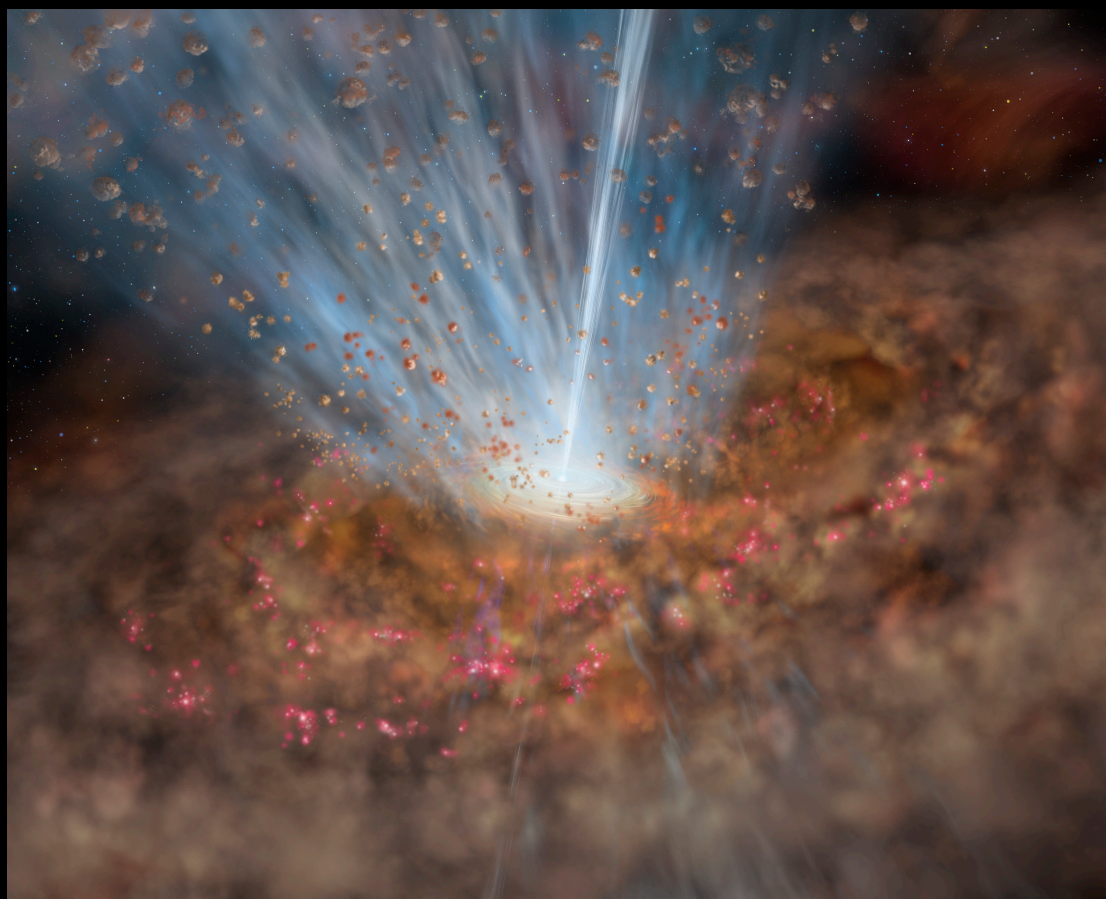
Powerful Neutral Atomic and Molecular Winds in Galaxies

S. Veilleux (U. Maryland)



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

Gemini Press Release

(Rupke & SV 2011, 2013a)

Open Issues *(Circa 2005)*

(SV, Cecil, Bland-Hawthorn 2005, ARAA)

Theory:

1. **Modeling the energy source (including possible AGN)**
2. **Modeling the host ISM**
3. **Coupling the radiation field to the gas**

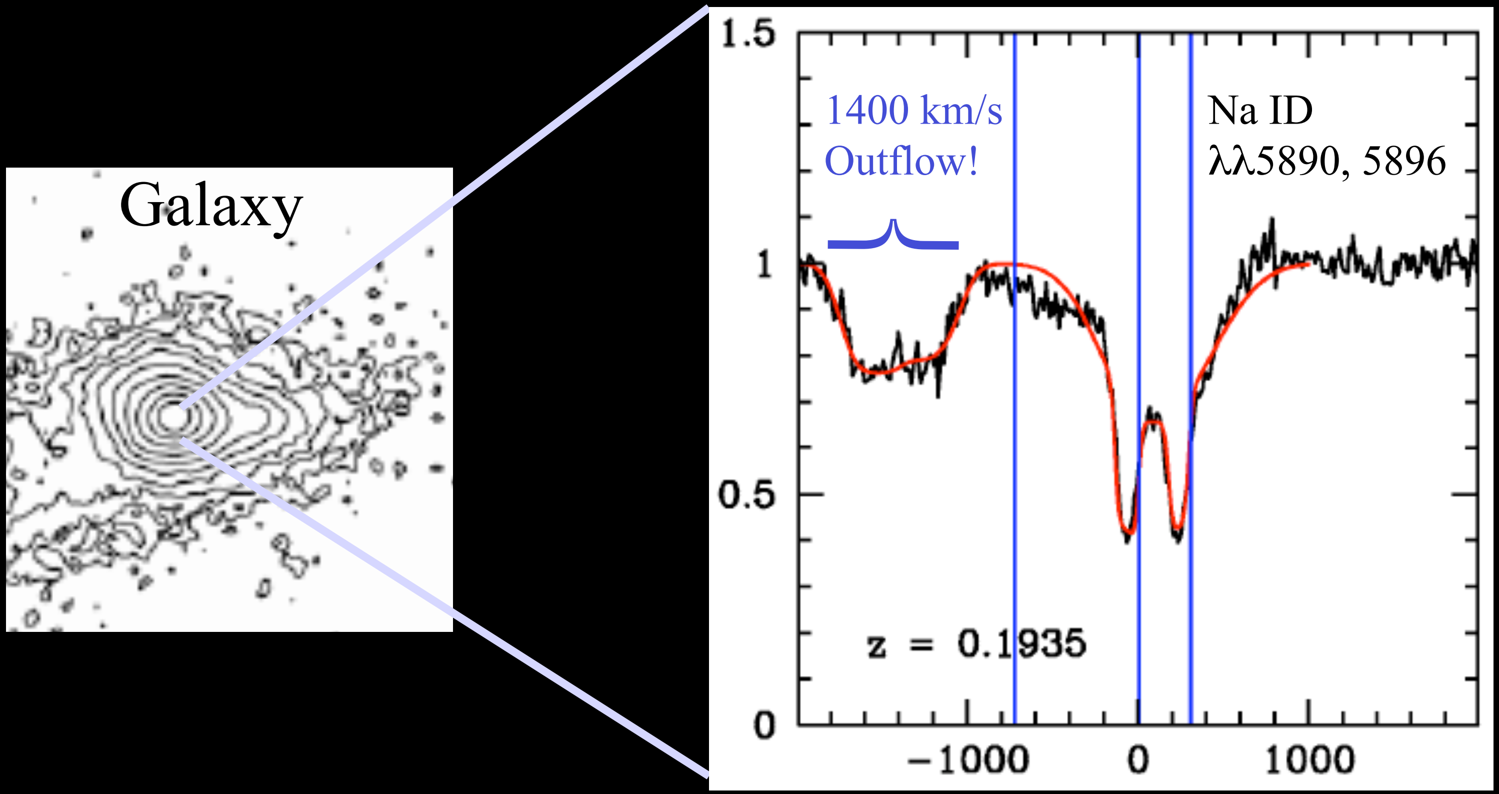
Data:

1. **Hot wind fluid**
2. **Entrained molecular gas & dust**
3. **Zone of influence & escape efficiency**
4. **Thermalization efficiency**
5. **Wind/ISM interface & magnetic fields**
6. **Positive feedback**
7. **Galactic winds in the distant universe**

Plan

- **Recent results on neutral atomic winds**
- **Recent results on molecular winds**
- **Summary & open issues**

Neutral Atomic Winds @ $z = 0 - 0.5$

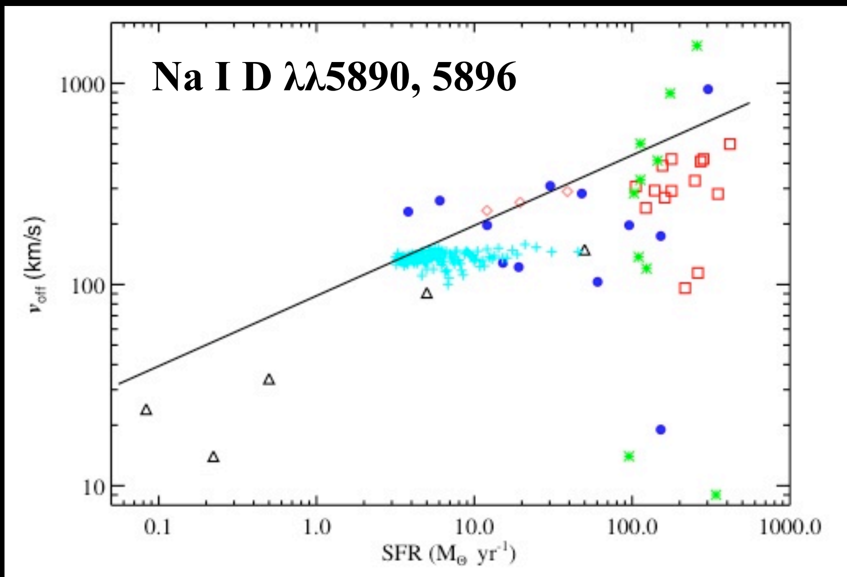


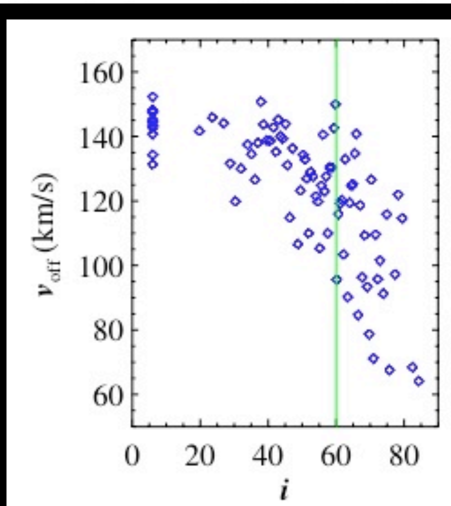
Rupke, SV, & Sanders (2002, 2005abc); Rupke & SV (2005);
AGN: Krug, Rupke, & SV (2010); Krug, SV et al. (in prep)

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)*
- $\eta = (dM/dt) / SFR \sim 0.5 – 5$

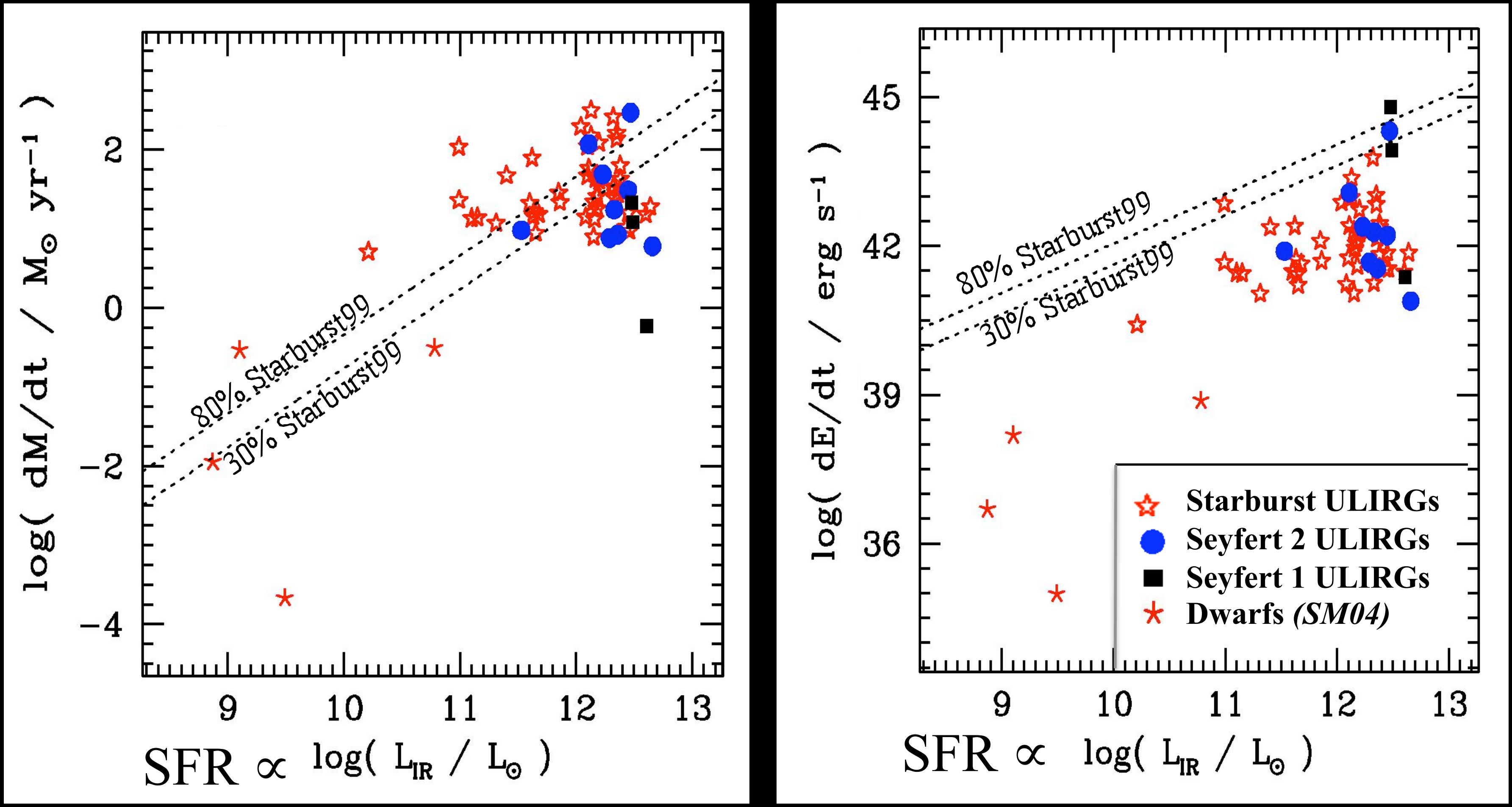
  $\sim \sigma^{-1}$??? *(e.g., Murray+05; Oppenheimer+10)*
- f_{esc} ~ *5–20%* (if no halo drag)

  → **pollute CGM** *(Steidel+10; Tumlinson+11; Stocke+13)*

  → **pollute IGM?** *(e.g., Danforth+14)*

These winds have a profound effect on the hosts

M_{out} → $10^8 – 10^{10}$ M_{sun} **E_{kin} → $10^{56} – 10^{57}$ ergs**

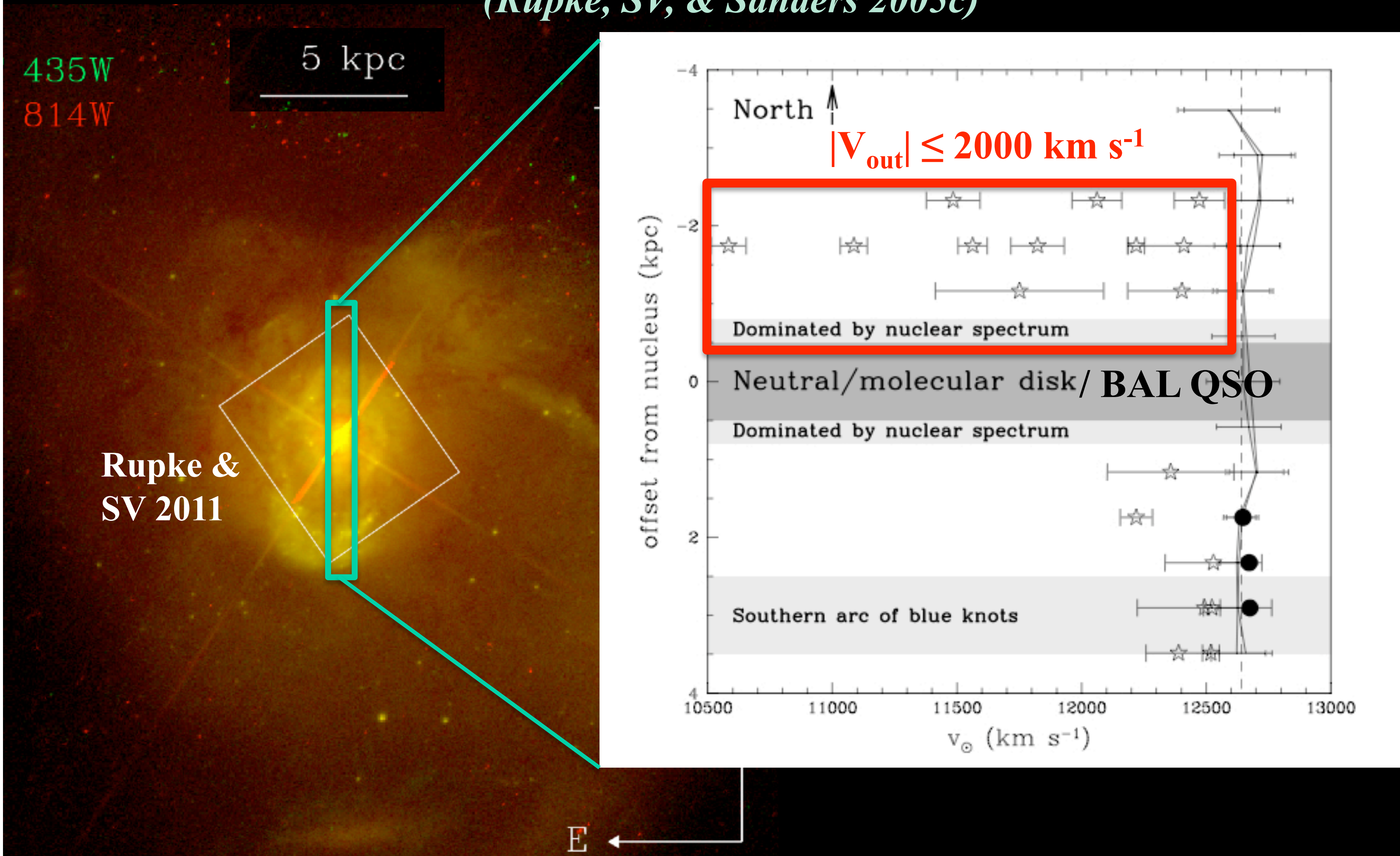


(Rupke+05abc)

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

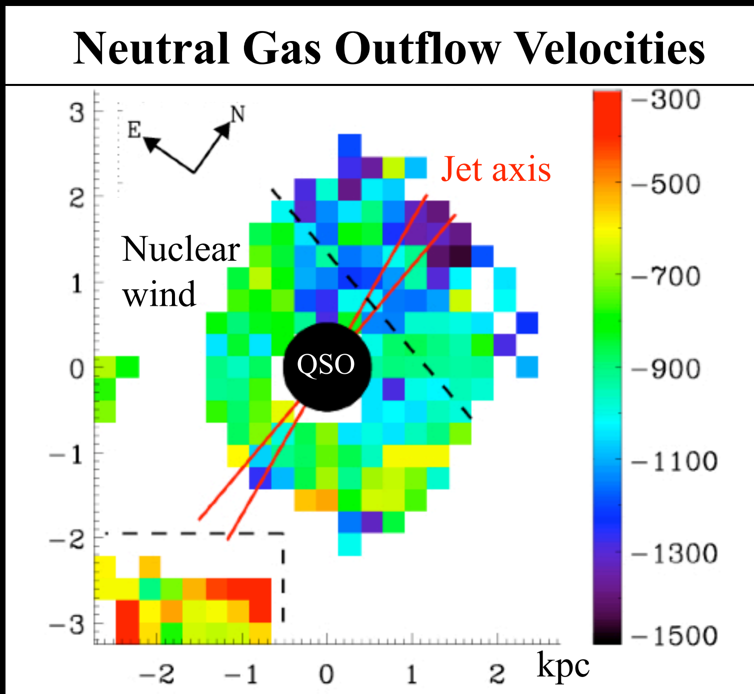
Extended *Neutral* (Na I) Outflow in Mrk 231

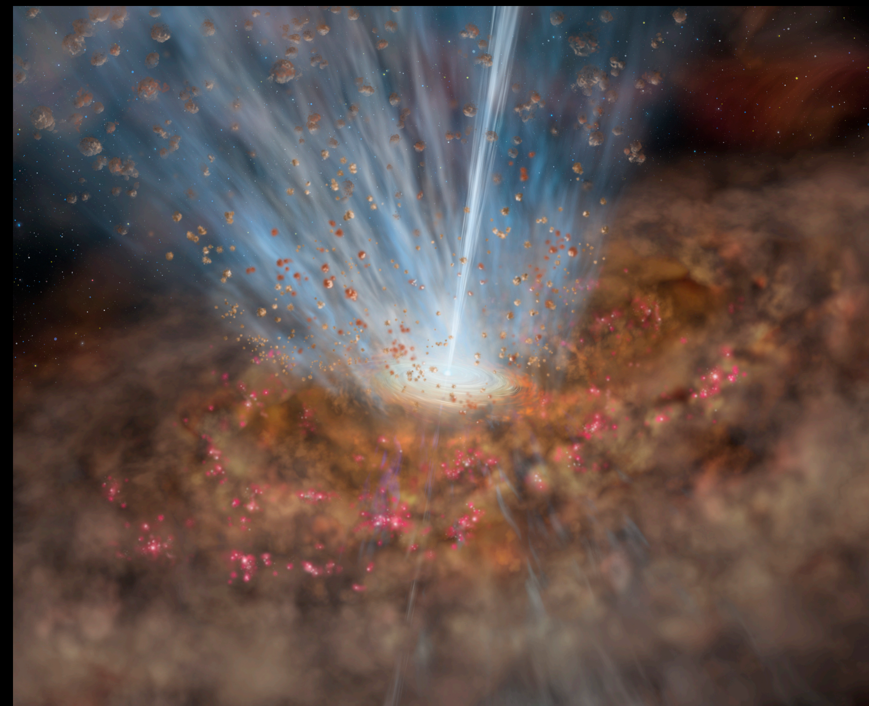
(Rupke, SV, & Sanders 2005c)



Extended *Neutral* Quasar-driven Wind in Mrk 231

(Rupke & SV 2011 and *2013a)*





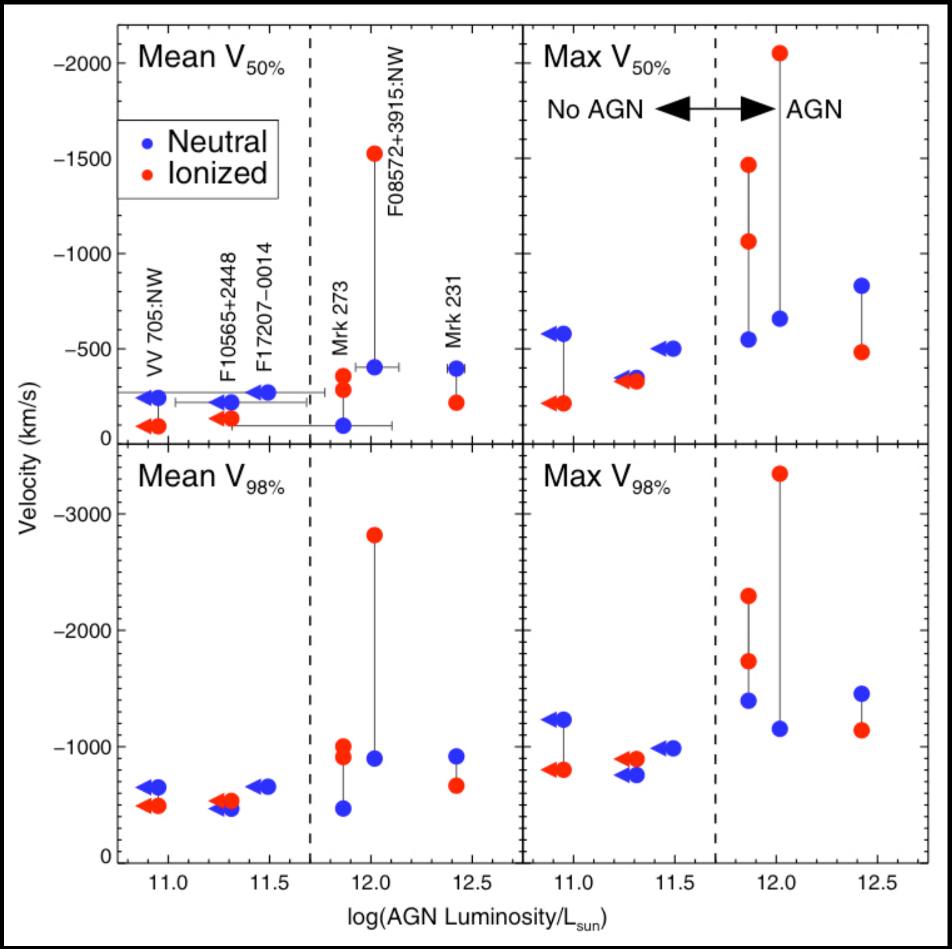
2011 Gemini Press Release

- Gemini/IFU: Na I absorption
- > 2-3 kpc from nucleus
- $| V_{out} |$ in excess of 1100 km s^{-1}
- $dM/dt \geq 160\ M_{sun}\ yr^{-1} \sim 1.1\ SFR$
- $L_{mech} = dE_{kin}/dt \geq 10^{43.6}$ ergs $s^{-1} \sim 1.1 \times dE_{*}/dt \sim 0.5\%\ L_{BOL}$ (AGN)
- $dp / dt \geq 5\ L_{SB} / c$ but $\geq 2\ L_{IR} / c$ → AGN driving

Neutral / Ionized Outflows in ULIRGs

(Rupke & SV 2013a; see also Arribas et al. 2014)

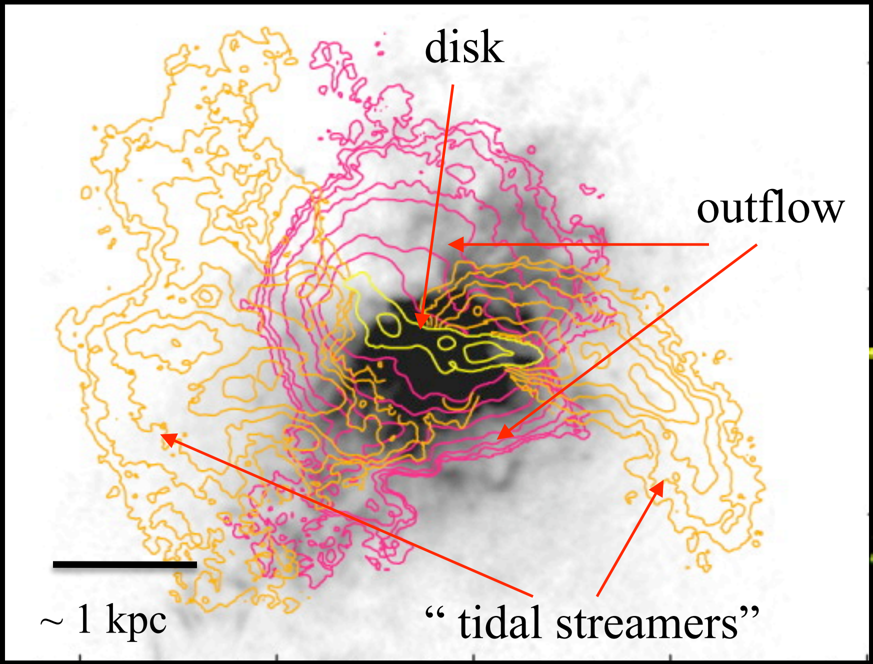
- **The outflow velocities increase above $L_{AGN} \sim 10^{11.7}\ L_{sun}$ (?)**
- **The AGN becomes the dominant driver of the outflow (?)**



Plan

- **Recent results on neutral atomic winds**
- **Recent results on molecular winds**
- **Summary & open issues**

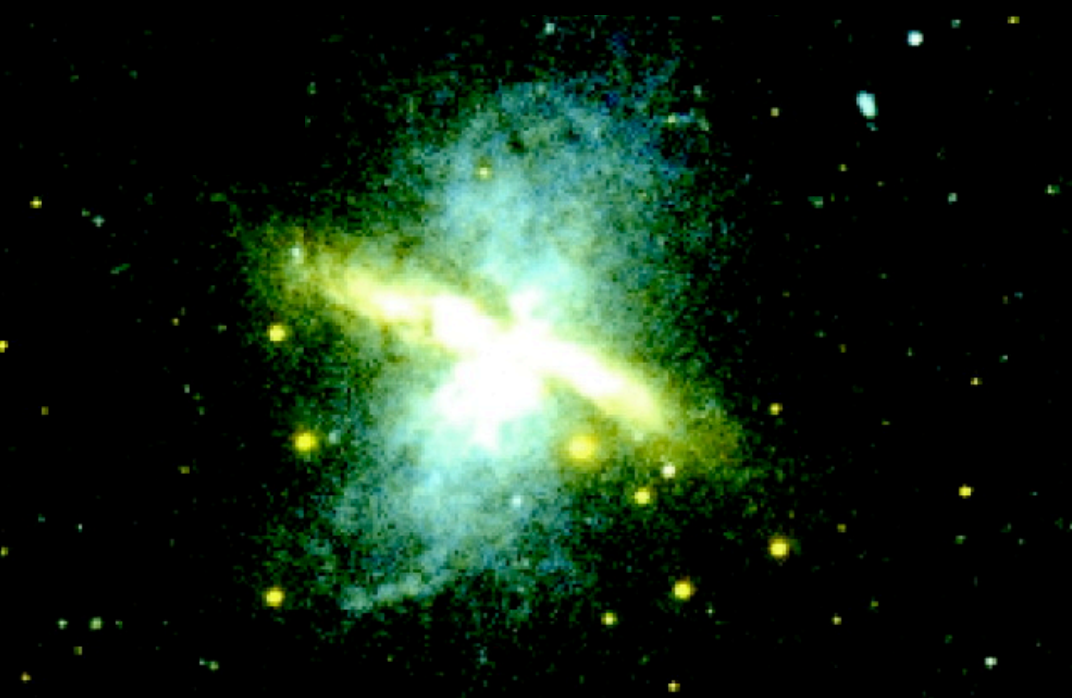
Molecular and *Dust* Outflows of M82
(*circa* 2005)



Cold Molecular Gas (~3.6")

(CO 1→0: Walter, Weiß, & Scoville 2002)

(also CO 3→2: Seaquist & Clark 2001)



Dust Scattering of UV

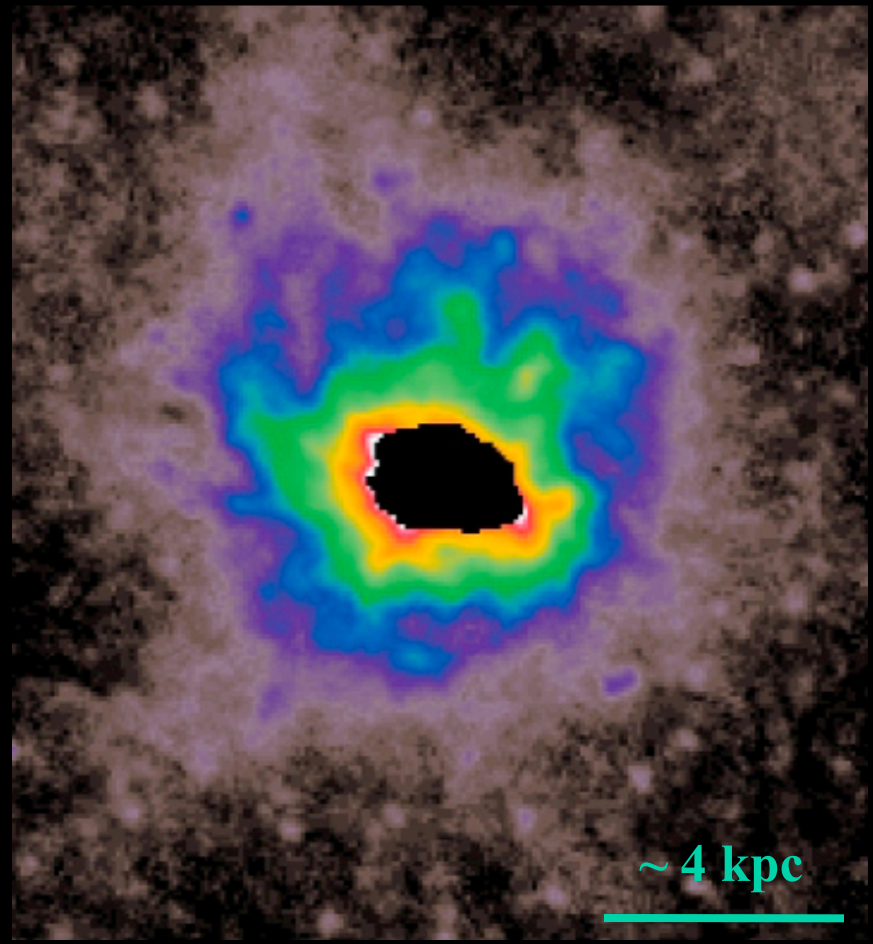
(GALEX: Hoopes et al. 2005)

Dust Outflows of M82

Warm Dust (PAH 8 μm)

(Spitzer: Engelbracht et al. 2006)

(also Akari PAH 3.3 μm: Yamagishi et al. 2012)

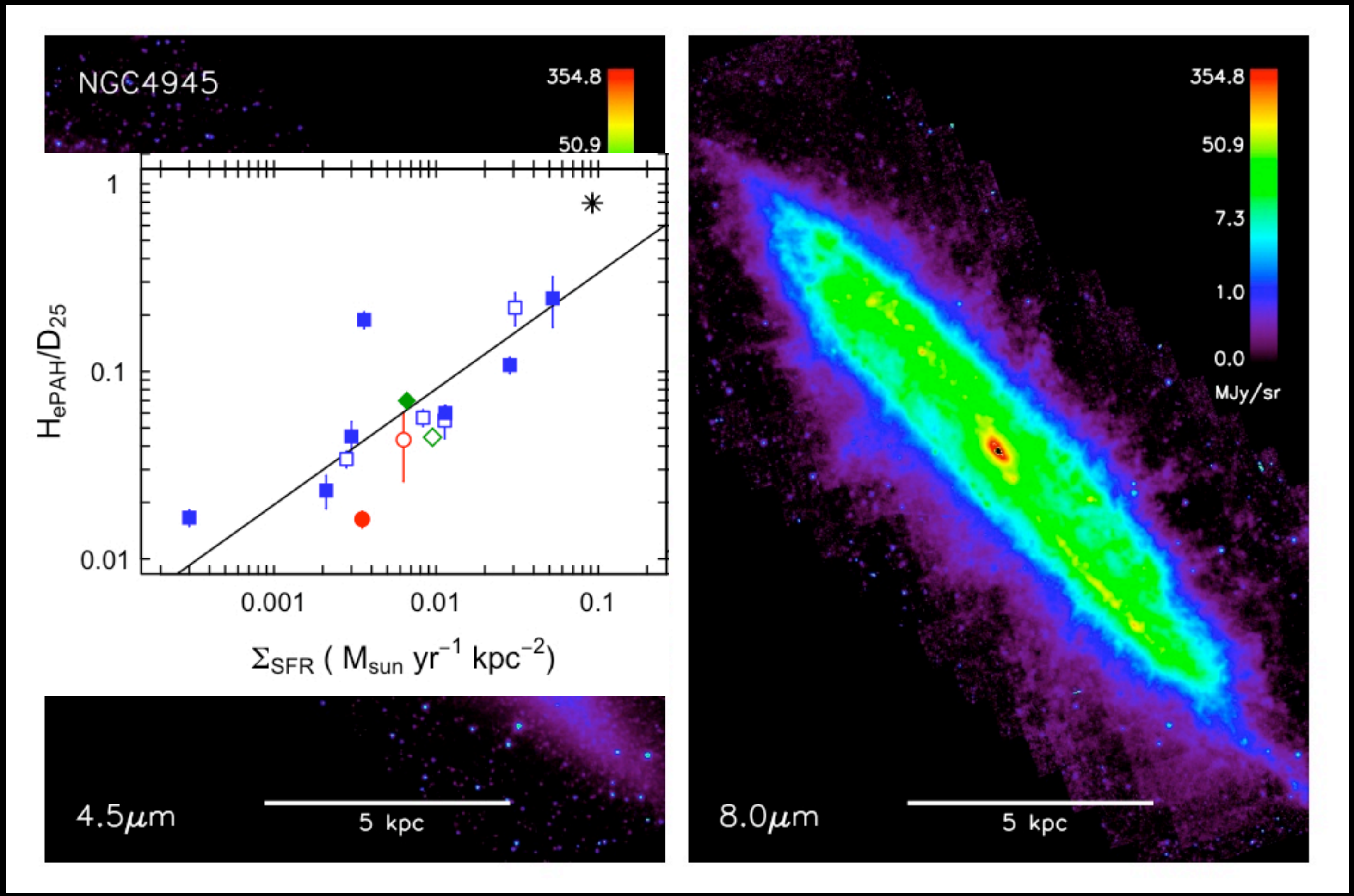


Cold Dust (250 μm)

(Herschel: Roussel et al. 2010)

Warm Extraplanar *Dust* in Galaxies

(Spitzer: McCormick, SV, & Rupke 2013)

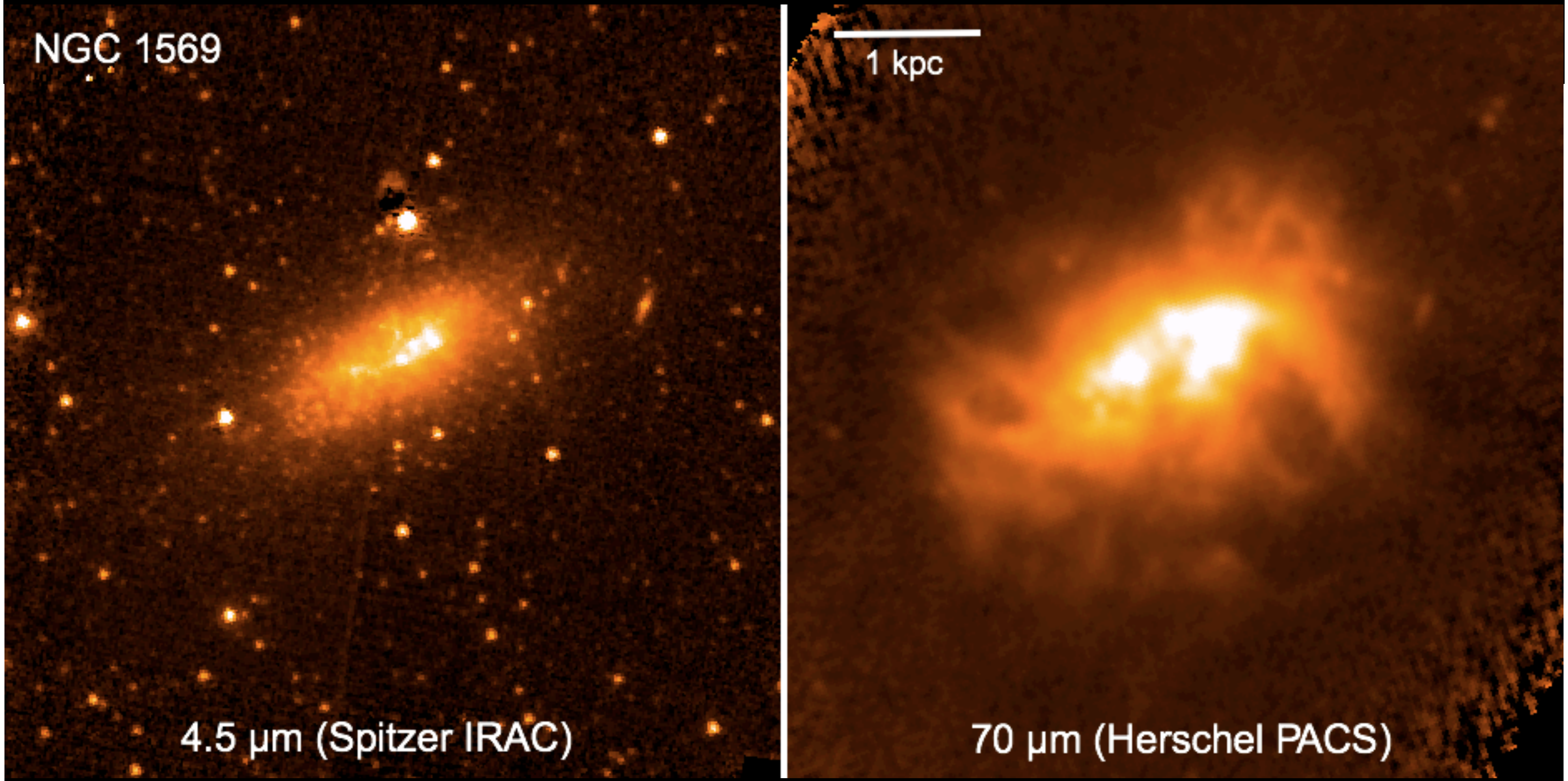


Stars

Warm Dust (PAH 8 μm)

Cold *Dust* in Wind Galaxies

(Herschel: Meléndez, SV, et al. 2014; McCormick, SV, et al. 2014 in prep)

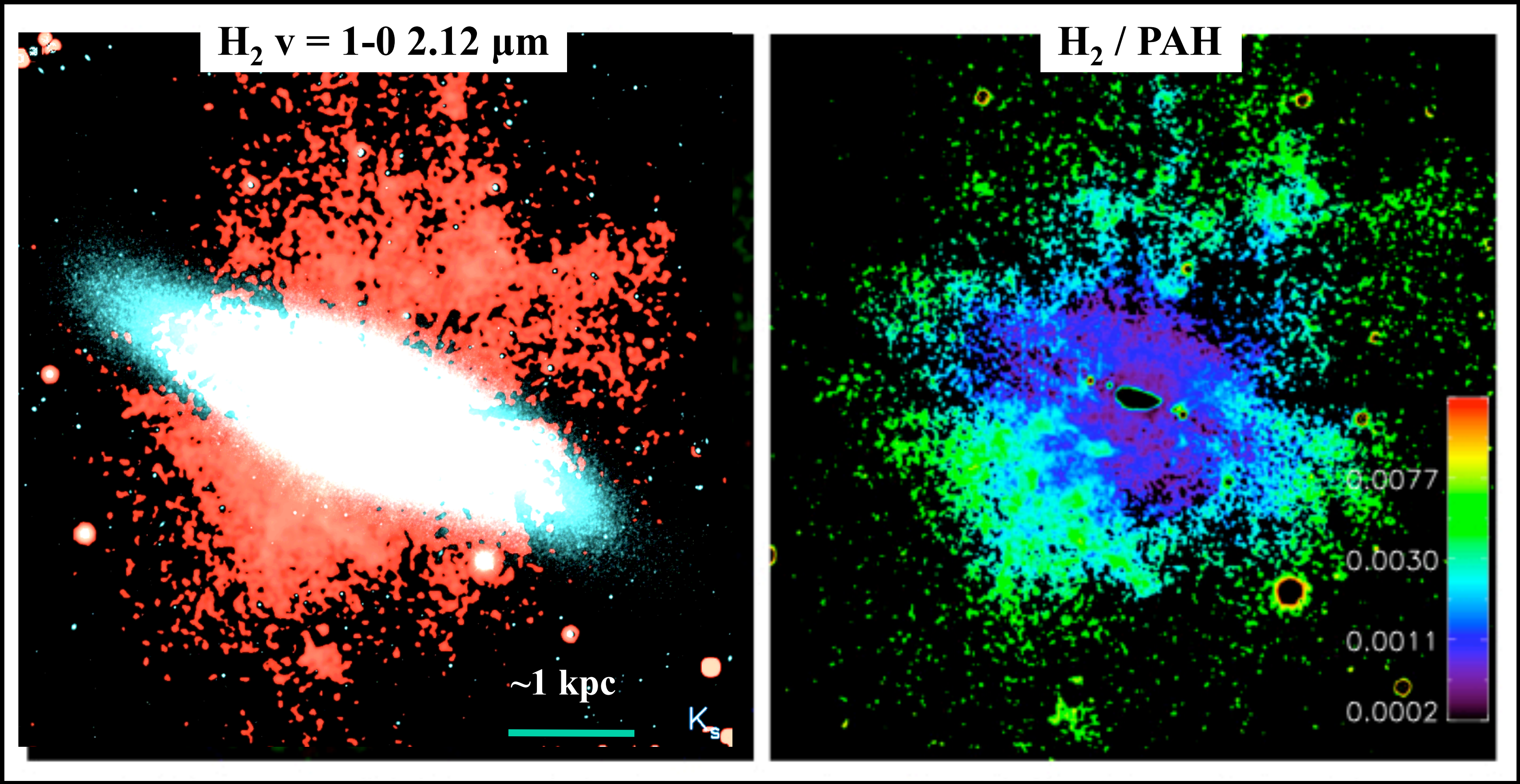


Stars

Cold Dust

Warm Molecular Wind in M82

(SV, Rupke & Swaters 2009)

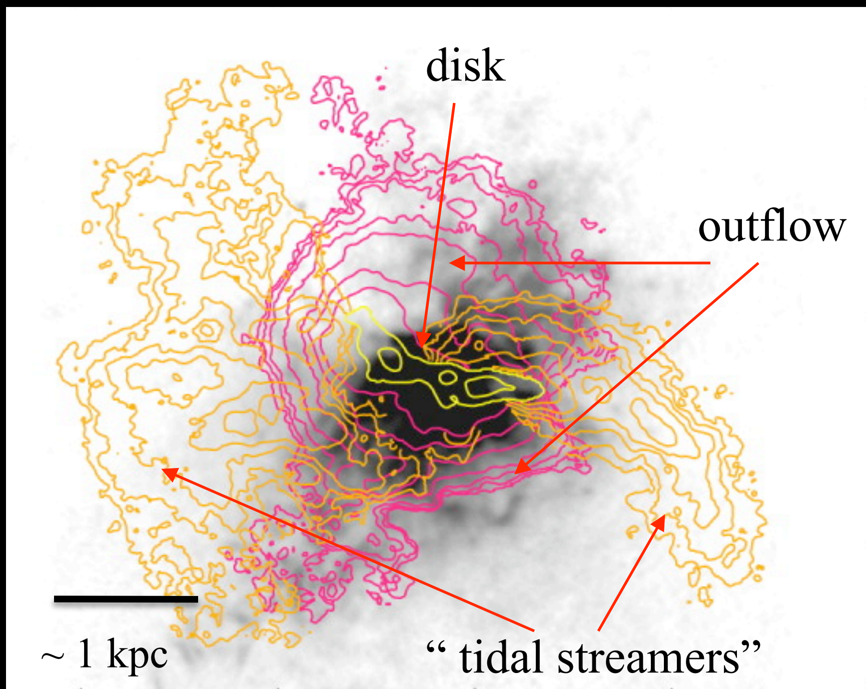


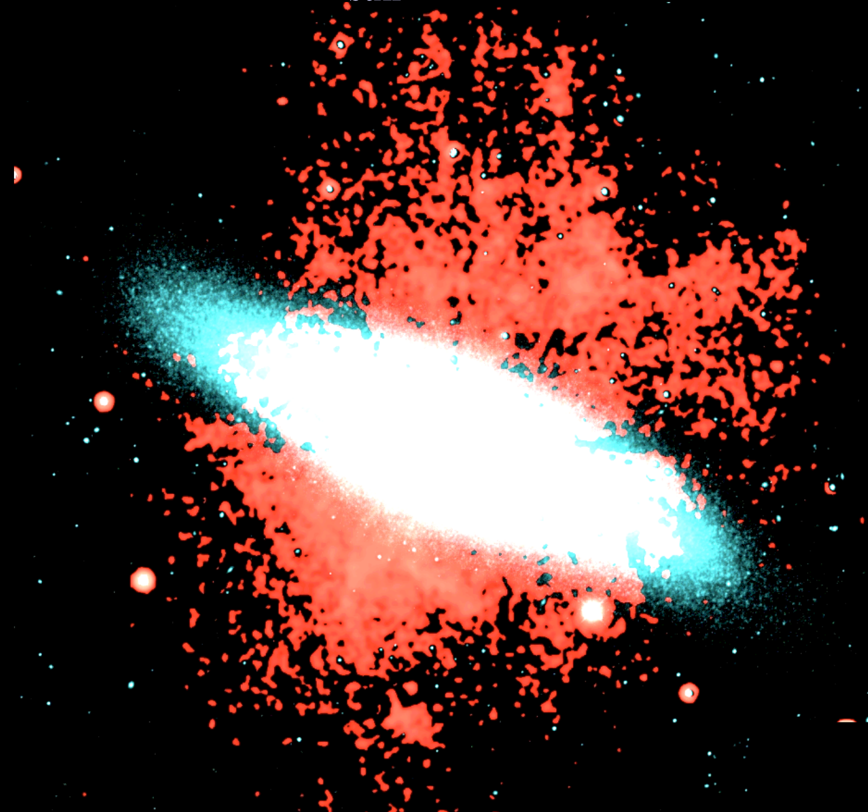
Influence of shock heating of H_2 in outer region?

Cold vs *Warm* Molecular Outflows of M82

M ~ 3 x 10^8 M_{sun} E ~ 1 x 10^{55} ergs

M < 10^4 M_{sun} E < 1 x 10^{51} ergs?





Cold Molecular Gas (~3.6")

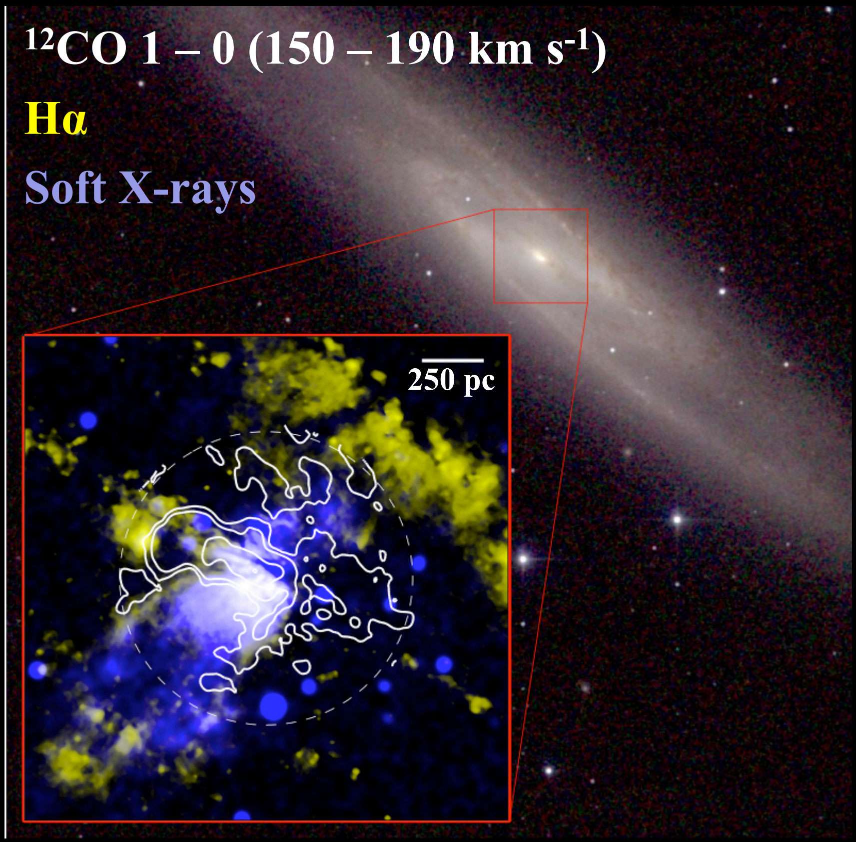
(CO 1→0: Walter, Weiß, & Scoville '02)

Warm Molecular Gas (~4")

(H_2 2.12 um: SV, Rupke, & Swaters '09)

Cold Molecular Outflow in Starburst NGC 253

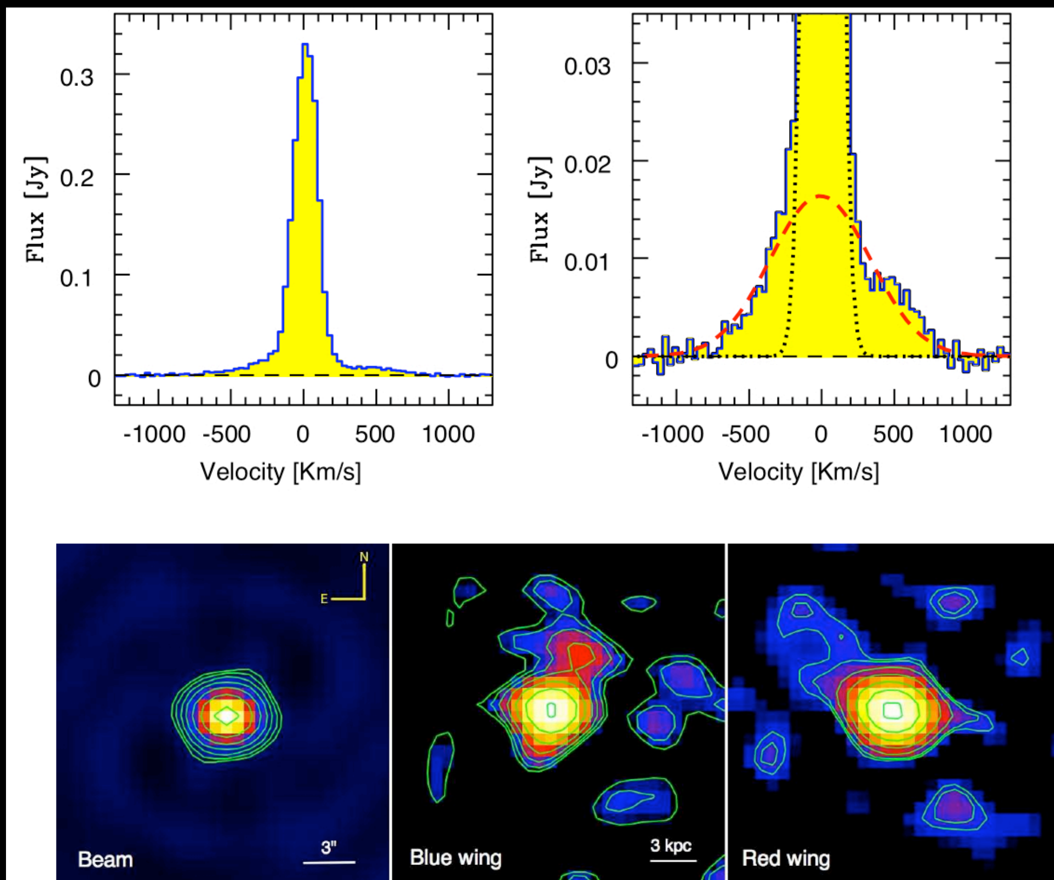
Bolatto, Warren, Leroy, Fabian, SV, Ostriker, et al. (2013, Nature)

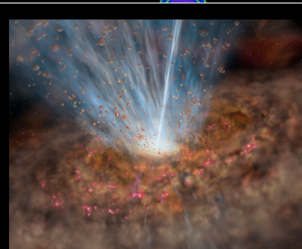


- ALMA Cycle 0 Observations
- Resolution: ~ 50 pc (~3")
- V(observed) = 30 – 60 km s^{-1}
- V(deprojected) = 100 – 200 km s^{-1} (i = 72^{o})
- t_{dyn} = 0.3 – 1 Myr
- dM/dt ~ 3 – 9 M_{sun} yr^{-1}
- η = dM/dt / SFR = 1 – 3 (H_2/CO ~ 0.1 x Galactic value)

Extended Molecular Quasar-driven Outflow in Mrk 231

(IRAM: Feruglio et al. 2010; Aalto et al. 2012; Cicone et al. 2012)





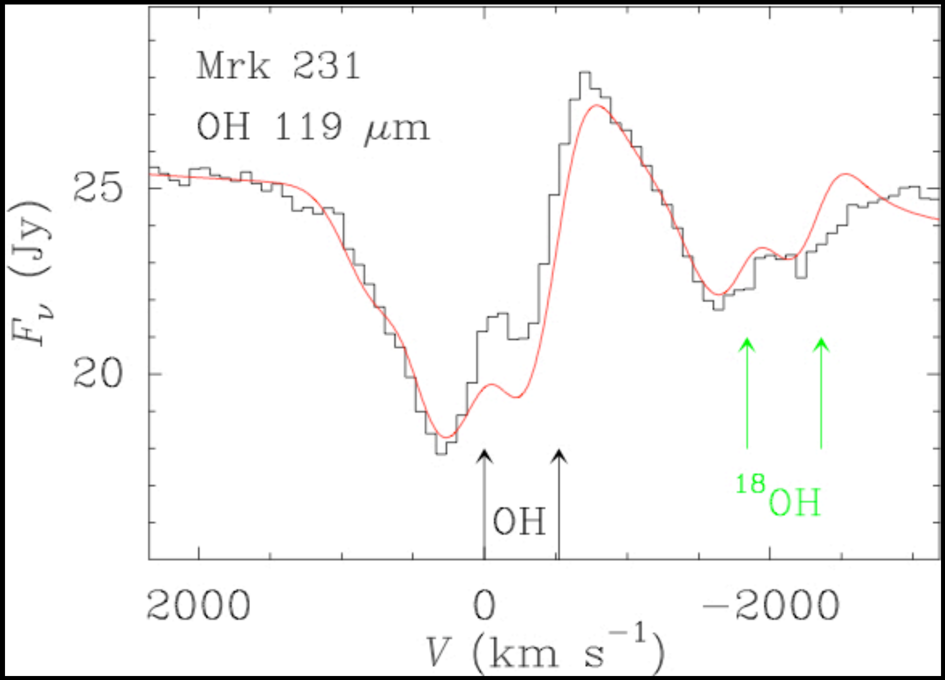
- *CO J = 1-0:*
  - V_{out} up to ~*750* km s^{-1}
  - M_{out} ~ 6 x 10^8 M_{sun} (H_2/CO ~ 0.1 x Galactic value)
  - Kpc scale
  - d*M*/dt ~ 700 M_{sun} yr^{-1}
  - η = d*M*/d*t* / *SFR* ~ *5*
- *HCN, HCO+, HNC 1-0:*
  - *n* > 10^4 cm^{-3} clumps; compressed, fragmented by shocks in outflow?
- *CO J = 2-1 vs 3-2:*
  - Blue and red wing material is more compact at higher density

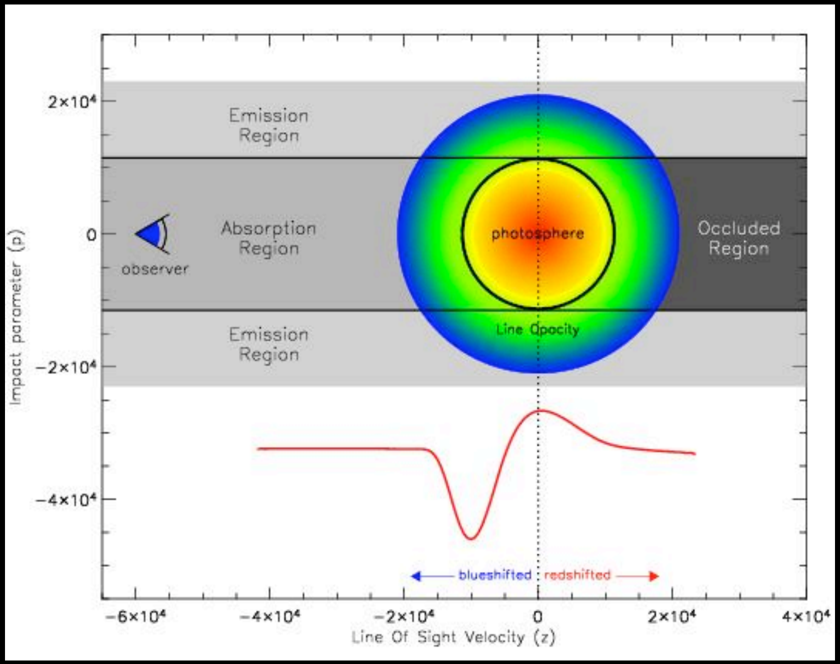
(Na I: Rupke+05c; Rupke & SV 2011, 2013a)

Herschel: Massive Molecular Outflow in Mrk 231

(*SHINING* Survey: *Fischer et al. 2010, A&A, 518, L42*)

- OH 79 / 119 um PACS spectra
- P-Cygni profiles!
- Outflow: $|V_{out}|$ in excess of 1000 km s^{-1}

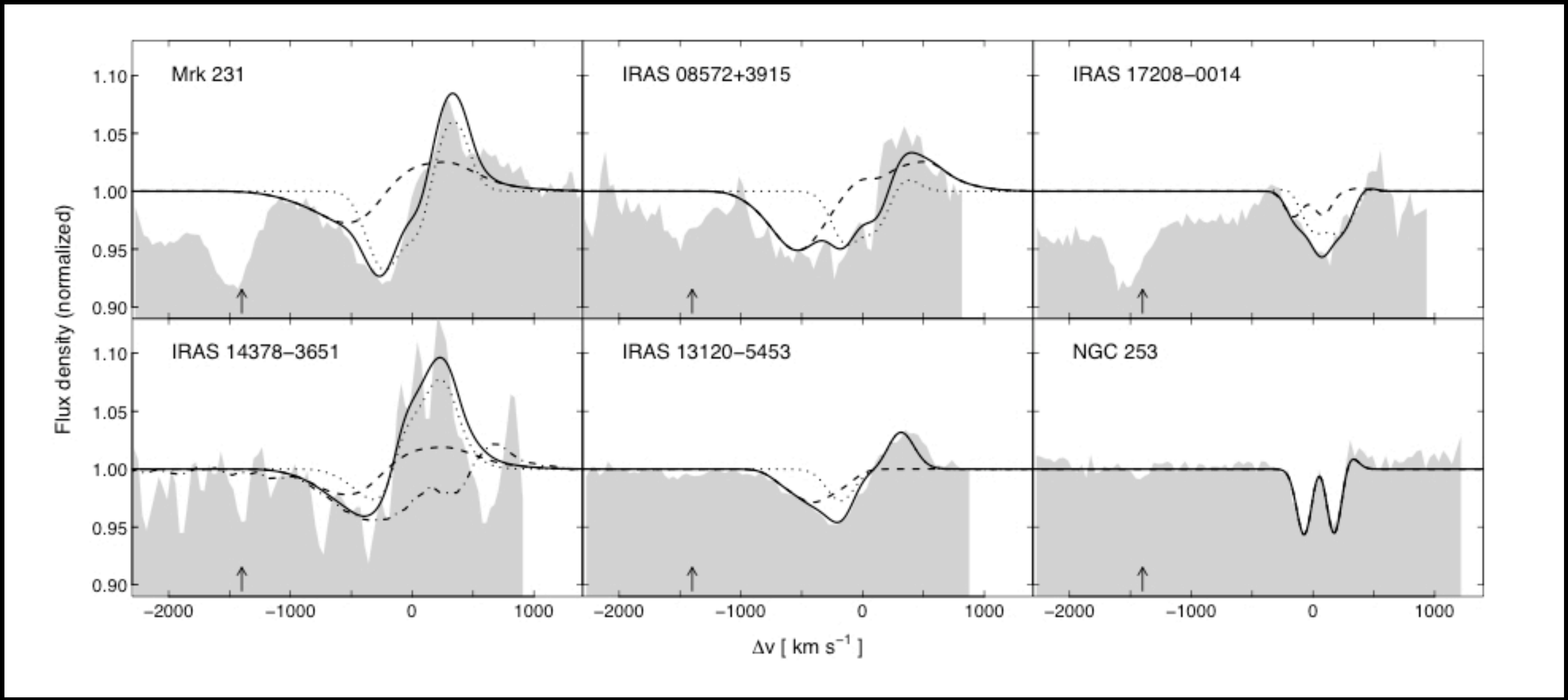




Herschel: Massive Molecular Outflows in ULIRGs

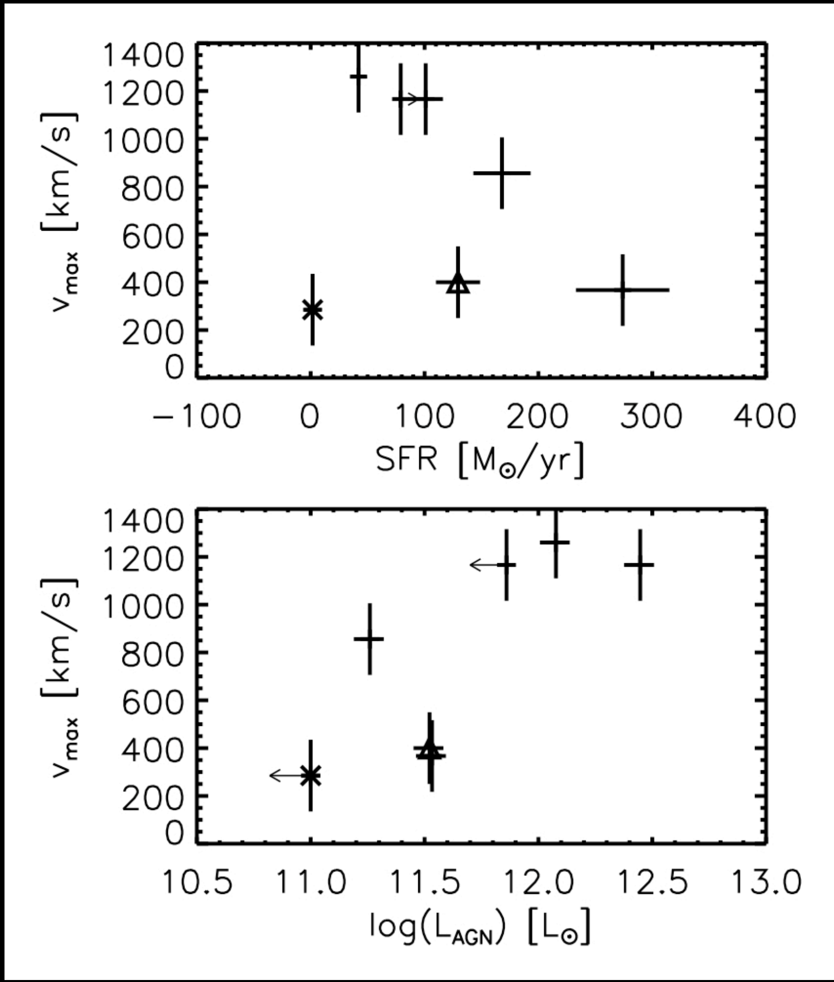
(SHINING Survey: *Sturm, Gonzalez-Alfonso, SV, et al. 2011)*

Herschel/PACS spectra of OH 65 / 79 / 119 µm transitions: P-Cygni Profiles



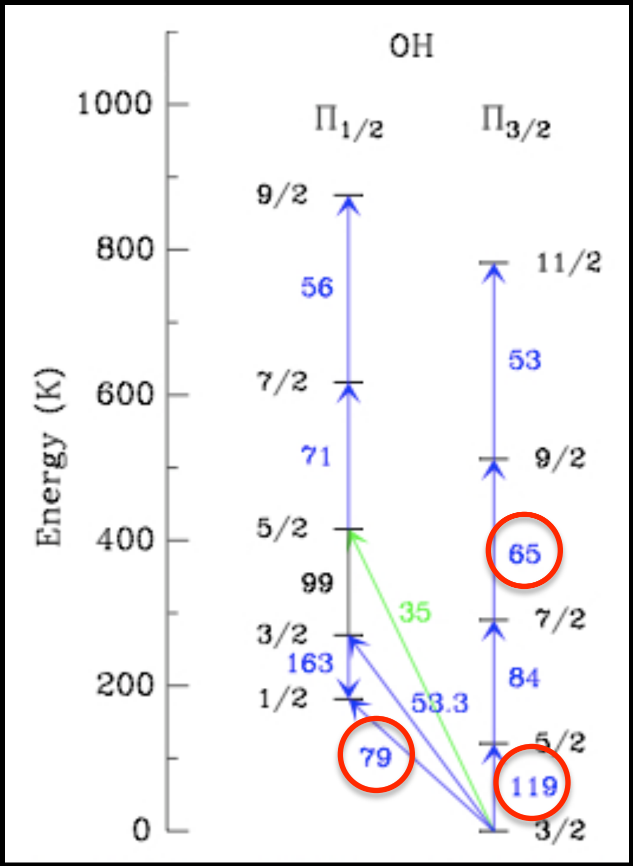
Molecular Wind Kinematics: AGN Driven?

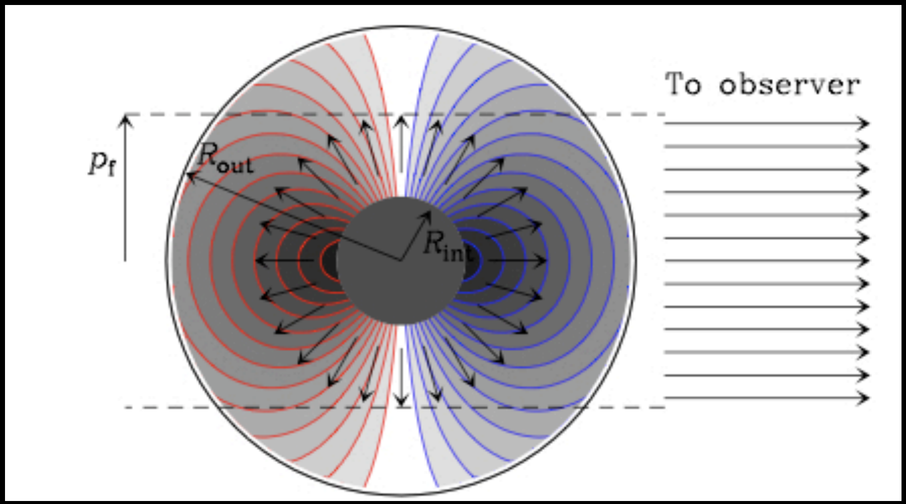
(Sturm, Gonzalez-Alfonso, SV, et al. 2011)



Molecular Wind Dynamics

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

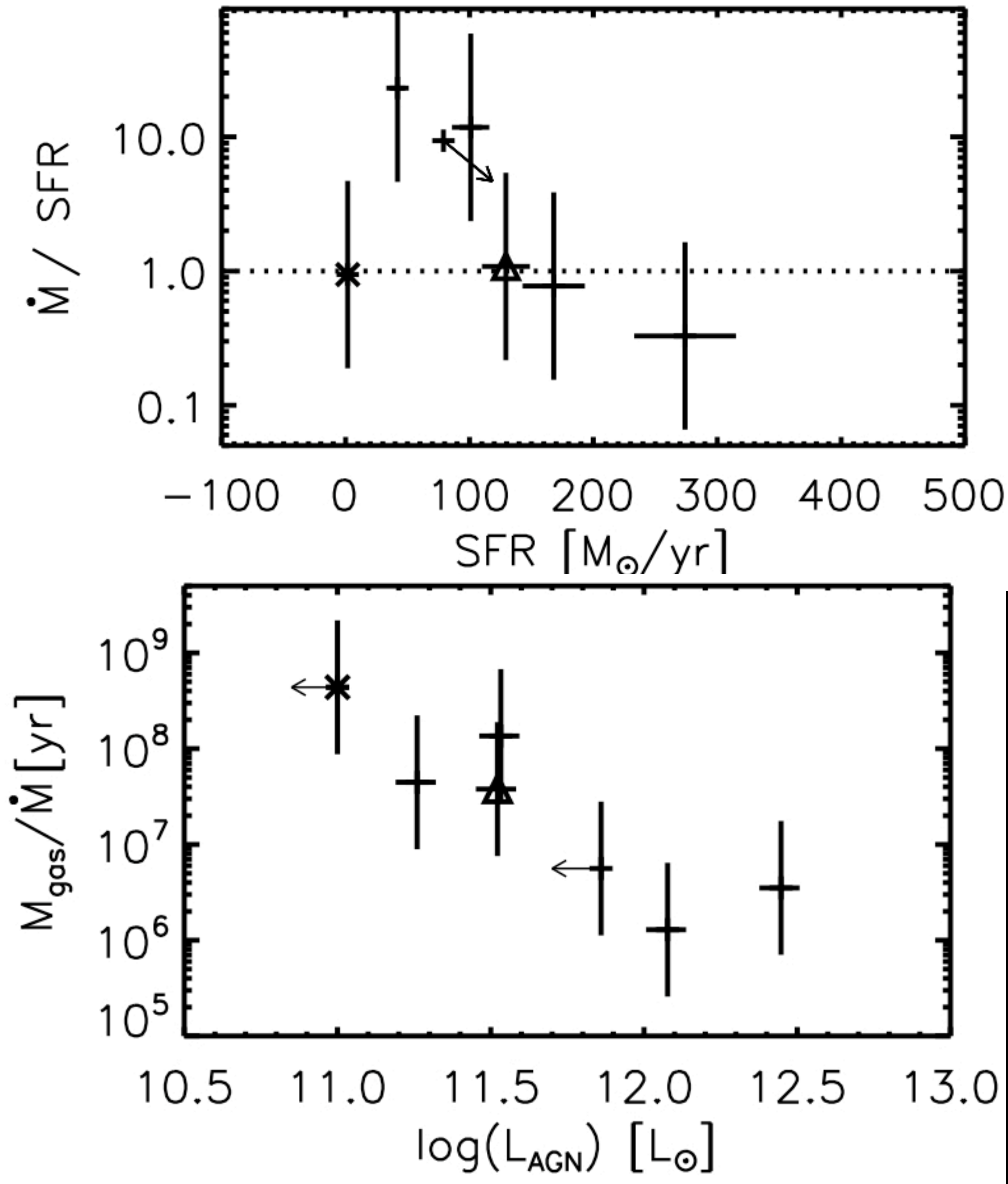




- ***Radiative transfer models:*** **1-2 concentric expanding shells**
- ***Free parameters:*** **R_{int}, R_{out}, velocity field of each component, covering factor of FIR continuum source (clumpiness *f*), solid angle of outflow (p_f)**
- ***Density profile of each shell:*** **derived from mass conservation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

Massive Molecular Winds in ULIRGs

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



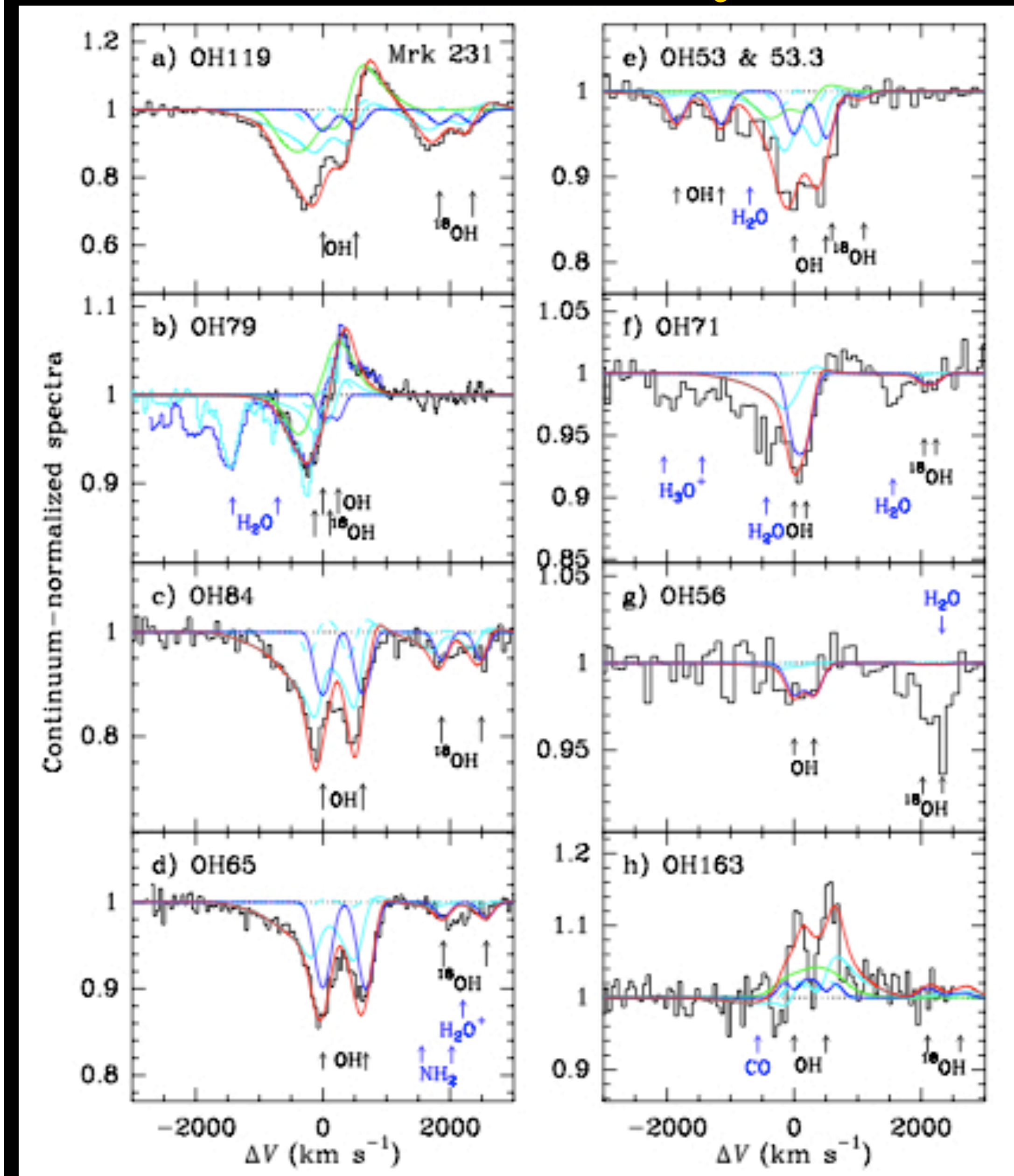
- **d*M* / d*t* ~ 100 – 1000 M_{sun} yr^{-1}**
  ~ (1 – 20) *SFR*

- **d*p* / d*t* ~ (1 – 30) L_{AGN} / c**

- **$\tau_{depletion}$ ~ M_{gas} / (d*M*/d*t*)**
  = 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*)

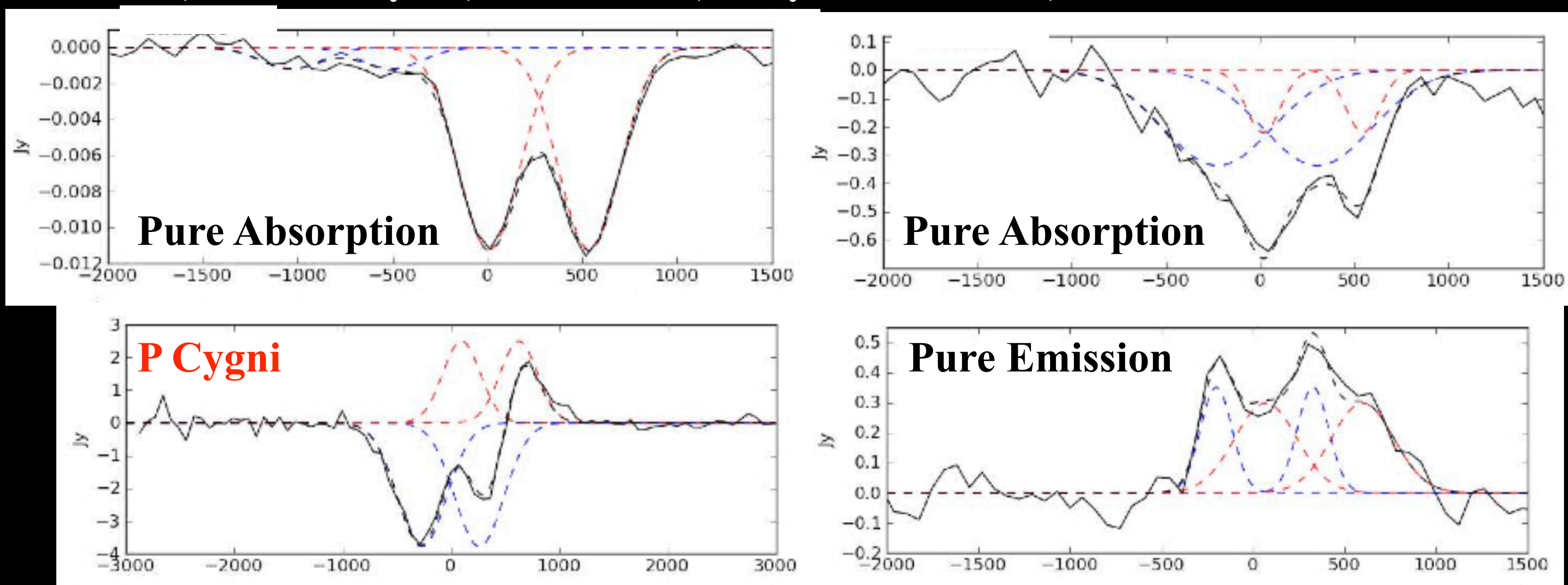
Parameter	QC	HVC	LVC[a]
R_{int} (pc)[b]	55–73	65–80	65–80
T_{dust} (K)	95–120	90–105	~90
τ_{100}	1–3	1.5–2.0	≲1
R_{out}/R_{int}	–	≲1.5	~1.5–2
v_{int} (km s^{-1})	–	1700	~300
v_{out} (km s^{-1})	–	100	~200
N_{OH} (10^{17} cm^{-2})	5–16[c]	1.5–3	~0.3
p_f/R_{out}[d]	1	~0.8	~1

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 Doublet Profiles (43 objects)

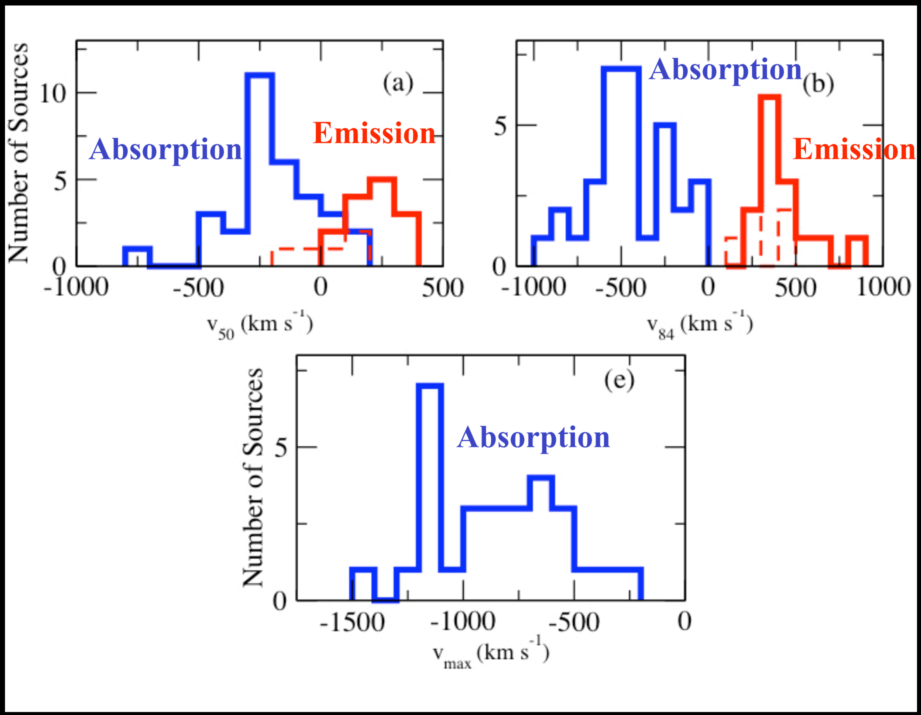
(SV, Meléndez, et al. 2013)

- **OH 119 µm doublet often shows a P Cygni profile → outflow**
- **OH 119 µm doublet is in emission when AGN fraction > 90%**
  (also seen by *Teng, SV, & Baker 2013* using GBT H I 21-cm feature)
- **EW(OH 119 µm) ↔ EW(9.7 µm silicate) ~ obscuration**



Kinematics (OH 119 μm)

(SV, Meléndez, 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)

(Heckman 2000; Rupke, SV, & Sanders 2002, 2005abc; Martin 2005; Rupke & SV 2011, 2013a)

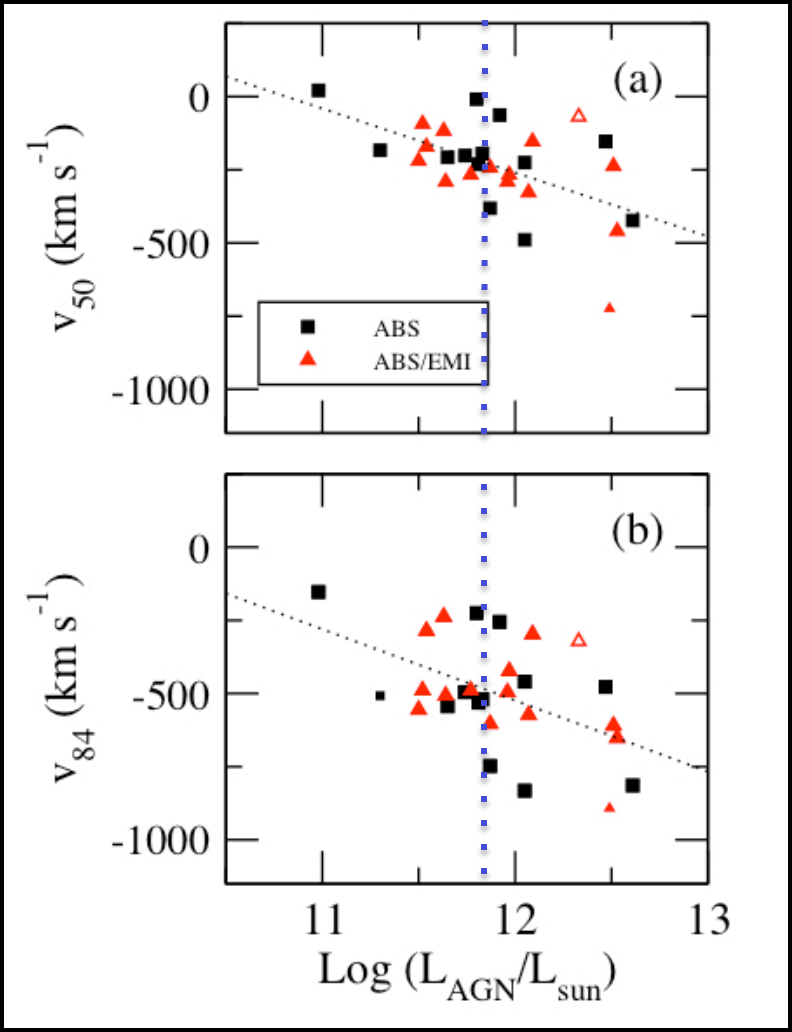
OH 119 µm Wind Detection Rates

(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?

Kinematics (OH 119 µm)

(SV, Meléndez, 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

Dependence on AGN Luminosity

- **The AGN becomes the dominant driver of the molecular outflow above**

$$L_{AGN}^{break} = 10^{11.8 \pm 0.3}\, L_{sun} \sim L_{min}(\text{quasar})$$

- **Limiting Eddington-like luminosity above which UV-IR radiation momentum deposition from the quasar (and/or starburst) is enough to clear *all* of the gas from the galaxy ("blow away" condition):**

$$L_M = \frac{4 f_g c}{G} \sigma^4,$$

(Murray et al. 2005)

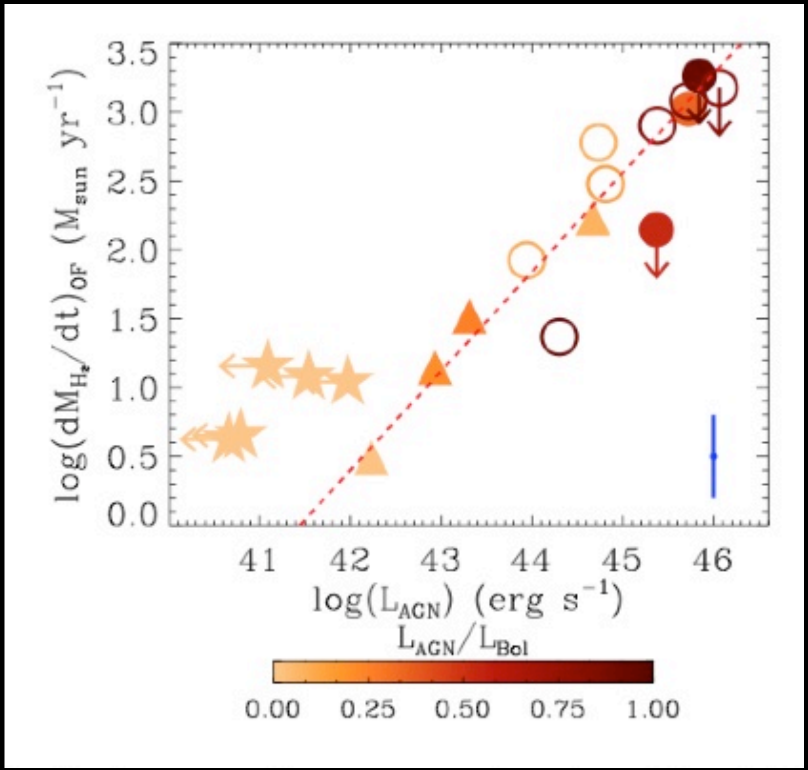
- **For our objects:**
  - $f_g \sim 0.1$ **on average**
  - $\sigma \sim 120 - 280$ **km** s^{-1}

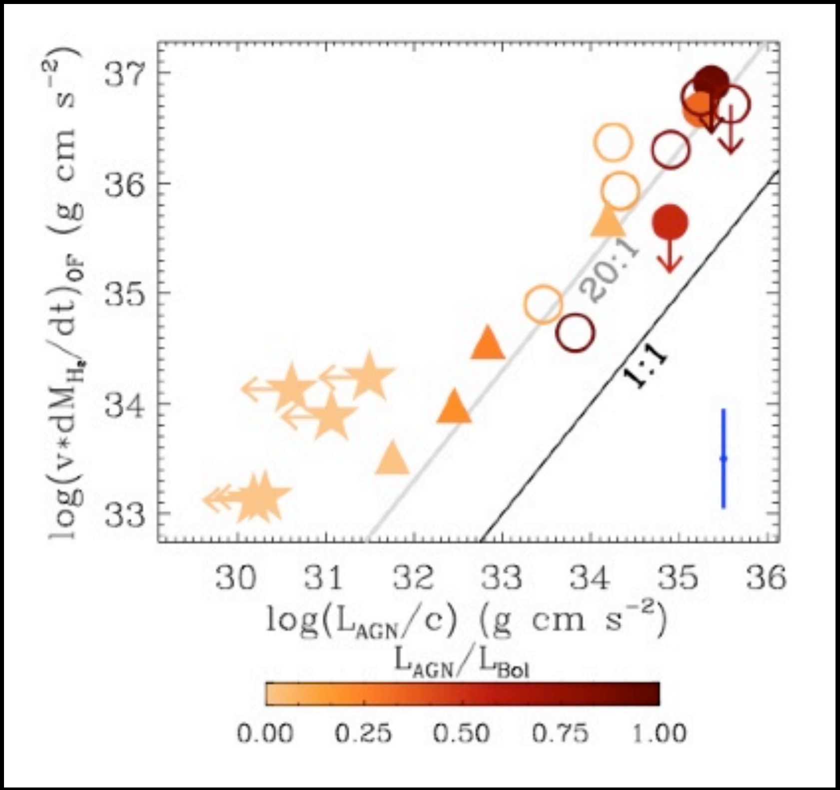
→ $L_{AGN}^{break} \sim (2 - 100\%) \bullet L_M$

CO Outflows in (U)LIRGs with IRAM

(Cicone et al. 2014)

Clear detections of spatially resolved outflows in 4 out of 7 ULIRGs / Quasars





Strong evidence for AGN driving

d*p*/d*t* ~ (1 – 30) L_{AGN} / *c*

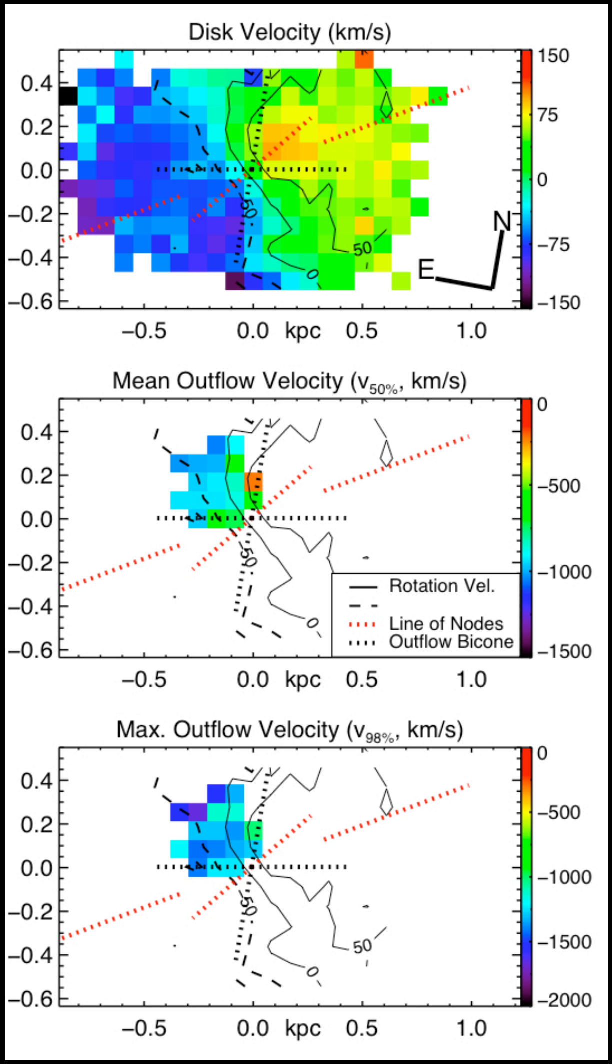
➔ **Consistent with *Herschel* OH results**

Probing the Wind Launching Region with H_2 2.12 μm

(used as a tracer of the cold molecular gas)

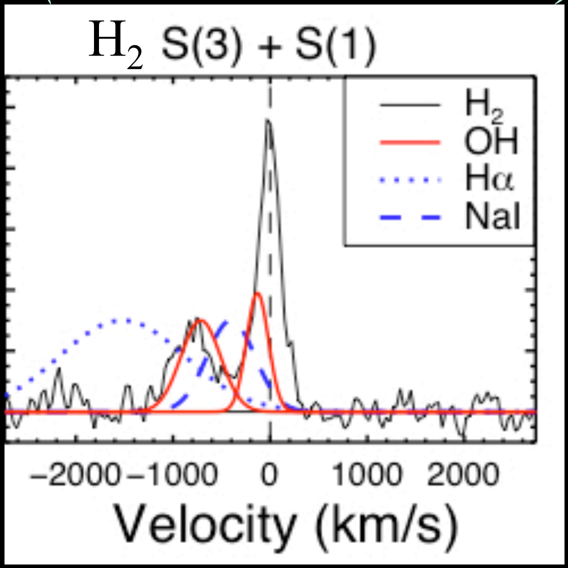
(Rupke & SV 2013b)

Buried QSO:
F08572+3915 NW



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

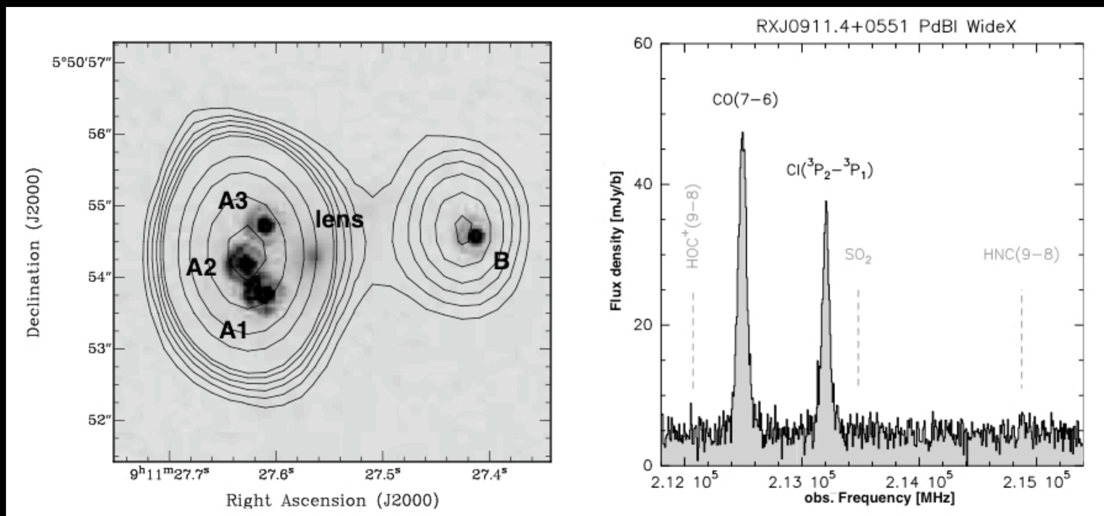
Opening angle = 100 ± 10 deg
(consistent with Sturm+11)

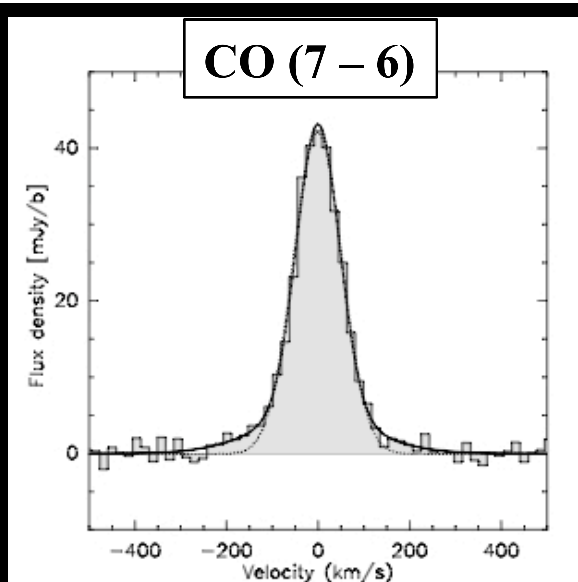


T(wind) = 2400 K
> T(disk) = 1500 K

AGN-Driven Molecular Outflows at High *z*?

(Weiss et al. 2012)

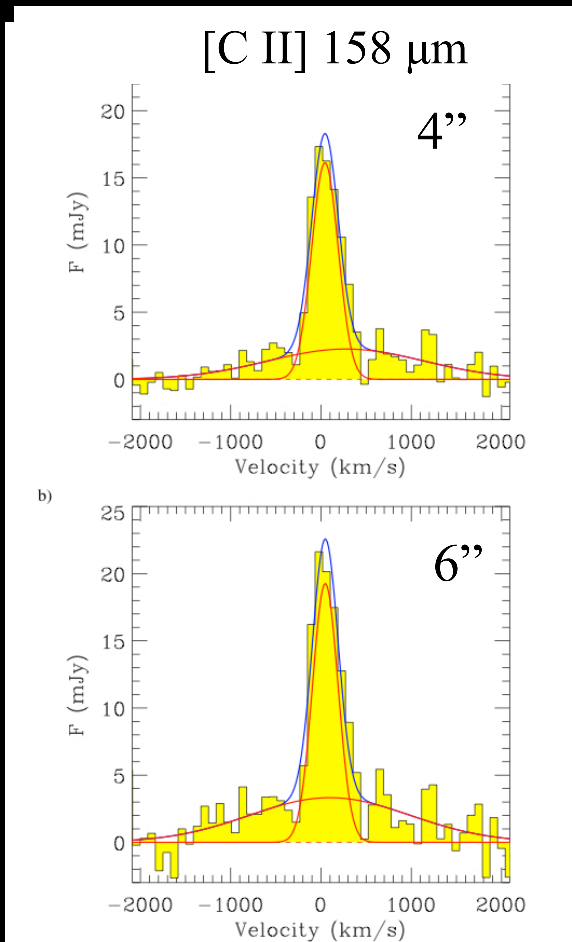


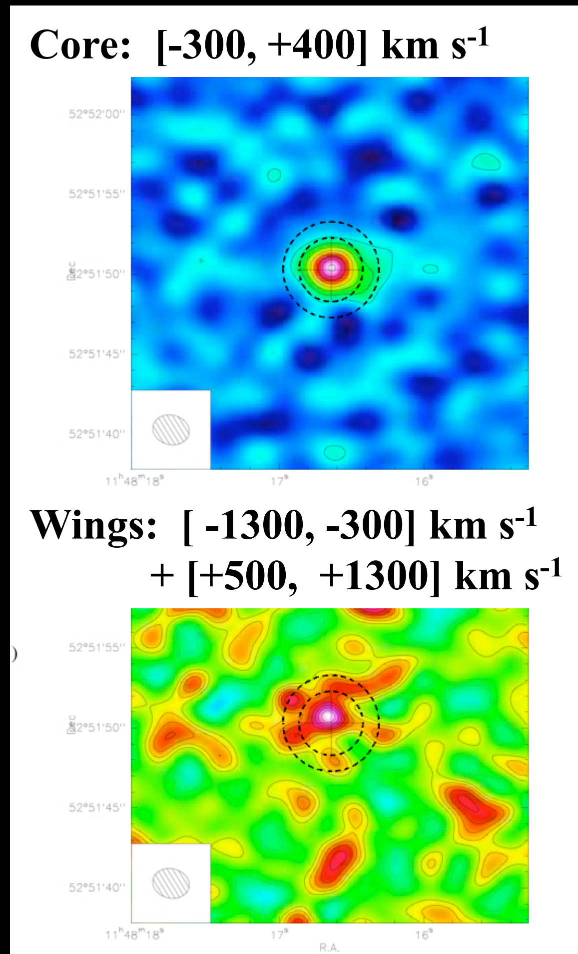


- **QSO RXJ0911.4+0551 @ z = 2.79 (lensed)**
- ***15-hr IRAM***
- **$SFR = 140\ M_{sun}\ \mathrm{yr}^{-1}$**
- **V_{out} up to 250 km s^{-1} ?**
- **$M_{out} \sim 1.7 \times 10^9\ M_{sun}$?**
- **$E_{kin} > 1 \times 10^{56}$ ergs ?**
- **dM/dt > 180 $M_{sun}\ \mathrm{yr}^{-1}$? (assuming $R_{out} \sim 0.5$ kpc ~ Mrk 231, NGC 1266)**

AGN-Driven Atomic Outflow at z ~ 6.4 ?

(Maiolino et al. 2012)



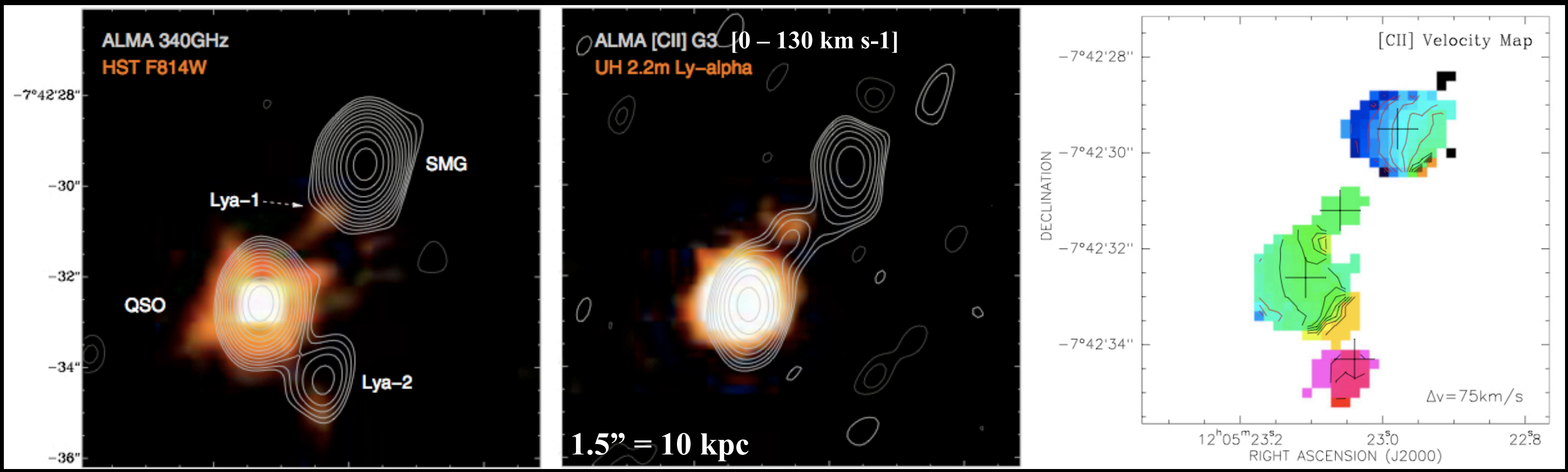


- QSO SDSS J1148+5251
- *17.5-hr IRAM [C II] PDR*
- V_{out} up to 1300 km s^{-1}
- M(atomic)$_{out}$ > 7 x 10^9 M_{sun} (high density, $X(C^+)$ ~ 1.4 x 10^{-4} ~ ionization level of Galactic PDR)
- R ~ 8 kpc
- dM/dt > 3500 M_{sun} yr^{-1}
- $\tau_{depletion}$ < 6 x 10^6 yrs
- dE_k/dt > 2 x 10^{45} erg s^{-1} ~ 0.6% L_{BOL} (AGN)

1” = 5.5 kpc

ALMA: AGN-Driven Atomic Outflows at High z

(Carilli et al. 2013)



- Group of galaxies BRI 1202-0725 @ $z = 4.7$
- 25-min "snapshot" (17 antennae, SV phase*)*
- [C II] PDR outflow in the QSO?
- V_{out} up to 500 km s^{-1} ?
- M(atomic)$_{out}$ > 3 x 10^8 M_{sun} ? (making the same assumptions as in Maiolino+12)
- R_{out} ~ 10 kpc ?
- dM/dt > 80 M_{sun} yr^{-1} ?

Summary & Open Issues

- **What are the basic properties of molecular winds?**
  - **Statistics: ~70% of local ULIRGs have molecular winds**
  - **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} = 10^{10} – 10^{11} erg s^{-1}; E_{mech} = few x 10^{56} ergs; dp/dt = (1 – 30) L_{AGN}/c**
  - **Growing consensus between multi-transition analysis (*Herschel*), spatially resolved CO data (IRAM, ALMA) and ground-based IFU data on the warm-H_2 and neutral gas components (+ JVLA)**
- **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**
- **How is this gas driven?**
  - **Forces: radiation pressure on dust, energy-conserving shocked wind, thermal / jet ram / cosmic ray pressure, … ?**
  - **Survival time scale to cloud erosion? In-situ formation?**