Cool Atomic and Molecular Outflows

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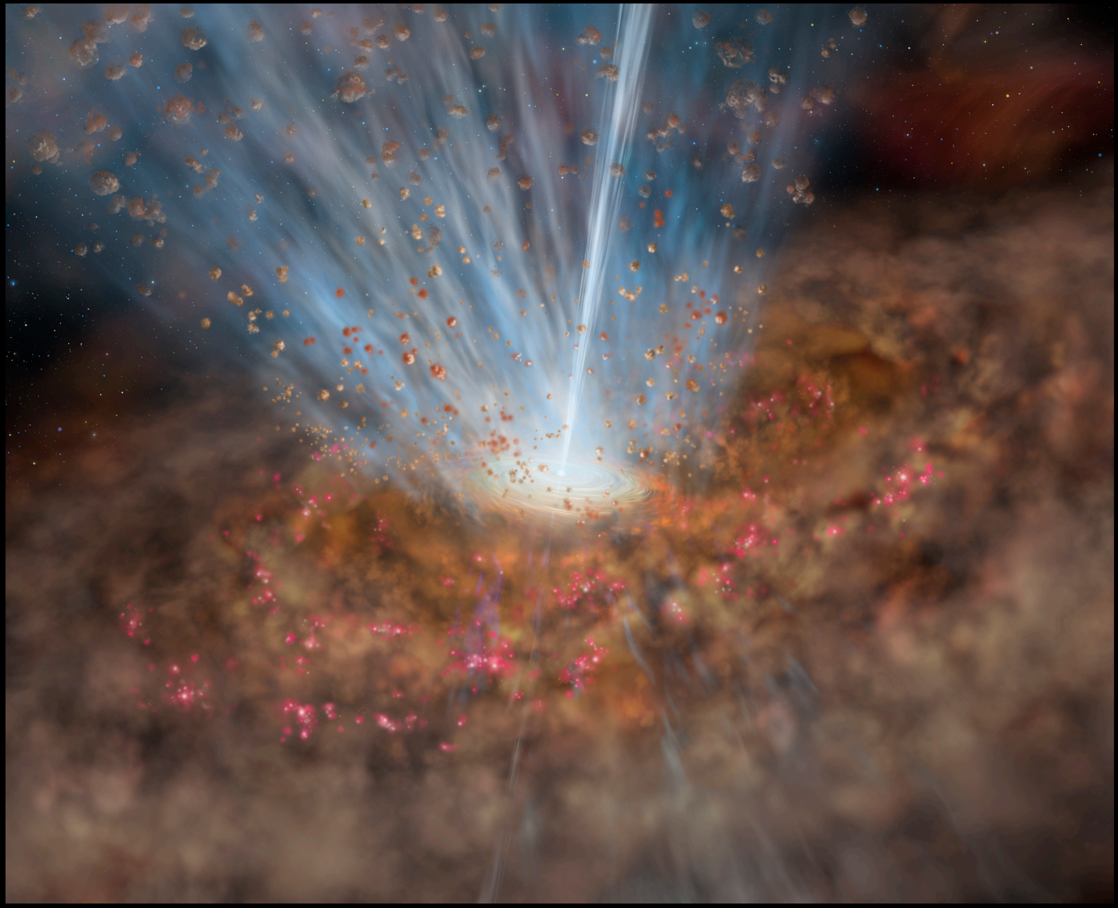


Powerful wide-angle outflow in Mrk 231, the nearest quasar

Gemini Press Release

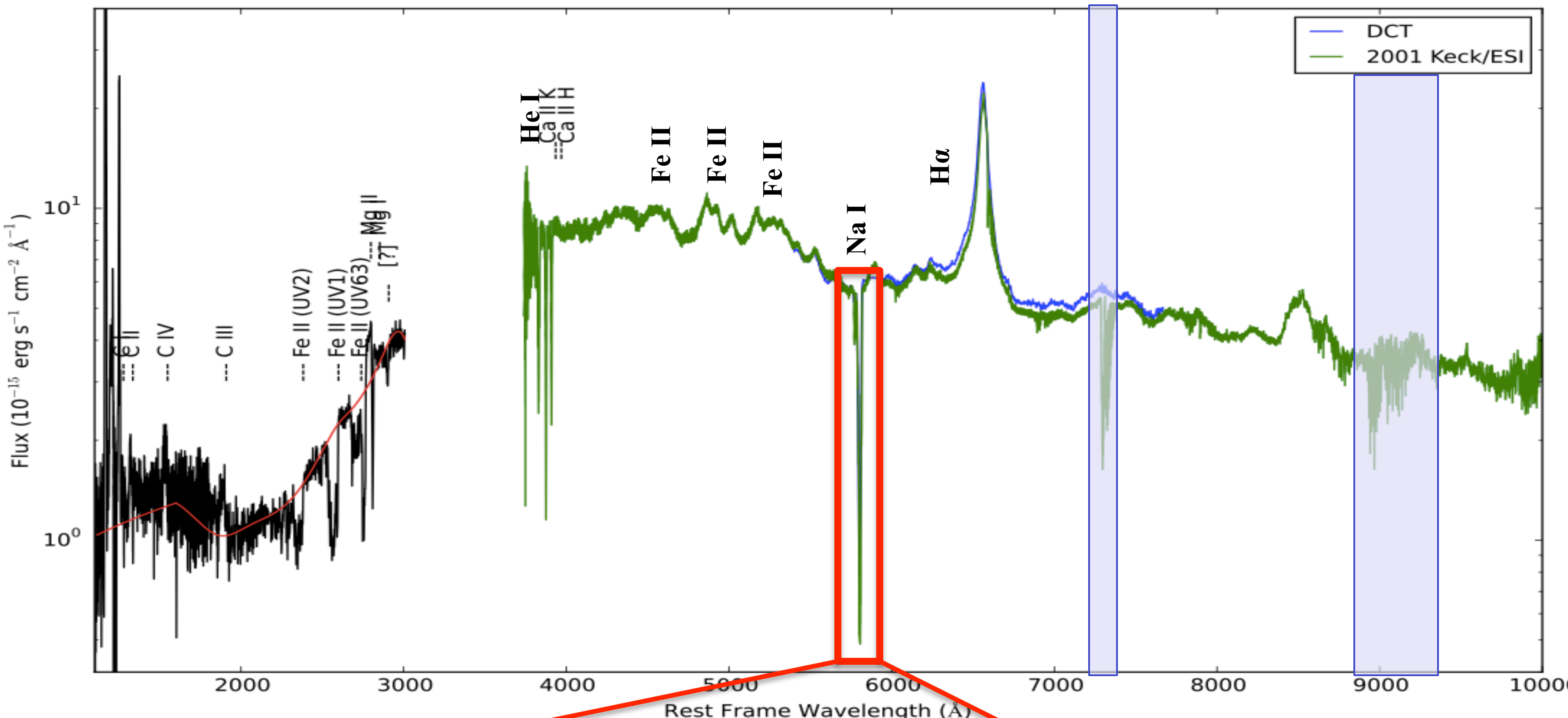
(based on the results of Rupke+Veilleux 2011)

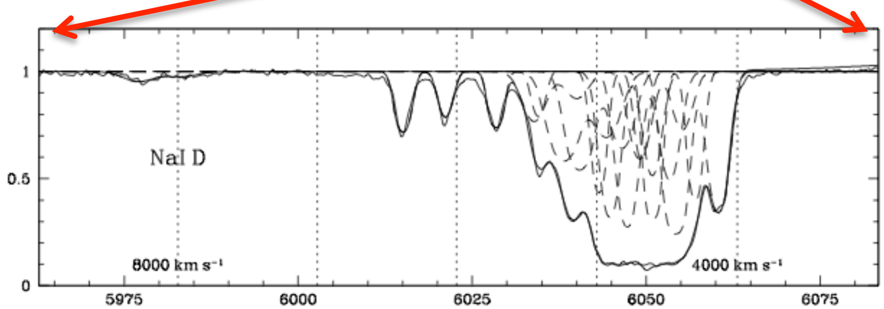
Questions: Cool Atomic and Molecular Outflows

- **Outflow statistics, energetics, extent, hence large-scale impact?**
- **Connection between the small- and large-scale outflows?**
- **How does Nature do it: entrainment of the cool ISM or *in-situ* formation of cool clumps in the hot wind?**

High-Speed Dusty *Nuclear* Outflow in Mrk 231

FeLoBAL *(Boksenberg+77; … ; Rupke+02; Veilleux+13b, 16; Leighly+14)*

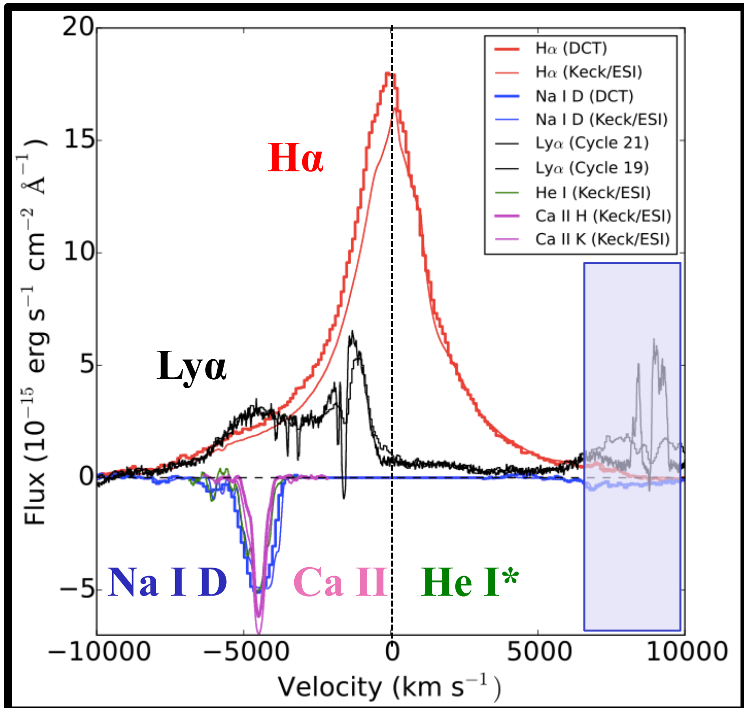




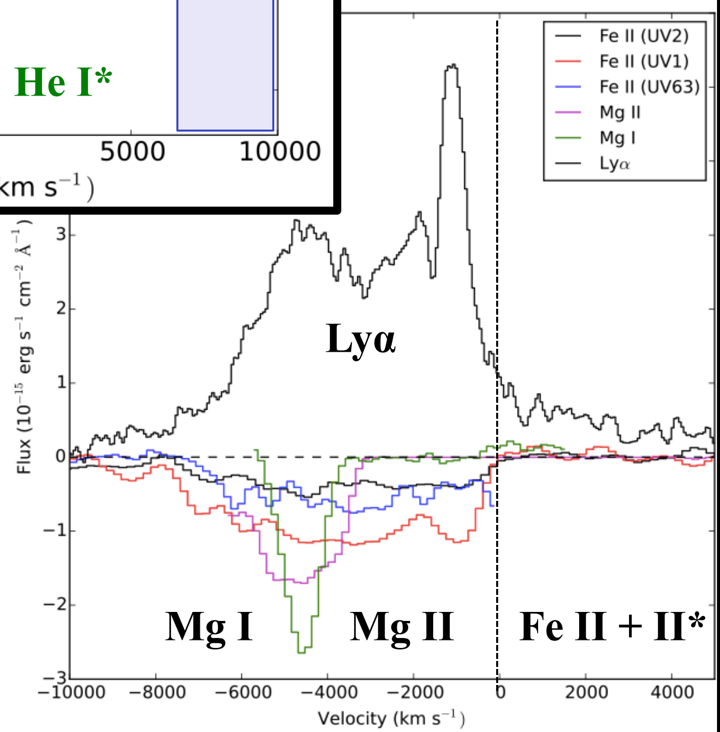
Na I D (5.1 eV)

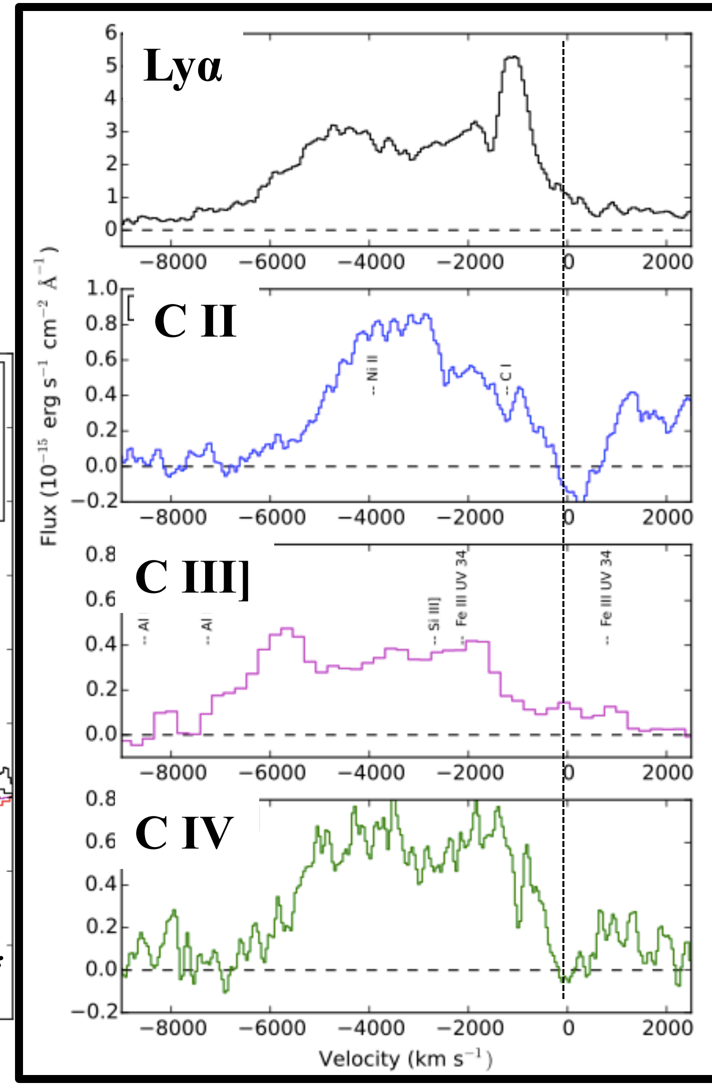
(Rupke+02)

High-Speed Dusty *Nuclear* Outflow in Mrk 231



(Boksenberg+77; Veilleux+13b, 16; Leighly+14)



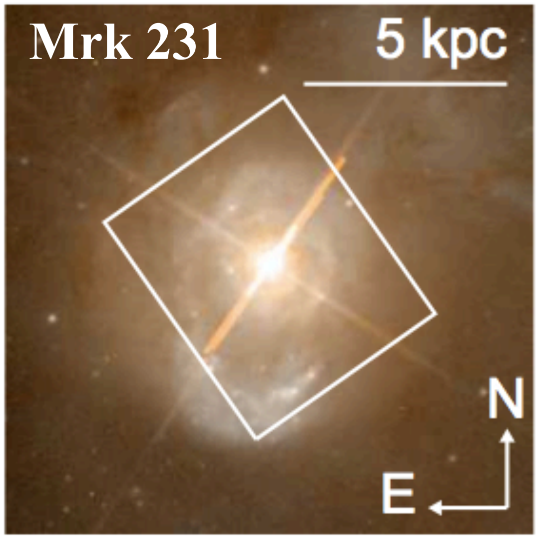


Wind-dominated quasar with high Eddington ratio and geometrically thick ("slim") accretion disk

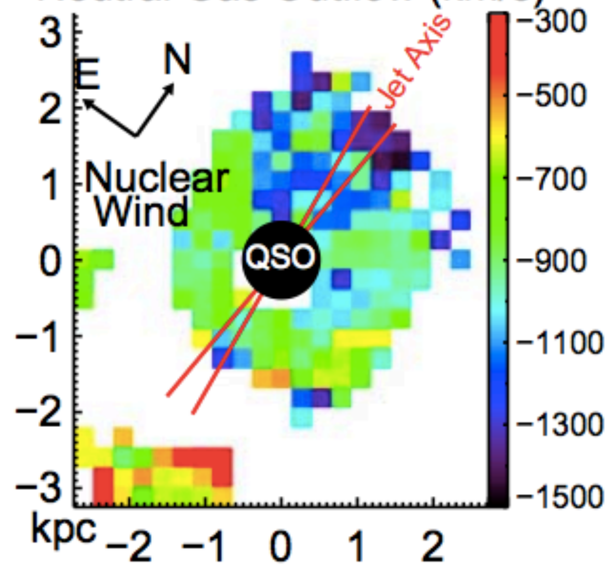
Extended Na I Outflow in Mrk 231

(Long-slit: Rupke, Veilleux, & Sanders 05c; IFU: Rupke & Veilleux 11, 13a)

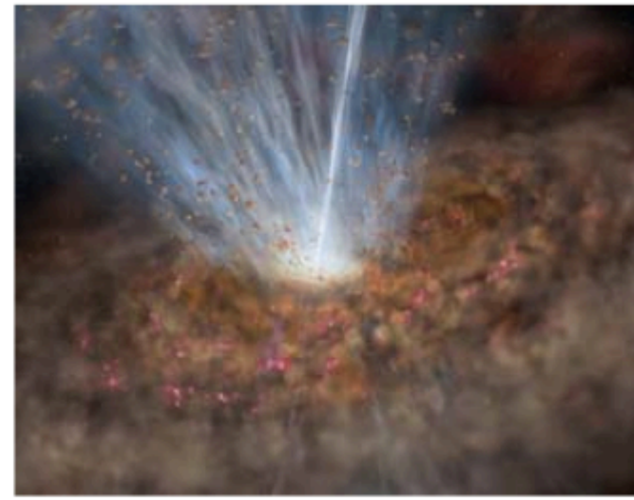
HST Continuum



Neutral Gas Outflow (km/s)



Artist's Conception



2011 Gemini Press Release

- **Gemini/IFU: Na I D 5890, 5896 Å absorption**
- **R ≥ 2-3 kpc from the nucleus**
- **$| V_{out} |$ in excess of 1100 km s^{-1}**
- **d*M*/dt ≥ 160 M_{sun} yr^{-1} ~ 1.1 *SFR***
- **d*p* / dt ≥ 5 L_{SB} / *c* , ≥ 3 L_{AGN} / *c*, ≥ 2 L_{IR} / *c***
- **L_{mech} = dE_{kin}/dt ≥ $10^{43.6}$ ergs s^{-1} ~ 1.1 x dE_{SB}/dt ~ 0.5% L_{Edd} (AGN)**

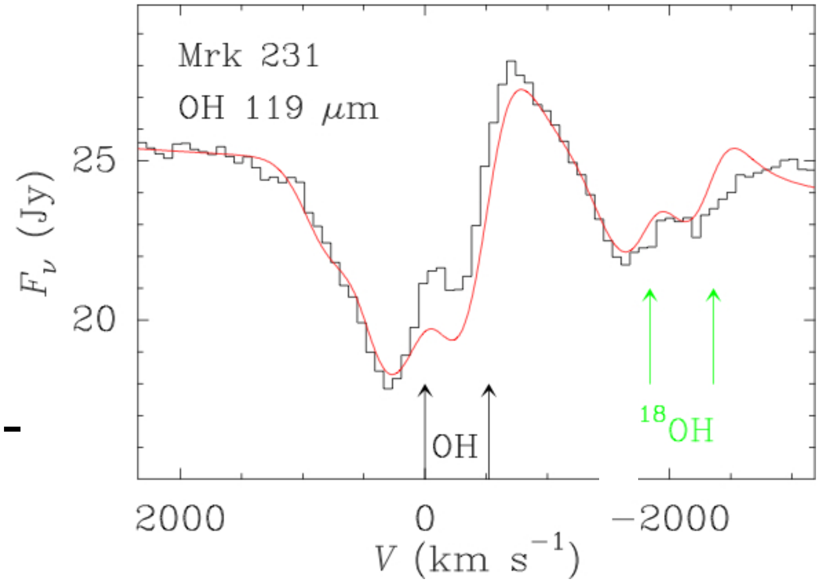
→ AGN driving

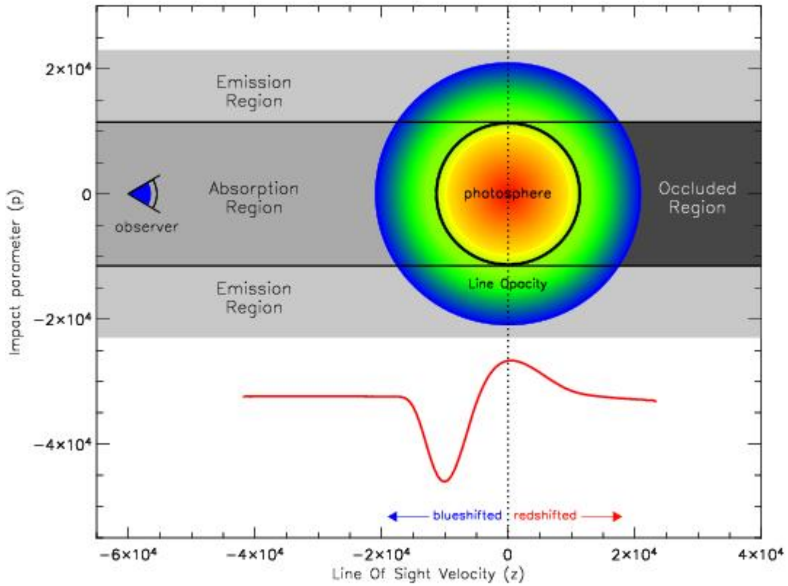
Molecular Outflow in Mrk 231

Herschel: **unresolved P-Cygni profiles of OH** *(e.g., Fischer+10; Sturm+11; Gonzalez-Alfonso+14, 17)*

- ***Herschel*/PACS + *Spitzer* spectra: multiple OH transitions**
- **P-Cygni profiles!**
- **Outflow: $|V_{out}|$ in excess of 1000 km s^{-1}**
- **d*M*/dt ~ 620 - 1100 M_{sun} yr^{-1}**
- **dp/dt ~ 6 L_{BOL}(AGN) / c**
- **dE_{kin}/dt ~ 1% L_{Edd}(AGN)**

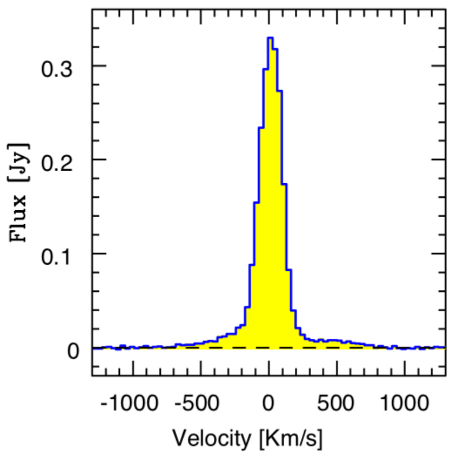
-

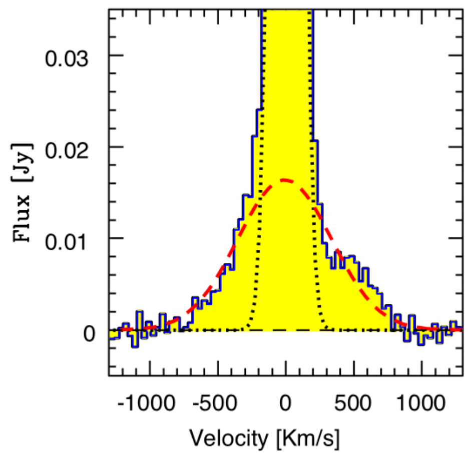




Molecular Outflow in Mrk 231

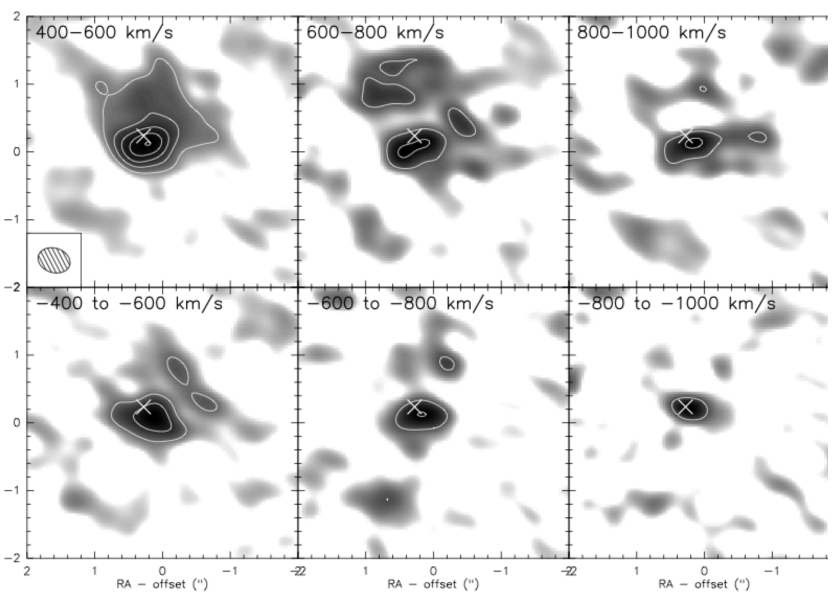
IRAM: ***Spatially resolved molecular line emission (Feruglio+10; Aalto+12; Cicone+12; Alatalo+10; Feruglio+15; Lindberg+16; …)***





Red Wing

Blue Wing



- ***CO J = 1-0:***
  - V_{out} **up to ~*750* km s**$^{-1}$
  - M_{out} **~ 6 x 10**^{8} M_{sun}
    (H_2**/CO ~ 0.1 x Galactic value)**
  - **Kpc scale**
  - **d*M*/dt ~ 700** M_{sun} **yr**$^{-1}$
- ***CO J = 2-1 vs 3-2:***
  - **Blue and red wing material is more compact at higher density**
- ***HCN, HCO+, HNC:***
  - n **> 10**^{4} **cm**$^{-3}$ **clumps; compressed, fragmented by shocks in outflow?**

Plan

- **Molecular outflows in ULIRGs & quasars**

  Gonzalez-Alfonso et al. 2017, ApJ, 836, 11

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  Rupke, Gultekin, & Veilleux 2017, refereed, being revised

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  Walter, Bolatto, Leroy, Veilleux, et al. 2017, ApJ, 835, 265

Molecular Outflows in U/LIRGs & Quasars

***Herschel* Surveys**: unresolved P-Cygni profiles of OH *(e.g., Fischer+10; Sturm +11; Veilleux+13a; Spoon+13; Gonzalez-Alfonso+14, 15, 17; Stone, Veilleux+16)*

MM-wave Interferometric Surveys: kpc-scale CO line emission *(e.g., Feruglio +10,+15; Aalto+12ab; 15, 16; Alatalo+11, 15; Cicone+12, 14; Garcia-Burillo+14, 15; Lindberg+16; Veilleux+17)*

- **Statistics**: ~70% of local U/LIRGs have molecular winds ($\Theta \sim 145^o$)
- **Outflow velocities**: $<v_{50}>$, $<v_{84}>$, $<v_{max}>$ ~ -200, -500, -925 km s^{-1}
- **Energetics**: Size ~ 0.1 – 10 kpc

  $dM/dt \sim 10 - 1000\ M_{sun}\ yr^{-1}$

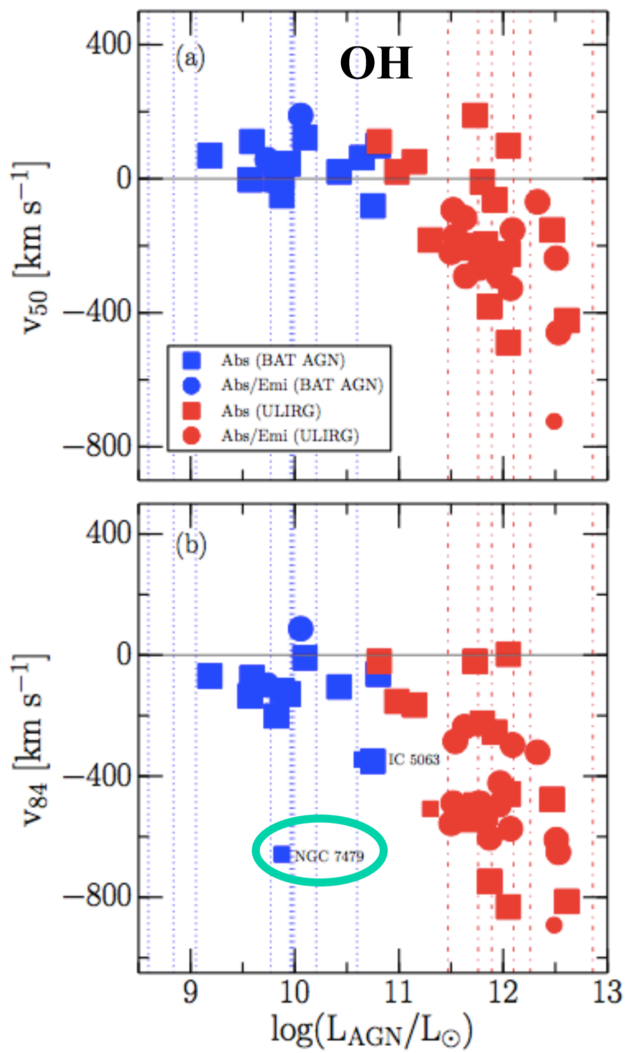
  $dp/dt = (0.1 - 20)\ L_{IR}/c$

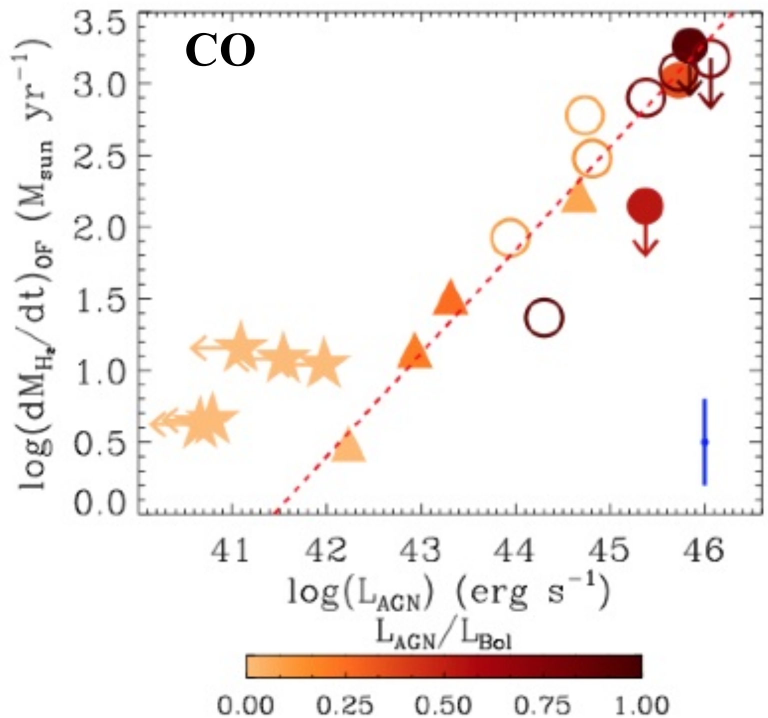
  $dE/dt < 2\%\ L_{IR}$

  Molecular gas = energetically dominant phase of *these* outflows
- **Trends with SFR and AGN luminosities**: suggest that we are seeing starburst + quasar feedback in action

Molecular Outflows in U/LIRGs & Quasars

(Veilleux+13a; Cicone+14; Stone, Veilleux+16)

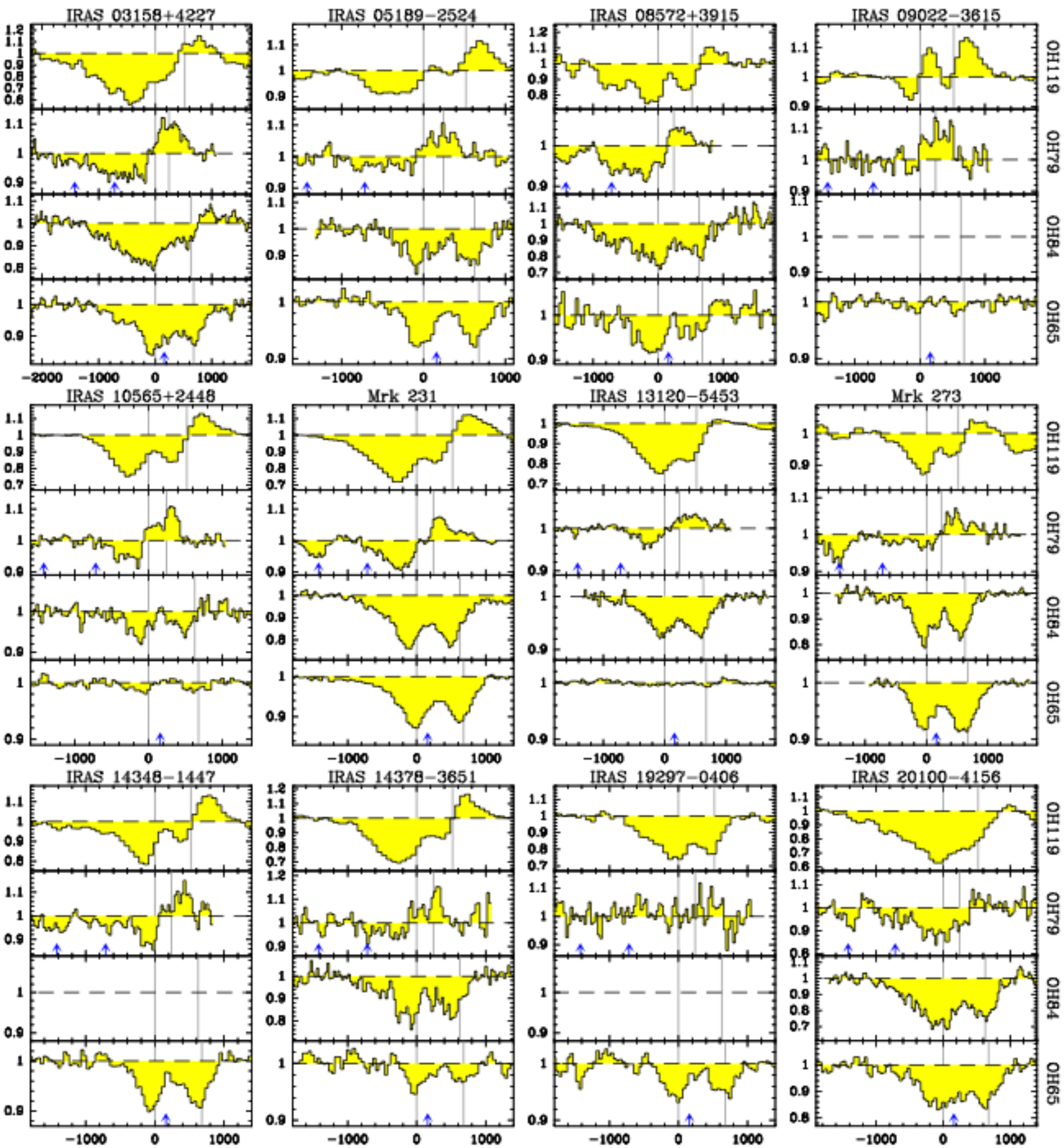




→ **AGN driving of the most extreme molecular winds**

Red = ULIRGs **Blue = BAT AGN**

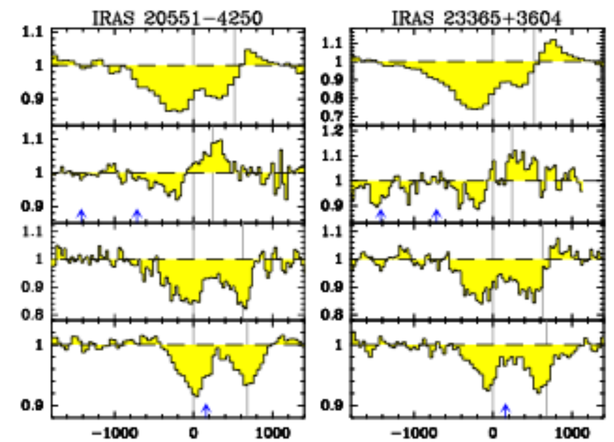
Molecular Outflows in U/LIRGs & Quasars



(Gonzalez-Alfonso + 17)

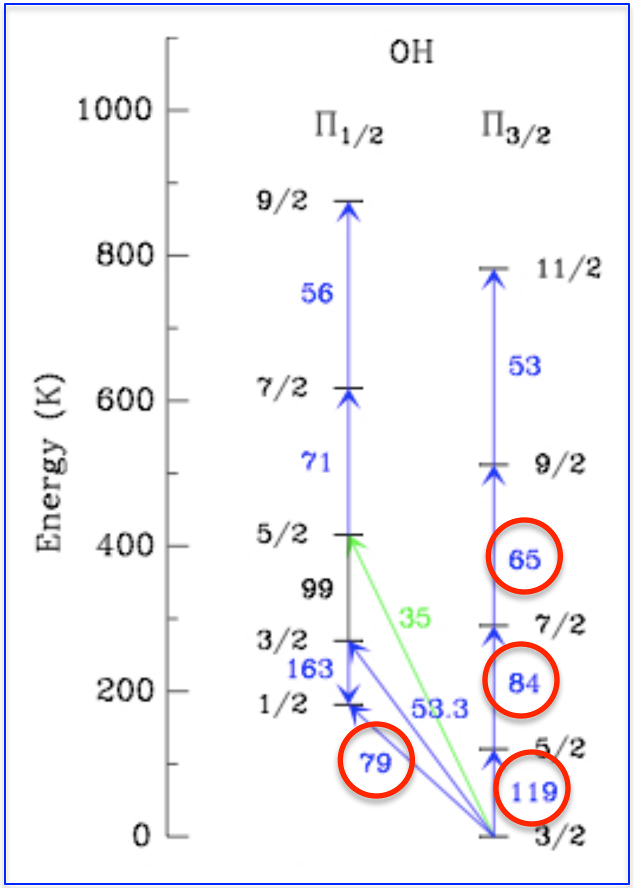
***Herschel*: 14 local ULIRGs**

4 OH transitions / ULIRG

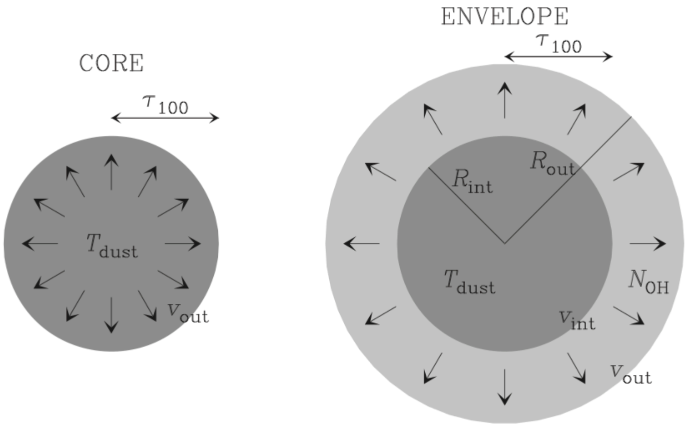


Molecular Outflow Dynamics

(Gonzalez-Alfonso + 17)



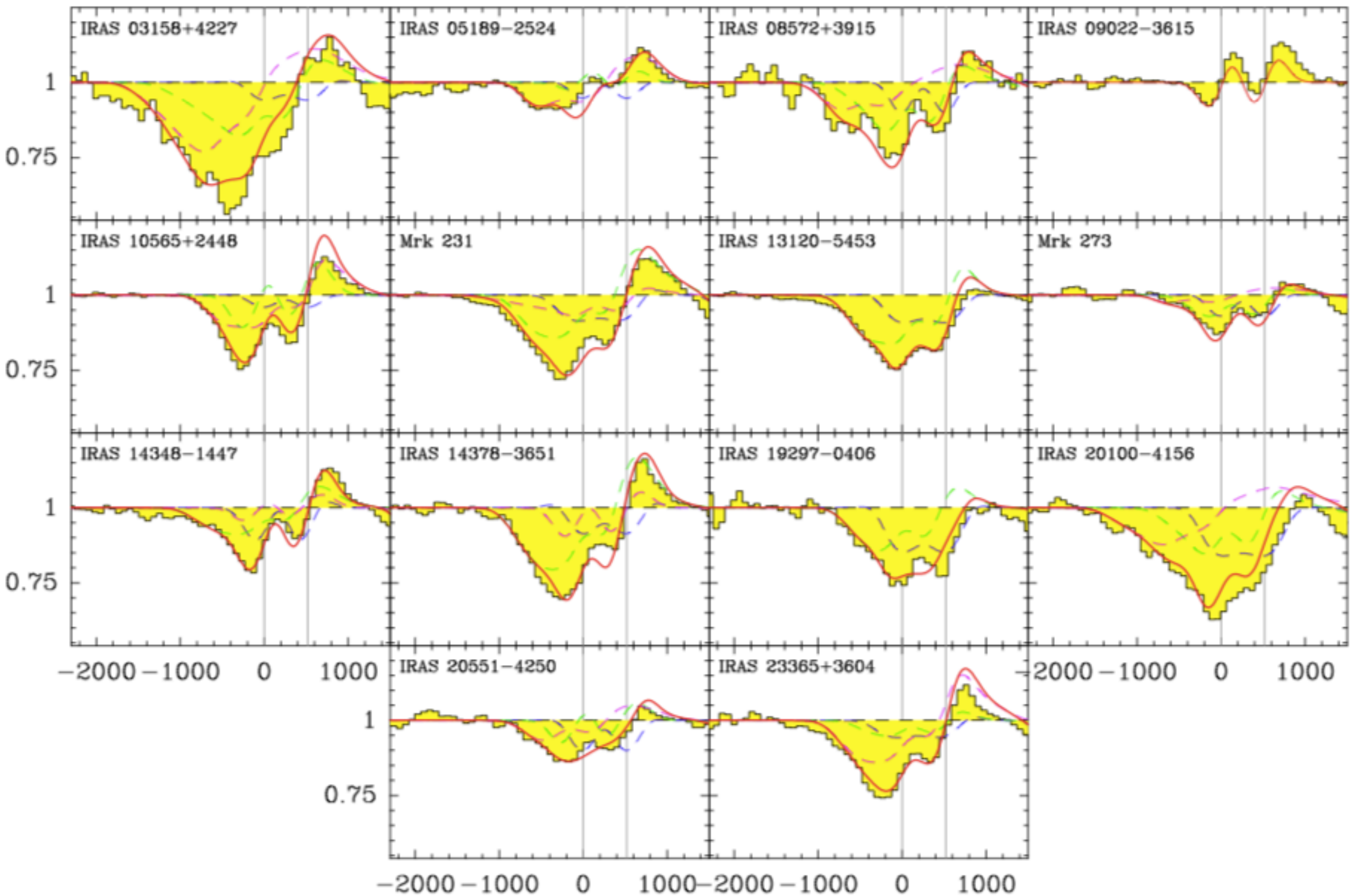
Non-LTE, non-local



- ***Radiative transfer models:*** **(1) statistical equilibrium populations in all shells of a spherically symmetric source, (2) emergent continuum, (3) velocity profiles of all lines**
- ***Core:*** T_{dust}, τ_{100}, f_{119}, V_{out}, ΔV_{turb}
- ***Envelope:*** T_{dust}, τ_{100}, f_{119}, R_{int}/R_{out}, V_{int}, V_{out}, ΔV
- ***Density profile of each shell:*** **derived from mass conservation (n_{OH} V R^2 independent of r)**
- ***Assumptions:*** **OH/H_2 abundance = 2.5 x 10^{-6}** ***(~ GMC Sgr B2; buried nuclei, PDRs, XDRs, CRDRs)*****; Galactic gas-to-dust ratio = 100 (well-mixed)**

OH 119 μm doublet

(Gonzalez-Alfonso + 17)



Molecular Outflow Energetics

- ***Local or instantaneous (maximum) values:***

$$\dot{M}_{\rm loc} = f_c\, 4\pi R^2 \mu\, m_{\rm H}\, n_{\rm H}\, v = \frac{M_{\rm out}\, v}{\Delta R}$$
$$\dot{P}_{\rm loc} = \dot{M}_{\rm loc}\, v,$$
$$\dot{E}_{\rm loc} = \frac{1}{2} \dot{M}_{\rm loc}\, v^2,$$

where $\Delta R = R_{\rm out} - R_{\rm int}$

(e.g., Sturm+11; Gonzalez-Alfonso+14; Tombesi+15)

- ***Average (minimum) values = "time-averaged thin-shell values":***

$$\dot{M}_{\rm out} = f_c\, 4\pi R^2 \mu\, m_{\rm H} \frac{N_{\rm H}\, v}{R} = \frac{M_{\rm out}\, v}{R}$$
$$\dot{P}_{\rm out} = \dot{M}_{\rm out}\, v$$
$$\dot{E}_{\rm out} = \frac{1}{2} \dot{M}_{\rm out}\, v^2$$

★

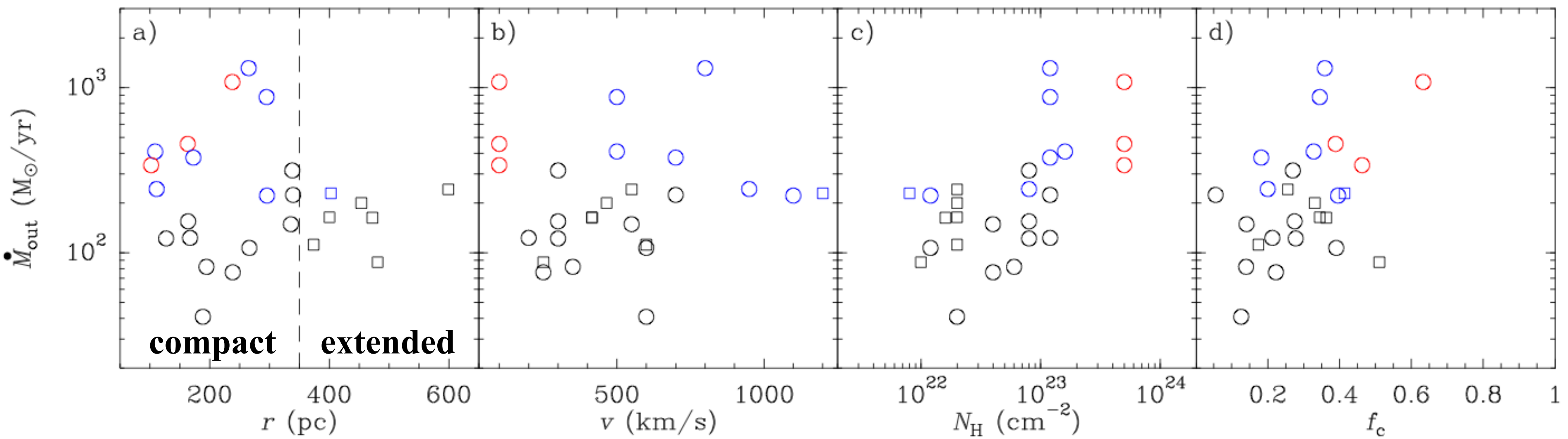
(e.g. Rupke+05c, Arav+13; Borguet+13; Rupke+Veilleux 13a, Heckman +15)

(The energetics *in Feruglio+10, 15, Maiolino+12; Rodriguez Zauri+13; Cicone+14; Harrison+14; Garcia-Burillo+15 are 3x higher → filled w/ uniform density)*

Molecular Outflow Energetics

(Gonzalez-Alfonso + 17)

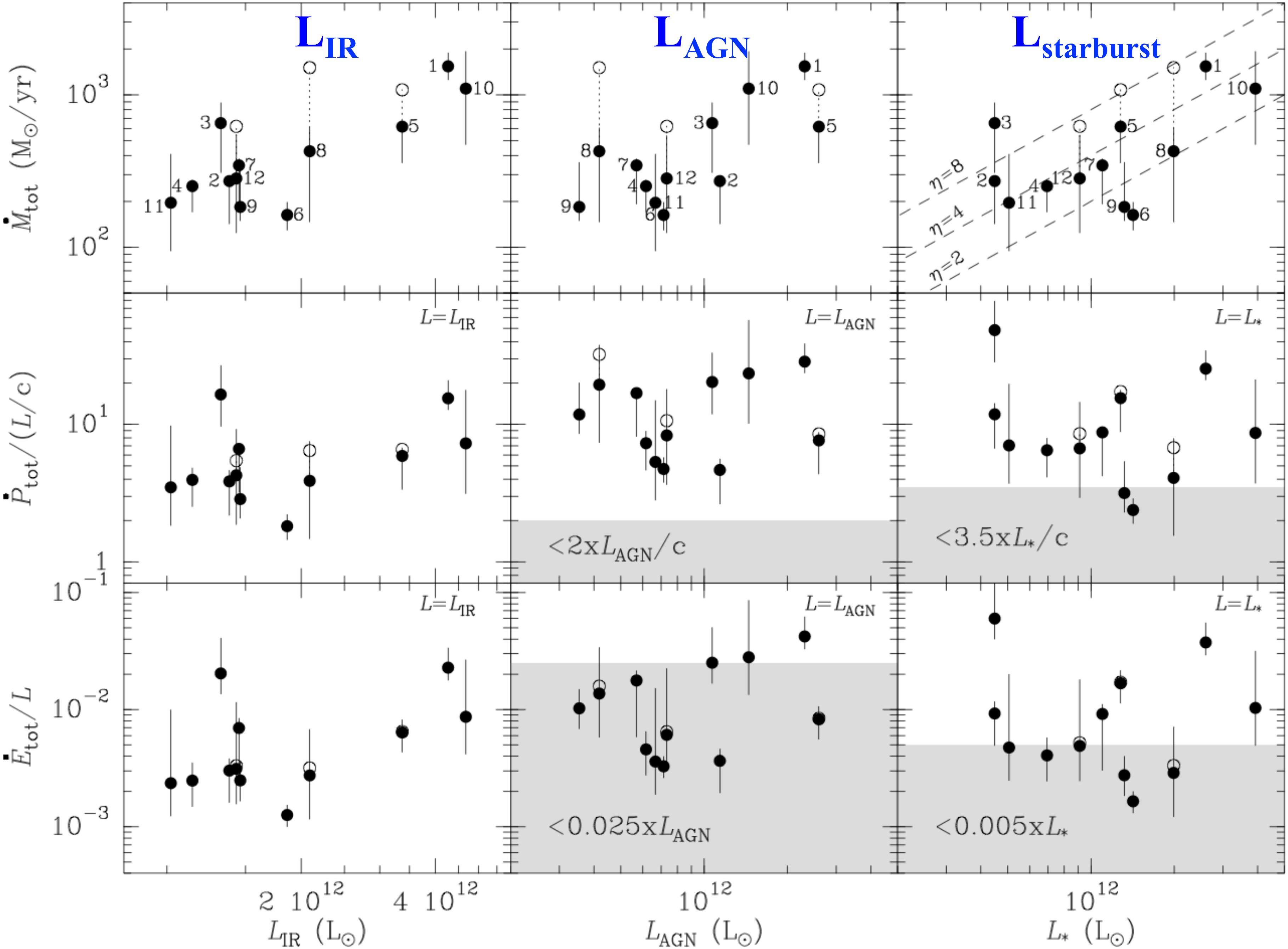
Reliable fits for 12 of the 14 ULIRGs



Red = Core component

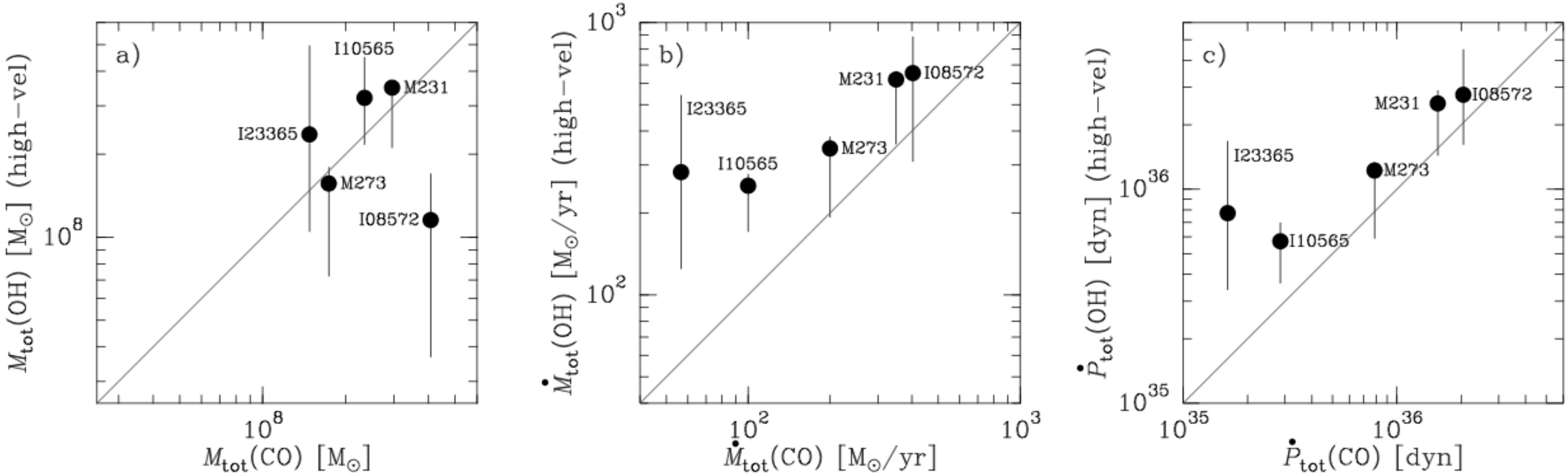
Blue / black = Envelope components

(dP/dt > 1 x 10^{36} dyn)

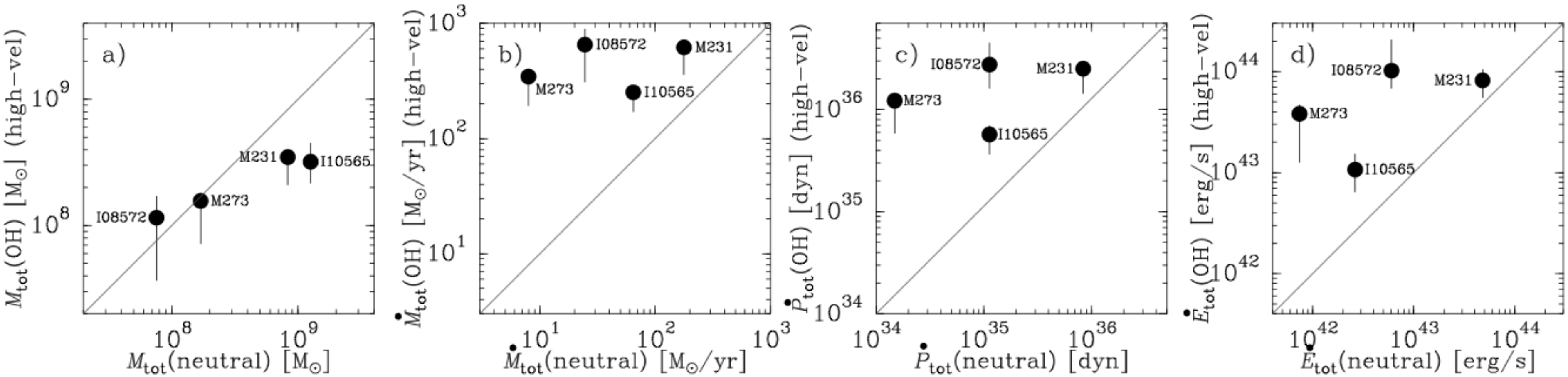


(Gonzalez-Alfonso + 17)

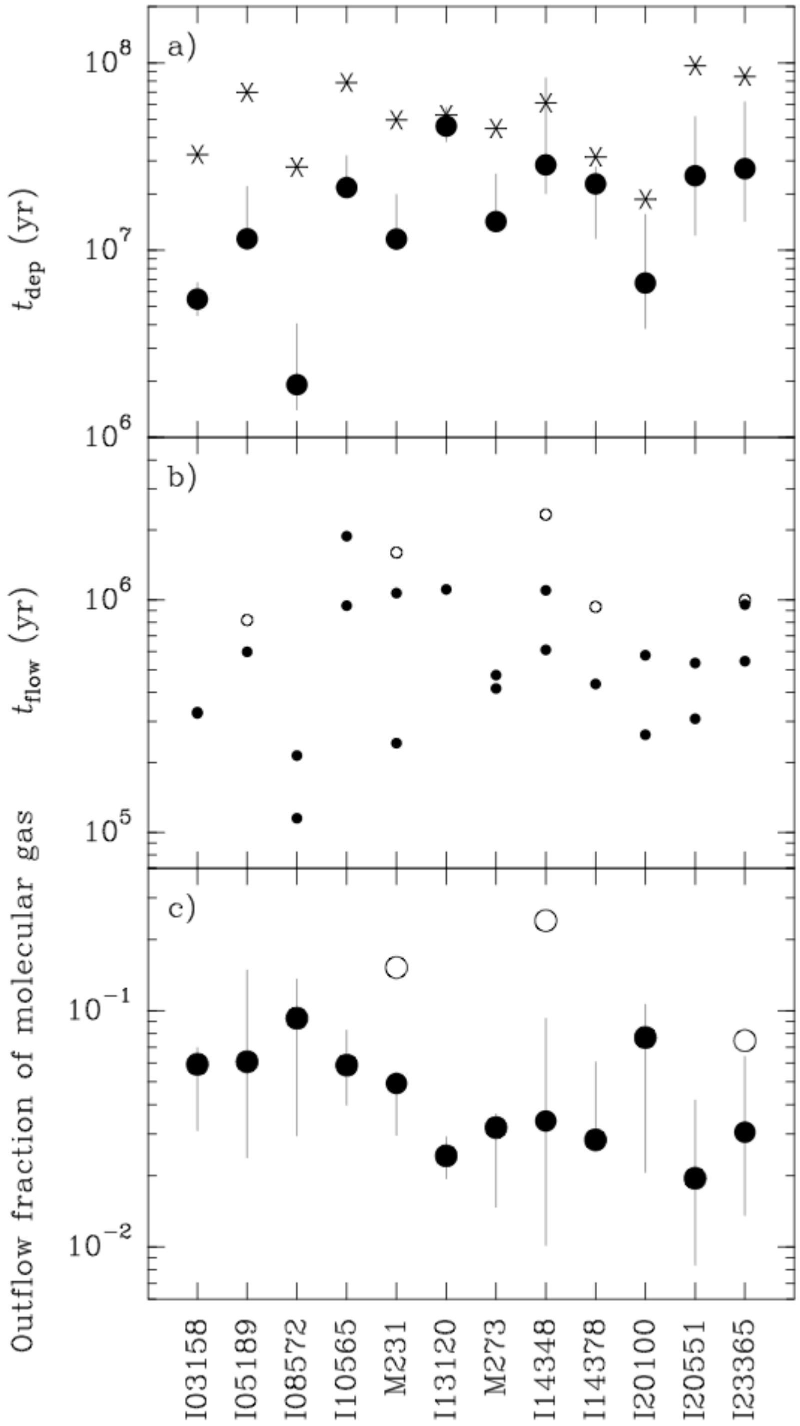
Comparison with CO-based Outflows *(Cicone+14 ÷ 3)*



Comparison with Na I D-based Outflows *(Rupke & Veilleux 2013a)*



(Gonzalez-Alfonso + 17)

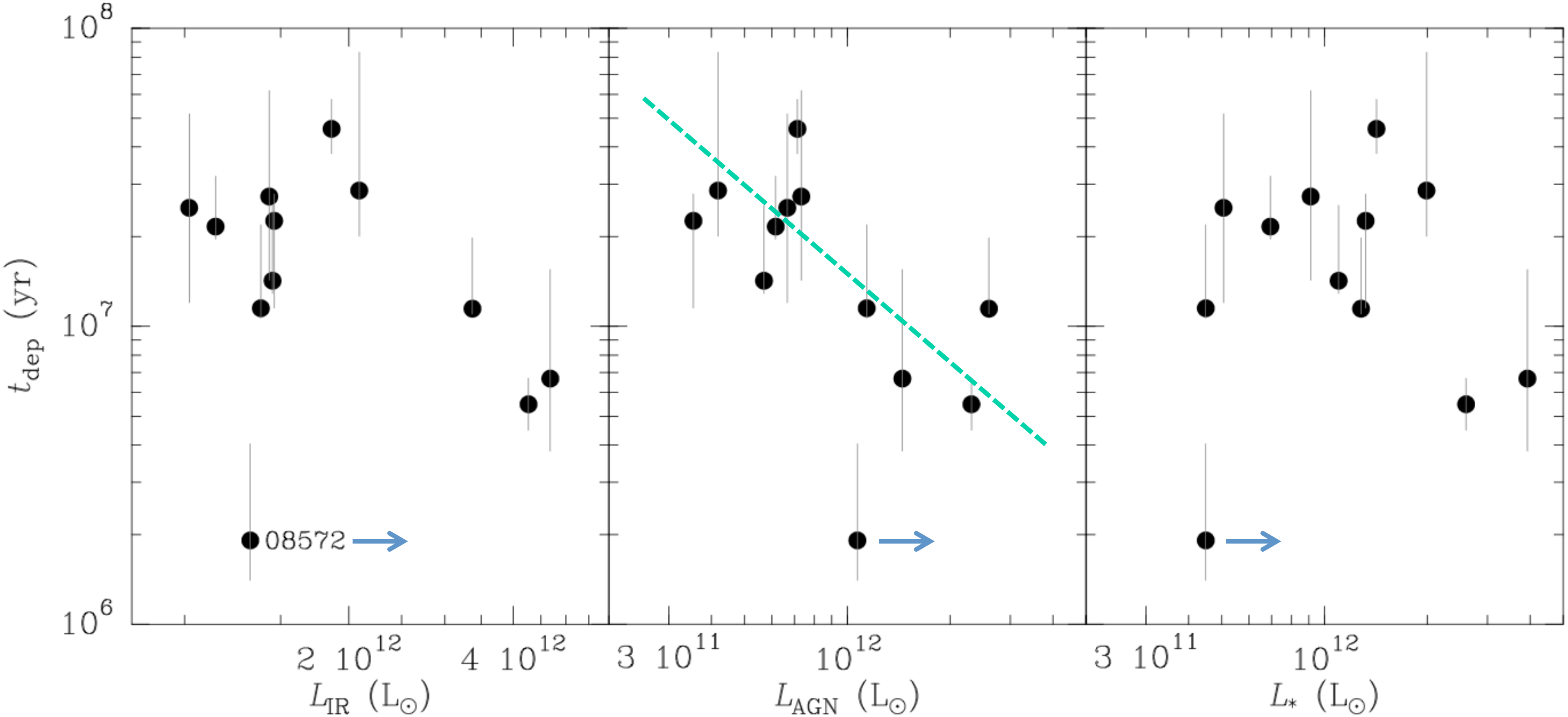


Filled circles: M_{H2} / $(dM/dt)_{out}$
Stars: M_{H2} / SFR

Open circles: v < 300 km/s components
Filled circles: v > 300 km/s components

Open circles: all
Filled circles: only v > 200 km/s

(Gonzalez-Alfonso + 17)



(Gonzalez-Alfonso + 17)

Plan

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Neutral and Ionized Atomic Outflows in ULIRGs & Quasars

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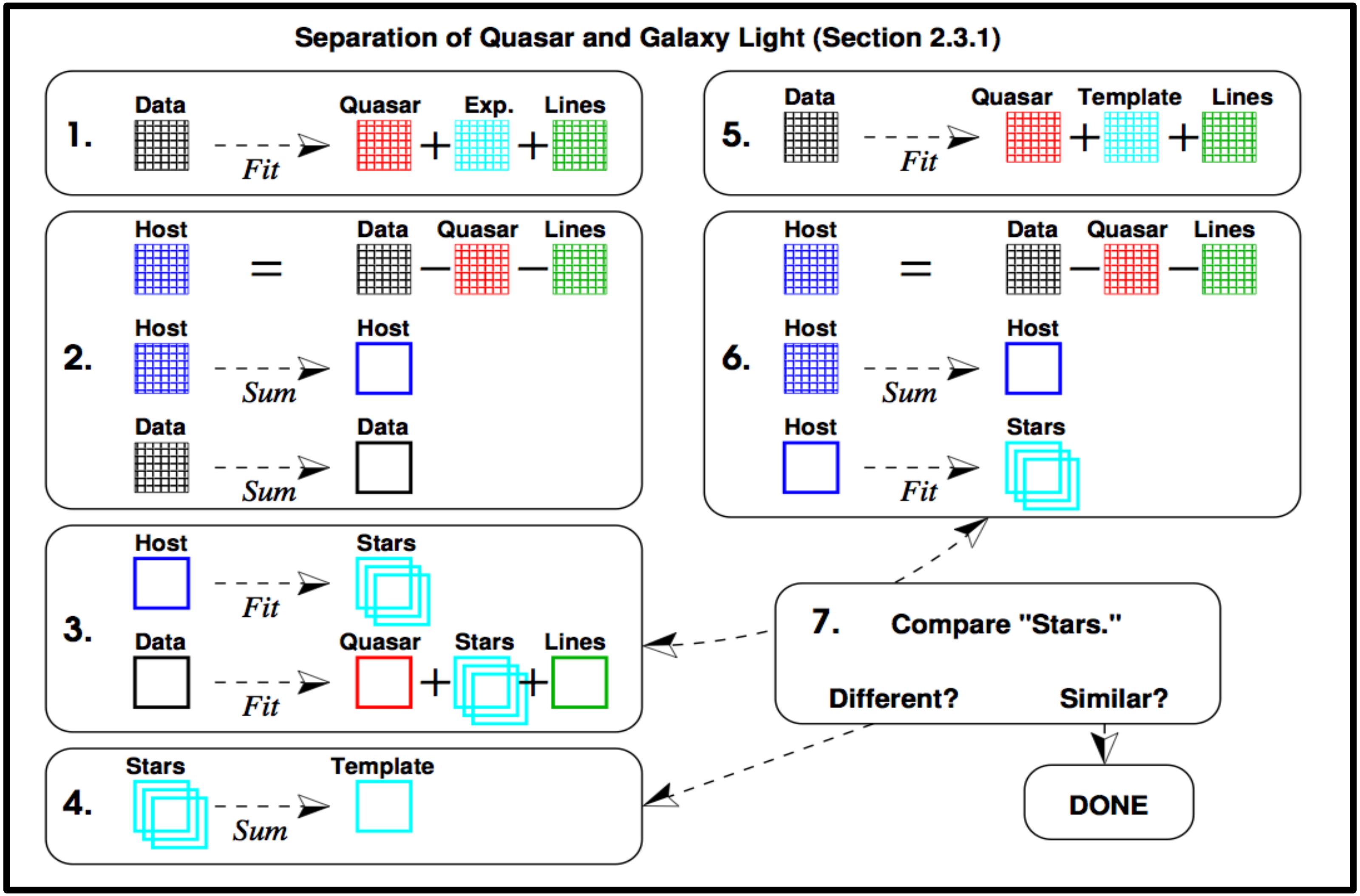
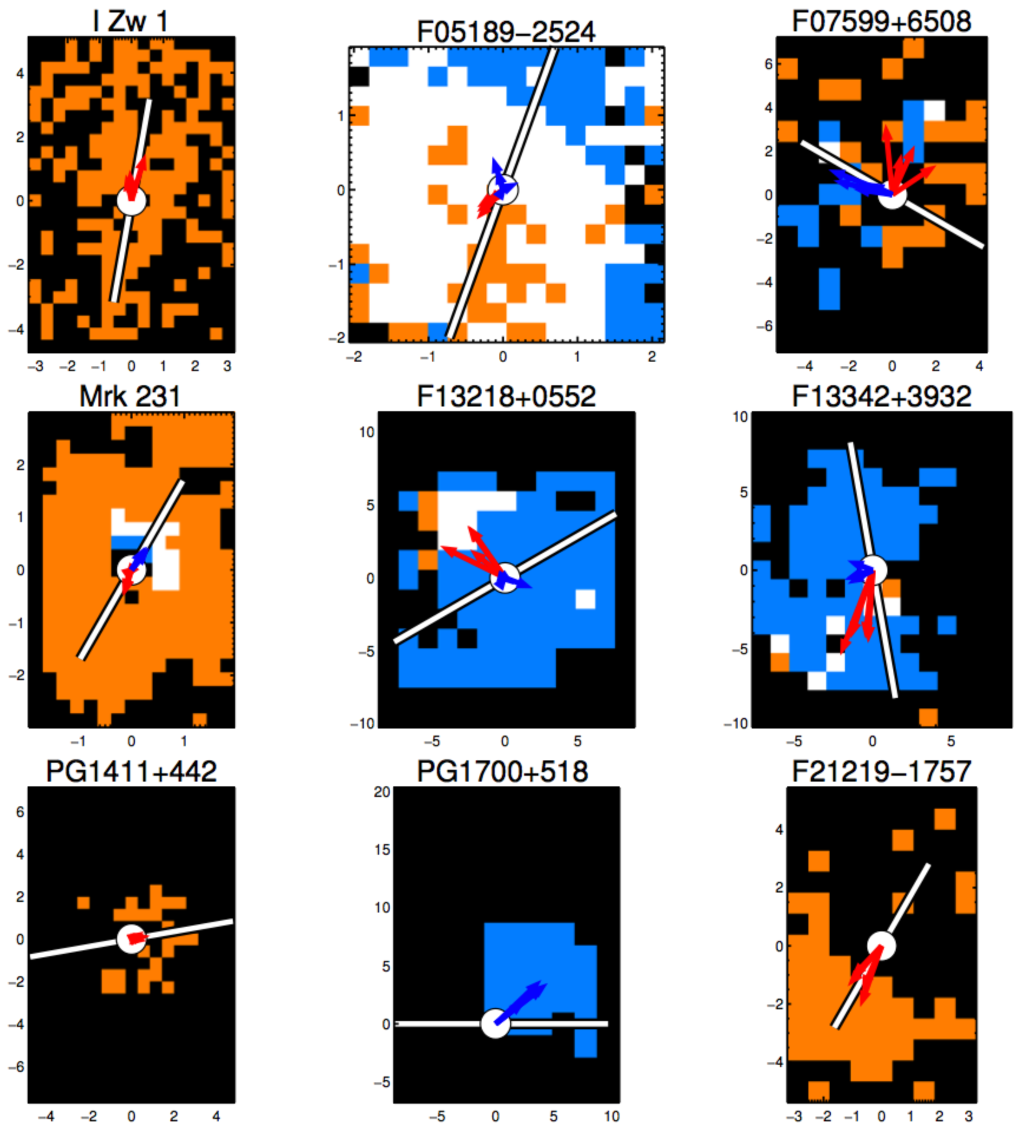


Gridded boxes = data cubes

Single boxes = spatially-summed spectra

Neutral and Ionized Atomic Outflows in ULIRGs and Quasars

(Rupke, Gultekin, & Veilleux 2017)



Na I outflow

Ionized outflow

Neutral and Ionized Atomic Outflows in ULIRGs and Quasars

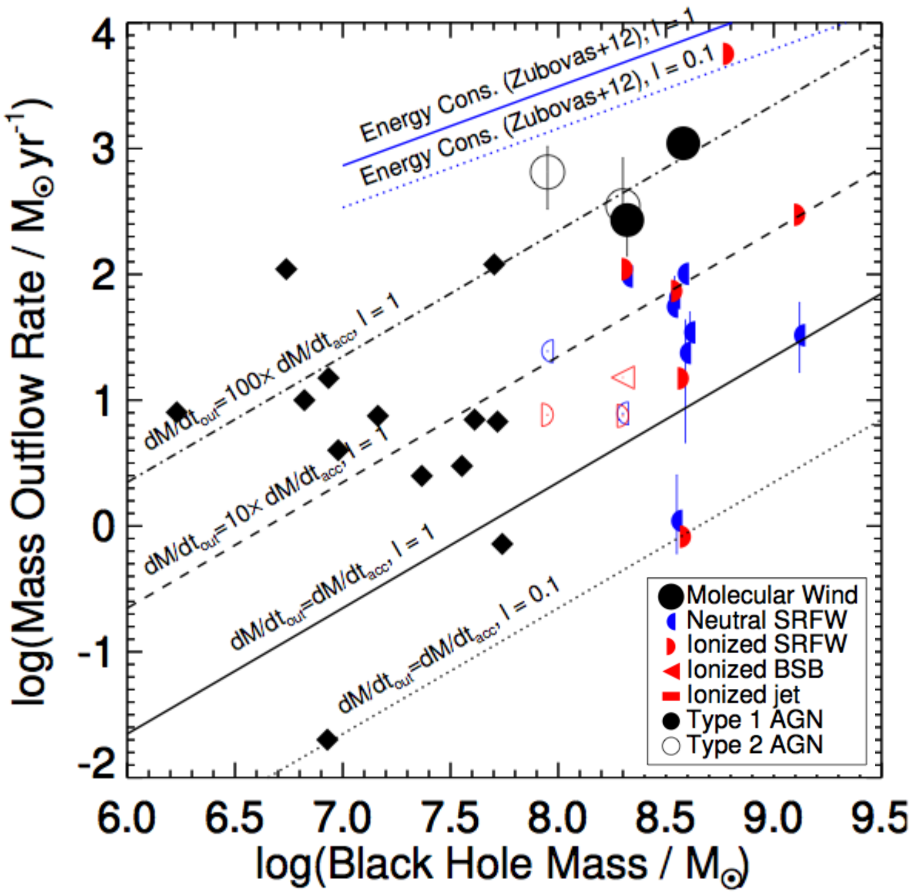
(Rupke, Gultekin, & Veilleux 2017)

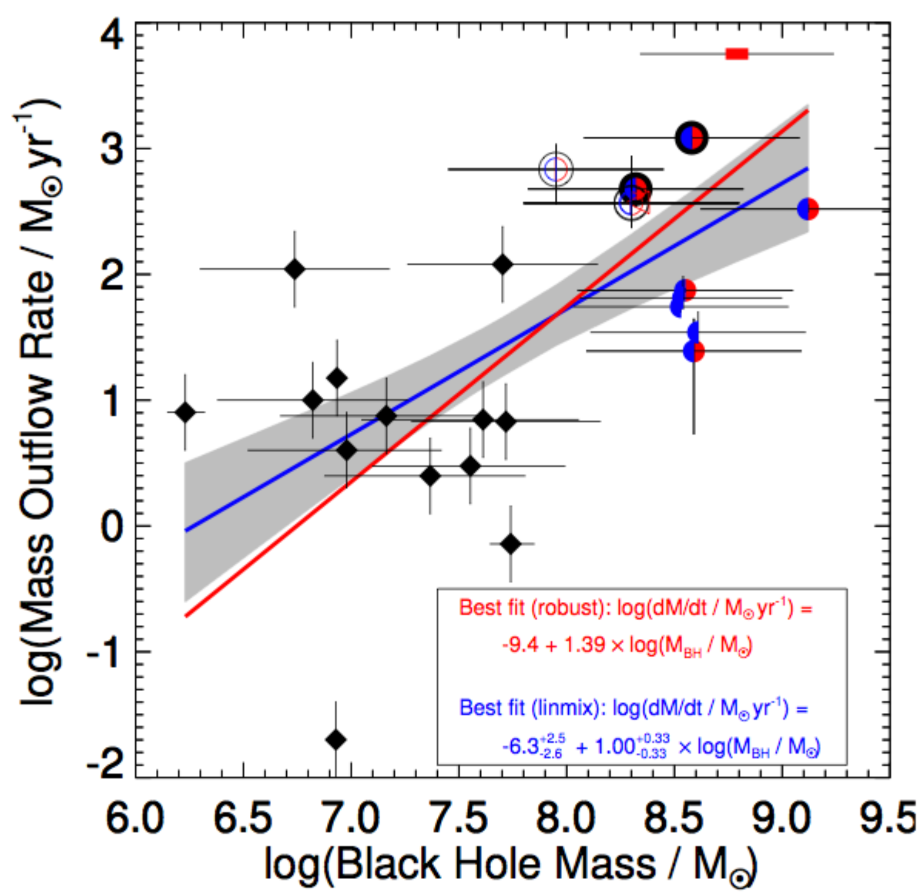
Table 6. Percent of Mass, Momentum, and Energy in Each Phase

Galaxy (1)	Phase (2)	M (3)	dM/dt (4)	p (5)	dp/dt (6)	E (7)	dE/dt (8)
F05189-2524	neutral	29	20	···	36	···	59
···	ionized	56	23	···	22	···	15
···	molecular	14	56	···	41	···	24
F07599+6508	neutral	98	96	96	89	97	89
···	ionized	1	3	3	10	2	10
Mrk 231	neutral	38	8	···	13	···	20
···	ionized	1	1	···	2	···	4
···	molecular	60	90	···	83	···	75
F13218+0552	neutral	3	1	1	0	3	1
···	ionized	96	98	98	99	96	98
F13342+3932	neutral	3	9	9	29	31	60
···	ionized	96	90	90	70	68	39

Neutral and Ionized Atomic Outflows in ULIRGs and Quasars

(Rupke, Gultekin, & Veilleux 2017)





◆ **13 Seyfert galaxies (from the literature)**

$$\mathbf{dM/dt \sim M_{BH}^{1.00\pm0.33}}$$

Neutral and Ionized Atomic Outflows in ULIRGs and Quasars

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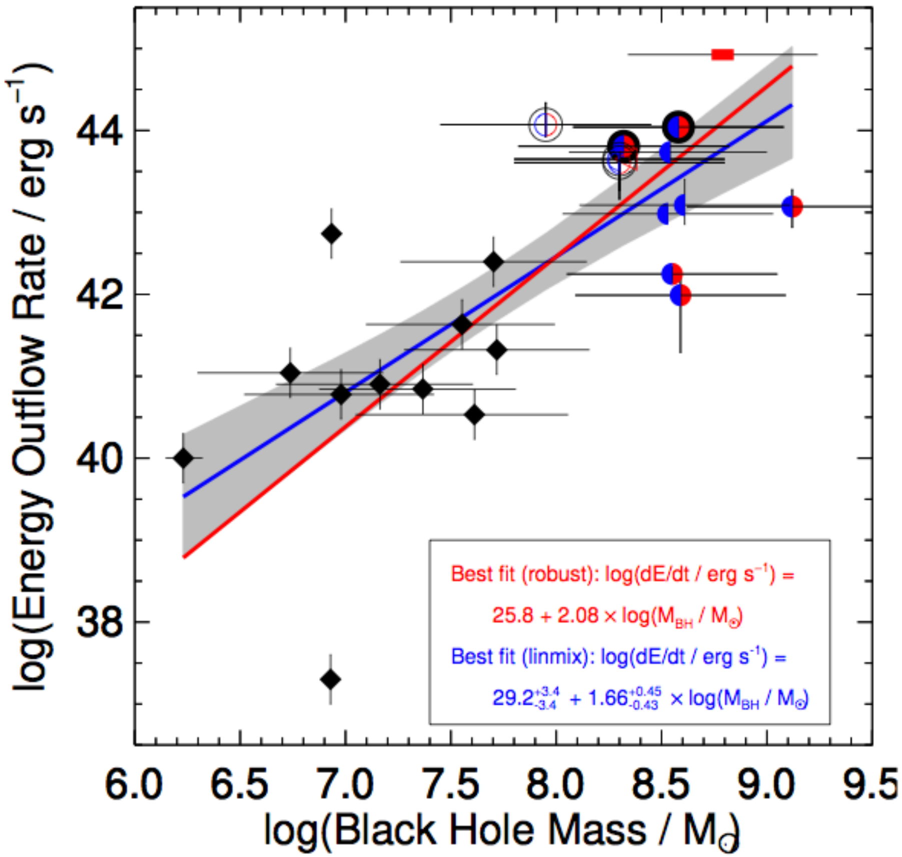
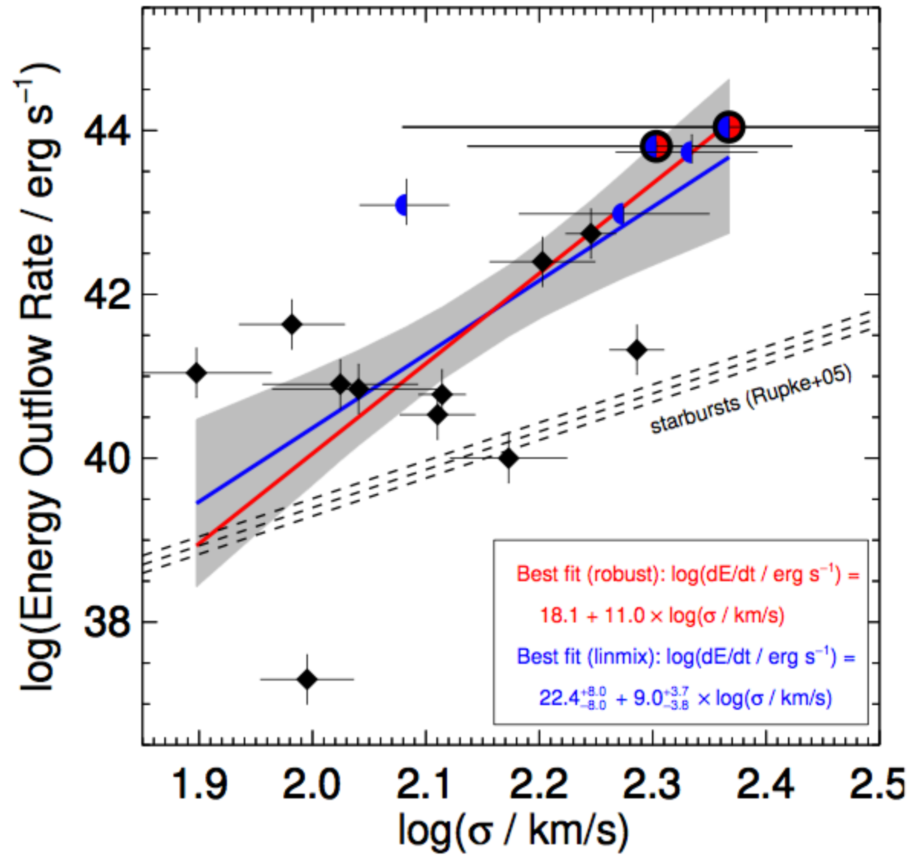


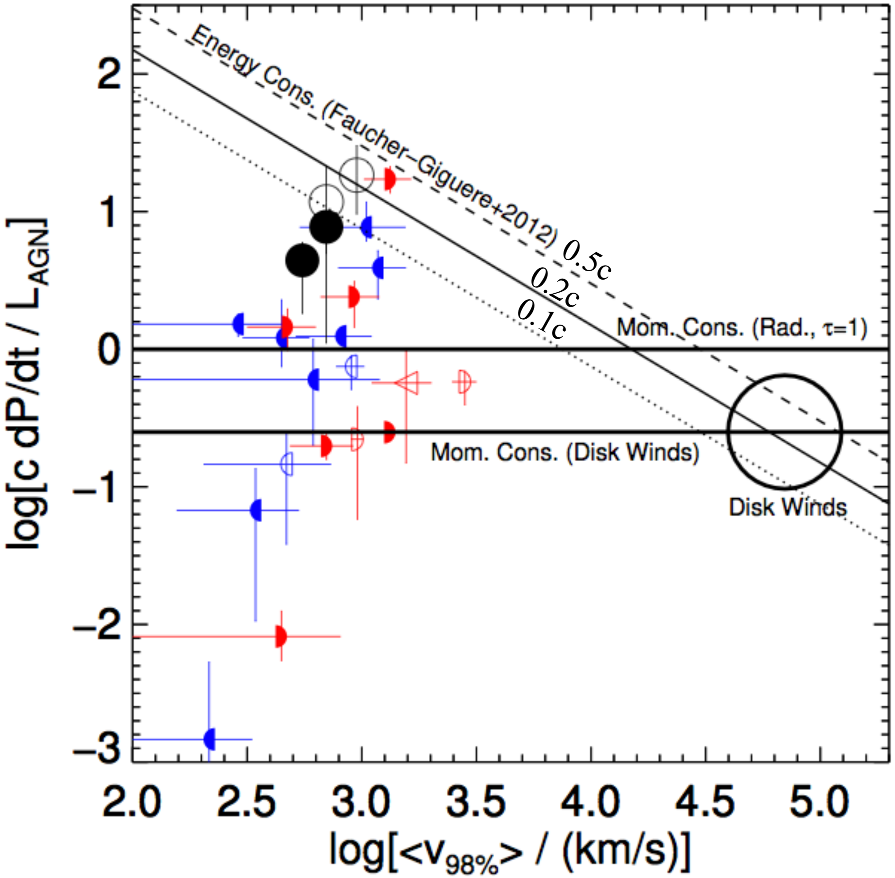


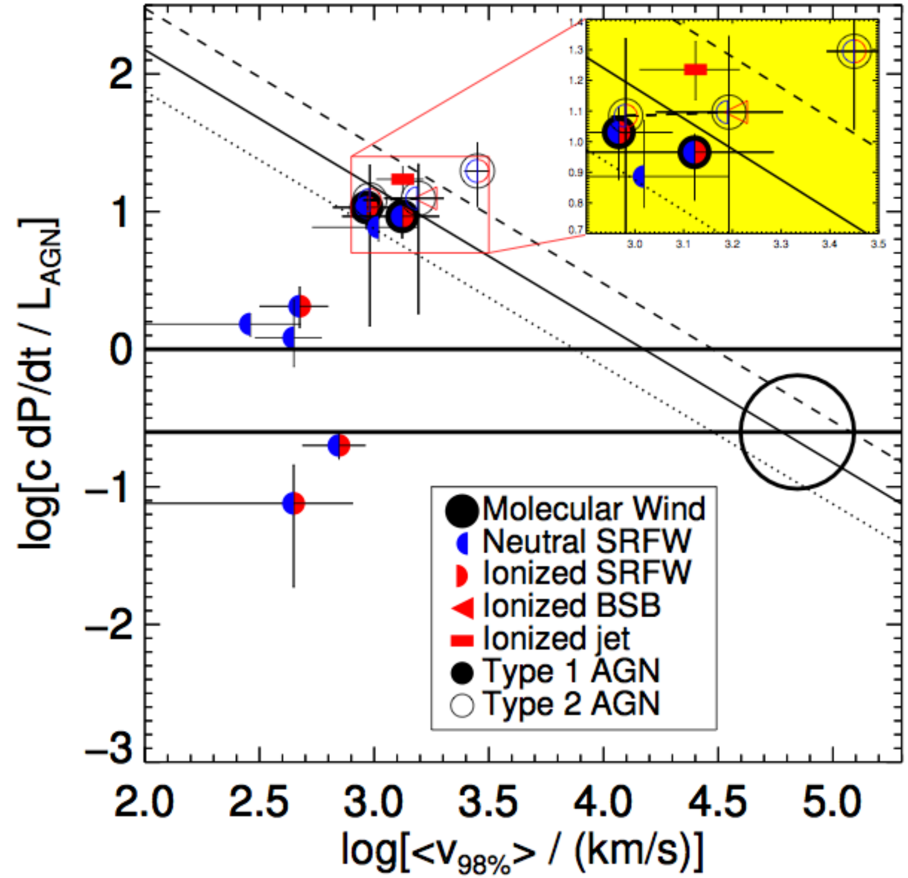
$dE/dt \sim M_{BH}^{1.66\pm0.45}$

$dE/dt \sim \sigma^{9.0\pm3.8}$

Neutral and Ionized Atomic Outflows in ULIRGs and Quasars

(Rupke, Gultekin, & Veilleux 2017)





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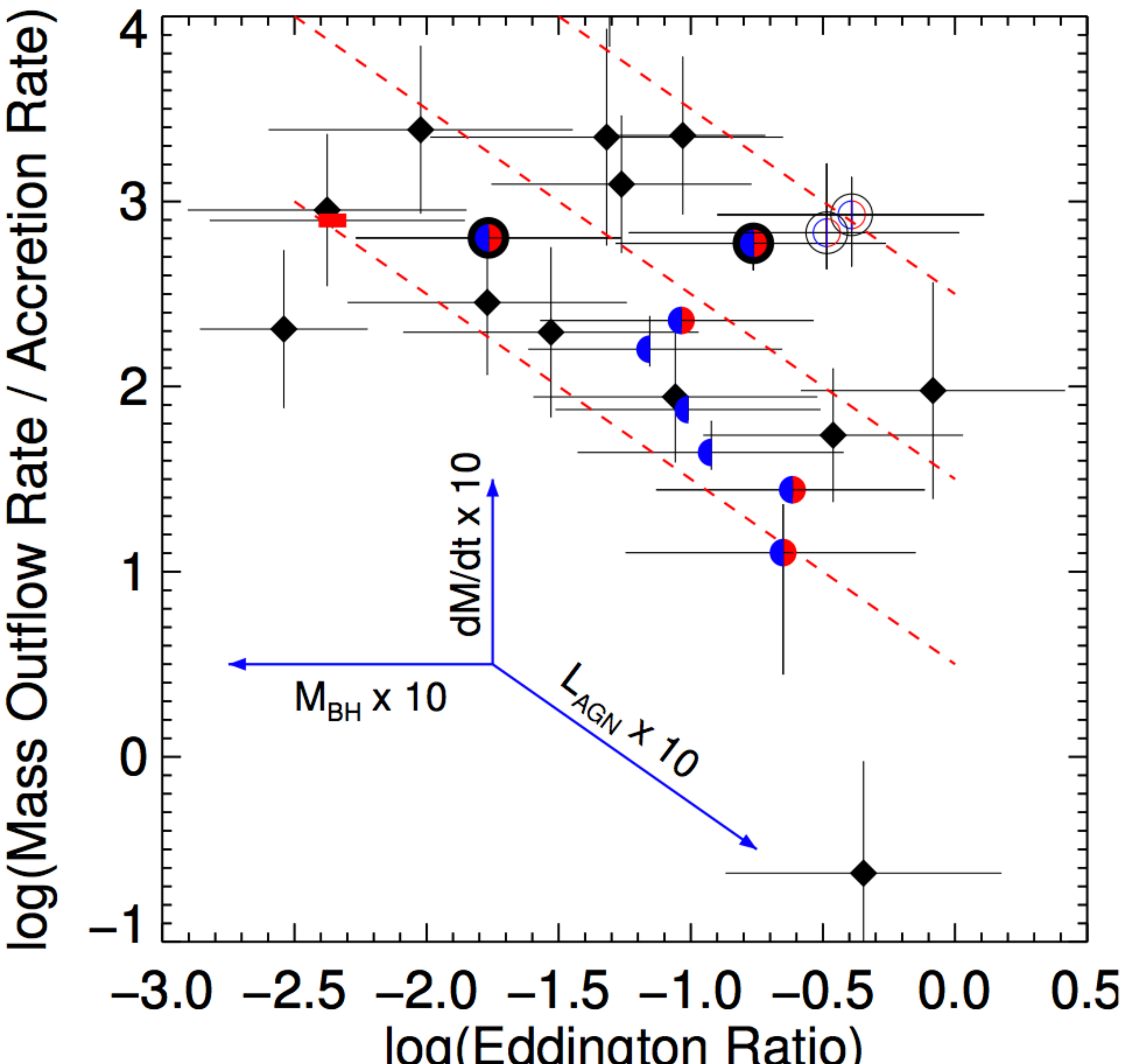

"Efficiency of feedback" decreases with increasing Eddington ratios

Variations in accretion rate (= L_{AGN}) on timescales much shorter than the outflow dynamical time could also explain this downward trend

This figure assumes 10% efficiency of energy released by accretion

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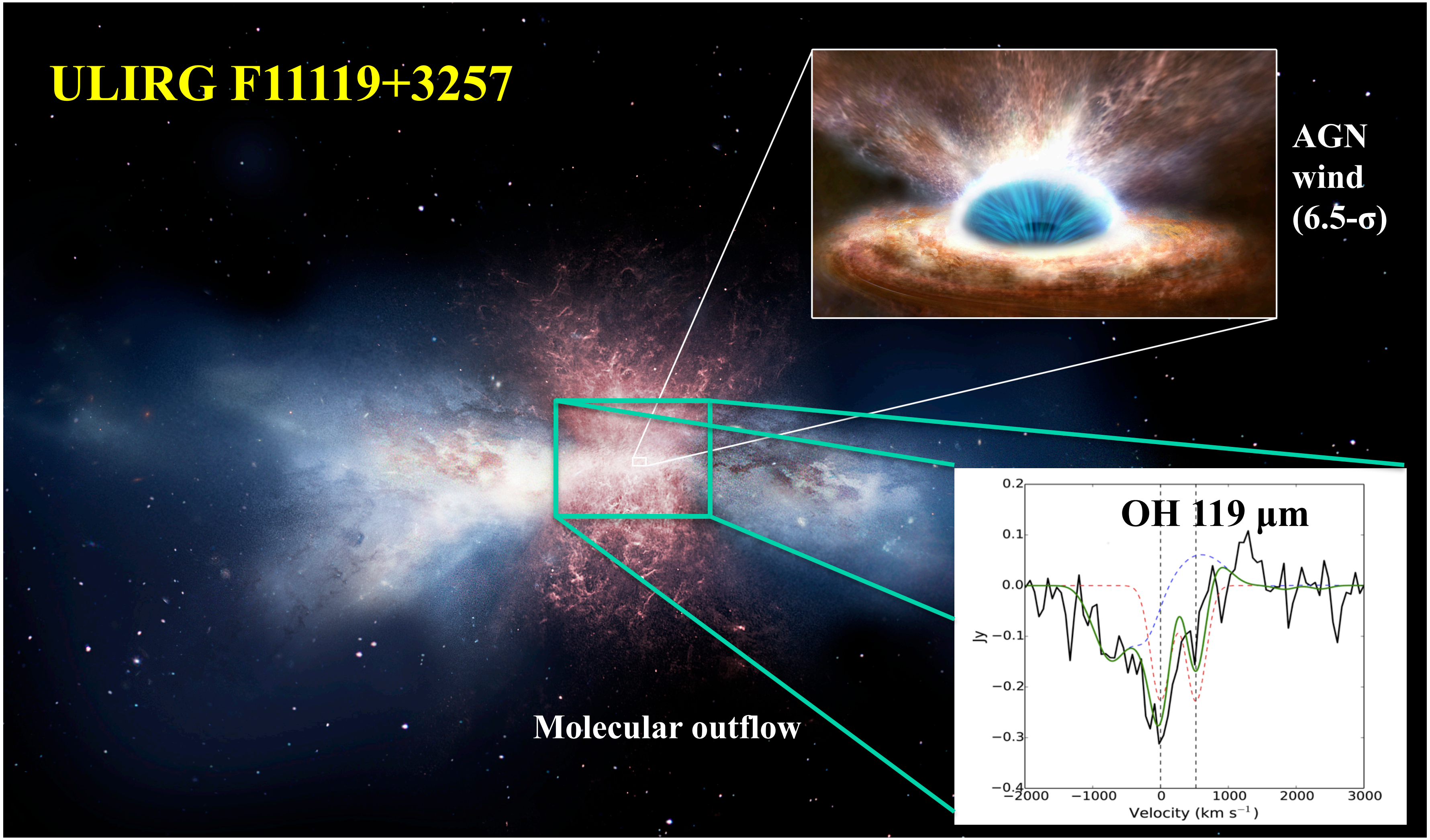
Connecting the Accretion Disk Wind with the Large-Scale Molecular Outflow

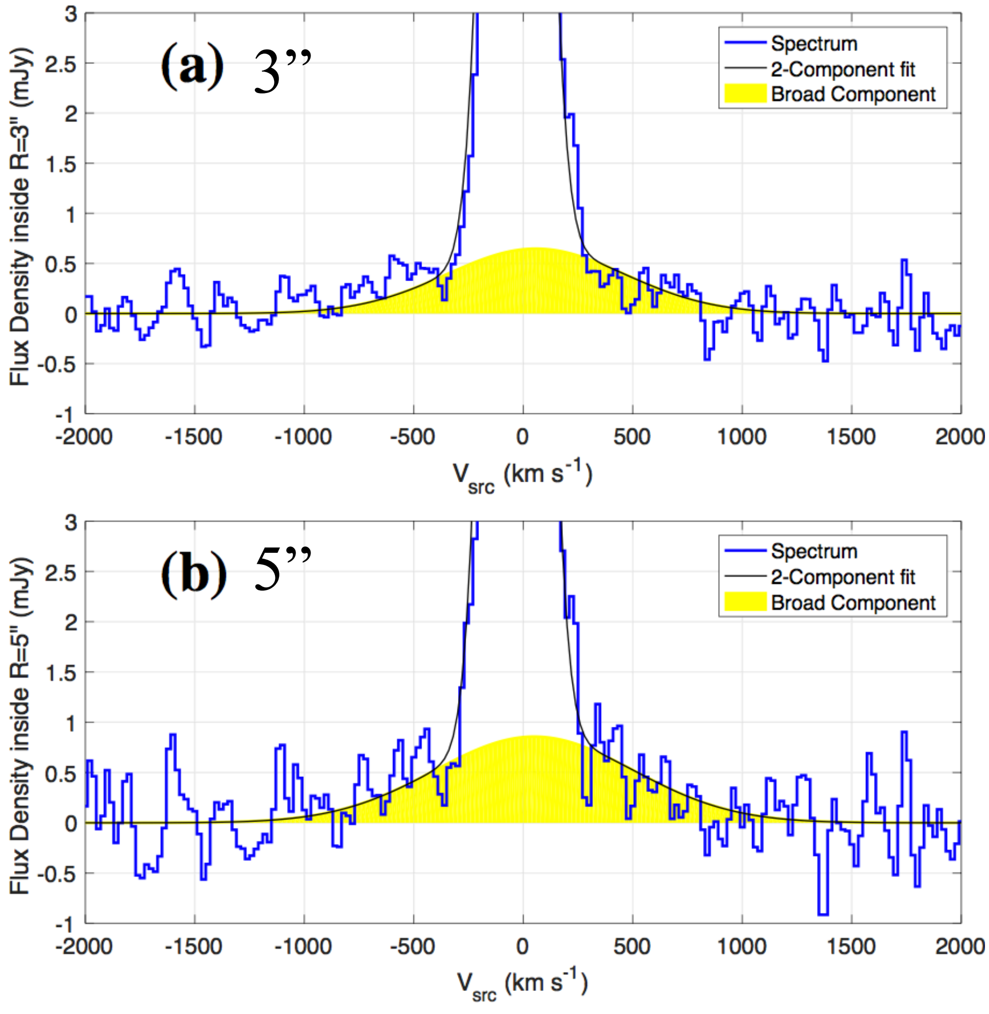


(based on *Tombesi, Meléndez, SV, et al. 2015, Nature*)

Connecting the Accretion Disk Wind with the Large-Scale Molecular Outflow

(Veilleux, Bolatto, Tombesi, Meléndez + 2017)

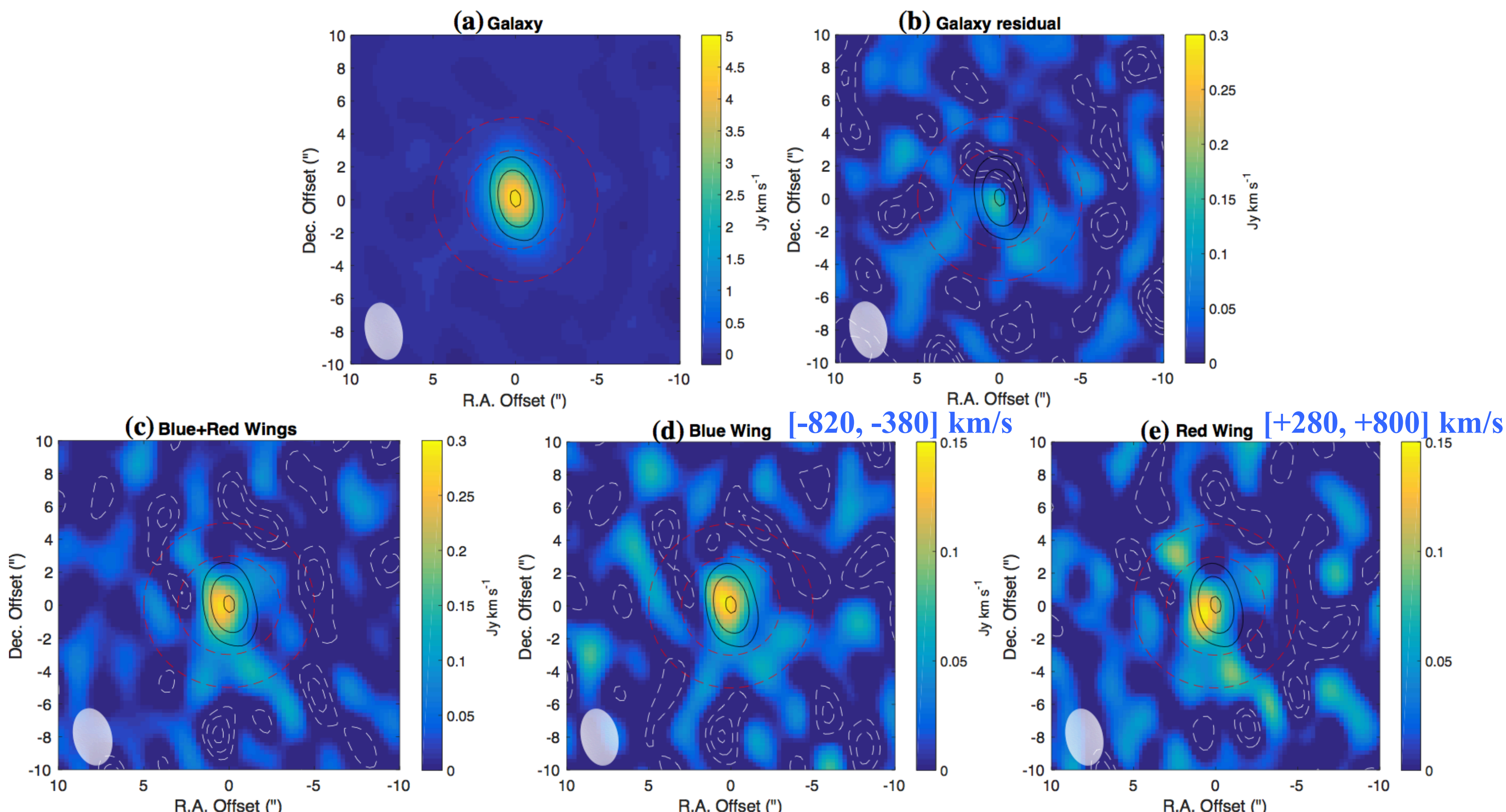
- ***ALMA***: **Integrated CO (1 – 0) line profile in F11119+3257**



Connecting the Accretion Disk Wind with the Large-Scale Molecular Outflow

(Veilleux, Bolatto, Tombesi, Meléndez + 2017)

- ***ALMA***: CO (1 – 0) emission from rotating disk + outflow
  - UV-plane fitting: FWHM(wings) ~ 4 – 5” ~ 12 – 15 kpc → R_{out} ~ 7 kpc



Connecting the Accretion Disk Wind with the Large-Scale Molecular Outflow

(Veilleux, Bolatto, Tombesi, Meléndez + 2017)

- ***ALMA***: **Derived properties of small- and large-scale outflows**

Outflow Type (1)	$\dot{M}$ [$M_\odot$ yr^{-1}] (6)	$\dot{P}$ [L_{AGN}/c] (7)	$\dot{E}$ [L_{AGN}] (8)
Accretion Disk Wind[(a)]	1.5 – 4.5 [(b)]	0.4 – 3.0 [(c)]	(6 – 50)% [(d)]
OH Outflow (local)[(e)]	250 – 2000 [(f)]	3.5 – 25 [(g)]	(0.5 – 5.0)% [(h)]
OH Outflow (average)[(i)]	**60 – 500 [(j)]**	**1.0 – 6 [(g)]**	**(0.1 – 1.0)% [(h)]**
CO Outflow (ULIRG-like)[(k)]	**80 – 200 [(m)]**	**1.5 – 3 [(n)]**	**(0.15 – 0.40)% [(o)]**

  - ***Time-averaged* CO outflow energetics ~ OH outflow energetics**
  - **But $(R/V)_{CO}$ ~ 7 x 10^6 yrs >> $(R/V)_{OH}$ ~ 4 x 10^5 yrs**
    → **Feedback efficiency has not changed drastically on this timescale**
  - **Only ~ 3 – 5% of the kinetic energy of the X-ray wind is needed to explain the bulk motion of the molecular gas**

Plan

- **Molecular outflows in ULIRGs & quasars**

  Gonzalez-Alfonso et al. 2017, ApJ, 836, 11

- **Neutral & ionized atomic outflows in ULIRGs & quasars**

  Rupke, Gultekin, & Veilleux 2017, refereed, being revised

- **Connecting the accretion-disk wind with the large-scale molecular outflow**

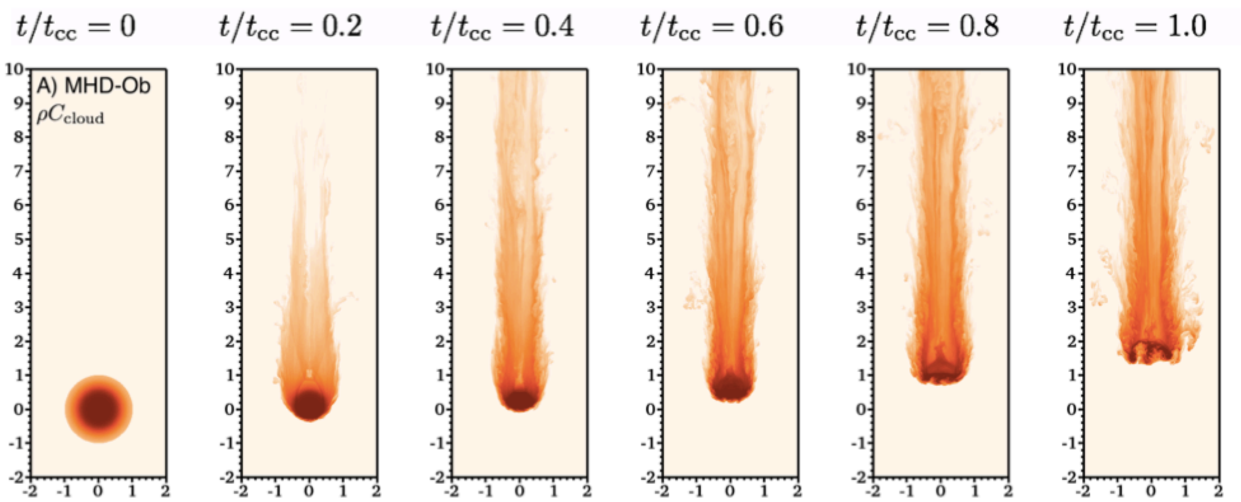
  Veilleux, Bolatto, Tombesi, et al. 2017, refereed, resubmitted

- **How does Nature do it: entrainment of the cool ISM or *in-situ* formation of cool clumps in the hot wind?**

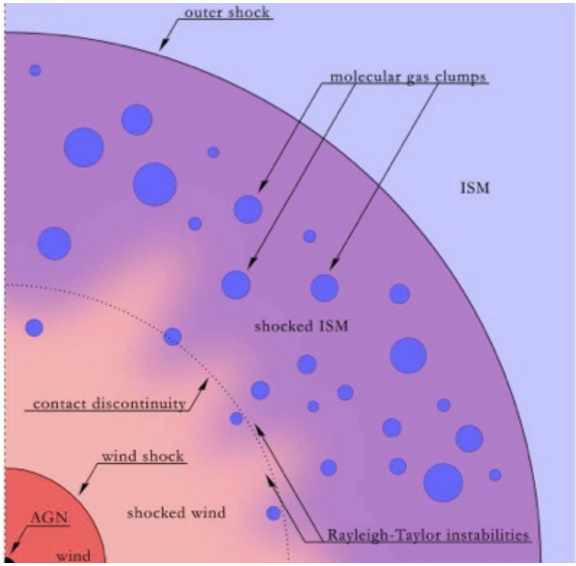
  Walter, Bolatto, Leroy, Veilleux et al. 2017, ApJ, 835, 265

Extreme Molecular Winds: How?

* How does *Nature* accelerate cool neutral / molecular clouds to V → 1000+ km s^{-1} out to *R* ~ kpc? Survival time scale? B?
* In-situ cloud formation via fragmentation + cooling → $v_{cloud} \sim v_{outflow}$? *(e.g., Faucher-Giguère+12; Zubovas+13; Zubovas & King 2014)*



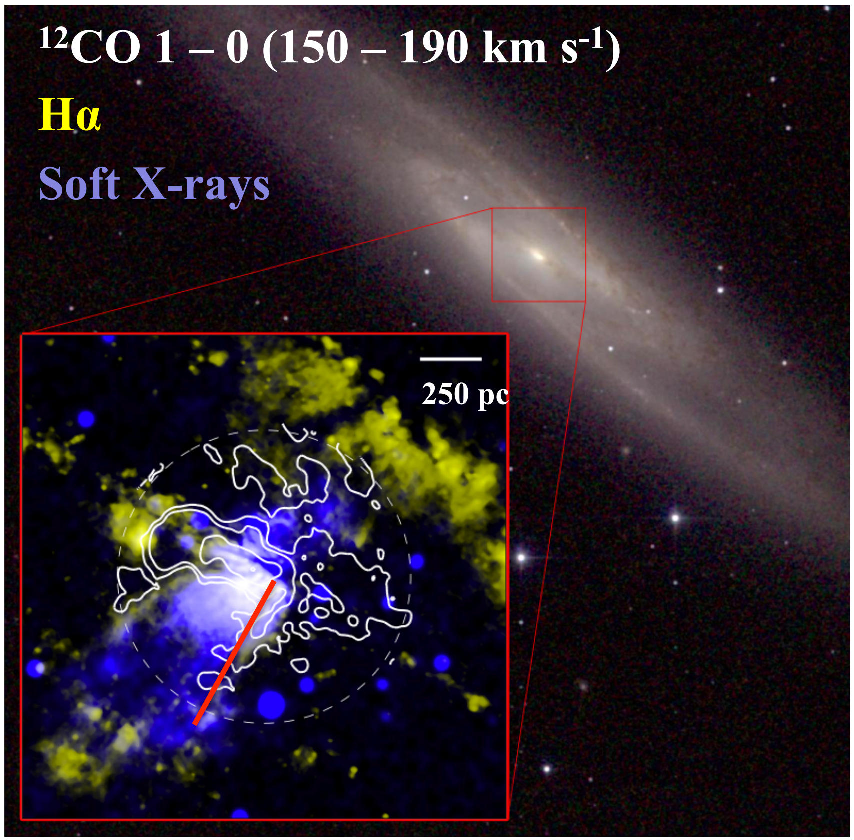
(Banda-Barragan+16)

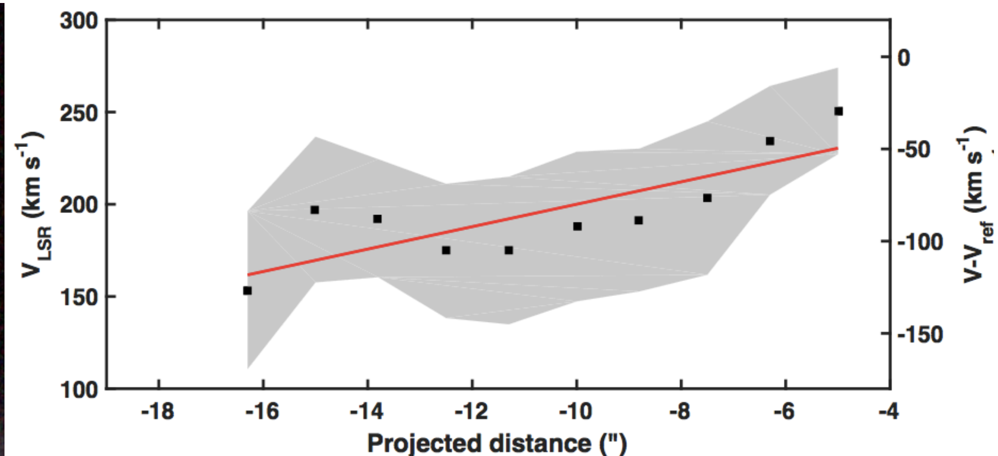


(Zubovas & King 2014)

Molecular Outflow in Starburst NGC 253

Bolatto, Warren, Leroy, Walter, SV, et al. (2013, Nature)
Walter, Bolatto, Leroy, SV, et al. (2017)





- *dM/dt* ~ 3 – 9 M_{sun} yr^{-1}
- η = *dM/dt / SFR* = 1 – 3

  (H_2/CO ~ 0.1 x Galactic value)
- **_Dense_ gas is entrained in the outflow (HCN, HCO, CS, and CN → ~10^4 cm^{-3})**
- **Properties of outflowing gas are similar to those in the central starburst disk**
- ***dV/dr* ~ +1 km s^{-1} pc^{-1} → accelerating?**

Cool Atomic and Molecular Outflows

- **Outflow statistics, energetics, extent, hence large-scale impact?**
  - **Statistics: ~70-100% of local ULIRGs / quasars have ionized or cool neutral or molecular winds**
  - **Size ~ 0.1 – 10+ kpc**
  - **d*M*/dt ~ $M_{BH}^{1.0 \pm 0.3}$ ~ 10 – 1000+ M_{sun} yr^{-1} → t_{dep} < 3 x 10^7 yrs (ULIRGs)**
  - **d*p*/dt = (0.1 – 20) L_{IR}/c**
  - **d*E*/dt ~ $M_{BH}^{1.7 \pm 0.4}$ < 3% L_{IR}**
  - **Quasar feedback efficiency decreases with increasing Eddington ratios**
- **Connection between the small- and large-scale outflows?**
  - **ALMA data have confirmed the molecular outflow in F11119+3257**
  - **Time-averaged CO outflow energetics ~ OH outflow energetics**
- **How does Nature do it?**
  - **Nature seems to have found a way to accelerate ~10^4 cm^{-3} molecular gas from rest to ~200 km s^{-1} over a distance of ~200 pc in NGC 253…**