure line deficit trends

No obvious trend in the deficit with transition λ (or n_{crit}) compared with AGN & SB

Deficit is more severe for higher ionization potential compared with AGN & SB, but for SB, [NeIII] is strong

(Spitzer lines from Armus et al 2007)



● Starburst sample

● AGN sample

*Comparison samples

Graciá-Carpio et al., in prep.

Fine-structure line deficit trends

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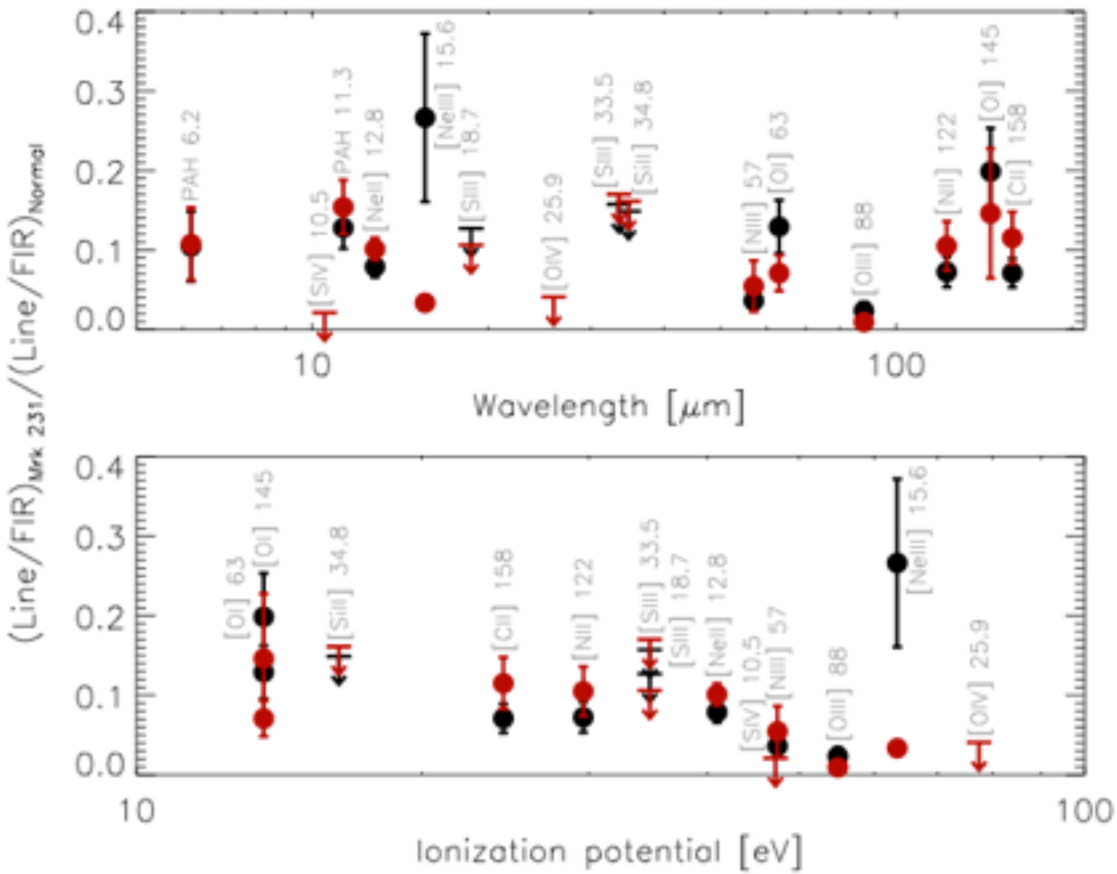

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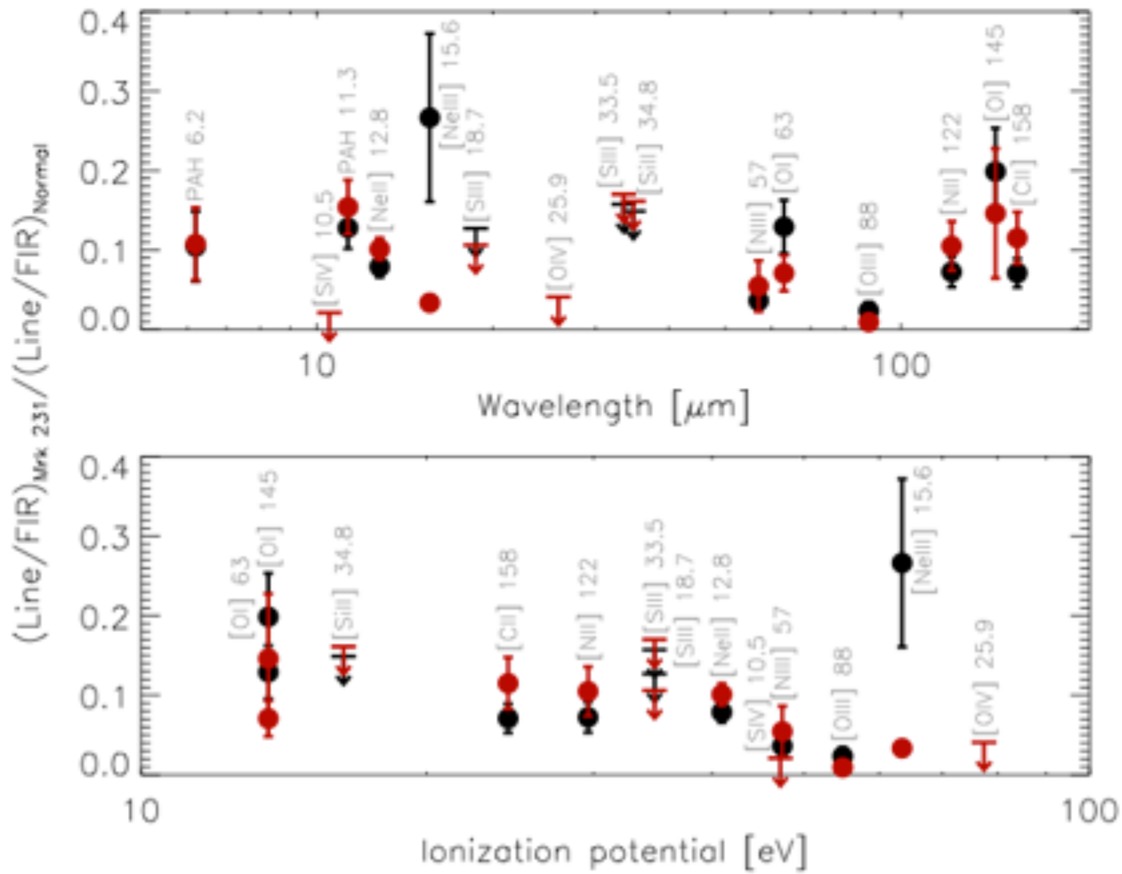
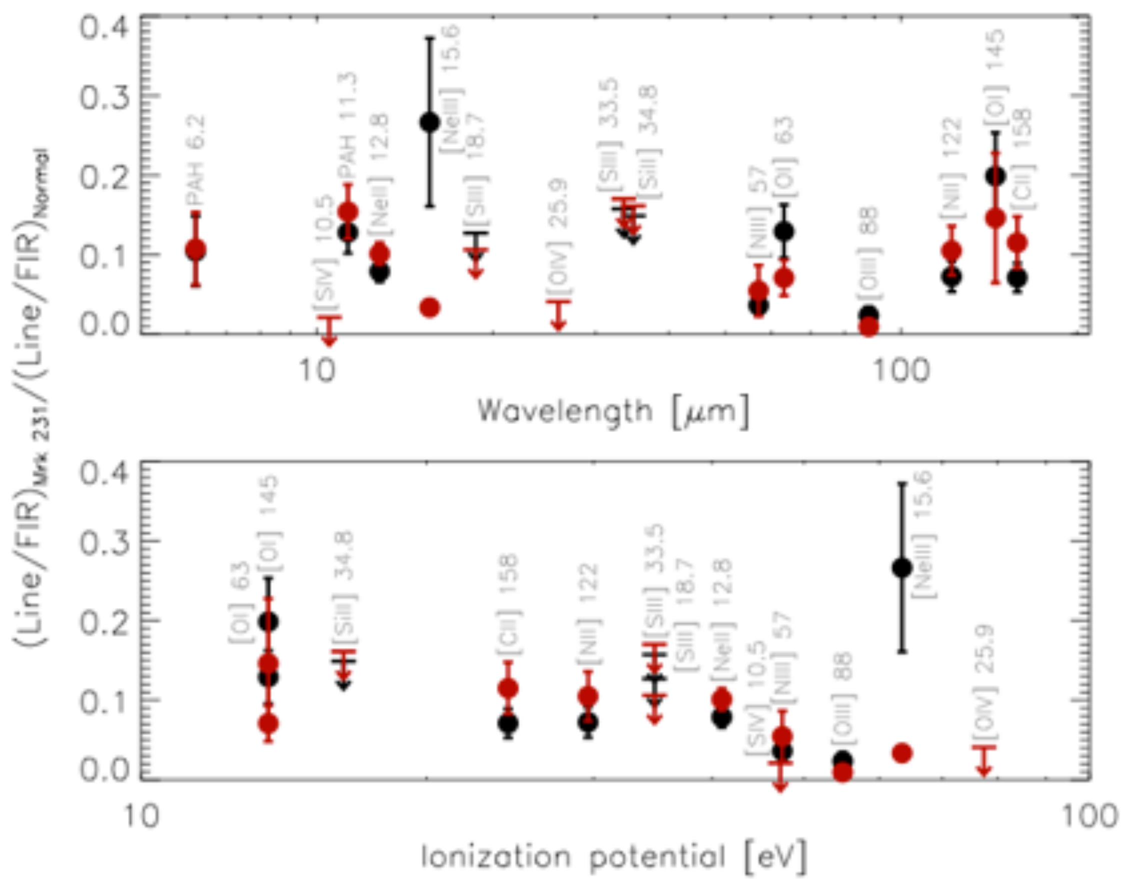


Fine-structure line deficit trends

If the deficits are caused by dust obscuration, it appears to be caused by extremely opaque clumps, all or nothing, with higher covering factors for species with higher ionization potentials.

(Spitzer lines from Armus et al 2007)



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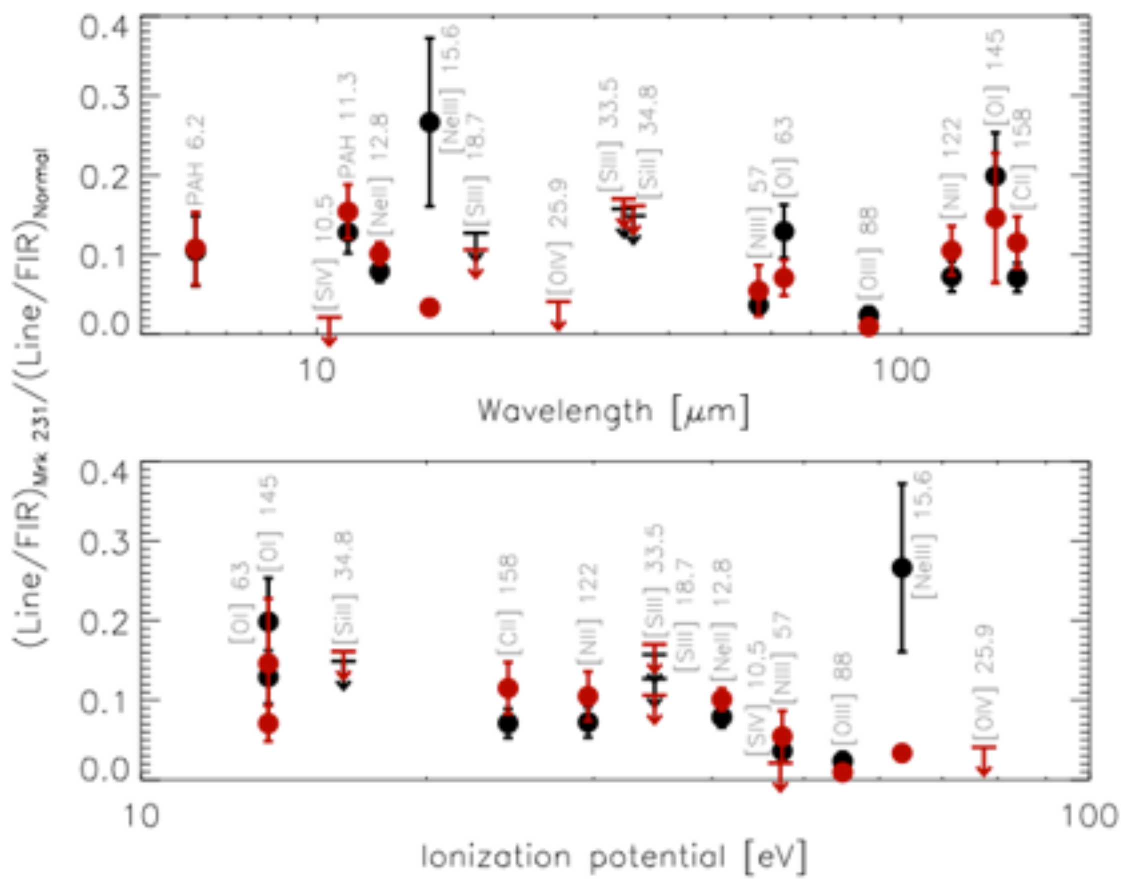

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Wiffle ball

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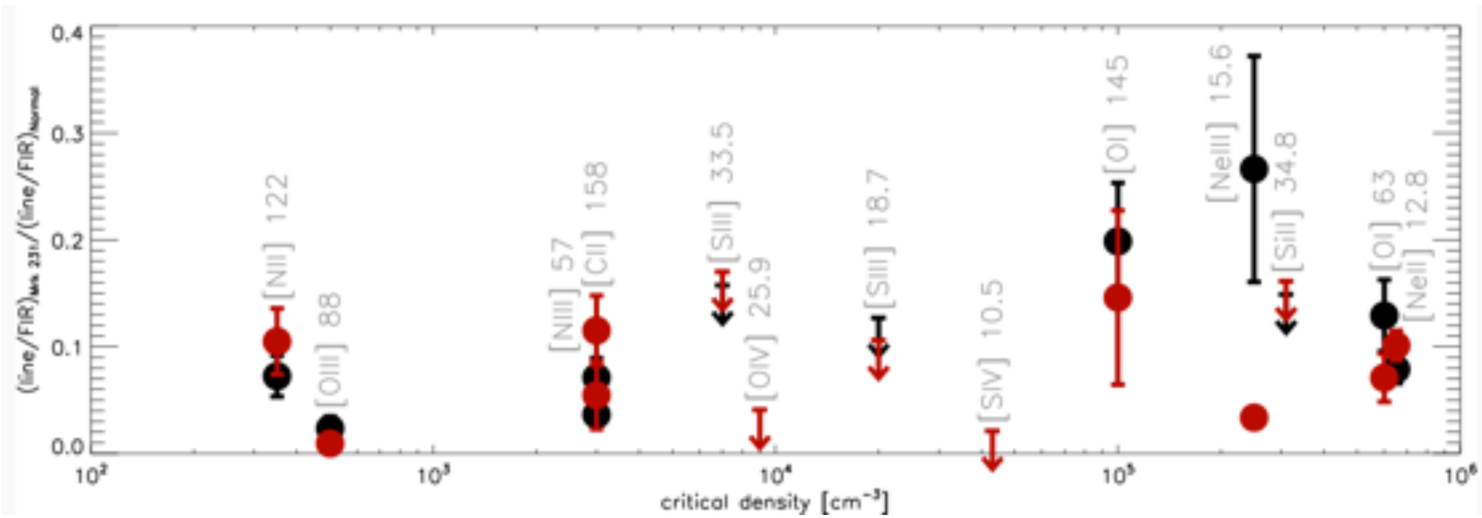
Wiffle ball

Is the "WYSIWYG" approach correct?

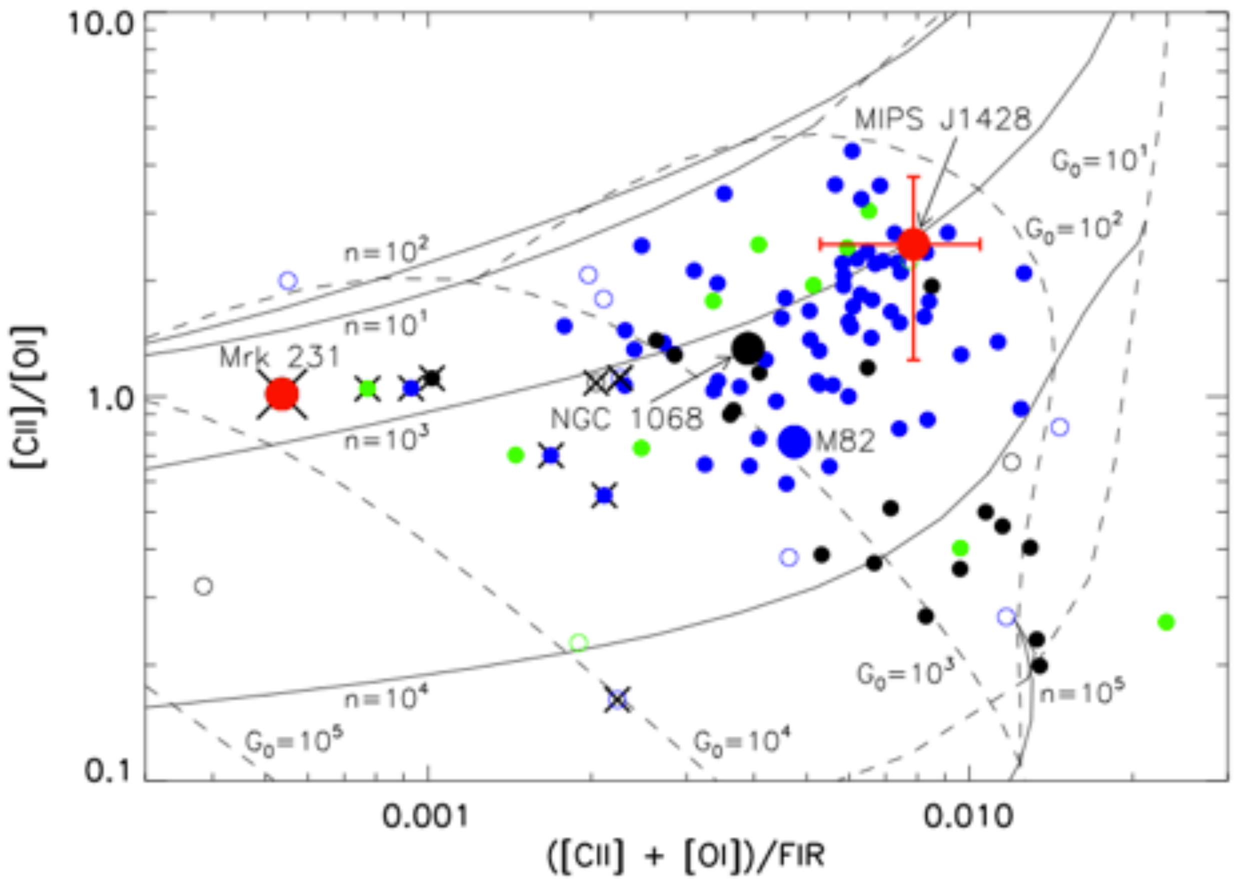
Density effects?

(Spitzer lines from Armus et al 2007)



There is only a marginal correlation with critical density.

Moderate PDR/Ionized Densities



Also, from the ratio of the [NII] 205 / [NII] 122 lines, find that n_e is near the low density limit.

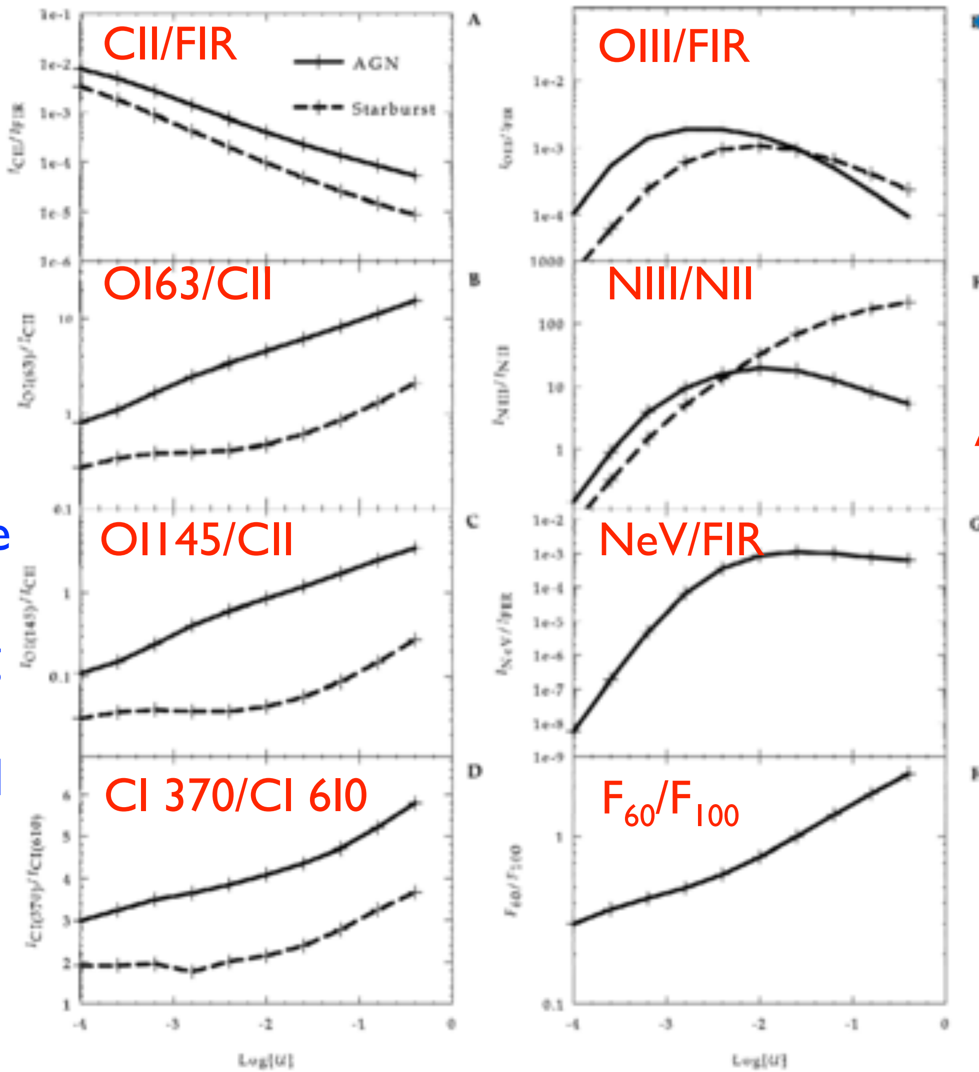
Sturm et al. "Herschel Observations IR-Bright Galaxies at High Redshift" A&A Special Issue 2010

Model predictions as a function of U

AGN

Starburst

Some, but not all predictions are observed in Mrk 231. Perhaps instead, we have a stratified medium with increased covering with ionization, as suggested for ionized gas in some ULIRGs by Spoon & Nolt 2009



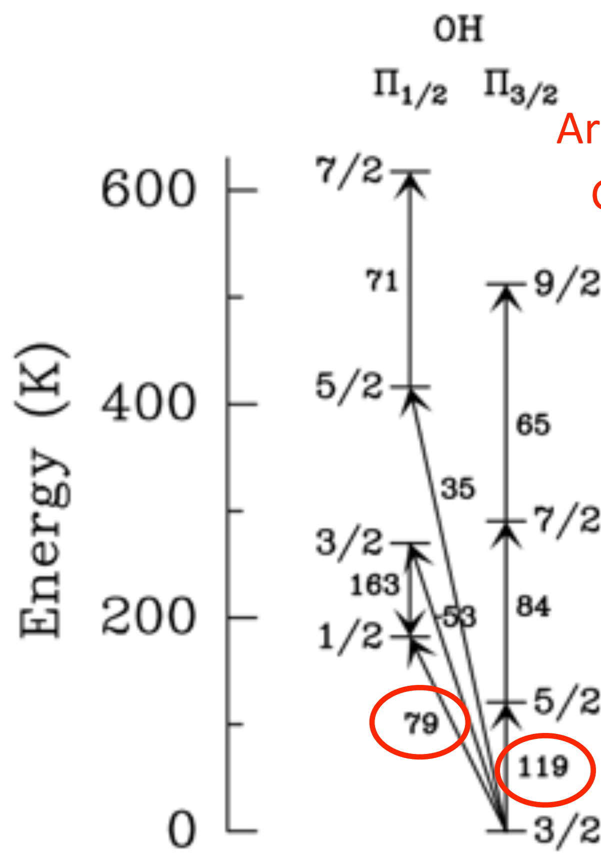
Abel et al. 2009

Predicted emission line and line-to-continuum ratios as a function of *U* and SED.

Observed OH, ^{18}OH transitions

We also observed the strong OH 119, 79 µm & the ^{18}OH 120 µm doublets in Mrk 231 (and will for the rest of the sample).

The OH lines are radiatively pumped by the strong FIR radiation density.



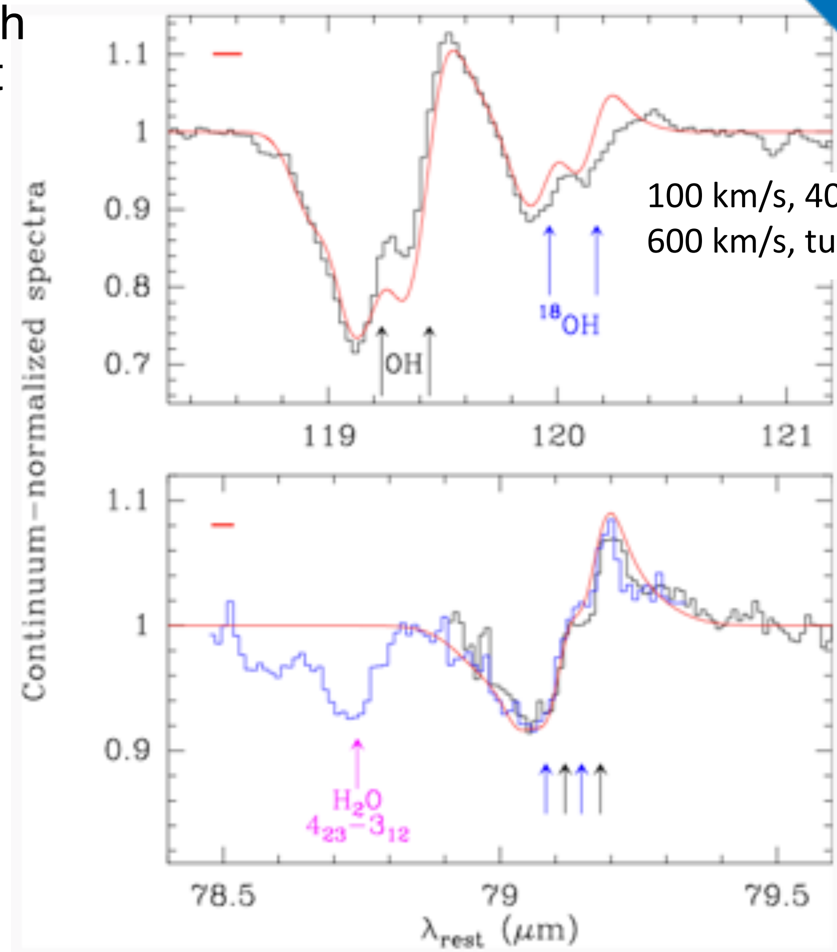
Arp 220/Mrk 231 ISO-LWS
González-Alfonso et al. 2004, 2008

120 µm for ^{18}OH

A massive molecular outflow

Spectacular P-Cygni profiles in both OH, and the ^{18}OH ground-state doublets with broad blue-shifted absorption as far out as -1400 km/s for OH 119 µm

Blue-shifted wings suggest that [CII], [NII], & excited H_2O/HF also participates in the outflow



100 km/s, 400 km/s, 600 km/s, turb=300 km/s

Based on model fits to continuum and line pumping (Gonzalez-Alfonso 2010), outflow lower limits:

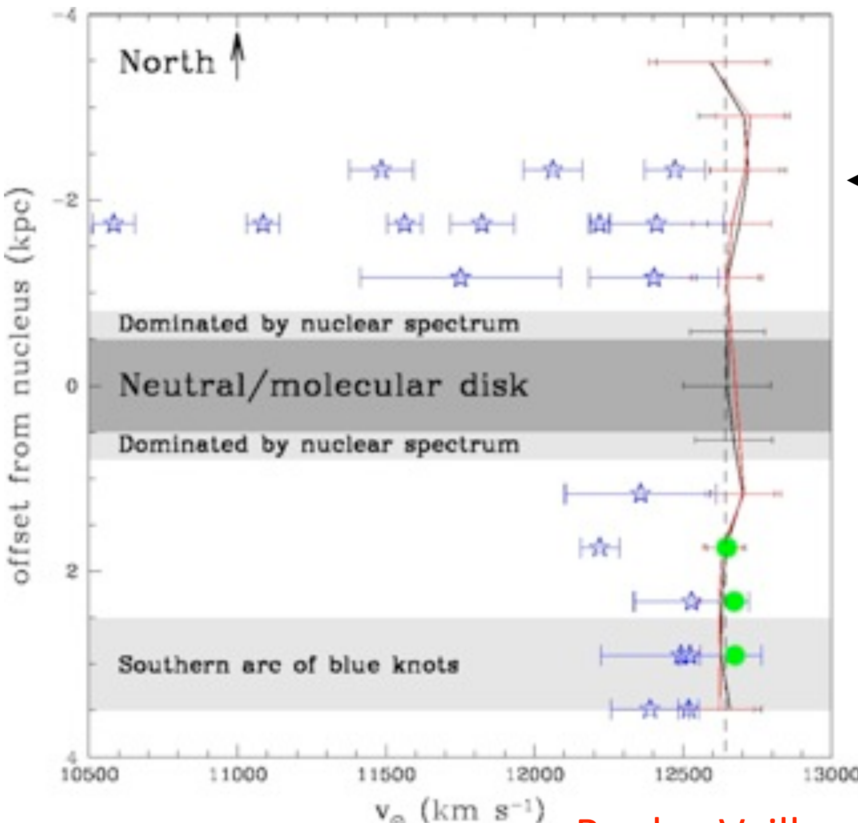
Mechanical energy ≥ 10^{56} ergs,

Mechanical luminosity ≥ 1% of L_{TIR},

Mass ≥ 7×10^{7} $M_\odot$ (see also Feruglio et al., submitted)

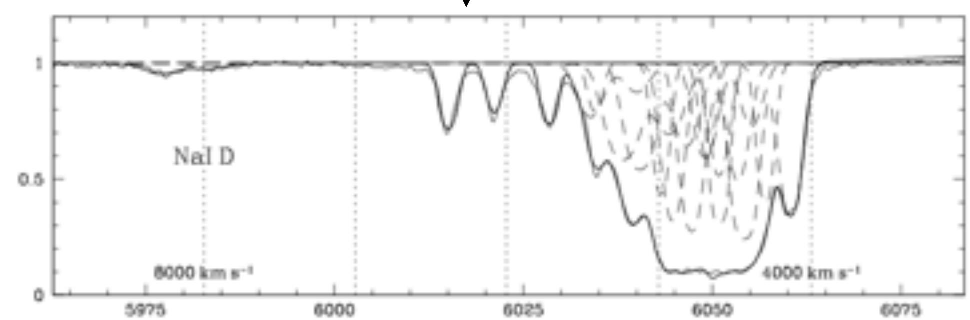
Comparison to Na I D doublet

Molecular Outflow traced by OH



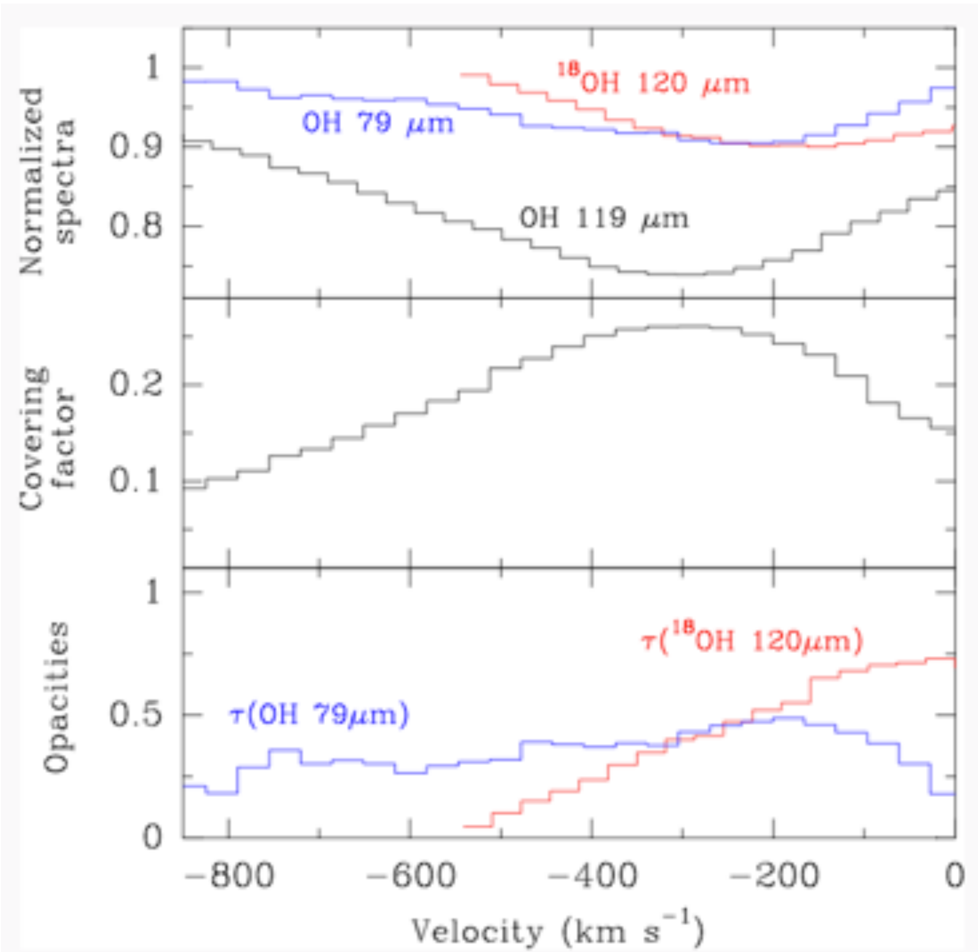
Blue shifted velocity range suggests kpc scale, similar to Na I D optical outflow velocities

Not the nuclear -8000 – -4000 km/s,



Rupke, Veilleux & Sanders 2002, 2005

High $^{18}O/^{16}O$ abundance



^{18}OH 120 µm absorption is deeper than OH 79 µm at low negative velocities (top)

We use the covering factor measured from 119 µm (middle); not too sensitive to this

At these velocities, it appears that:

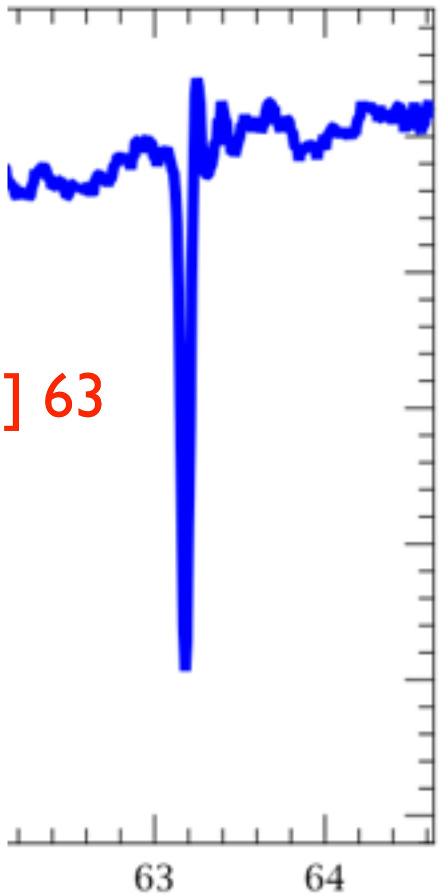
$\tau(^{18}OH\ 120) \geq \tau\ (OH\ 79)$ (bottom)

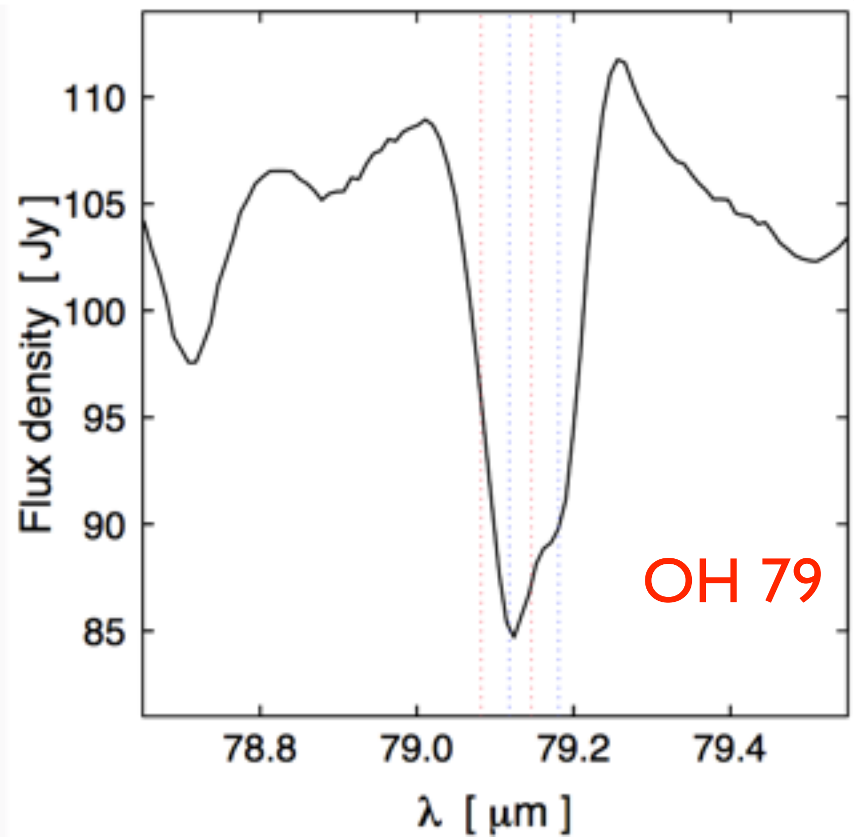
$N(^{18}OH)/N(OH) > 1/40$

Need observations of high OH levels

[OI] 63, OH79 in Arp 220

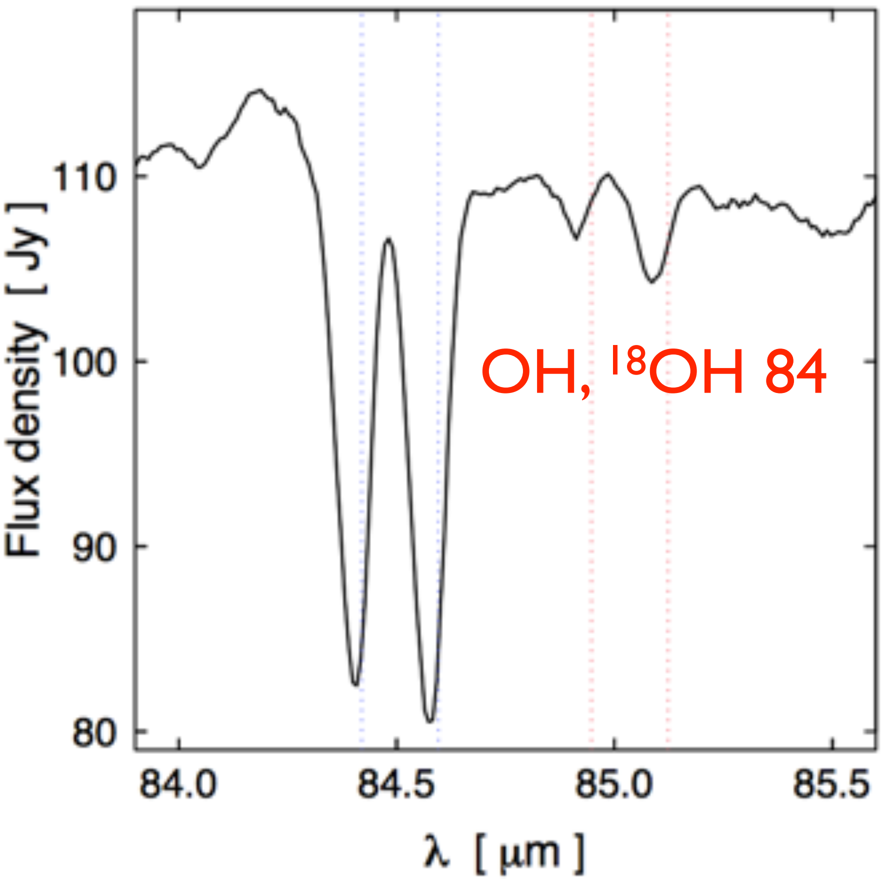
[O I] 63

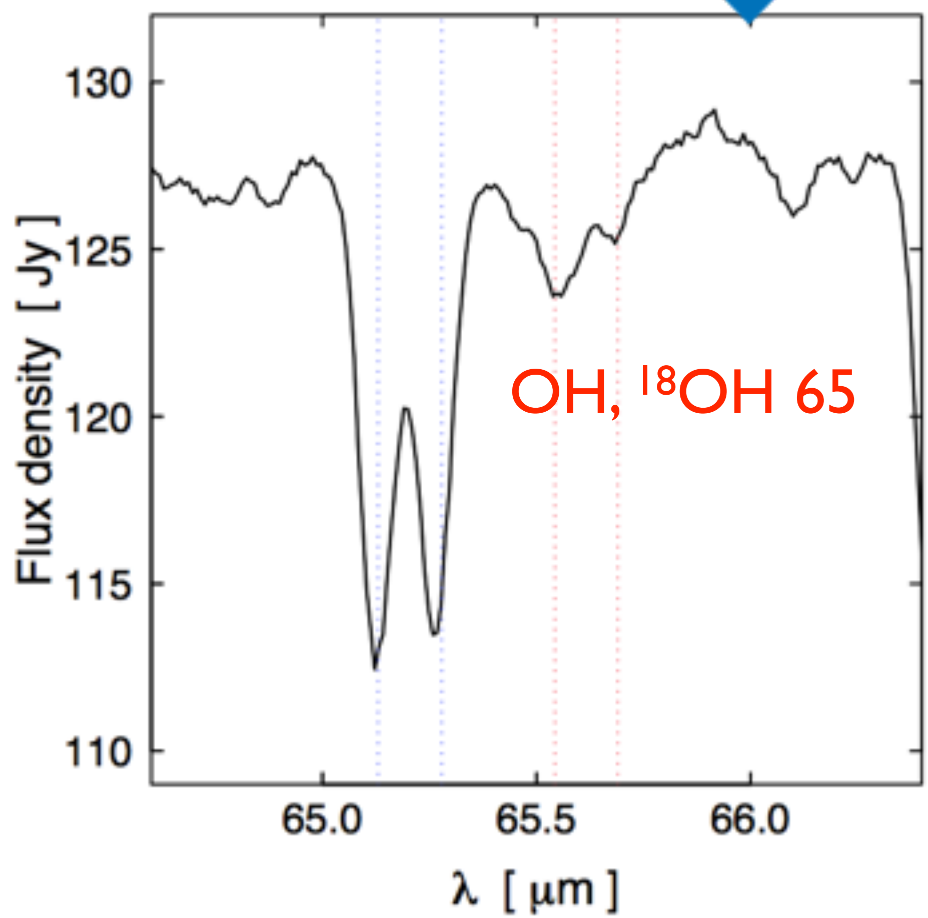




See also Sakamoto et al. 2009

OH, ^{18}OH in Arp 220





Summary

- The IR fine-structure lines in Mrk 231 are faint compared with both star-bursts and AGN, by ~ 1-2 orders of magnitude
- No correlation of line deficits with λ, weak correlation with n_c, but strong inverse correlation with ionization potential (IP) compared with AGN, and compared with starbursts up to the NeIII 15 μm line at IP ~ 60 eV. This may be an effect of higher covering factors for higher IP, due to a clumpy medium
- The OH lines show P-Cygni profiles indicating a kpc scale massive molecular outflow. Some H_2O/HF, [CII], [NII] participates in the outflow. Velocity profiles of higher, FIR pumped OH, H2O lines will help locate and quantify the parameters. (See also Feruglio et al. 2010 on CO outflow)
- $^{18}O/^{16}O$ appears very high compared with other galaxies, perhaps