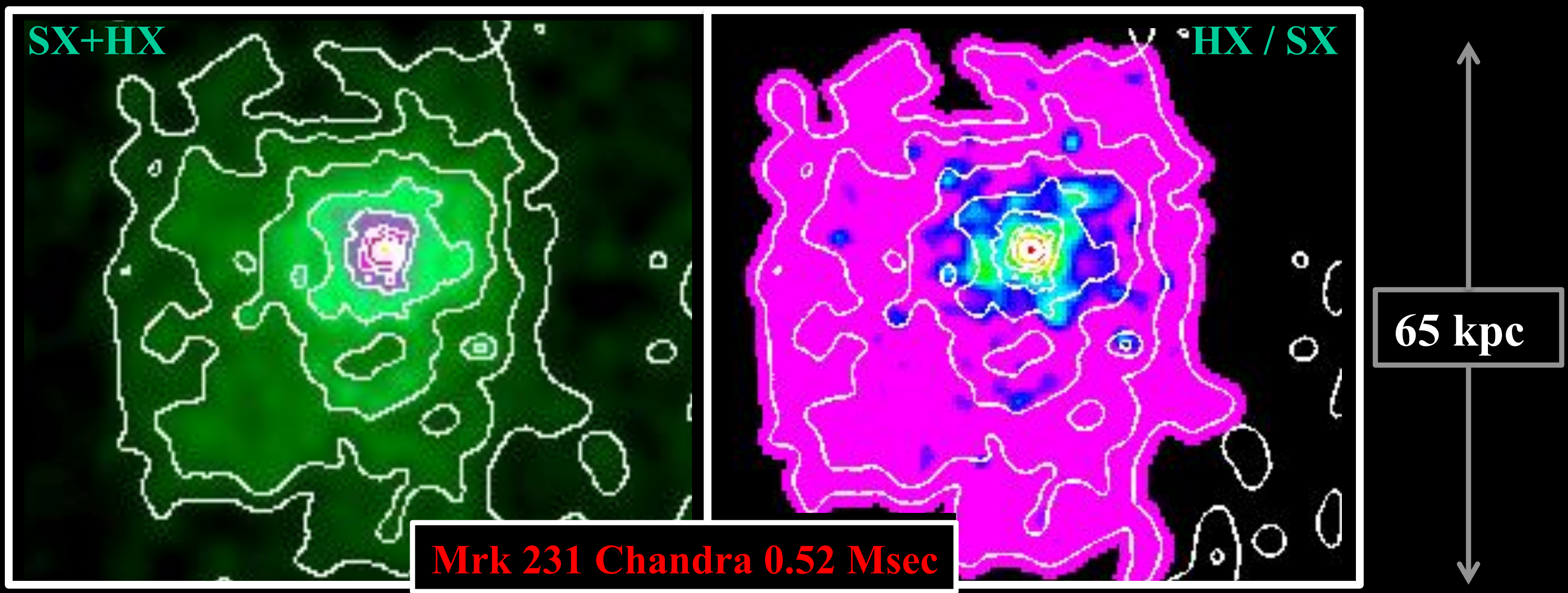
Powerful Neutral-Atomic and Molecular Outflows in Nearby Active Galaxies

S. Veilleux (U. Maryland)



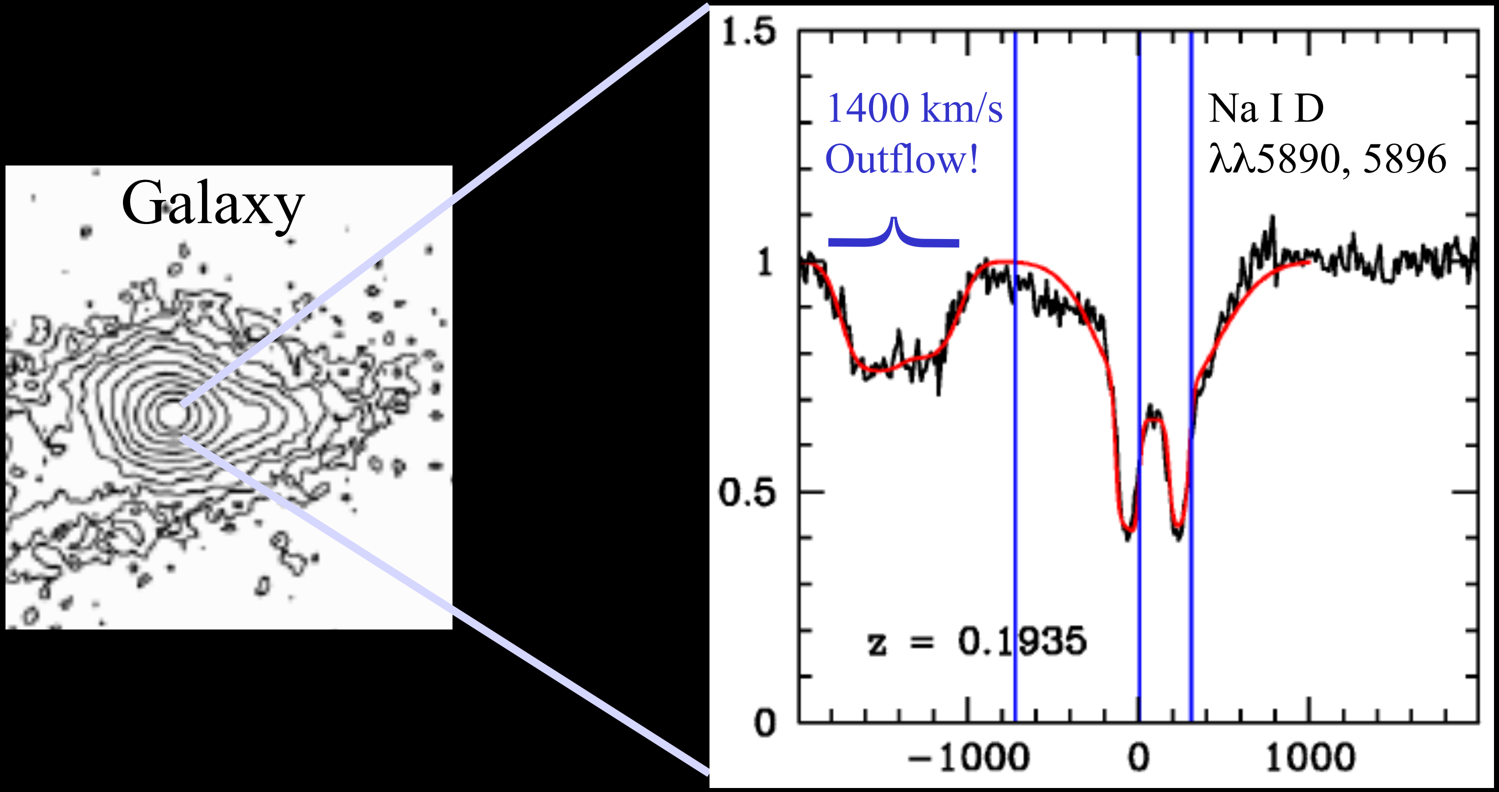
SV, Teng, Rupke, Maiolino, & Sturm (2014; in press arXiv:1405.4833)

Evidence for on-going and past (~10^8 yrs) outflow events in the X-ray data

Plan

- **Neutral-atomic winds: Na I D**
- **Molecular winds: OH, CO, H_2**
- **Open issues**
- **Summary**

Neutral Atomic Winds @ $z = 0 – 0.5$

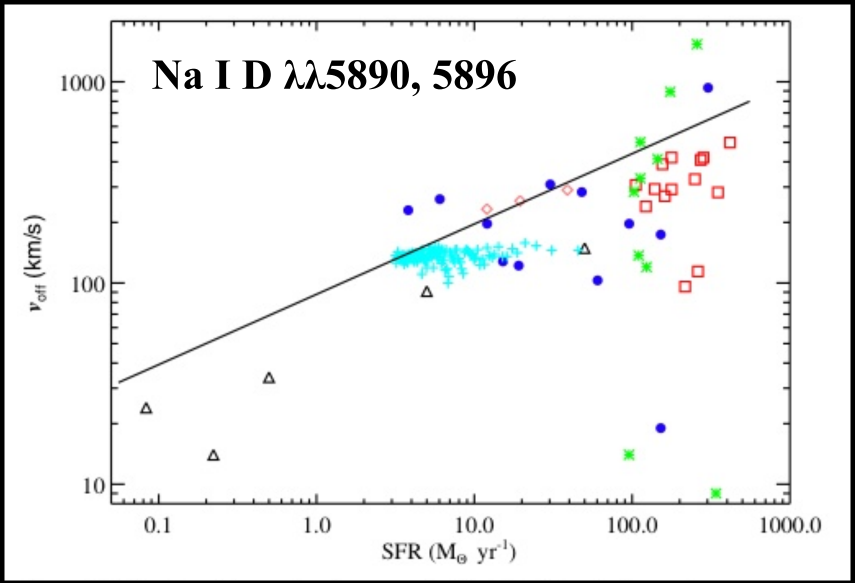


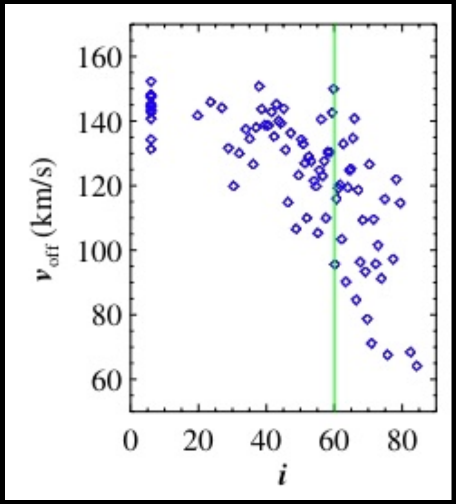
Rupke, SV, & Sanders (2002, 2005abc); Rupke & SV (2005);
AGN: Krug, Rupke, & SV (2010); Krug (2013)

also Heckman et al. (2000), Martin (2005, 2006), Chen et al. (2010)

Neutral Winds in $z < 0.5$ Star-Forming Galaxies

(Heckman+00; Rupke+02,05abc; Martin 05,06; Chen+10)

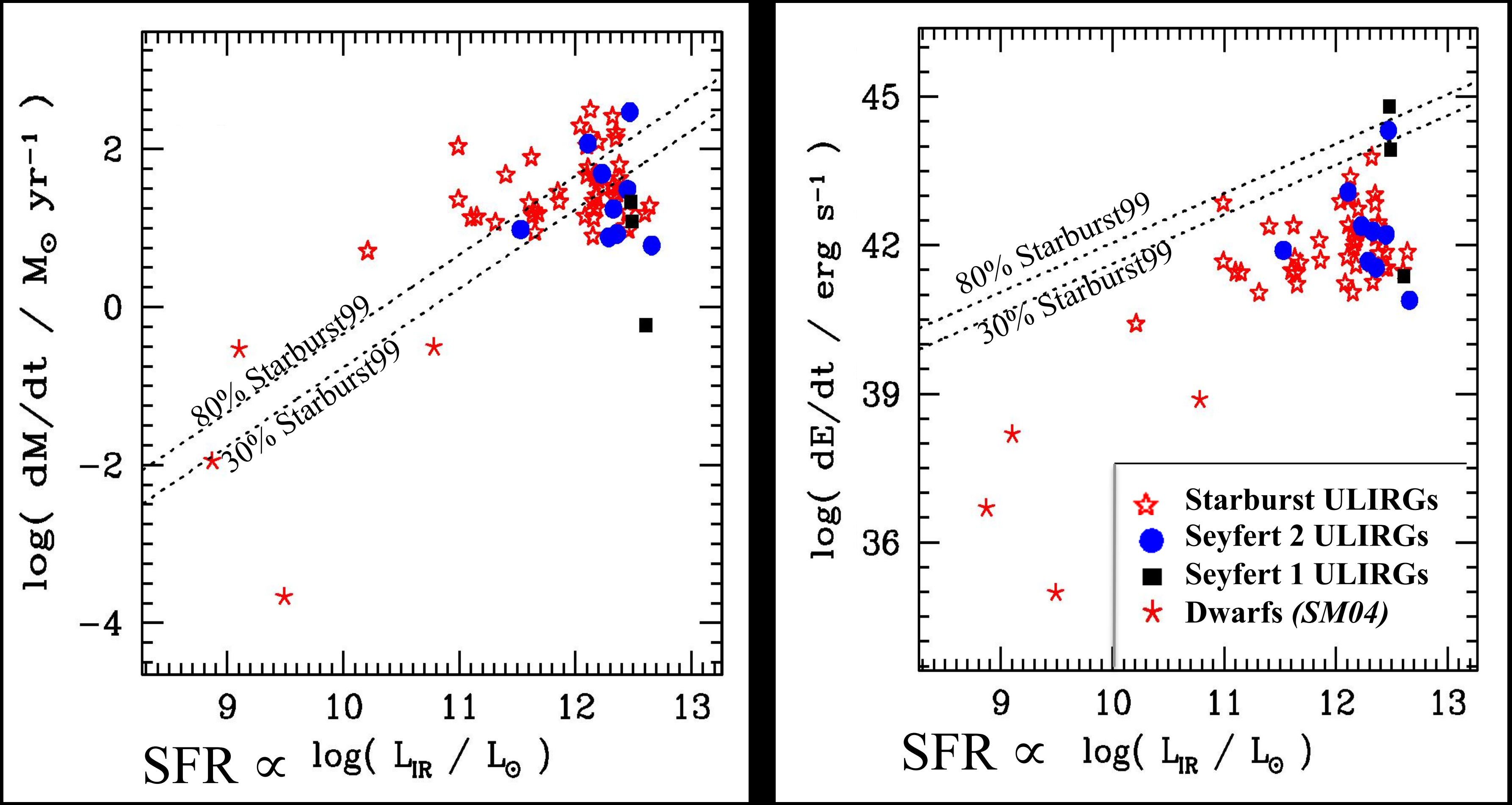




- **Detection rate:**
  - **~50% when *SFR* ~ 10's M_{sun} yr^{-1}**
  - **~75% when *SFR* > 100 M_{sun} yr^{-1}**
  - ***(Rupke, SV, & Sanders 2005a, b)***
- **All have $\Sigma_{SFR} \geq 0.1$ M_{sun} yr^{-1} kpc^{-2}** ***(Heckman 2002; SV, Cecil, & Bland-Hawthorn 05)***
- $V_{out} \sim SFR^{0.2\text{-}0.3}$ ***(also Σ_{SFR})***
  p*-driven winds: ~ *SFR*$^{0.25}$** ***(e.g., Murray+05)
- $V_{out} \sim V_{circ}^{\ 0.8 \pm 0.2}$ ***(also V_{escape}* and *M*)***
- **Inclination dependence at moderate SFR**
  ➔ collimated outflow ***(Chen+10)***
- $\eta = (dM/dt) / SFR \sim 0.5 - 5$
  $\sim \sigma^{-1}$??? ***(e.g., Murray+05; Oppenheimer+10)***
- $f_{esc} \sim 5\text{–}20\%$ (if no halo drag)
  - → **may pollute CGM** ***(e.g., Steidel+10; Tumlinson+11; Stocke+13; Werk+14; Bordoloi+14)***
  - → **may pollute IGM?** ***(e.g., Danforth+14)***

These winds are dynamically important

M_{out} ➔ $10^8 – 10^9\ M_{sun}$ E_{kin} ➔ $10^{56} – 10^{57}$ ergs

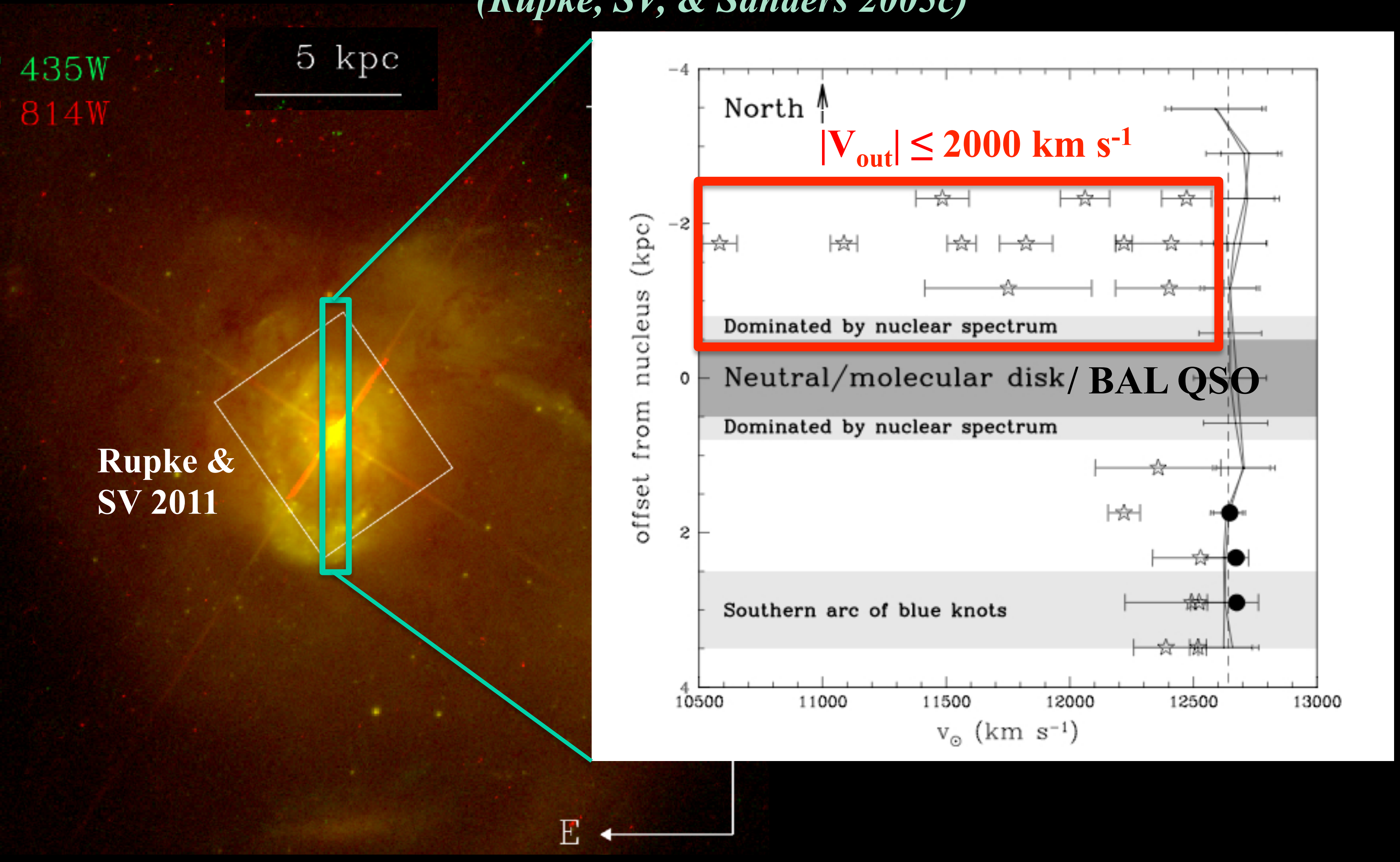


(Rupke+05abc)

Fewer and weaker winds in IR-faint Seyferts: Krug, Rupke, & SV (2010)

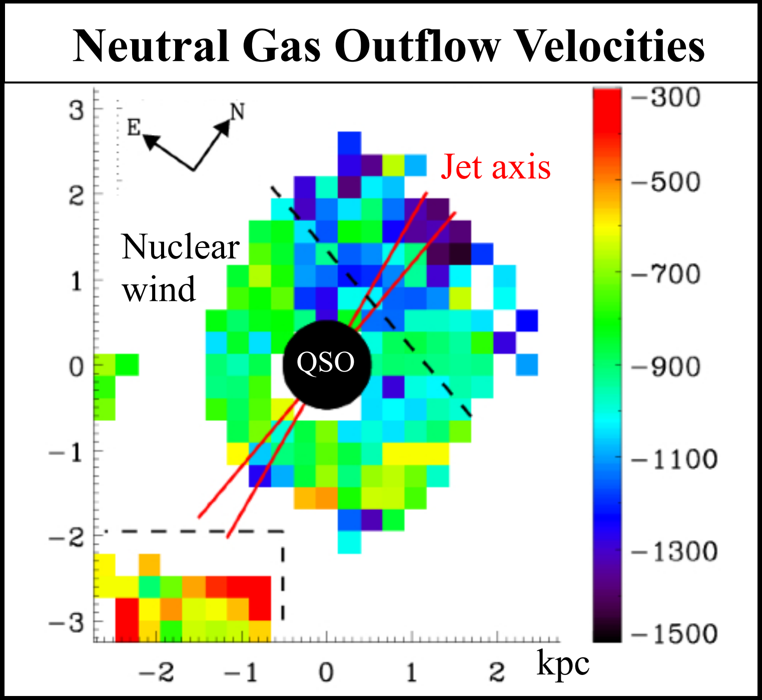
Extended *Neutral* (Na I) Outflow in Mrk 231

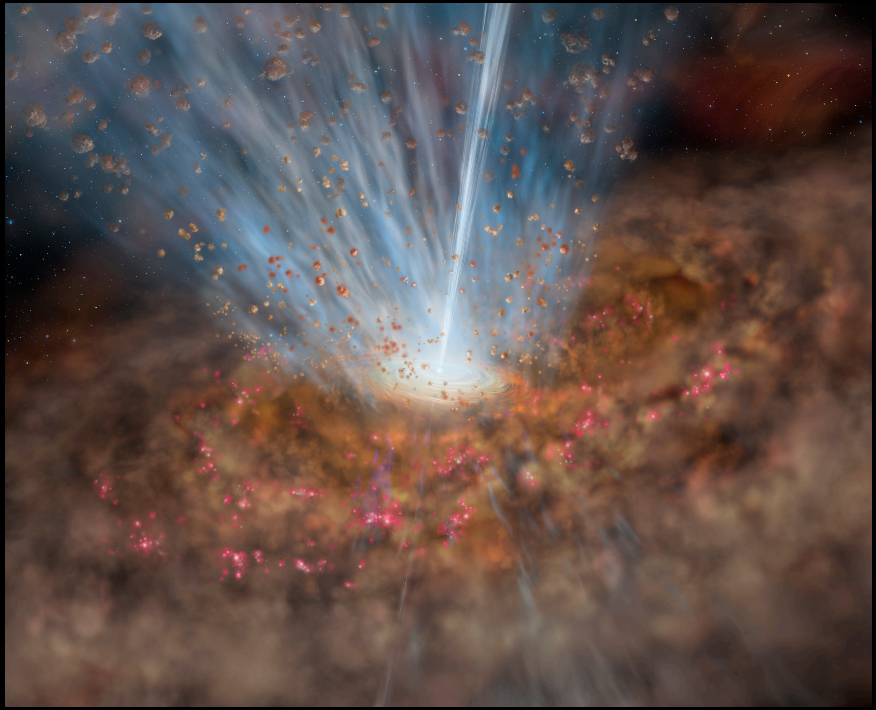
(Rupke, SV, & Sanders 2005c)



Extended *Neutral* Quasar-driven Wind in Mrk 231

(Rupke & SV 2011* and *2013a)





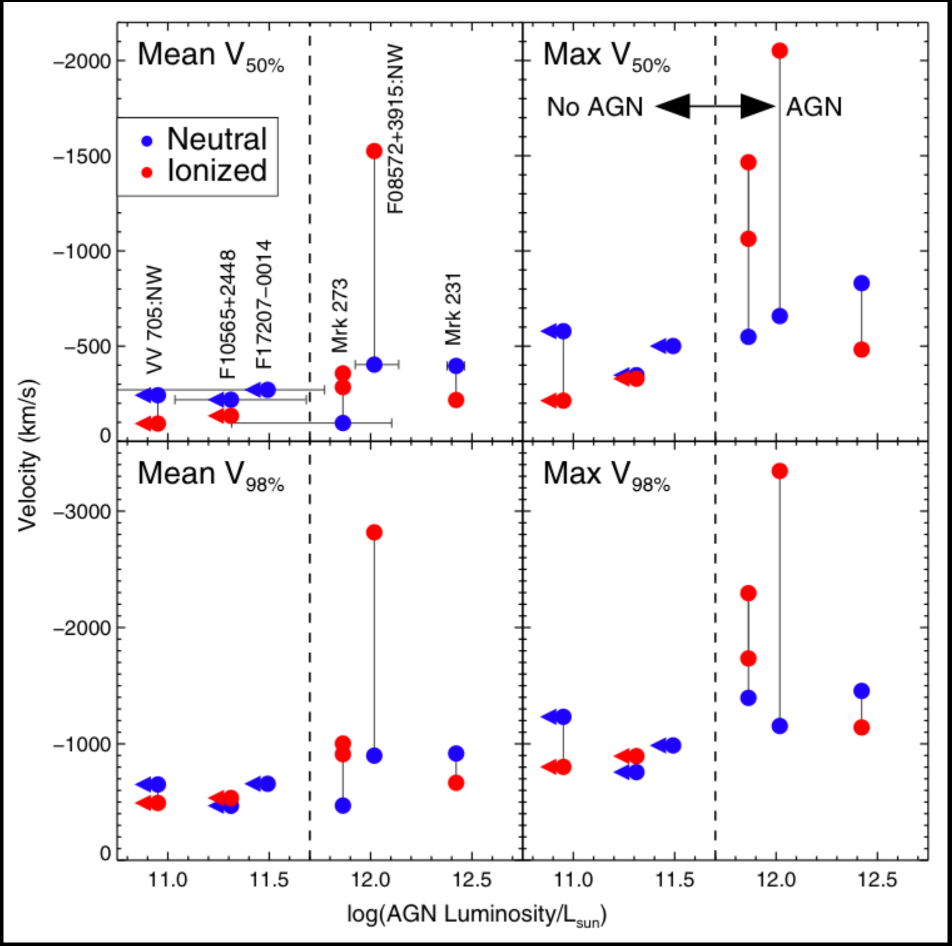
2011 Gemini Press Release

- **Gemini/IFU: Na I absorption**
- **> 2-3 kpc from nucleus**
- **$| V_{out} |$ in excess of 1100 km s^{-1}**
- **dM/dt $\geq$ 160 M_{sun} yr^{-1} ~ 1.1 *SFR***
- **L_{mech} = dE_{kin}/dt $\geq 10^{43.6}$ ergs s^{-1} ~ 1.1 x dE_*/dt ~ 1% L_{BOL} (AGN)**
- **dp / dt $\geq 5\, L_{SB} / c$ but $\geq 2\, L_{AGN} / c$ → AGN driving**

Neutral / Ionized Outflows in ULIRGs

(Rupke & SV 2013a; see also Arribas et al. 2014; Colina's talk)

- **The outflow velocities increase above $L_{AGN} \sim 10^{11.7}\ L_{sun}$ (?)**
- **The AGN becomes the dominant driver of the outflow (?)**



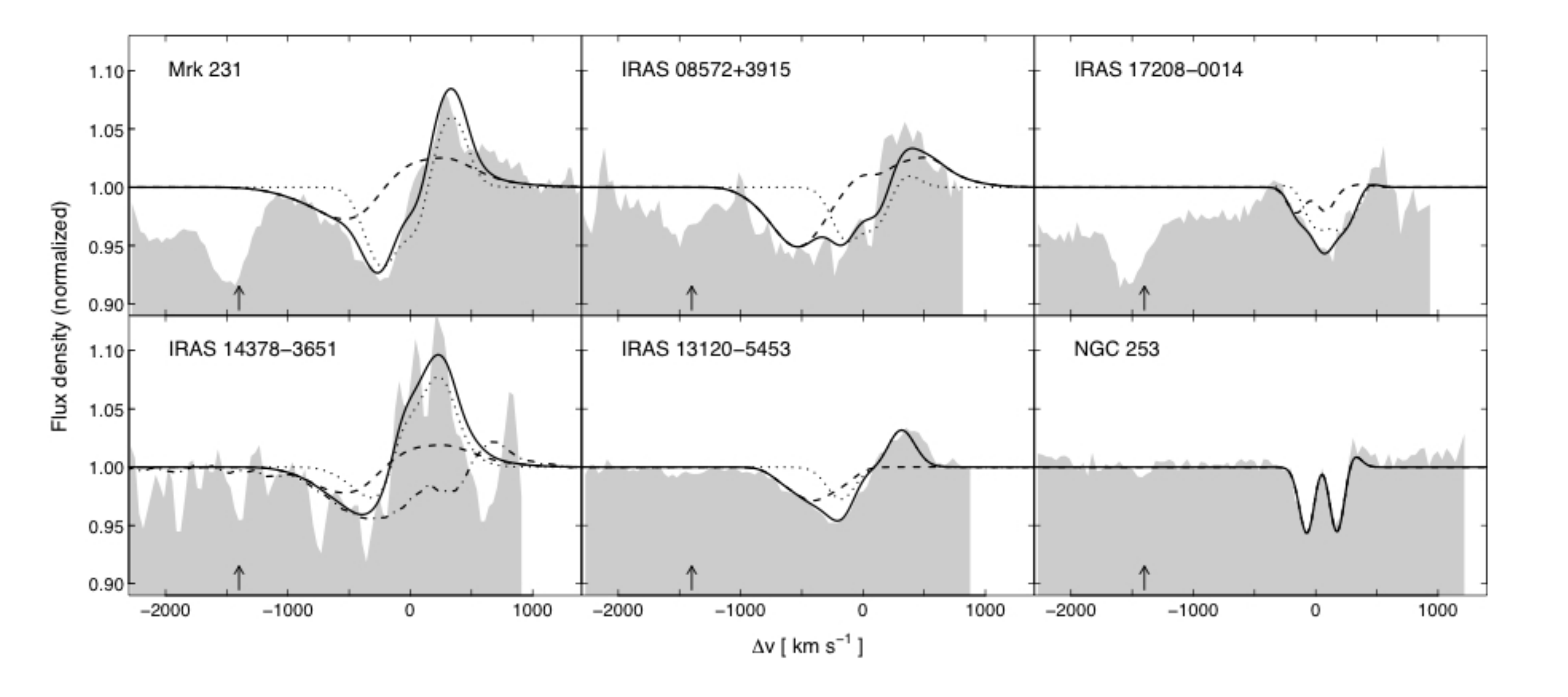
Plan

- **Neutral-atomic winds: Na I D**
- **Molecular winds: OH, CO, H_2**
- **Open issues**
- **Summary**

Early Results: Massive Molecular Outflows in ULIRGs

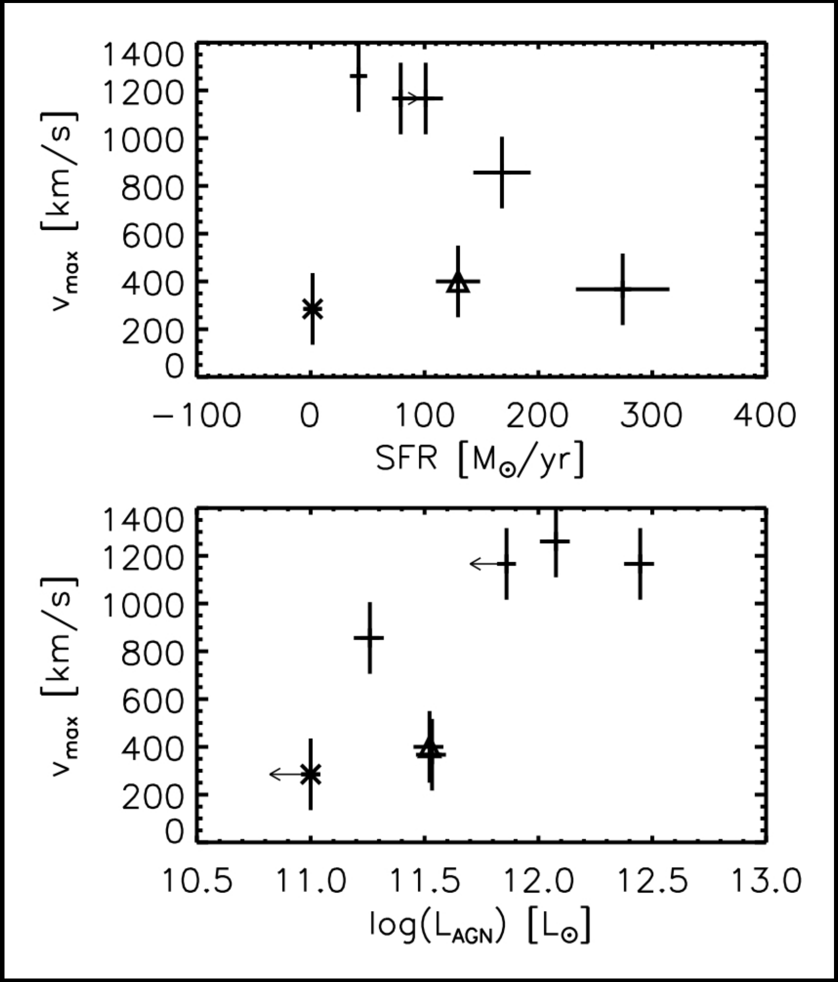
(SHINING Survey: *Fischer et al. 2010; Sturm, Gonzalez-Alfonso, SV, et al. 2011)*

Herschel/PACS spectra of OH 79 / 119 μm transitions: P-Cygni Profiles



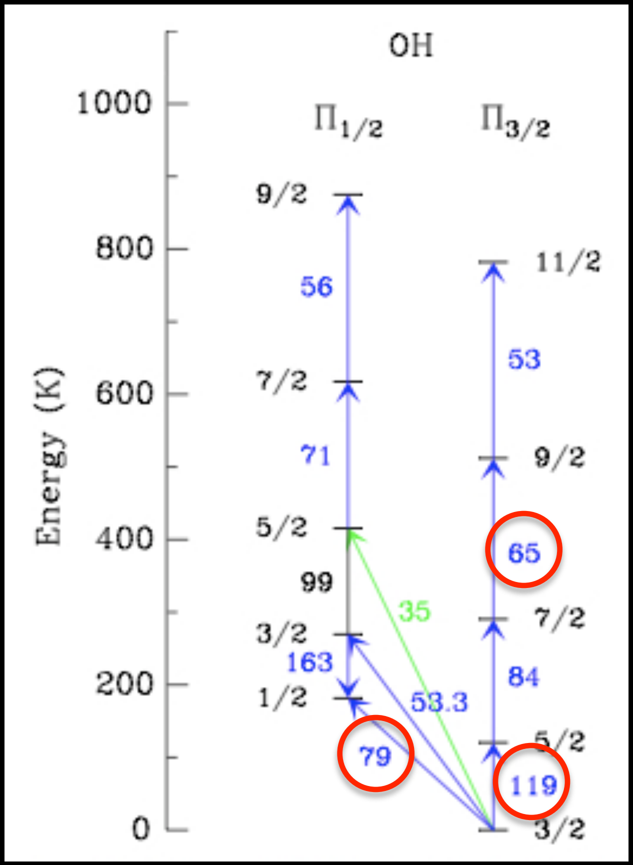
Molecular Wind Kinematics: AGN Driven?

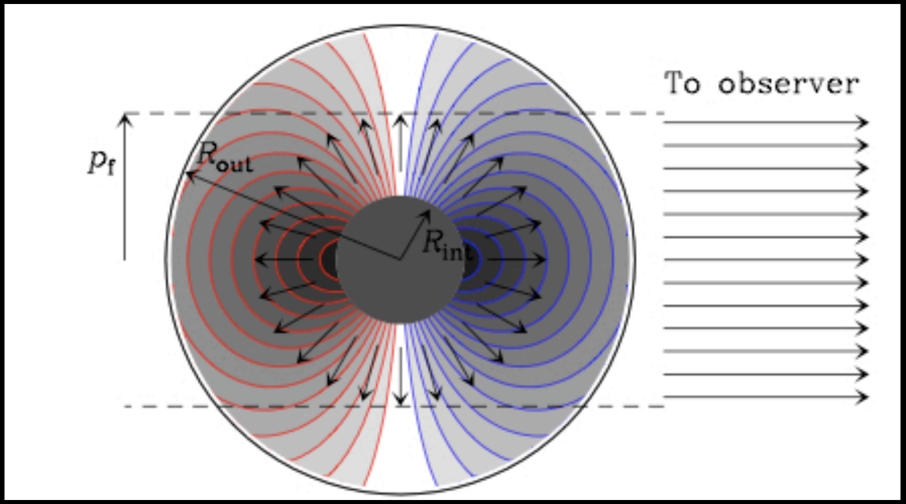
(Sturm, Gonzalez-Alfonso, SV, et al. 2011)



Molecular Wind Dynamics

(Sturm, Gonzalez-Alfonso, SV, et al. 2011)

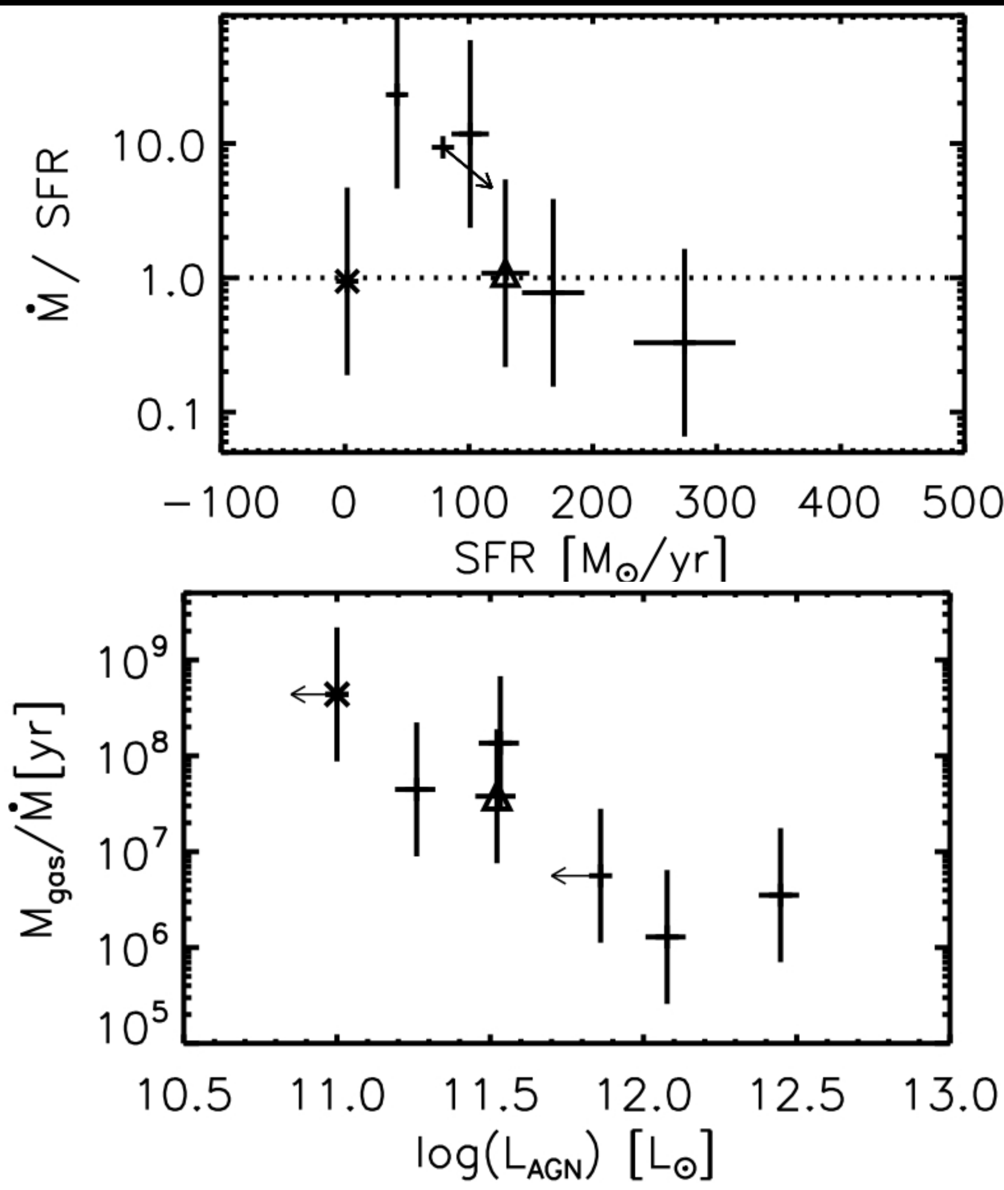




- ***Radiative transfer models*: 1-2 concentric expanding shells**
- ***Free parameters*: R_{int}, R_{out}, velocity field of each component, covering factor of FIR continuum source (clumpiness *f*), solid angle of outflow (p_f)**
- ***Density profile of each shell:* derived from mass conservation (n_{OH} x r^2 x v is independent of r)**
- ***Conservative Assumption*: OH/H_2 = 5 x 10^{-6}**
  (= GMC Sgr B2; Goicoechea & Cernicharo 2002)

Massive Molecular Winds in ULIRGs

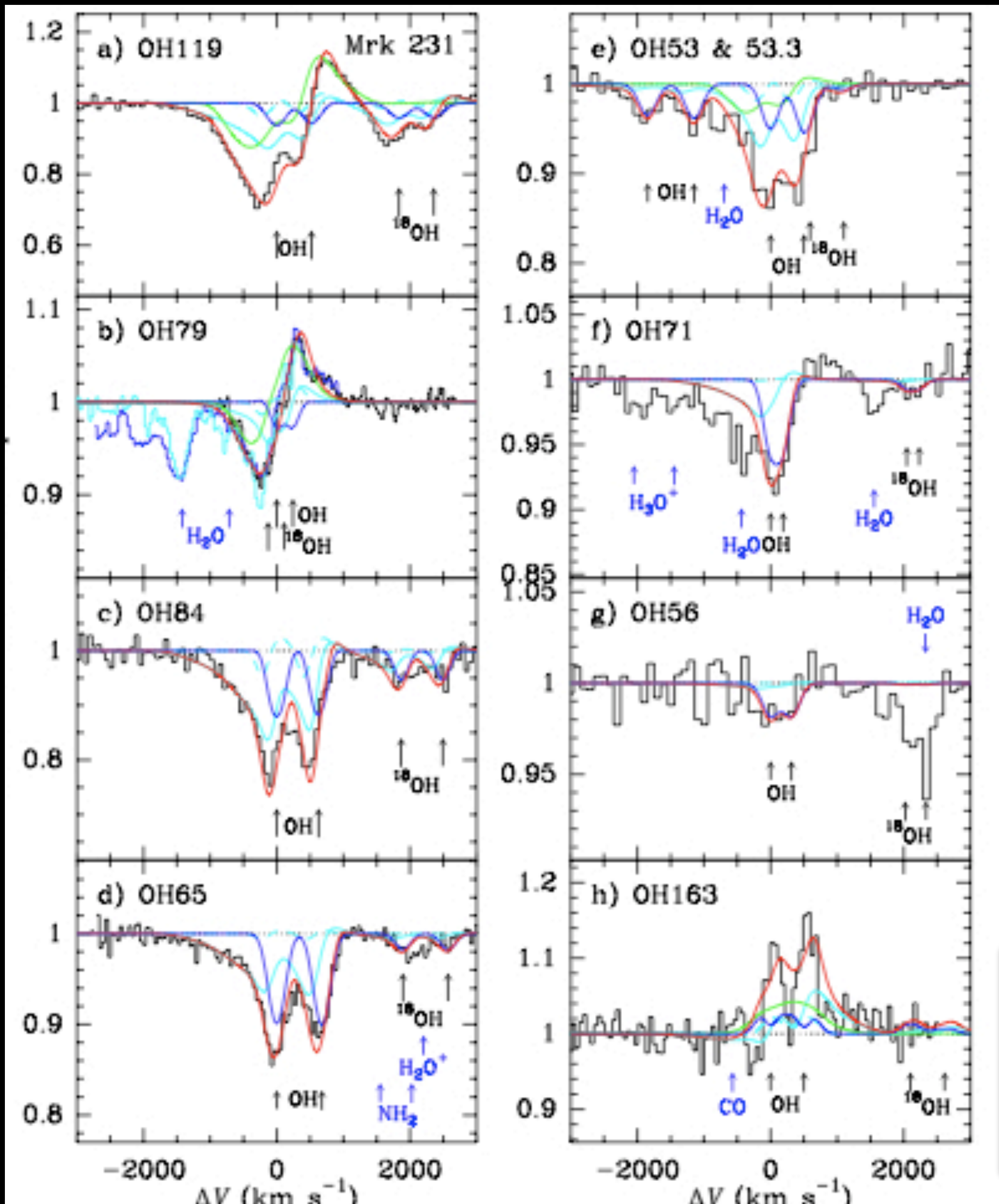
(Sturm, Gonzalez-Alfonso, SV, et al. 2011)



- **dM / dt ~ 100 – 1000 M_{sun} yr^{-1}**
  ~ (0.3 – 20) *SFR*
- **dp / dt ~ (1 – 30) L_{AGN} / c**
- **$\tau_{depletion}$ ~ M_{gas} / (dM/dt)**
  = few 10^6 – 10^8 yrs

  → remove "fuel" for new stars
  → quench star formation?

Molecular Wind Dynamics in Mrk 231 (*Revisited*)



(Gonzalez-Alfonso et al. 2014)

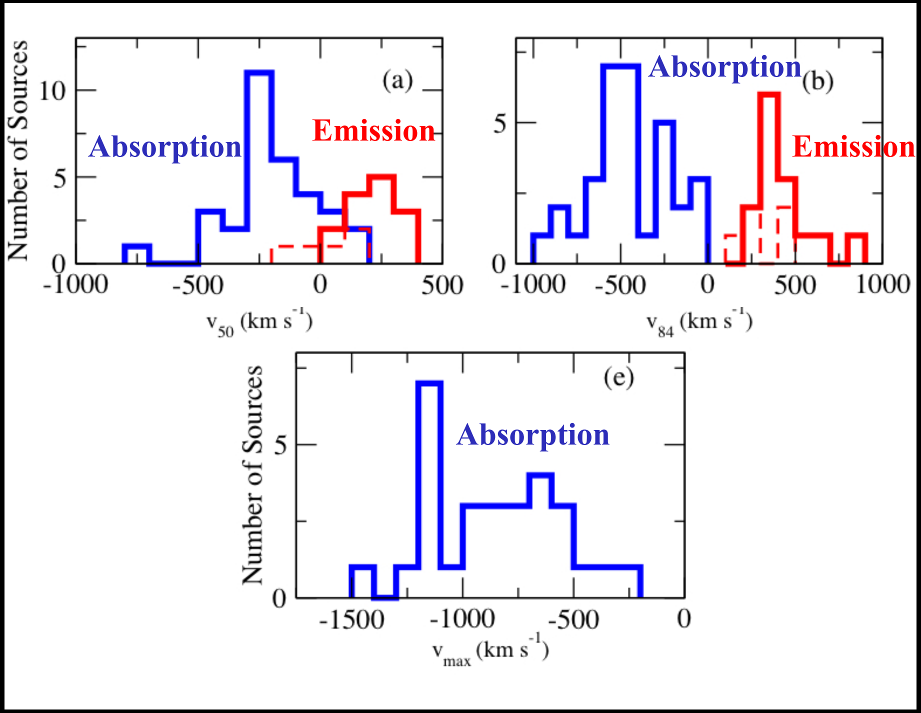
- **9 + 1 OH transitions (*Herschel* + *Spitzer*)**

Parameter	QC	HVC	LVC[a]
R_{int} (pc)[b]	55–73	65–80	65–80
T_{dust} (K)	95–120	90–105	~90
τ_{100}	1–3	1.5–2.0	≲1
R_{out}/R_{int}	–	≲1.5	~1.5–2
v_{int} (km s^{-1})	–	1700	~300
v_{out} (km s^{-1})	–	100	~200
N_{OH} (10^{17} cm^{-2})	5–16[c]	1.5–3	~0.3
p_f/R_{out}[d]	1	~0.8	~1

Parameter	QC	HVC
n_H (10^4 cm^{-3})	1–2[a]	0.04–0.3[b]
N_H (10^{24} cm^{-2})	1.3–4	0.06–0.12
M_{gas} (10^8 $M_\odot$)	2.5–5.0	0.2–0.4
$\dot{M}$ ($M_\odot$ yr^{-1})	–	500–1200
$\dot{P}$ (10^{36} g cm s^{-2})	–	~5–7[c,d]
L_{mech} (10^{10} $L_\odot$)	–	~6–10[c,d]
T_{mech} (10^{56} erg)	–	~2–4[d]

OH 119 μm Wind Kinematics *(revisited: 43 objects)*

(SV, Meléndez, et al. 2013; also Spoon et al. 2013)



- **Velocities**
  - **$\langle v_{50} \rangle$ (abs) ~ -200 km s^{-1}**
  - **$\langle v_{84} \rangle$ (abs) ~ -500 km s^{-1}**
  - **$\langle v_{max} \rangle$ (abs) ~ -925 km s^{-1}**
- **Similar to neutral gas (Na I)**

(Rupke, SV, & Sanders 2002, 2005abc; Martin 2005; Rupke & SV 2011, 2013a)

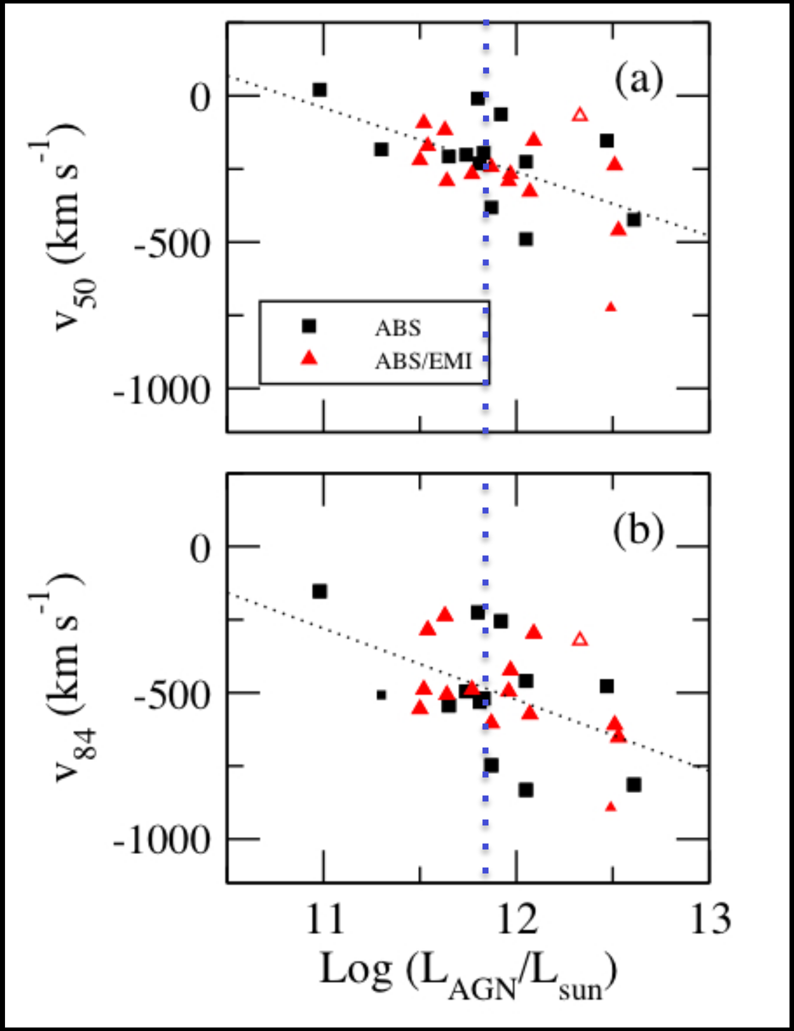
OH 119 μm Wind Detection Rates

(SV, Meléndez, et al. 2013)

- ***Criterion***: v_{50}(abs) < -50 km s^{-1}
- **Winds are detected in 70% of the 37 objects with OH 119 μm**
  - ➔ **Wide-angle geometry (~145°)**
- **This detection rate does not seem to depend on *SFR*, AGN fractions, and L_{AGN}**
- **Infall with v_{50}(abs) > +50 km s^{-1} is detected in only 4 objects**
  - ➔ **Disky or filamentary geometry?**

OH 119 μm Wind Kinematics *(revisited)*

(SV, Meléndez, et al. 2013; also Spoon et al. 2013)



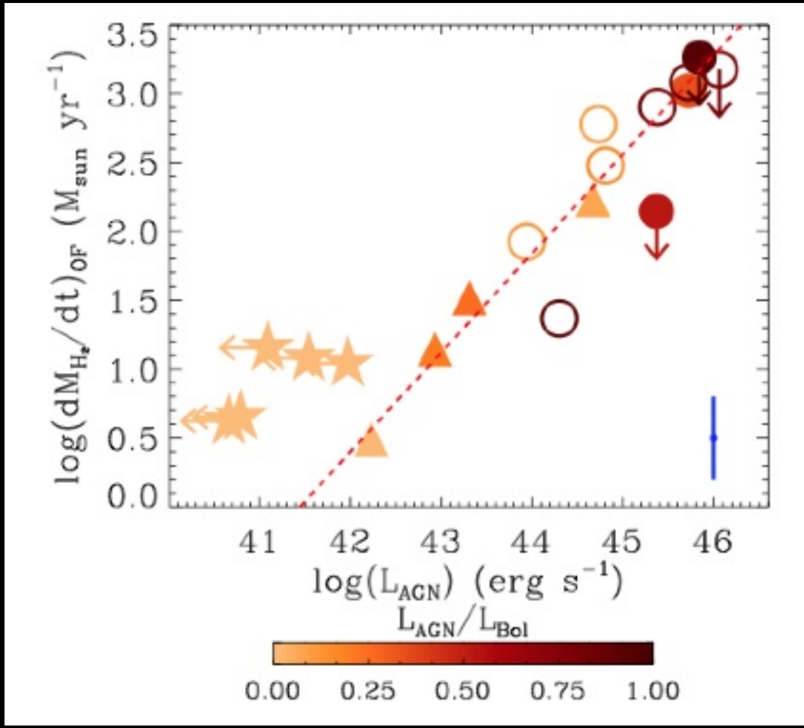
- No significant correlation between the OH velocities and the SFR, stellar velocity dispersions, or stellar masses (over ~1 dex)
- A trend is present with AGN fractions
- A stronger trend is present with AGN luminosities (P[null] = 0.4 – 4%)

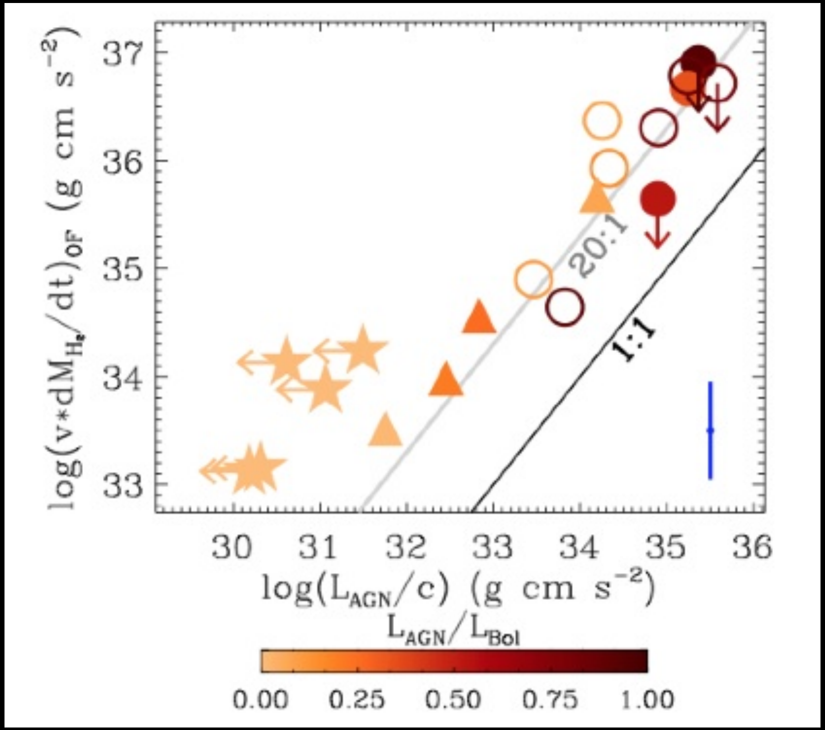
→ AGN driving above $L_{AGN} = 10^{11.8 \pm 0.3}\ L_{sun}$ $\sim L_{min}$(quasar)

Resolved CO Outflows in (U)LIRGs with IRAM

(Cicone et al. 2014)

* Clear detections of spatially resolved outflows in 4 out of 7 ULIRGs / Quasars
* Combined with detections from the literature





Strong evidence for AGN driving

$dp/dt \sim (1 - 30)\ L_{AGN} / c$

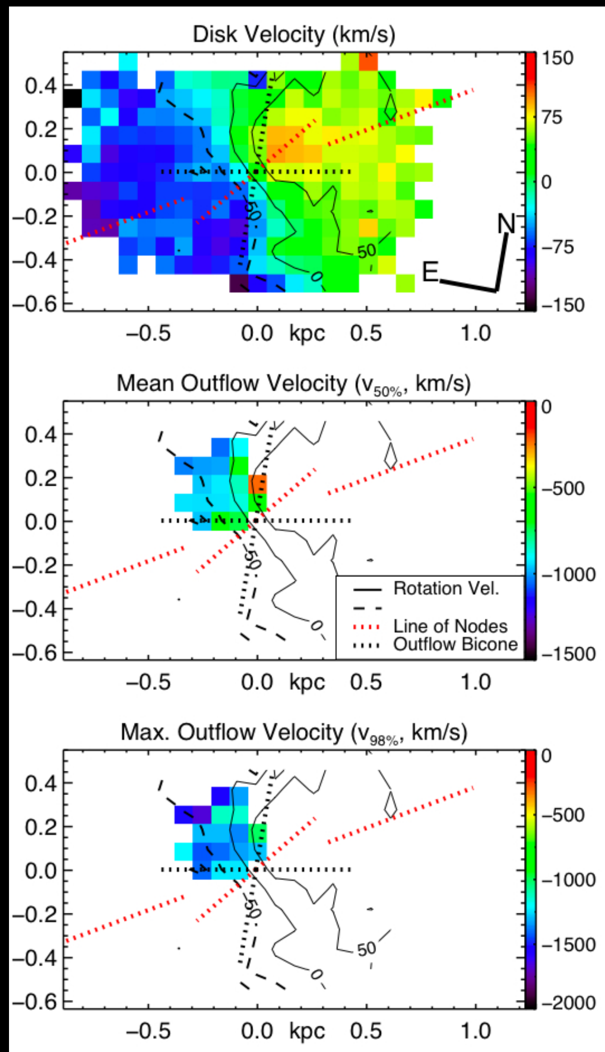
➔ Consistent with *Herschel* OH results

Spectral Imaging of Molecular Winds in Active Galaxies

(H_2 2.12 µm as a *tracer* of the cold molecular gas; e.g. M82 SV+09)

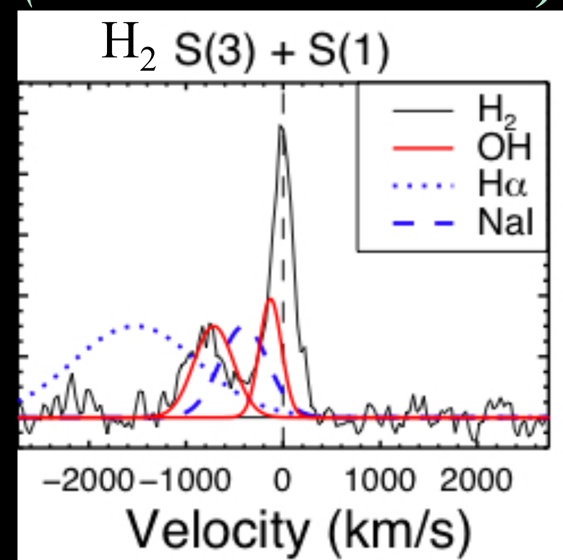
(Rupke & SV 2013b)

Buried QSO:
F08572+3915 NW



Keck OSIRIS: IFU + AO + Laser
Resolution ~ 0.09" ~ 100 pc

Wind size ~ 400 pc
Opening angle = 100 ± 10 deg
(consistent with Sturm+11)



T(wind) = 2400 K
> T(disk) = 1500 K

Plan

- **Neutral-atomic winds: Na I D**
- **Molecular winds: OH, CO, H_2**
- **Open issues**
- **Summary**

Molecular Winds: How?

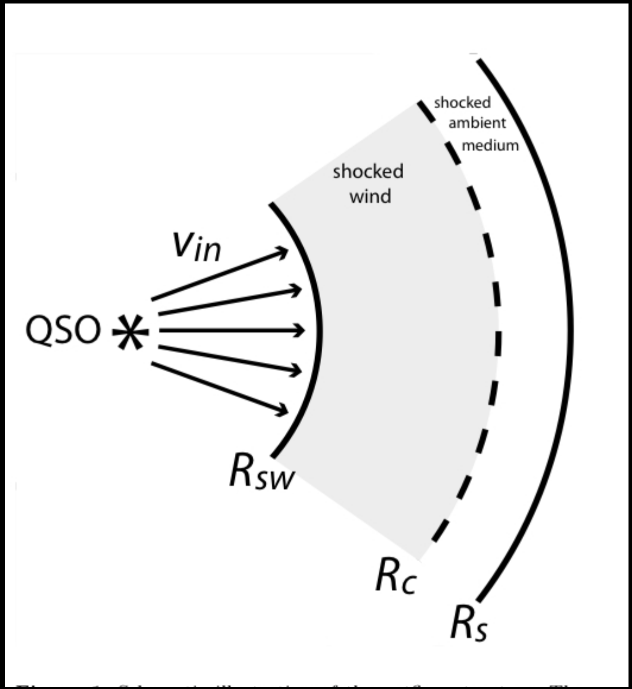
- **d*M*/dt → 1000 M_{sun} yr^{-1}**
- **L_{mech} → 10^{11} L_{sun} and E_{mech} → few x 10^{56} ergs**
- **d*p* / d*t* → few x 10^{36} g cm s^{-2} ~ (1 – 30) L_{AGN} / c**

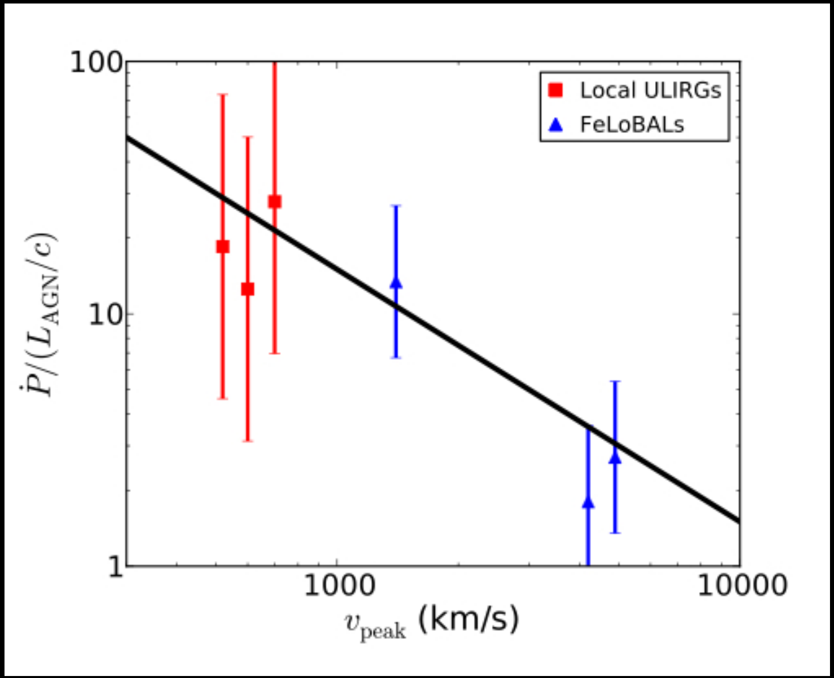
  → Momentum boost ?

- **Novak, Ostriker, & Ciotti (2012):** *"despite the large opacity of dust to UV radiation, the momentum input to the flow from radiation very rarely exceeds L/c"*
- **Davis, Jiang, Stone, & Murray (2014):** *"Rayleigh-Taylor instabilities develop in radiation supported atmospheres, leading to inhomogeneities that limit momentum exchange between radiation and dusty gas, …"*
- **Possible solution: two-stage acceleration process**
  (e.g., Faucher-Giguère & Quatert 2012; Zubovas & King 2012, 2014)
  1) **Gas is first radiatively launched with momentum flux ≤ L/c (e.g., nuclear UV BAL or X-ray winds?)**
  2) **Then boosted to ~10 L/c on galaxy scales in a Sedov-Taylor-like (energy-conserving) phase**

Molecular Winds: How?

(e.g., Faucher-Giguère & Quataert 2012; Zubovas & King 2012, 2014)

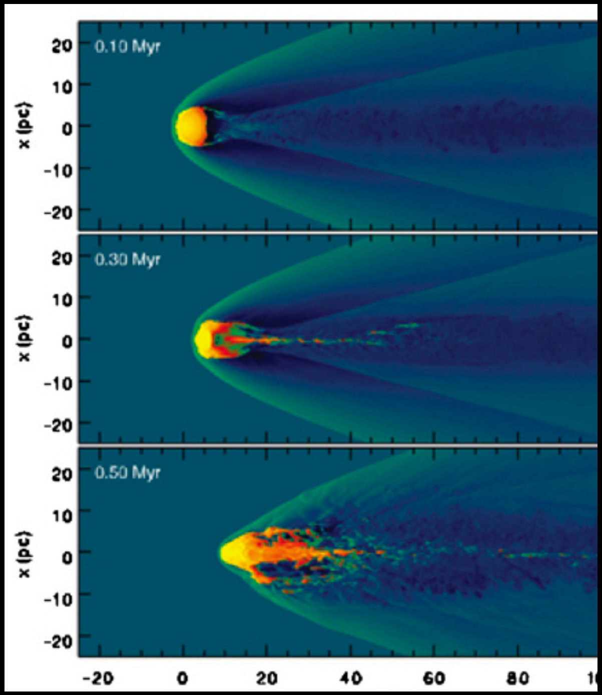




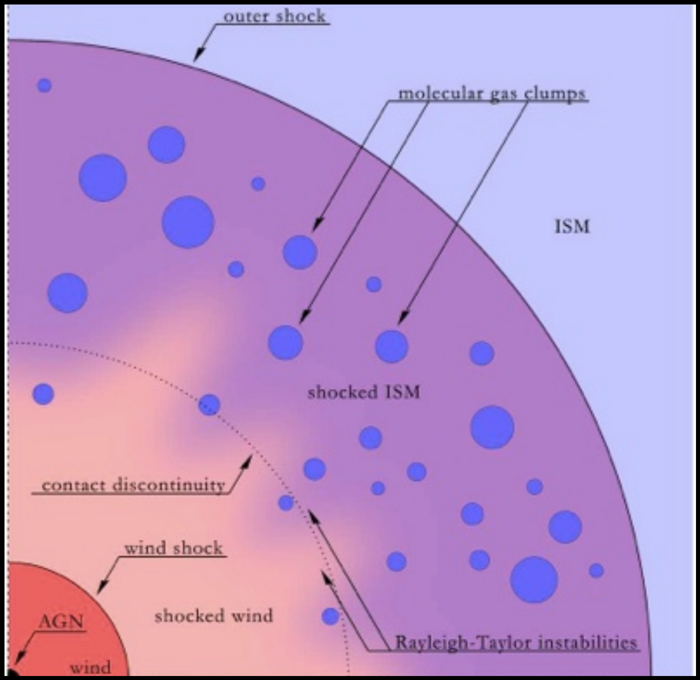
- $T_{shock} \sim 10^{10}$ K (V_{shock} / 30,000 km $s^{-1})^2$ ➔ Two-temperature plasma
- Cooling of high-velocity shocked wind in AGN is inefficient
  ➔ energy-conserving outflow
- Boost factor = d*p*/dt / (L_{AGN} / c) ~ (1/2) V_{in} / V (large-scale)
  ~ 15 if V_{in} ~ 0.1 c and V(large-scale) ~ 1000 km s^{-1}

Molecular Winds: How?

* How does *Nature* accelerate cold neutral / molecular clouds to $V \rightarrow 1000+$ km s^{-1} out to R ~ kpc? Survival time scale?
* In-situ formation via fragmentation + cooling $\rightarrow v_{cl} \sim v_{out}$?
  (e.g., Faucher-Giguère et al. 2012; Nayakshin & Zubovas 2012; Zubovas et al. 2013; Zubovas & King 2014)



(Cooper, Bicknell, et al. 2009: radiative spherical cloud)



(Zubovas & King 2014)

Summary

- **What are the basic properties of molecular winds?**
  - Statistics: ~70% of local ULIRGs have molecular winds ($\Theta \sim 145^o$)
  - Outflow velocities: $\langle v_{50} \rangle$, $\langle v_{84} \rangle$, $\langle v_{max} \rangle$ ~ -200, -500, -925 km s^{-1}
  - Energetics: dM/dt up to ~1000 M_{sun} yr^{-1}; L_{mech} up to ~10^{11} erg s^{-1}
    E_{mech} up to a few x 10^{56} ergs; dp/dt = (1 – 30) L_{AGN}/c
- **Who is driving these winds: starburst *vs* AGN?**
  - Kinematic trend with L_{AGN} suggests that the AGN is playing a dominant role in local ULIRGs when $L_{AGN}^{break} \geq 10^{11.8 \pm 0.3}$ L_{sun}
  - L_{AGN}^{break} likely only applies to local gas-rich ULIRGs (same f_g σ^4)
- **How is this gas driven?**
  - Energy-conserving shocked wind?
  - Survival time scale to cloud erosion? In-situ formation?