Herschel Observations of ULIRGs:
the Strong Coupling between Radiation, Gas, & Dust

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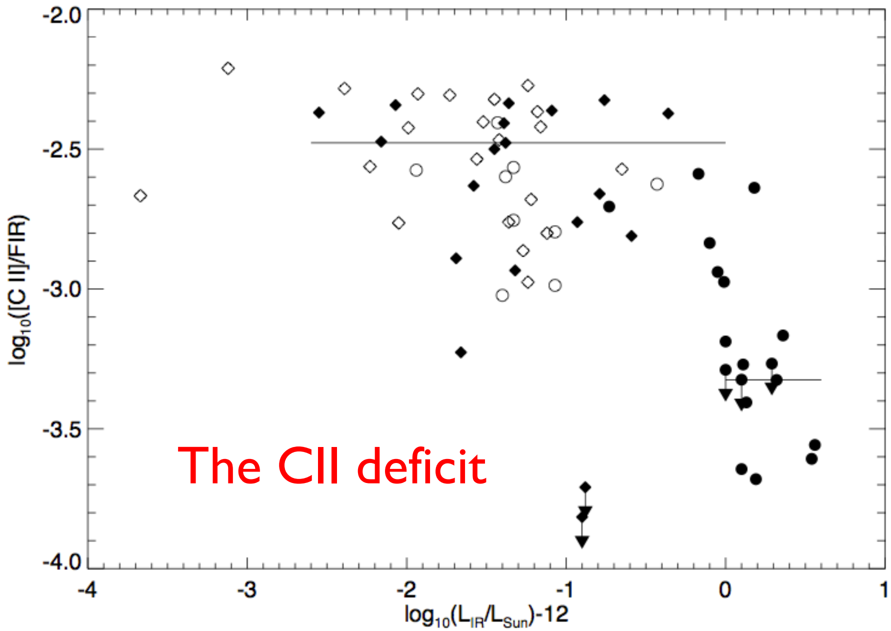
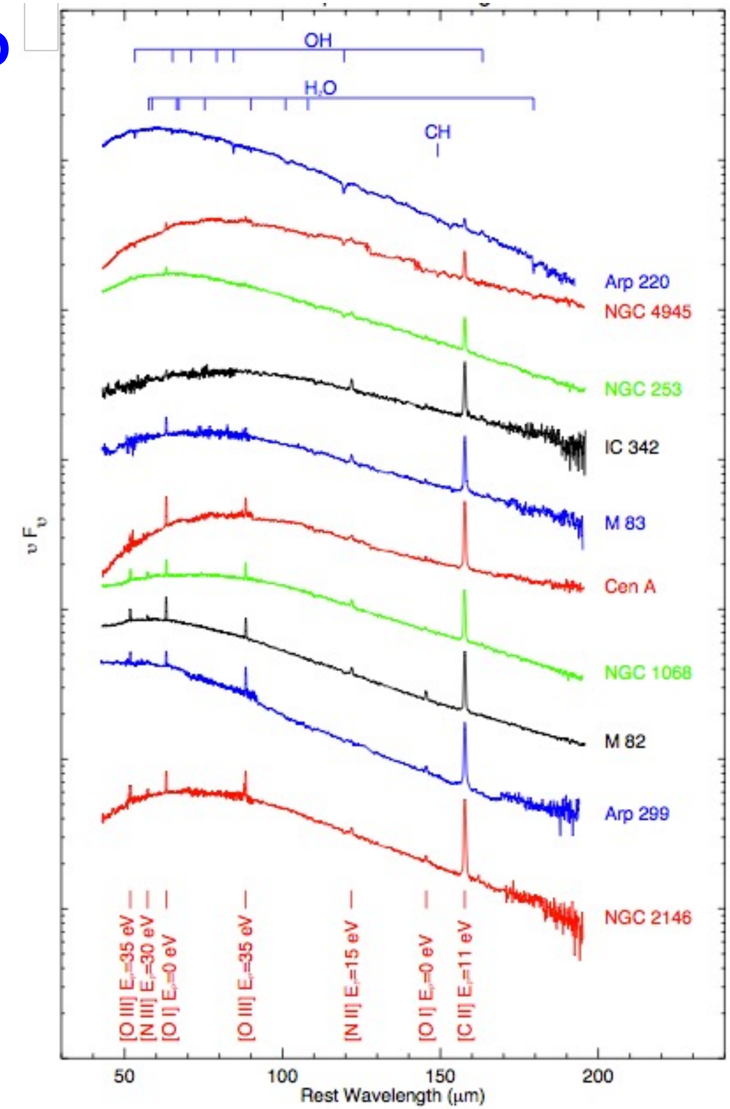
Why study local ULIRGs?

- 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?
- ULIRGs are 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 the Herschel Space Observatory is helping us out!

Dust-Bounded ULIRGs?





What is responsible for the line deficits in ULIRGs?

- FIR optical depth? Density? Old population?
- A high ionization parameter, U?
  (Luhman et al. 2003, Abel et al. 2009)

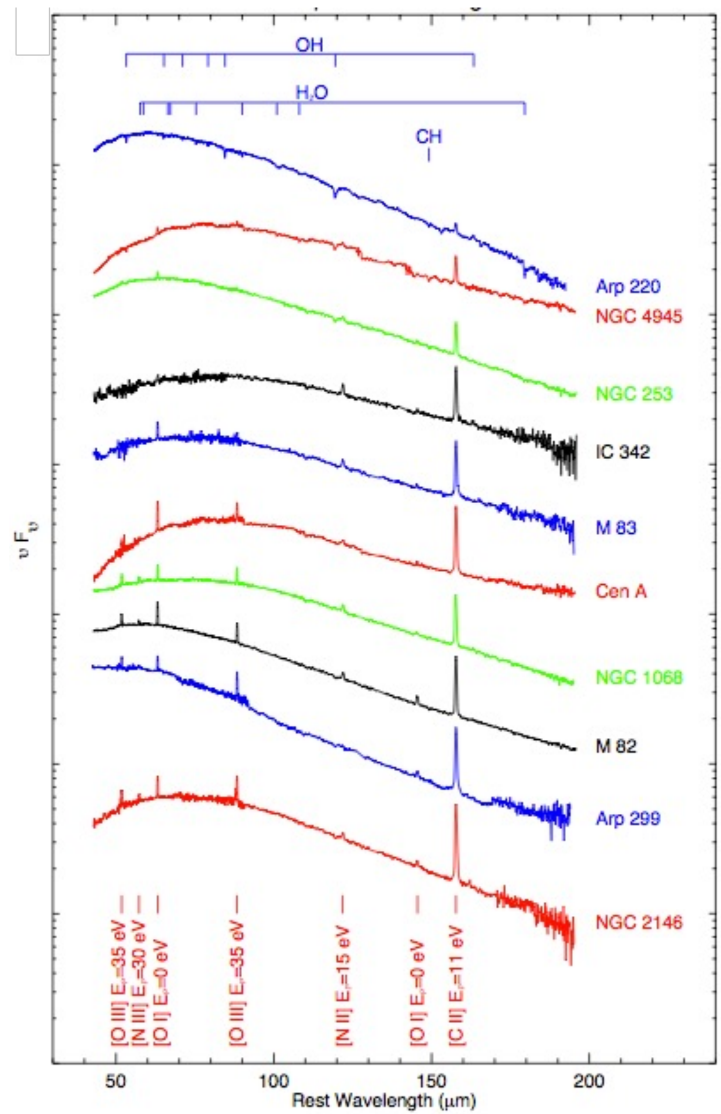
U, the ratio of ionizing radiation density to particle density

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

Why is this important?

The validity of many conclusions on the power source and evolutionary stage of ULIRGs depends on the use of mid- and near IR diagnostics. These conclusions are suspect if conditions in ULIRG nuclei are very different than in normal AGN and starbursts. For example:

- If ULIRG nuclei have optical depths $\tau(100\ \mu m) \geq 1$, then mid-IR line ratios characterize only the outer parts, or low τ lines-of-sight.
- If deficits are due to old population, then star formation has already ceased and very young stars do not power the FIR
- What process shuts down SF and when?



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

Cloudy code capabilities (esp. wrt XDR/PDRs)

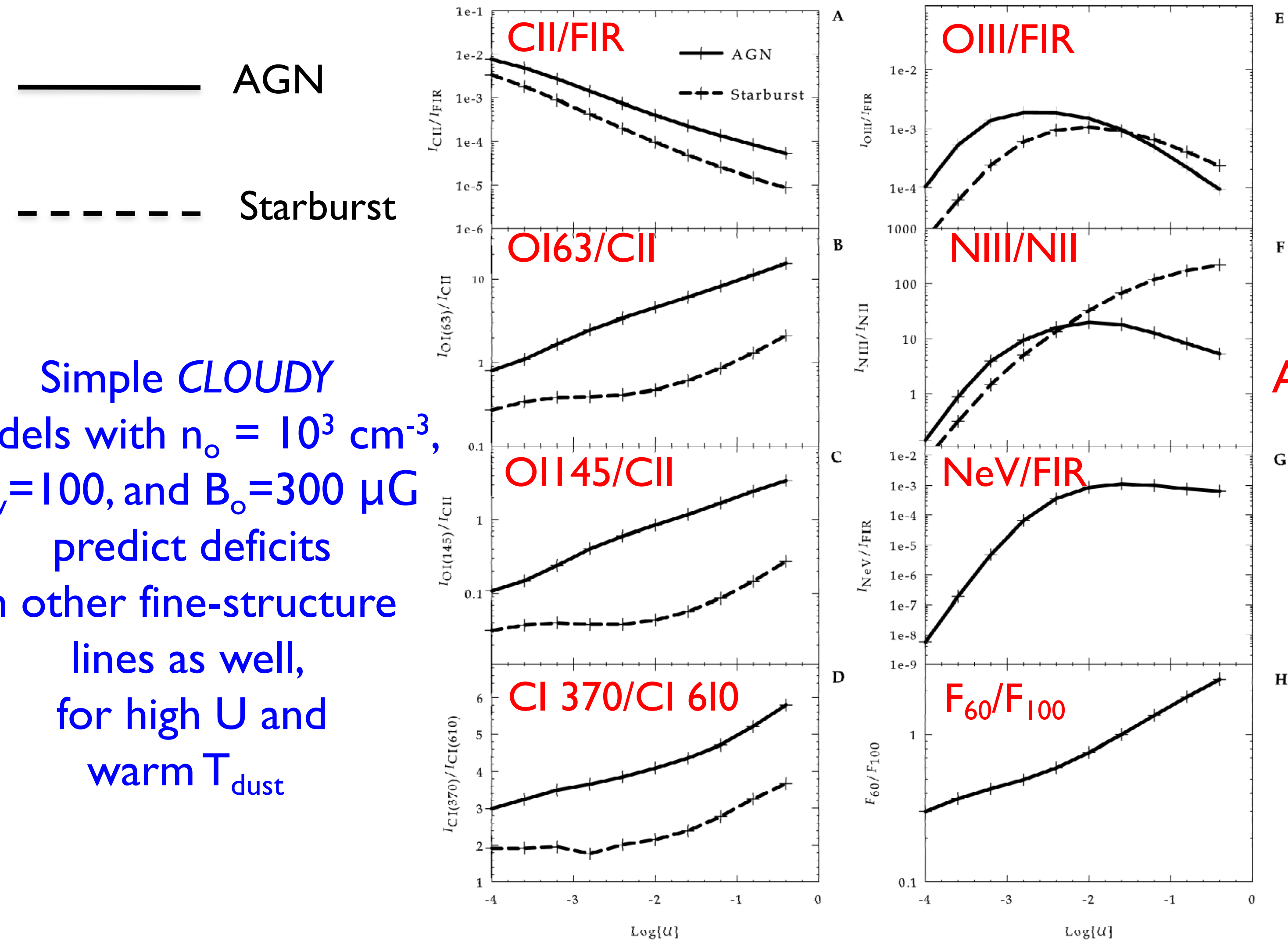
- Photoelectric heating of grains
  - ➡ Grain temperature and charge (function of size & mat'l)
- 68 molecules including ~ 1000 reactions
- Size-resolved PAH distribution, where H is atomic
- H_2 formation on grains, temp. & material dependent
- Can extend calculation to a particular A_V or other condition
- 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, 2005, 2008 (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)

Cloudy Input Parameters

- SED: AGN (T_{UV}, α_{OX}, α_{uv}, α_x)
  SB (age, IMF index, SFR)
- n_H: hydrogen density at H^+ face
- B_o, B(n): B at face; versus density
- Equation of state: eg. Isobaric (gas, magnetic, radiation)
- Abundances: Gas phase abundances
- Dust properties: including PAHs
- Ionization param: $U = Q/4\pi r^2 nc$
- Cosmic rays: CR ionization rate
- Stopping cond.: A_v ($N(H_2)$)

Model predictions as a function of U

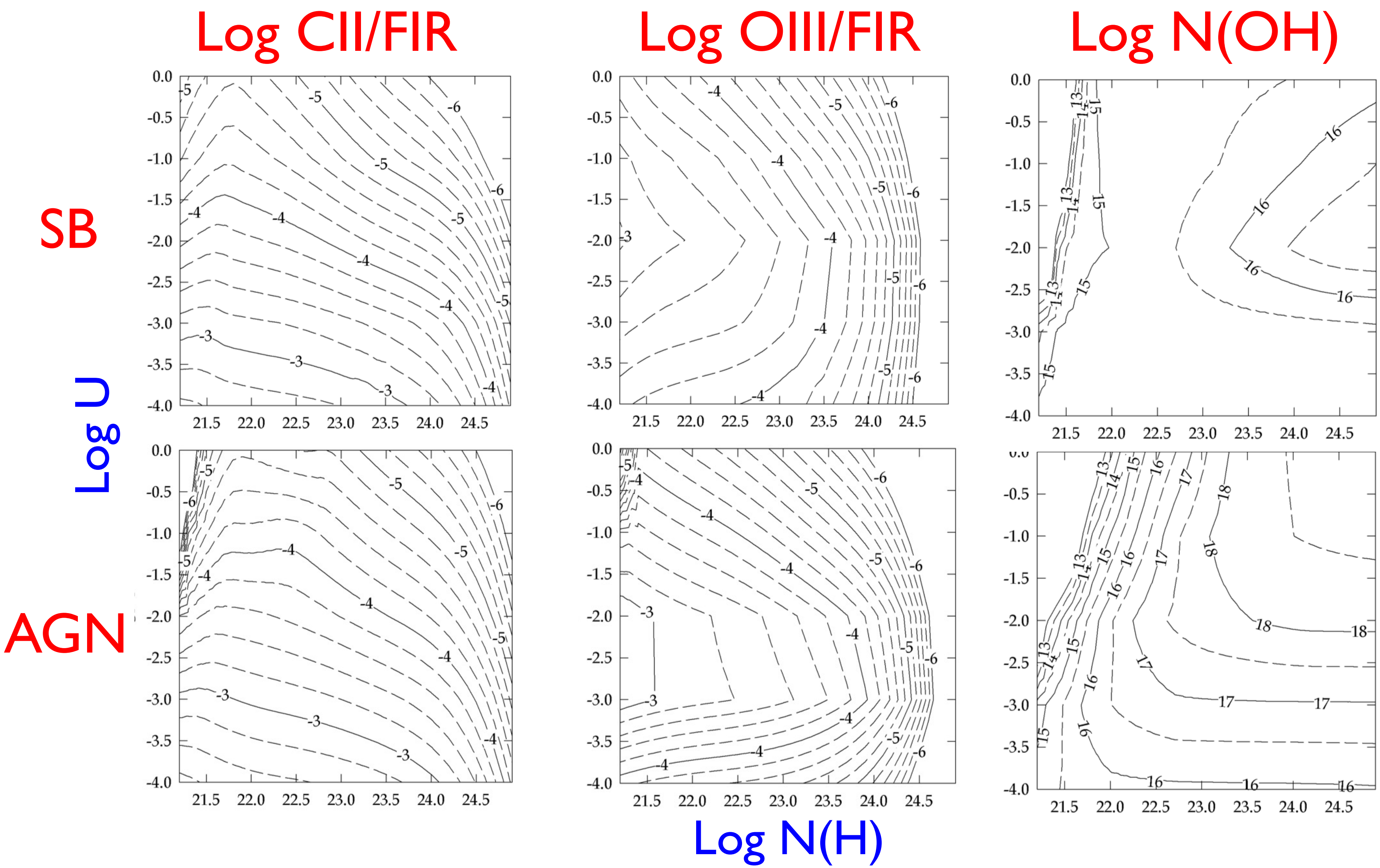


Abel et al. 2009

Simple *CLOUDY* models with $n_o = 10^3\ cm^{-3}$, A_v=100, and B_o=300 μG predict deficits in other fine-structure lines as well, for high U and warm T_{dust}

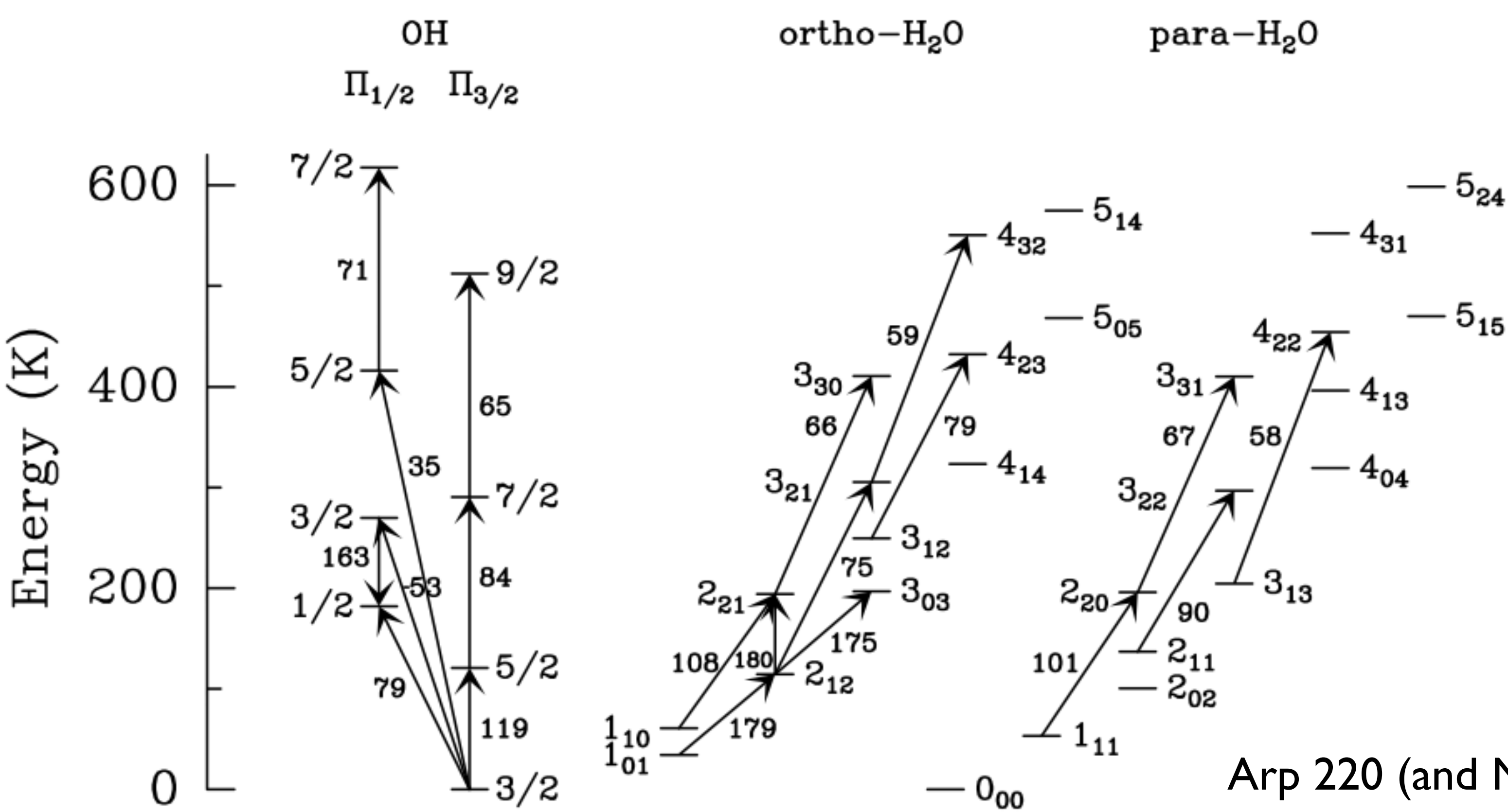
Predicted emission line and line-to-continuum ratios as a function of *U* and SED.

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



From ISO: Far-IR absorption spectrum in ULIRGs is due to high FIR radiation density!

GONZÁLEZ-ALFONSO ET AL. 2004, 2008



Arp 220 (and Mrk 231)

SHINING ULIRG Observations

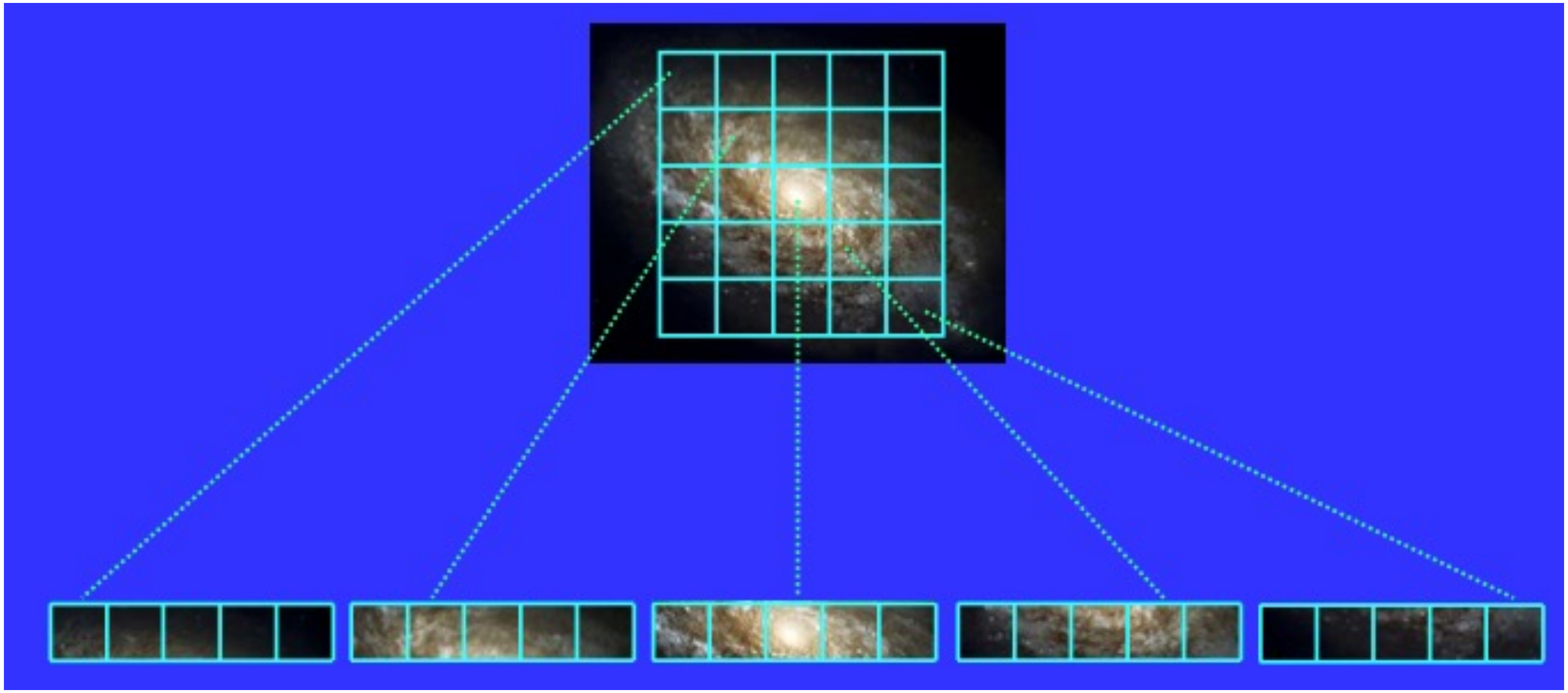
- About 80 hrs is devoted to PACS IF spectroscopy of ULIRGs
- Full PACS highly sampled scan of Arp 220
- Range scans ≥ (± 1300 km s^{-1}) of IRAS RGBS galaxies with
- $L \geq 10^{12} L_{\odot}$ plus NGC 6240 and UGC 5101 (23 galaxies):
  - Fine-structure lines tracing atomic and ionized gas, [CII]158, [OI]145,63, [NII]122, [OIII]88, [NIII]57
  - ^{16}OH, ^{18}OH 119, 79, 65 µm lines
  - H_2O 78.7 µm, 121.7 (HF 2-1) lines
  - CO (20-19)

Herschel Space Observatory

Herschel Space Observatory

Spacecraft

Herschel PACS Spectroscopy



R ~ 1500

9" x 9" pixels

Red and blue array yield parallel data in different orders

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)

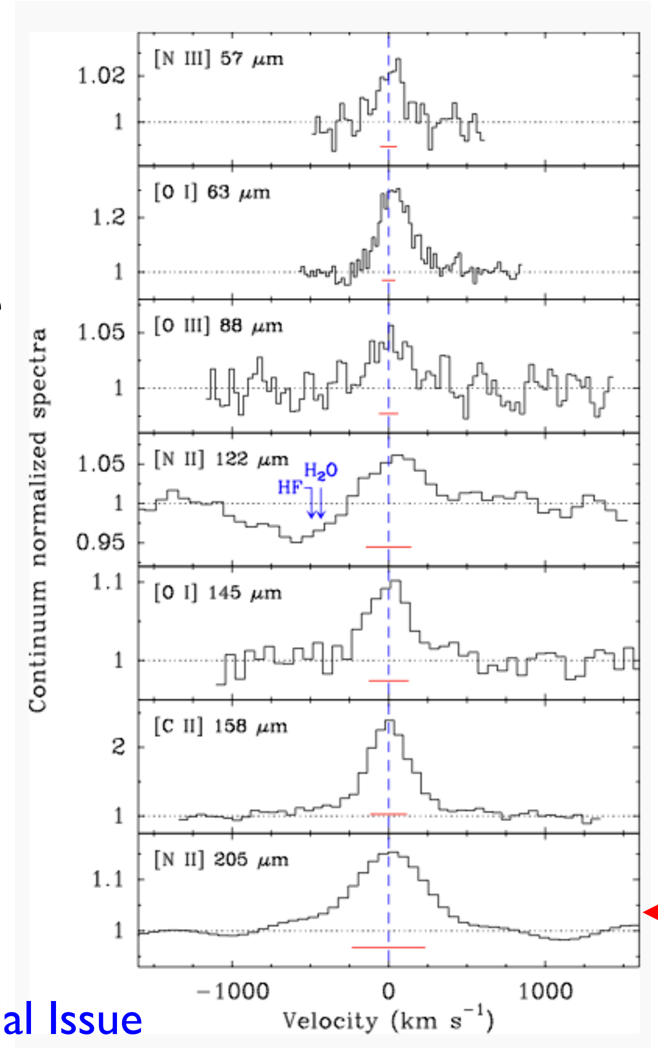
Fine Structure Lines & Kinematics

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



Fischer et al. 2010, A&A Special Issue

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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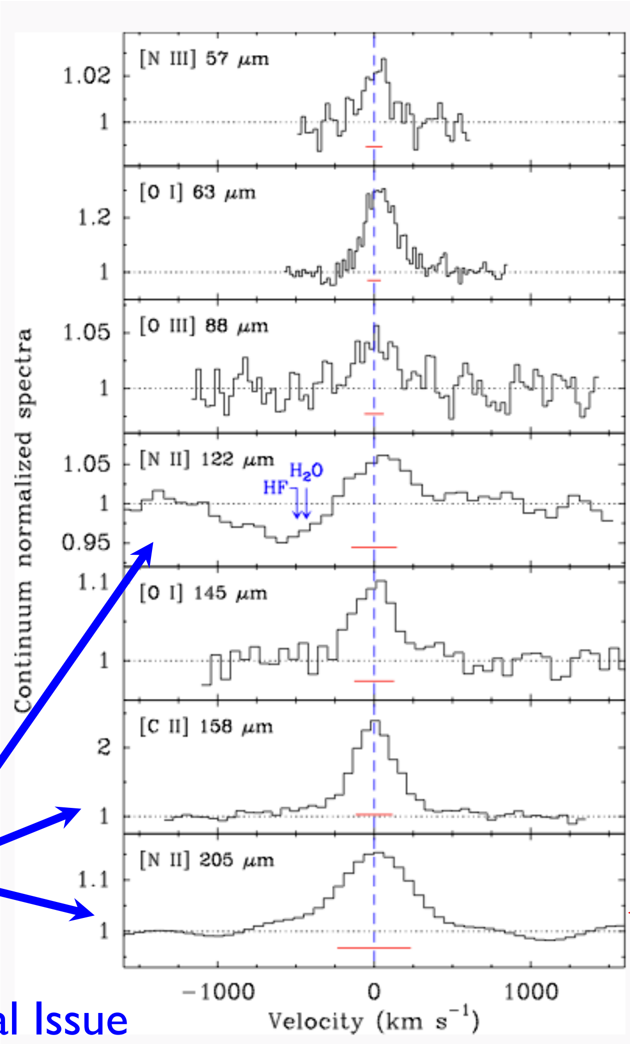

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Fine-structure line deficit trends

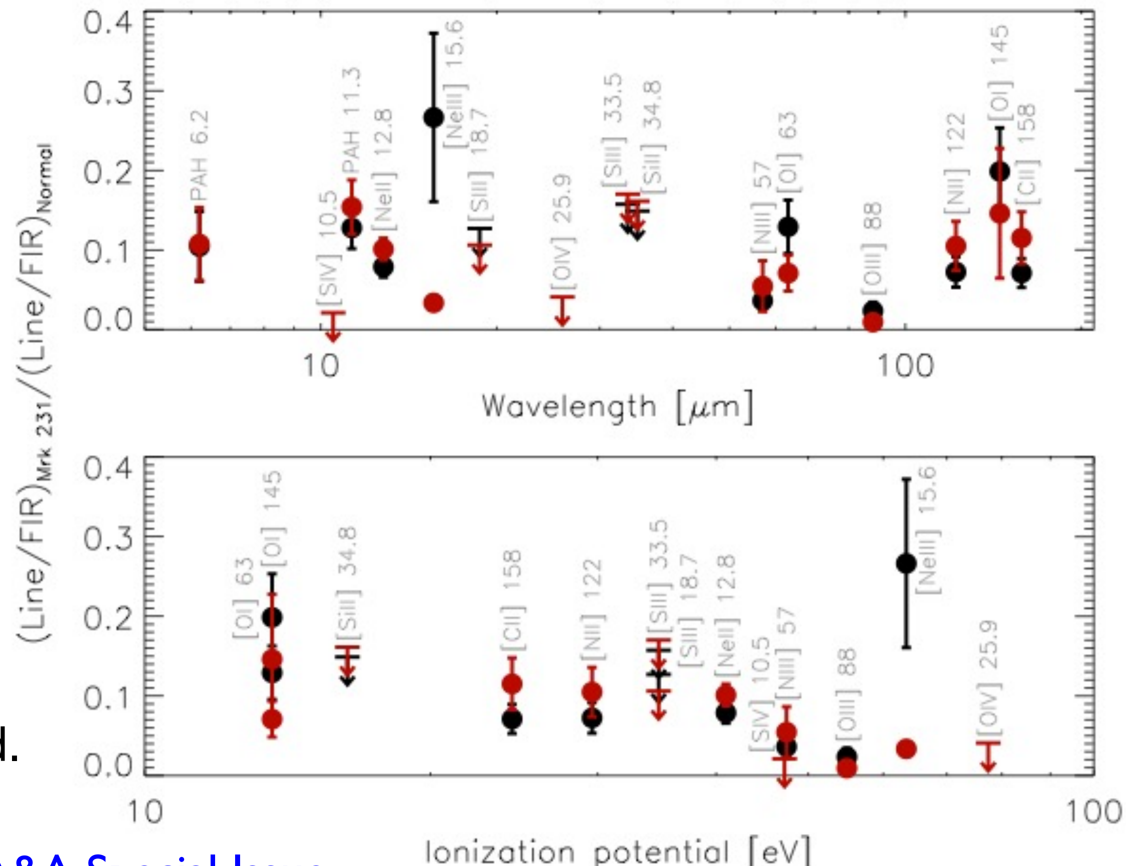
No obvious trend in the deficit with transition λ (or n_{crit}) compared with AGN & SB

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

● Starburst sample

● AGN sample

*Comparison samples
Graciá-Carpio et al., submitted.

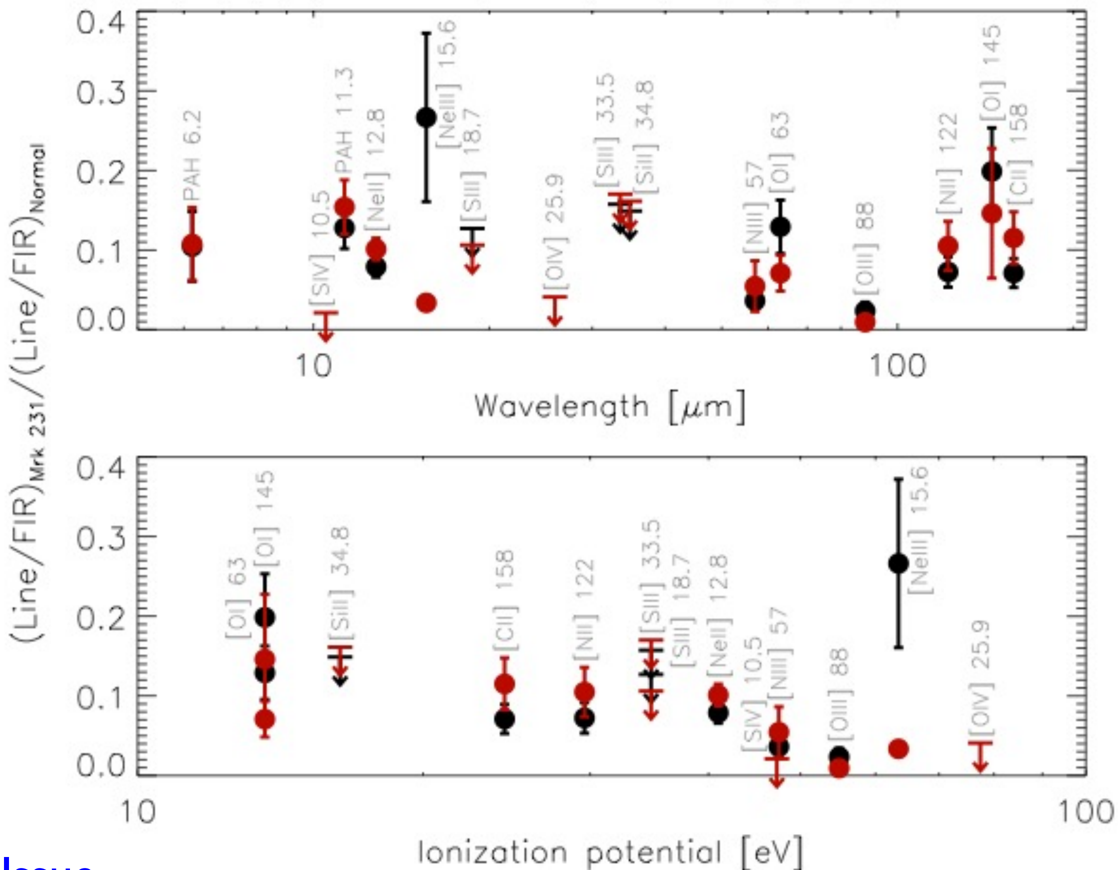


Fischer et al. 2010, A&A Special Issue

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.

*Note importance of comparison sample (Herschel will enlarge it).



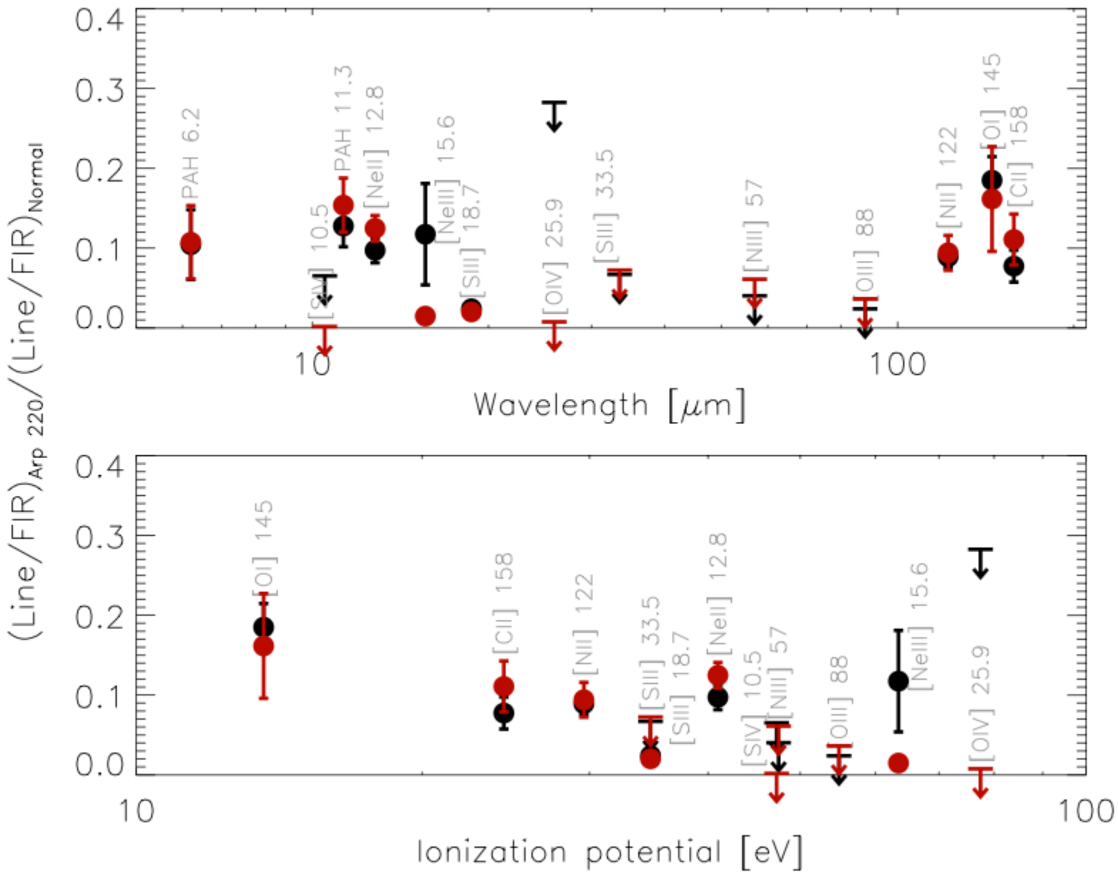
Fischer et al. 2010, A&A Special Issue

Fine-structure line deficit trends

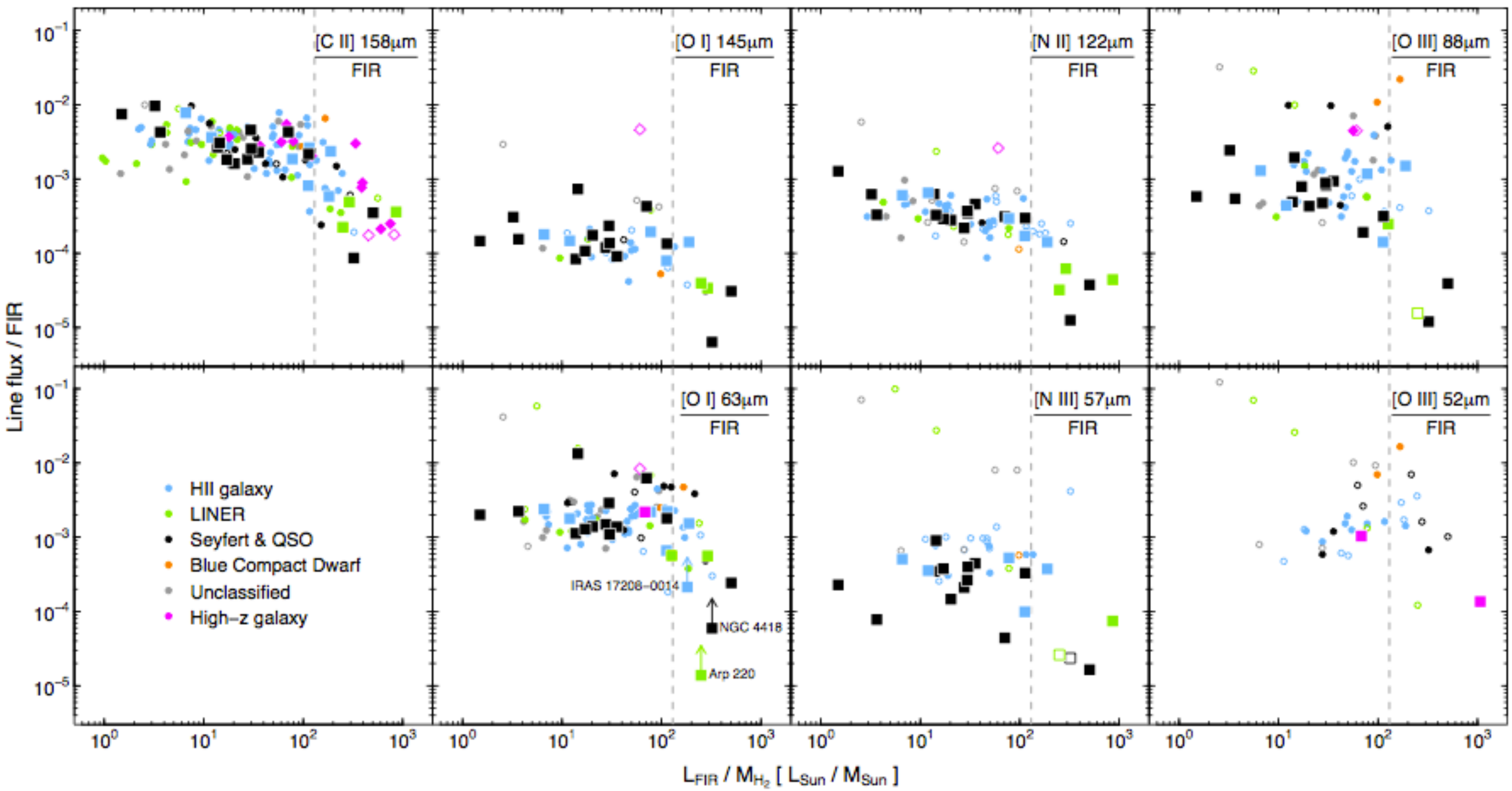
If the deficits are caused by dust obscuration, it appears to be caused by extremely opaque clumps, all or nothing, with higher covering factors for species with higher ionization potentials.

*Note importance of comparison sample (Updated comparison will be discussed by Javier Gracia Carpio this afternoon).

Arp 220



Fine-structure line deficit trends

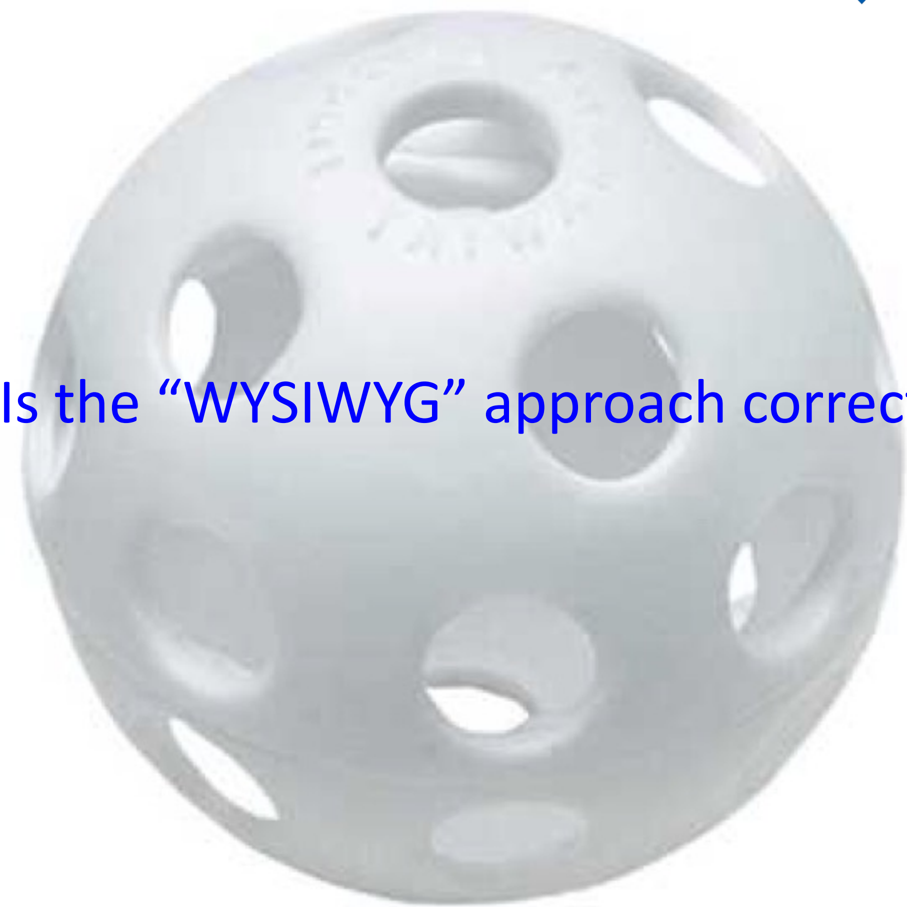


J. Gracia Carpio et al. ApJL, submitted

Fine-structure line deficit trends

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

Wiffle ball

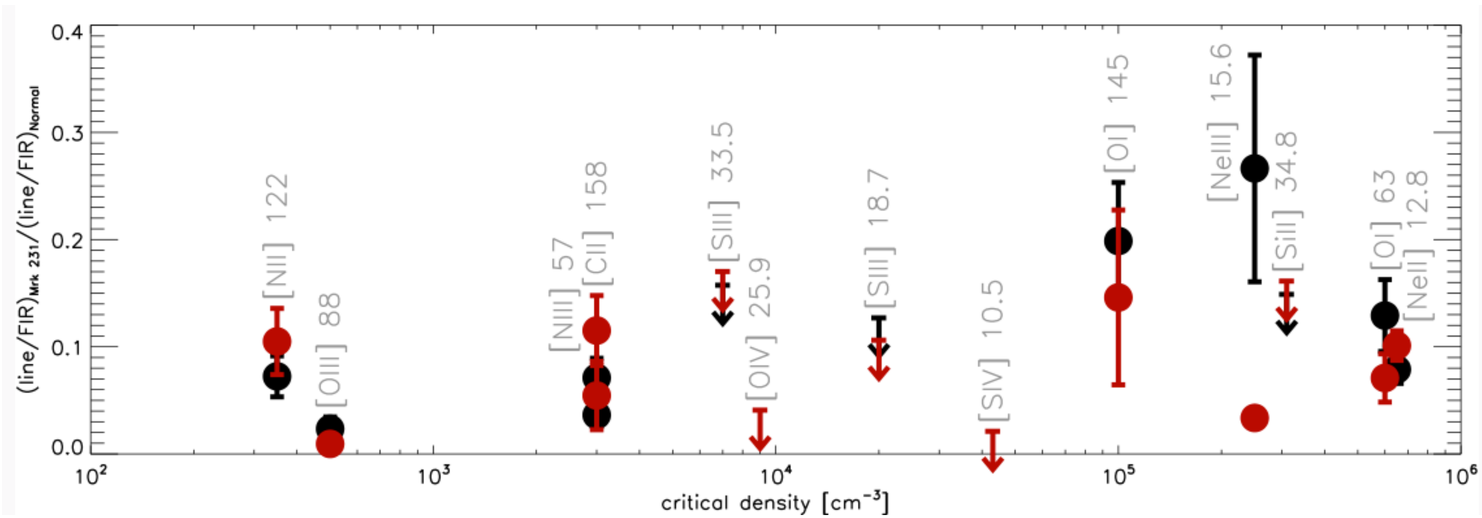


Is the "WYSIWYG" approach correct?

$(\mathrm{Line/FIR})_{\mathrm{Mrk\ 231}}/(\mathrm{Line/FIR})_{\mathrm{Normal}}$

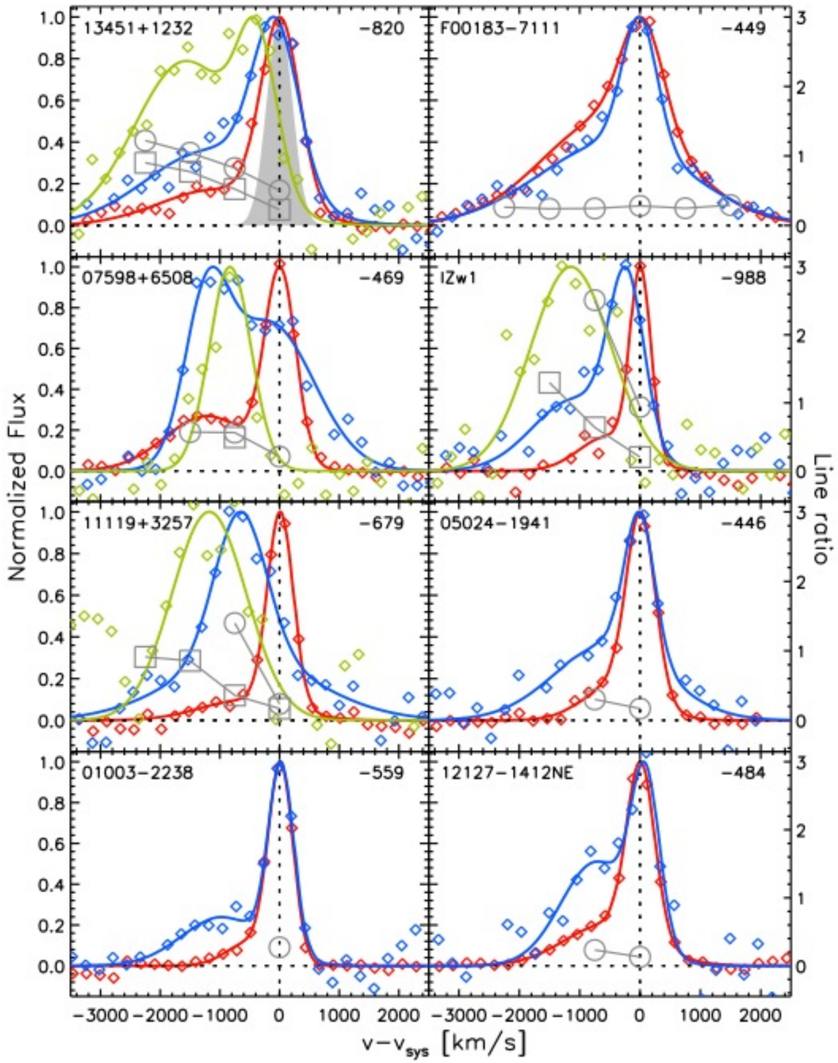
0

Density effects?



There is only a marginal correlation with critical density.

EXAMPLE: Decelerating outflows in a stratified medium, photoionized by AGN in ULIRGs



Spitzer result: 25 of 82 ULIRGs have strongly blueshifted mid-IR NeIII and NeV emission compared with NeII

Spoon & Holt 2009

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

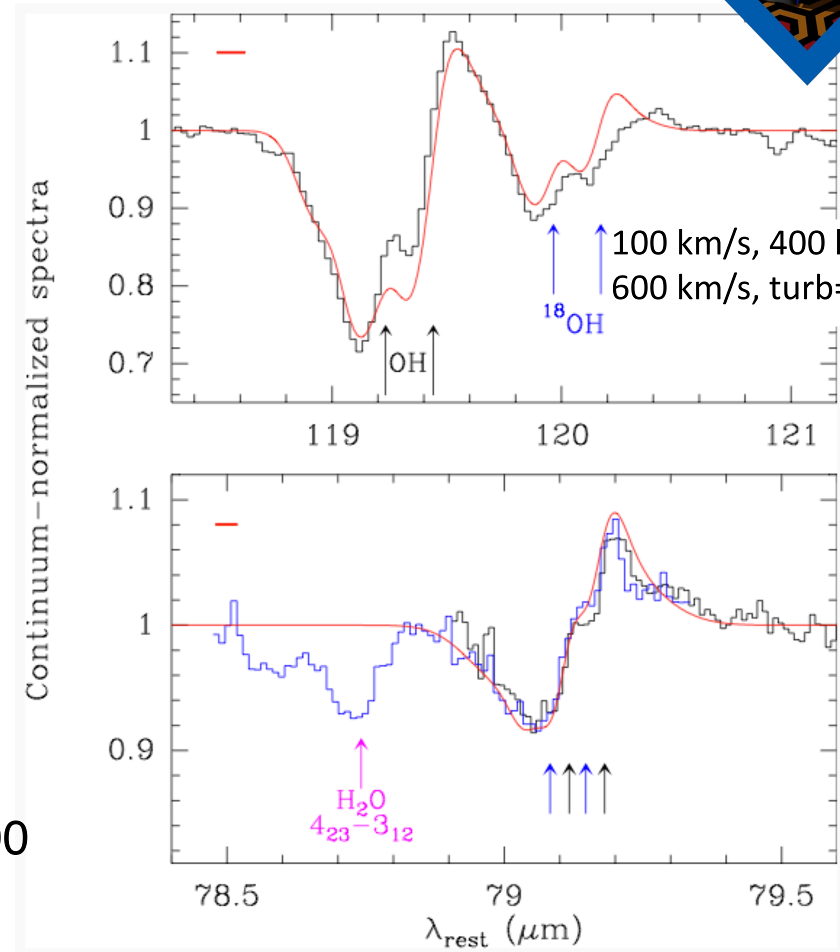
Blue-shifted wings suggest that [CII], [NII], & excited H_2O/HF also participates in the outflow

Based on model fits to continuum and line pumping, outflow lower limits:

Mechanical energy ≥ 10^{56} ergs,

Mechanical luminosity ≥ 1% of L_{TIR},

Mass ≥ 7×10^7 $M_\odot$, Mass loss ~ 400-4000 $M_\odot$/yr

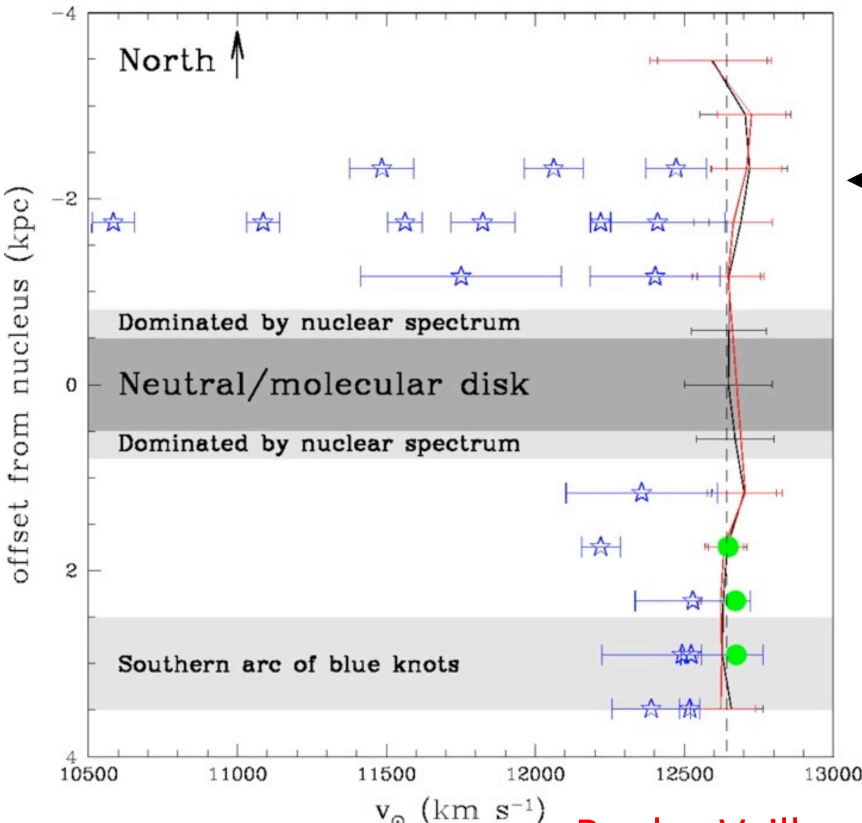


Fischer et al. 2010, A&A Special Issue

But stay tuned, soon the 65 µm line will be observed => extent

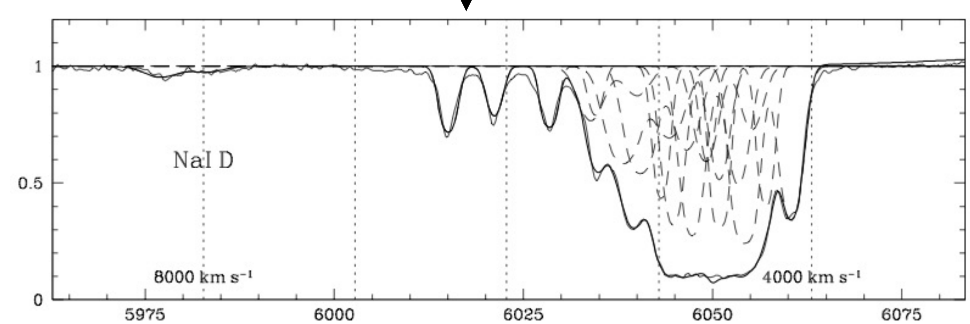
Comparison to Na I D doublet

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, (whose velocities were not observed)

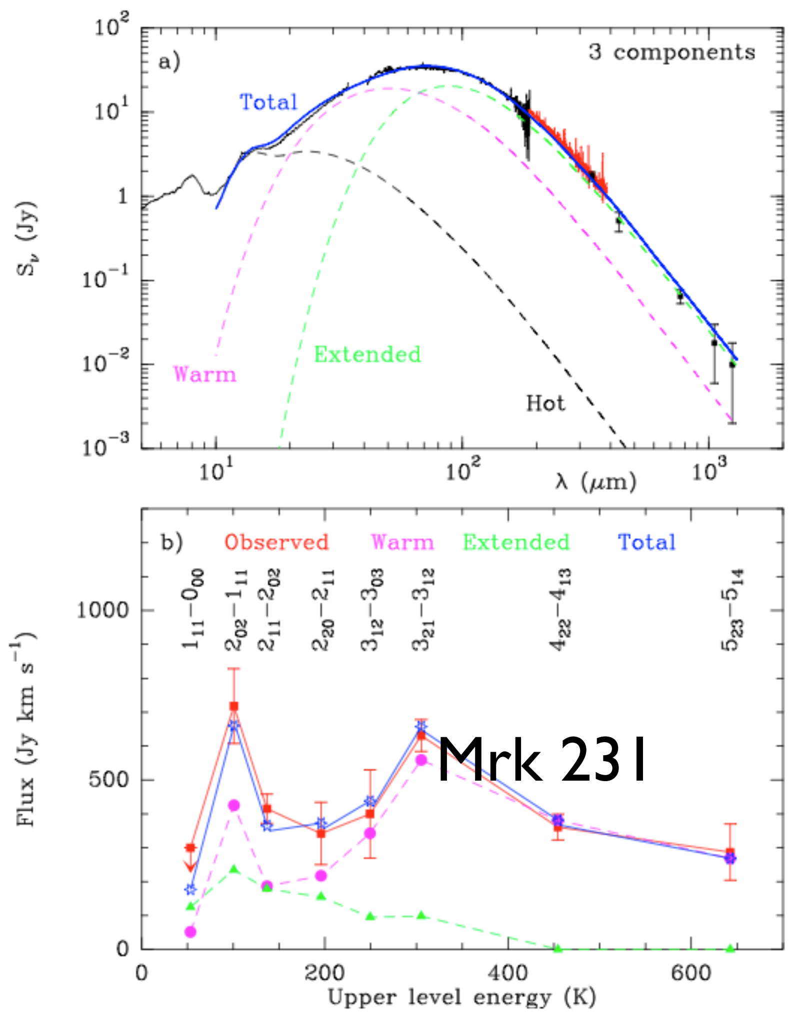


Rupke, Veilleux & Sanders 2002, 2005

Constraints on extents of the outflows

By self-consistently modeling the continuum, approximated by several components, and the lines, the molecular extent and column densities can be derived in each component (eg Gonzalez-Alfonso et al 2010).

For outflows, this can then constrain the mass loss rates, mechanical luminosity and energy content.

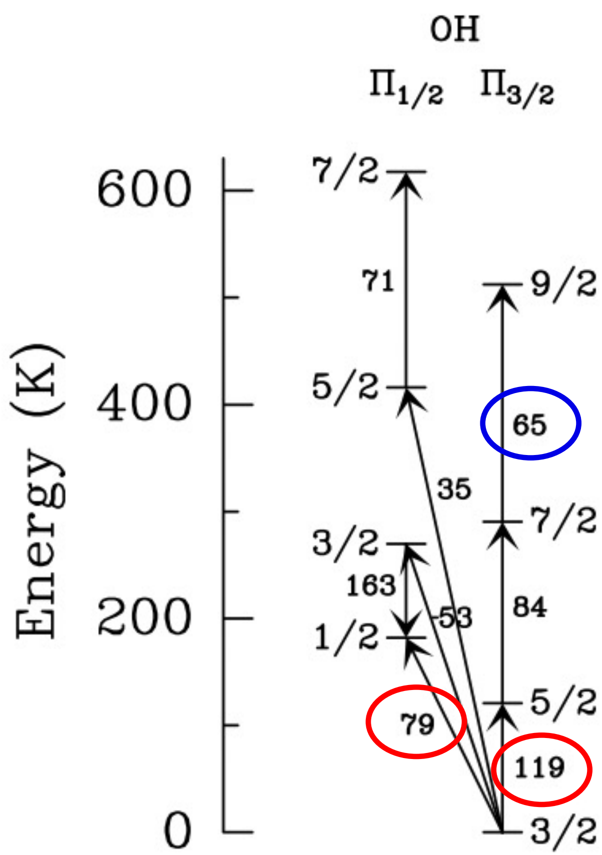


Gonzalez-Alfonso et al. 2010

Enter Herschel PACS Observations

Observed OH, ^{18}OH transitions

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



OH 65 µm line will be observed in SHINING ULIRGs

120 µm for ^{18}OH

Summary

- The IR fine-structure lines in Mrk 231 & Arp 220 are faint compared with both SBs 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 starbursts
- This may be an effect of higher covering factors for higher IP, due to a clumpy, FIR thick, medium. Or, a high U component in addition to a normal one needs to be further explored
- Thus, IR line diagnostics may not probe the central power source!
- The OH lines show P-Cygni profiles indicating a kpc scale massive molecular outflow that may halt SF. Profiles of higher, FIR pumped OH, H_2O lines will help locate and quantify the parameters

SOFIA work to explore

- SOFIA mid- to far- IR spectroscopy can help understand the effects of high ionization parameters, high density, and high FIR optical depth in Galactic compact HII regions (need to find isolated ones!)
- SOFIA EXES can carry out detailed line profile studies of the OH 34 micron line and H2 mid-IR rotational lines in nearby ULIRGs
- SOFIA FIFI LS and GREAT can carry out detailed line studies of nearby ULIRG molecular outflows in multiple lines to derive outflow extent and mass loss rates.