Massive Neutral and Molecular Winds in Nearby Galaxies

S. Veilleux (U. Maryland)

Powerful wide-angle outflow in Mrk 231

Gemini Press Release February 2011

(Rupke & SV 2011)

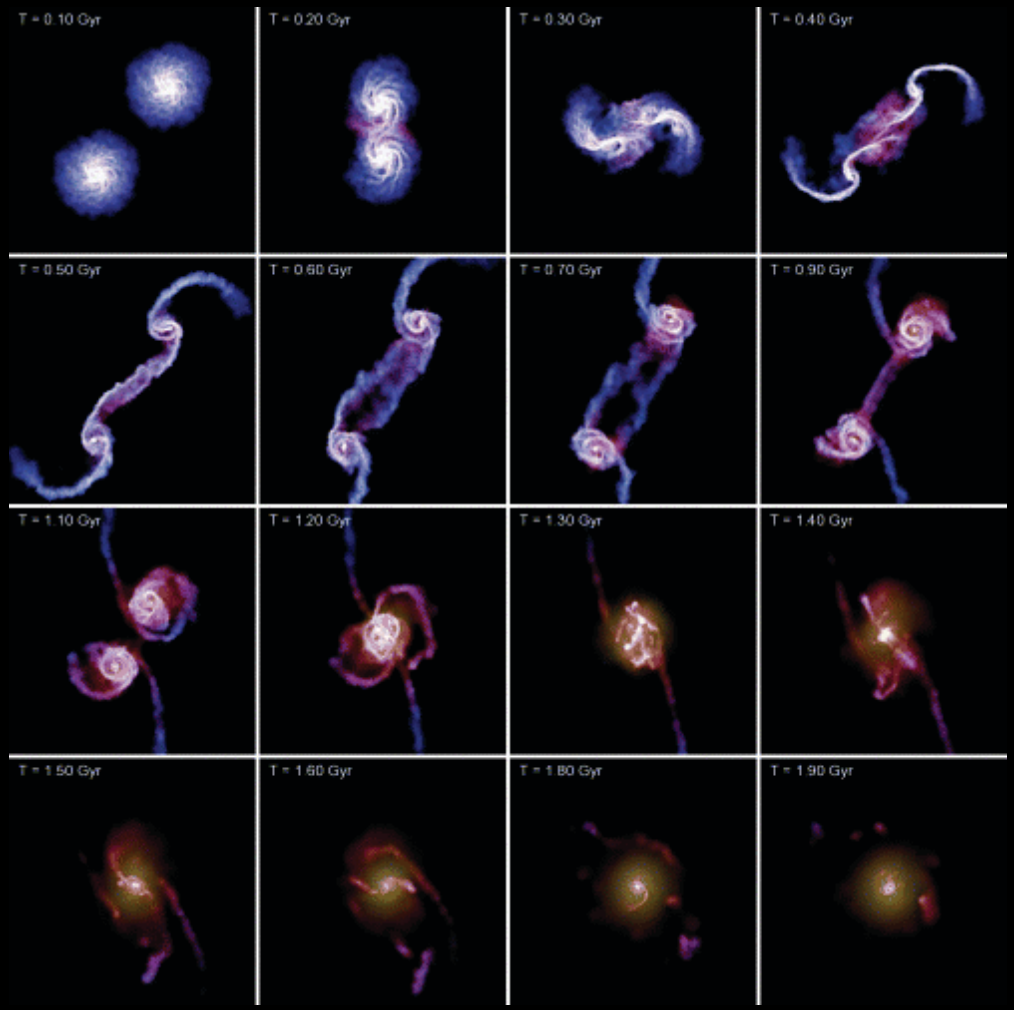
*QUEST: Q*uasar and *U*LIRG *E*volution *St*udy

(Keck/VLT/others, Spitzer, HST, Chandra/XMM/Suzaku, Herschel, Arecibo/GBT)

Sample: ~120 ULIRGs + ~30 QSOs at $z \leq 0.3$

- **Maryland: S. Veilleux, D.-C. Kim *(U. Va)*, H. Krug, D. Rupke *(Rhodes)*, S. Teng *(GSFC)*, A. Zauderer *(CfA)***
- **MPE: R. Genzel, E. Sturm, D. Lutz, L. Tacconi, A. Contursi, R. Davies, K. Dasyra *(CEA/Obs-Paris)*, M. Schweitzer**
- **Hawaii: D. Sanders, J. Barnes, R. Joseph, A. Stockton, O. Guyon**
- **CWRU: C. Mihos**
- **HIA: C. Peng *(Carnegie)***
- **Caltech/IPAC/SSC: J. Mazzarella, S. Lord**
- **Munich: A. Burkert**
- **NRL: C. Dermer, J. Fischer**
- **Carnegie: L. Ho**
- **Rutgers: A. Baker**
- **Tel Aviv U.: H. Netzer, A. Sternberg**
- **Toronto: H. Yee**

ULIRG – Spheroid/QSO Connection (Merger Scenario: low-to-moderate *z*)



- ***Gas dissipation / inflow***
- ***Star (spheroid) formation***
- ***Gas accretion onto BH***
- ***Negative feedback***

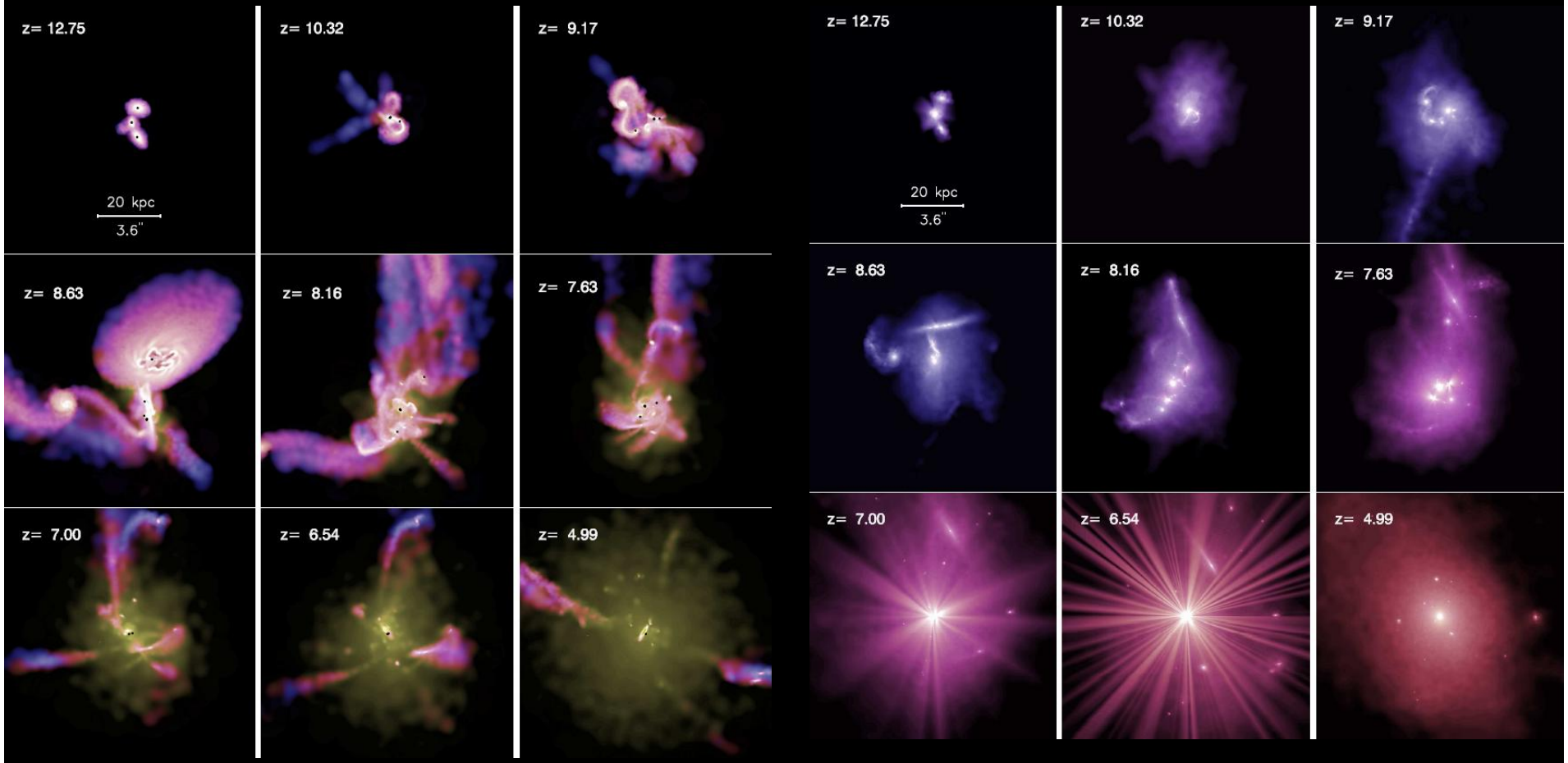
Gas

(Holmberg 41; Toomre[2] 71; Toomre 77; Sanders+88; Springel, di Matteo, & Hernquist 05; di Matteo + 05; Hopkins +…)

High incidence of interaction is also seen in BAT AGN of slightly lower L *(Koss+10)*

ULIRG – Spheroid/QSO Connection (Merger Scenario: high z)

Gas *(Li, Hernquist et al. 2007)* Stars

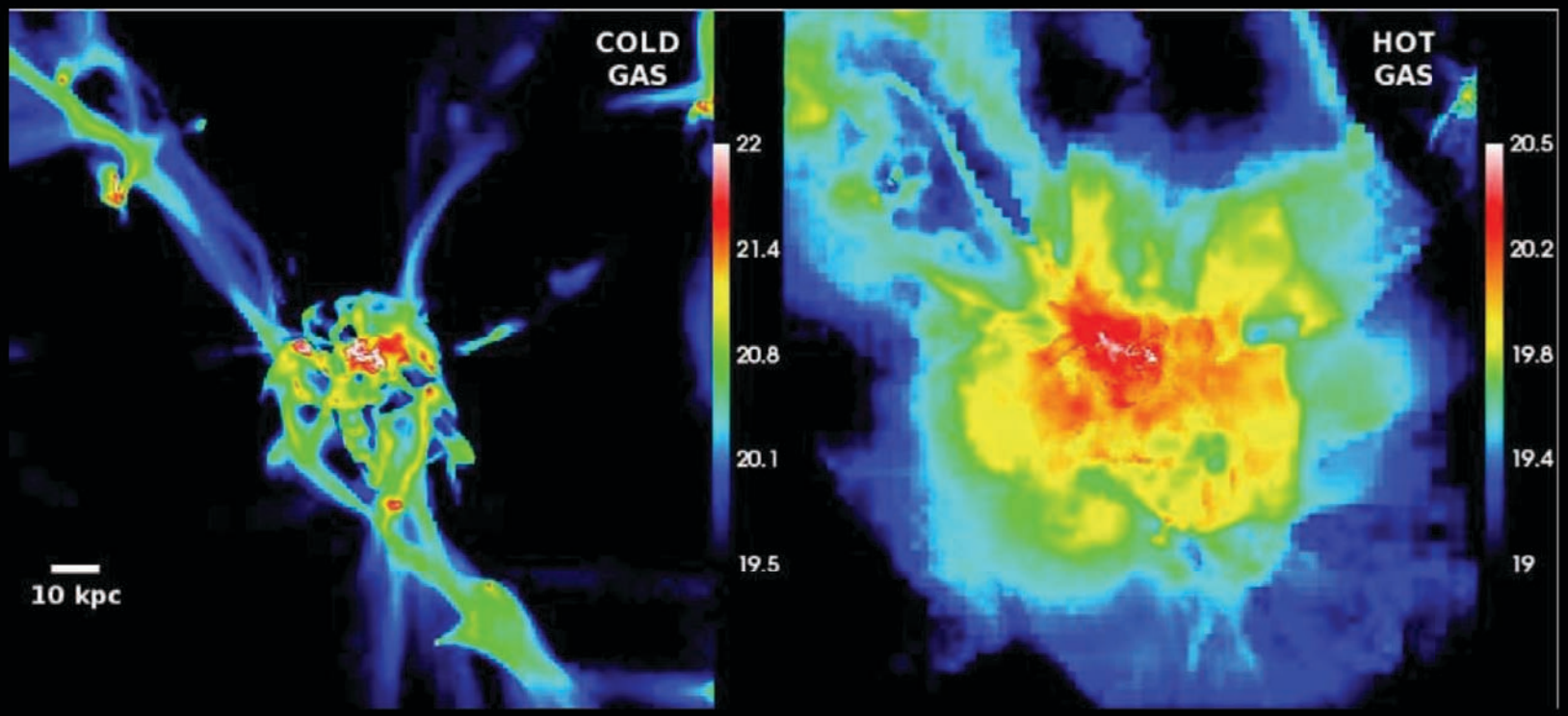


ULIRG – Spheroid/QSO Connection (Cold Stream Accretion: high z)

(e.g., Ceverino et al. 2009)

Cold Gas

Hot Gas

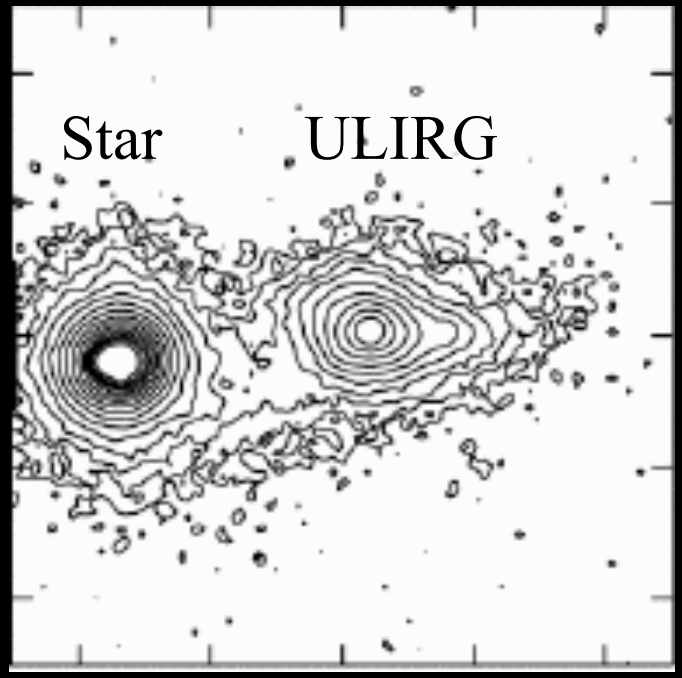


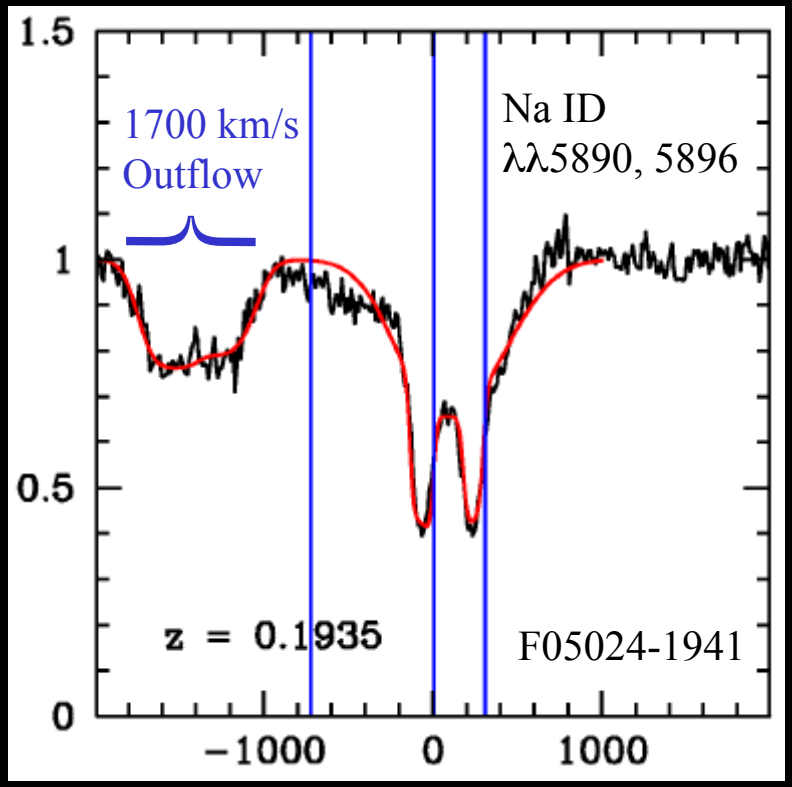
Important ULIRG-QSO Issues

- ***Gas inflows***
- ***Formation of spheroids***
- ***Black hole growth***
- ***Galactic winds***

Neutral Winds in ULIRGs @ z = 0 – 0.5

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

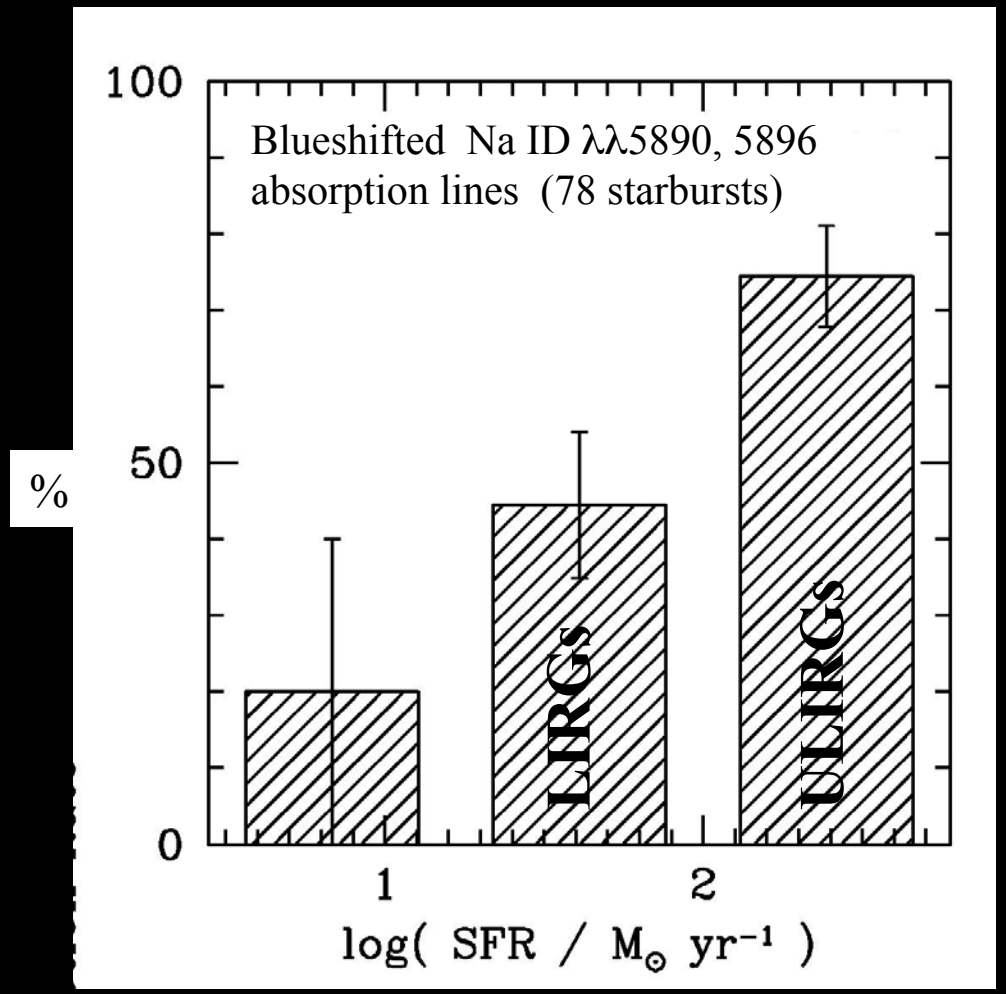




(also Martin 2005, 2006)

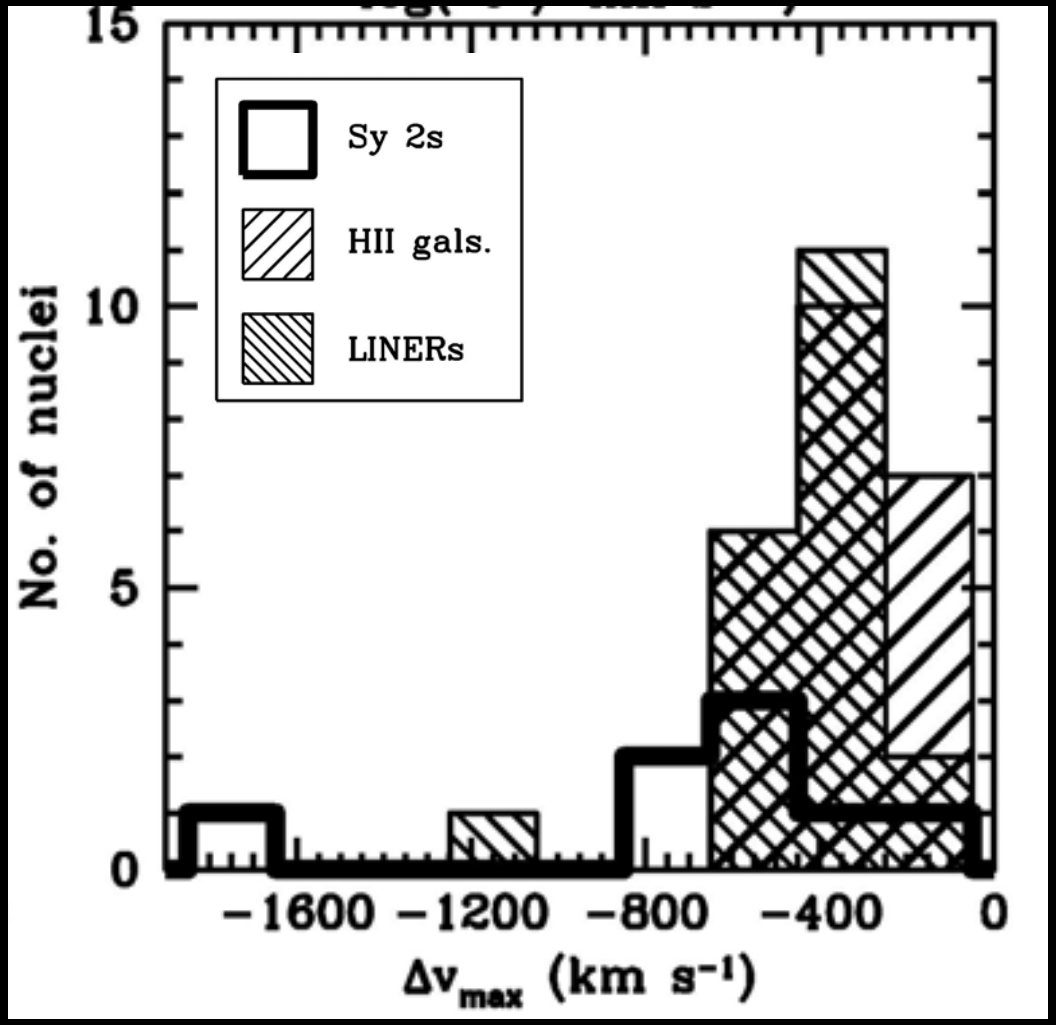
Wind Detection Rate in Local U/LIRGs

(Rupke, SV, & Sanders 2002, 2005ab)



Outflow Velocities of Neutral Gas

(Rupke, SV, & Sanders 2002, 2005abc; Martin+05, 06)



$V_{out} \sim V_{circ}^{0.8\pm 0.2}$

$V_{out} \sim SFR^{0.2\text{-}0.3}$

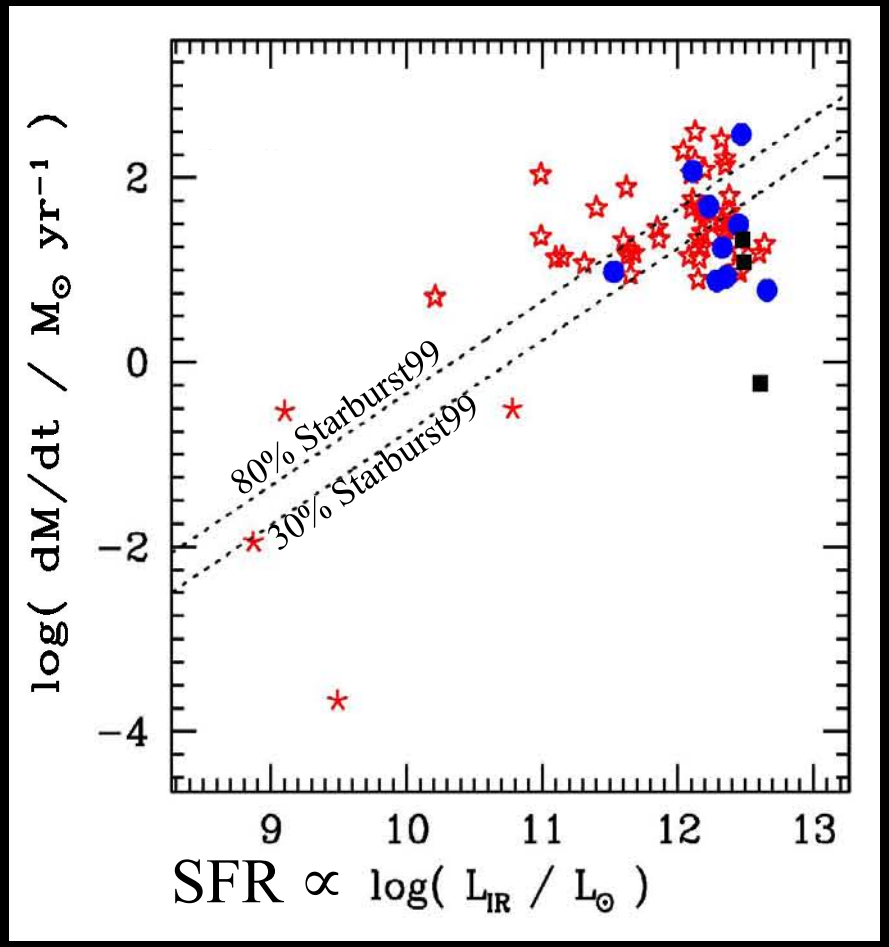
$f_{esc} \sim 5\text{–}20\%$
(if no halo drag)

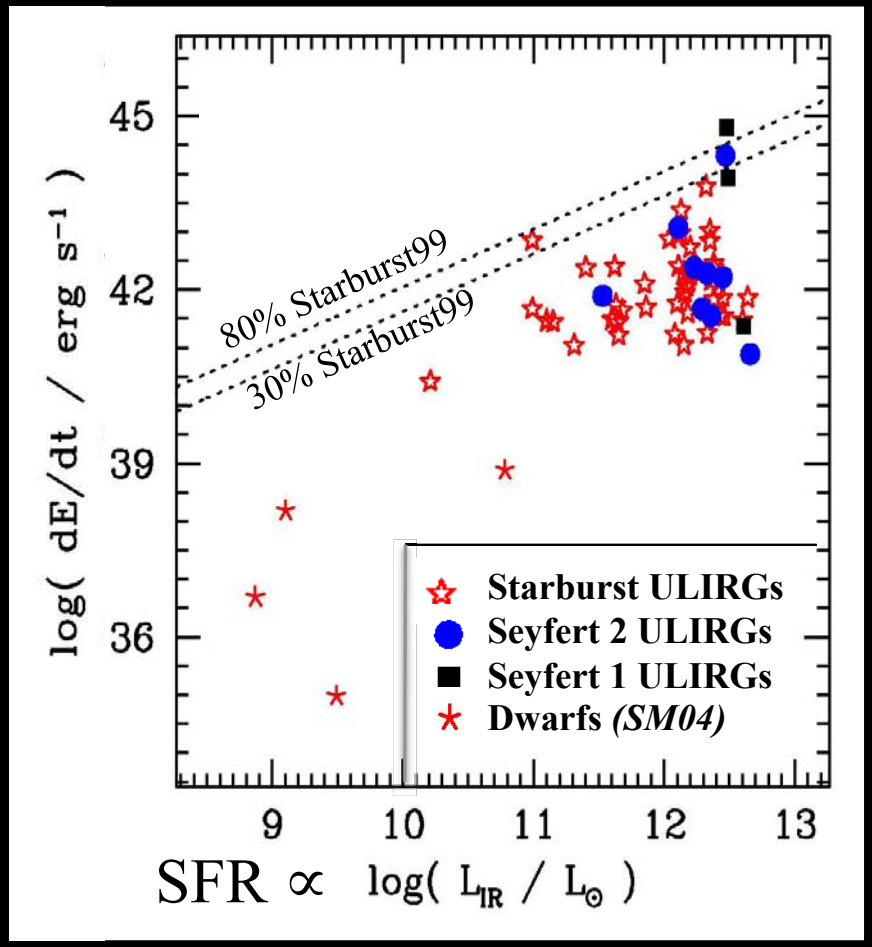
→ ***will*** **pollute circumgalactic medium**

→ ***may*** **pollute intergalactic medium!**

Winds have a profound effect on the hosts

$M_{wind} = 10^{8} – 10^{10}\ M_{sun}$ $E_{wind} = 10^{56} – 10^{58}$ ergs



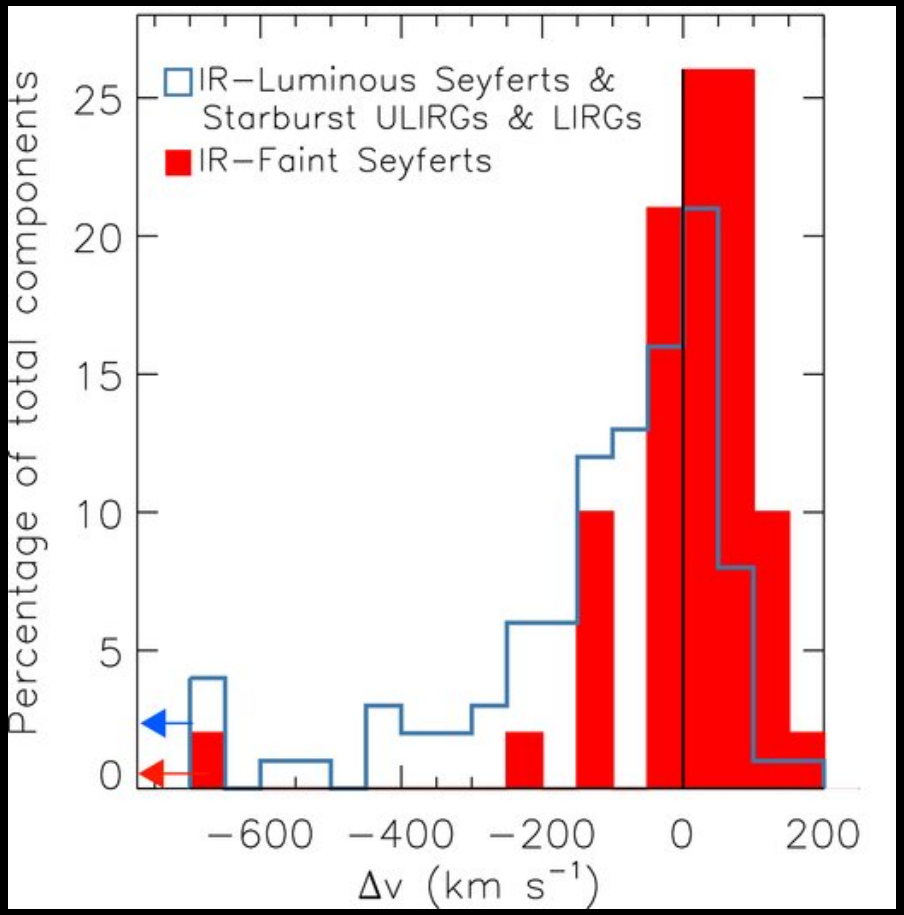


(Rupke+05abc)

IR-Faint "Pure" Seyferts

(35 objects; Krug, Rupke, & SV 2010)

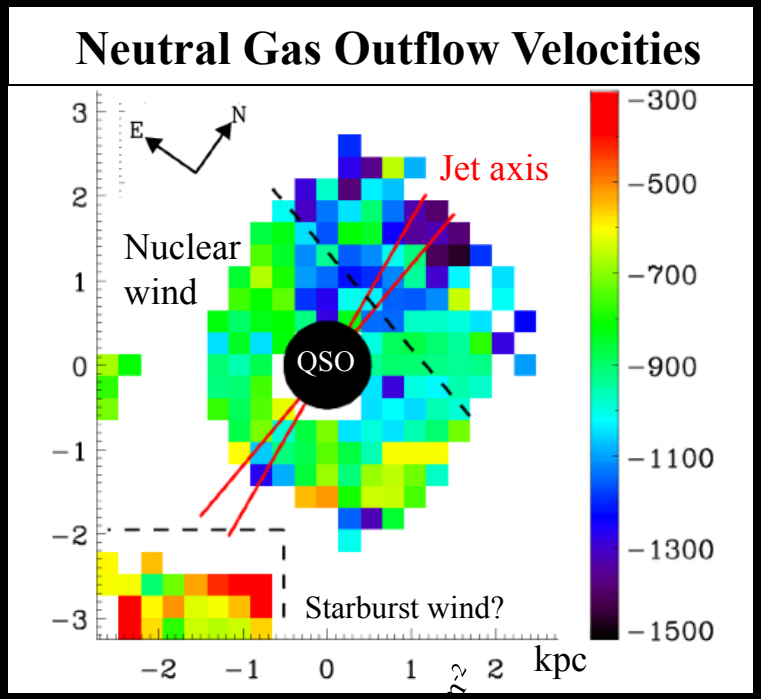
IR-faint AGN have fewer and weaker winds than IR-bright AGN



(biases? Being revisited on the BAT AGN; *Winter et al. in prep*)

Powerful Quasar-driven Wind in Mrk 231

(Rupke & SV 2011)



Gemini Press Release

- **Gemini/IFU: Na I absorption**
- **V_{out} → 1100 km s^{-1}**
- **> 2-3 kpc from nucleus**
- **dM/dt > 400 M_{sun} yr^{-1} ~ 2.5 x SFR**
- **dE/dt > 10^{44} ergs s^{-1} ~ 2.5 x dE_*/dt ~ 0.7% L_{AGN}**

Consistent with QSO feedback models
(e.g., Hopkins & Elvis 2010)

→ Rupke's talk

Open Issues on Galactic Winds *(Circa 2005)*

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

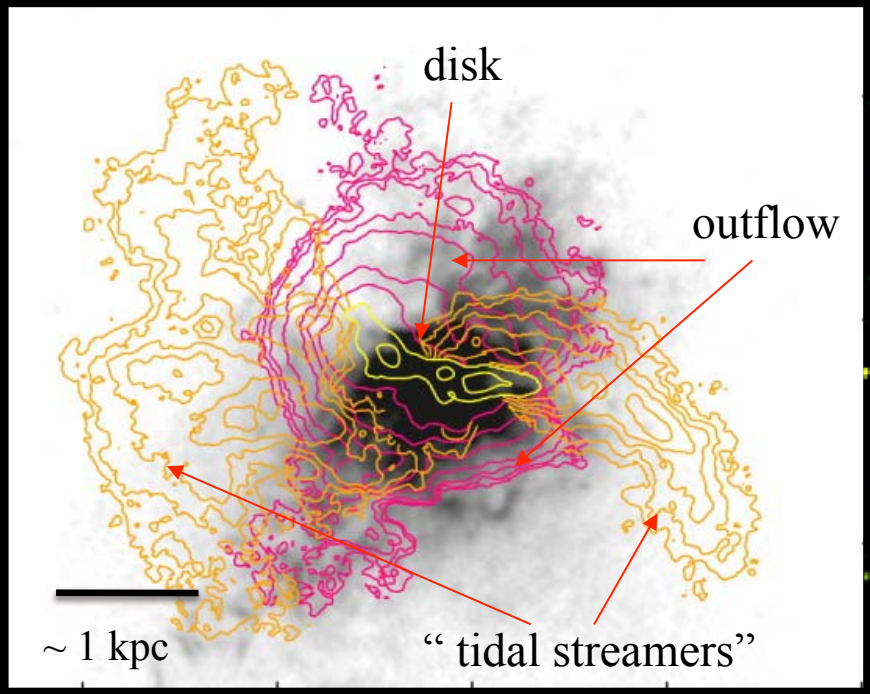
Theory:

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**

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



Cold Molecular Gas (~3.6”)

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

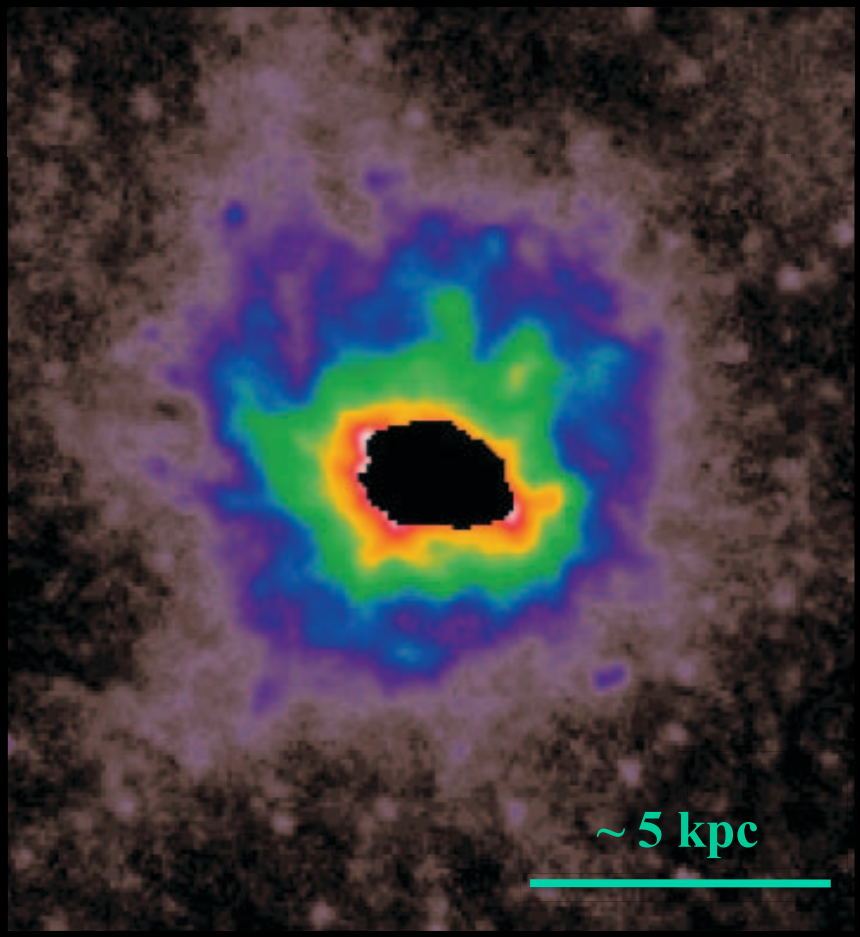
Dust Scattering

(GALEX: Hoopes et al. 2005)

Dust Outflows of M82

Warm Dust (PAH 8 μm)

(Spitzer: Engelbracht et al. 2006)

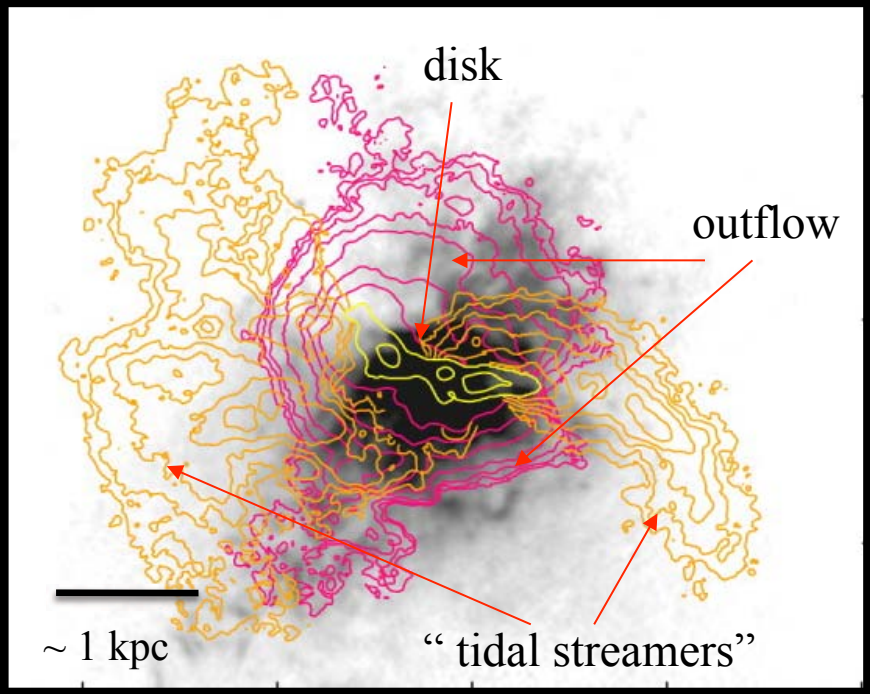


Cold Dust (250 μm)

(Herschel: Roussel et al. 2010)

Molecular Outflows of M82

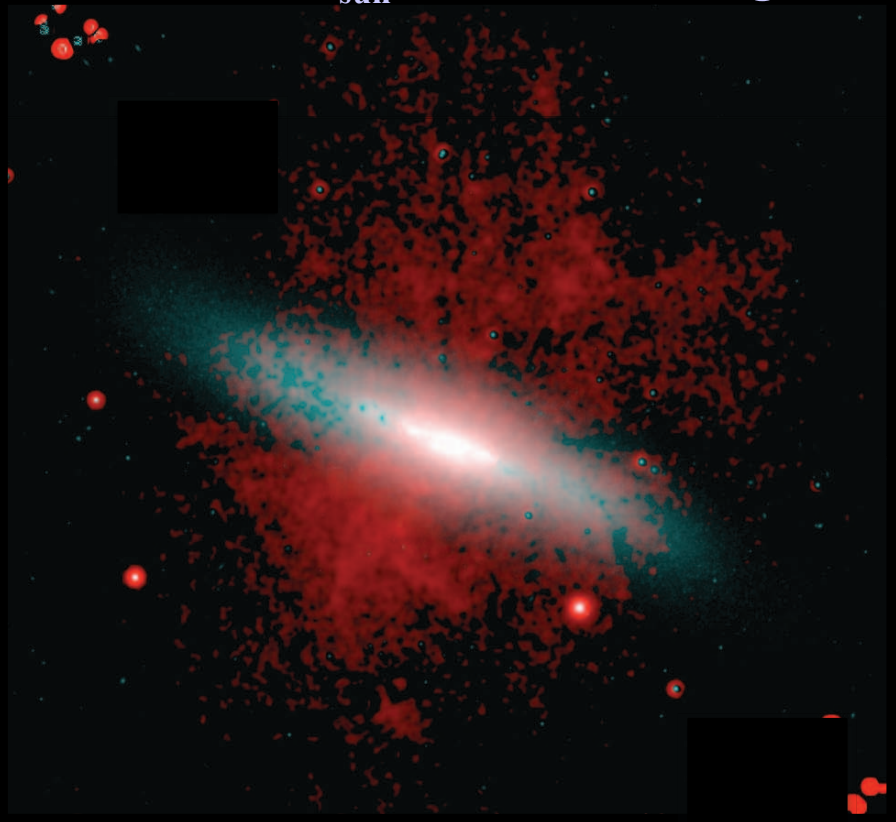
$M \sim 3 \times 10^8\ M_{sun}$ $E \sim 1 \times 10^{55}$ ergs



Cold Molecular Gas (~3.6”)

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

$M < 10^4\ M_{sun}$ $E < 1 \times 10^{51}$ ergs?

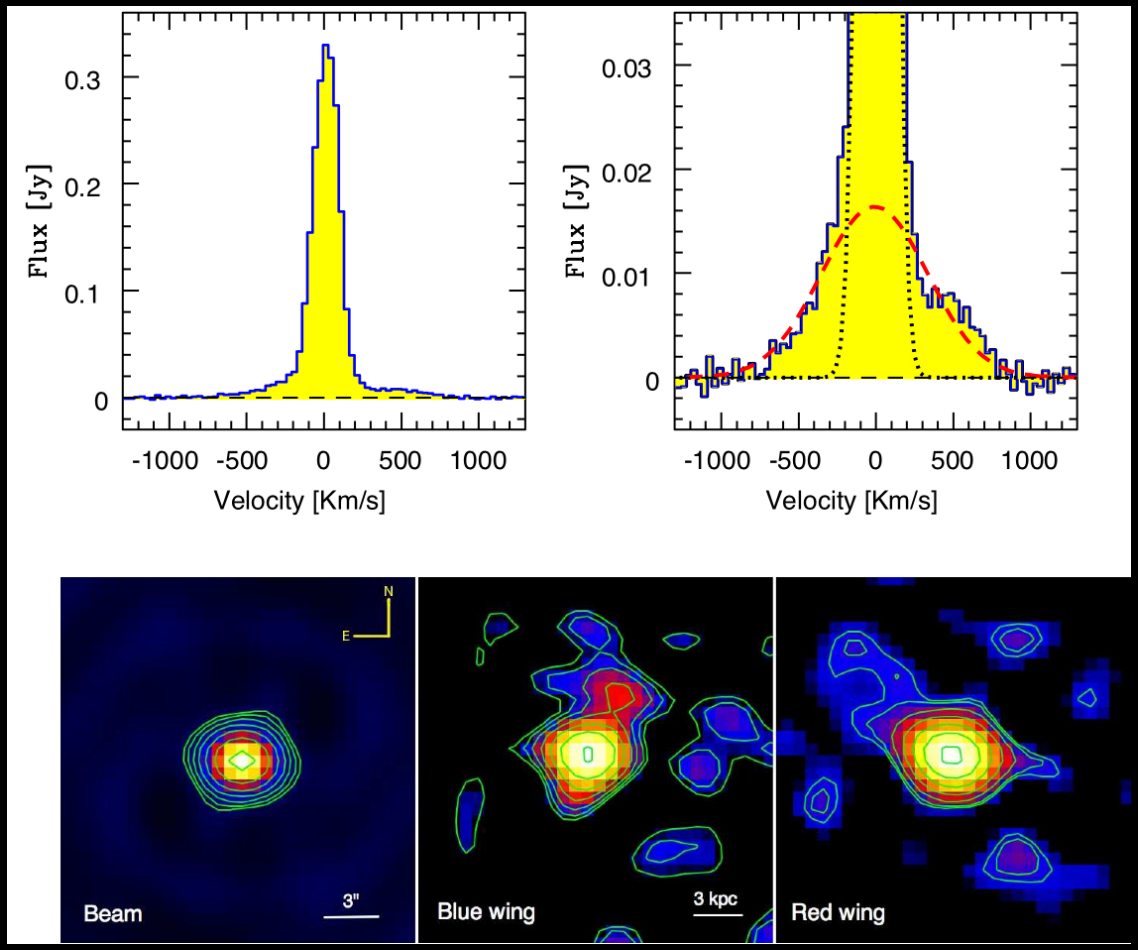


Warm Molecular Gas (~4”)

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

Powerful Quasar-driven CO Outflow in Mrk 231

(Feruglio et al. 2010)

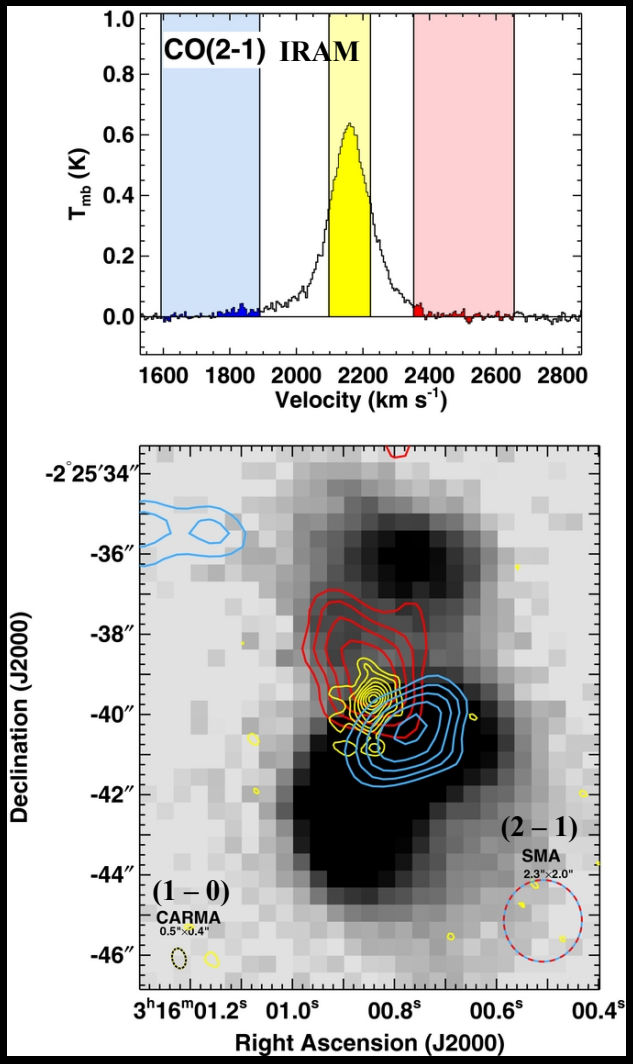


- ***IRAM: CO (J = 1-0)***
- ***V_{out} → 750 km s^{-1}***
- **Kpc scale**
- **dM/dt ~ 700 M_{sun} yr^{-1}**
- **SFR ~ 200 M_{sun} yr^{-1}**

(Na I: Rupke & SV 2011)

AGN-driven Molecular Outflow in NGC 1266?

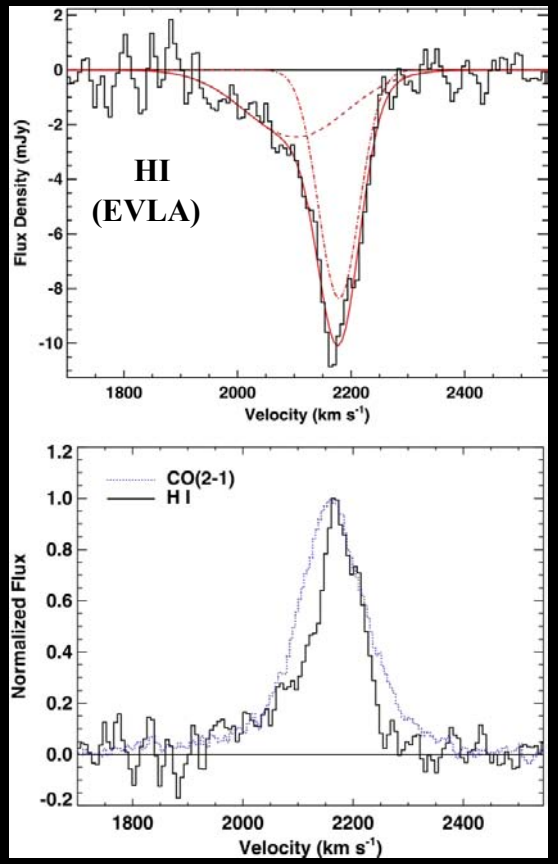
(Alatalo et al. 2011)

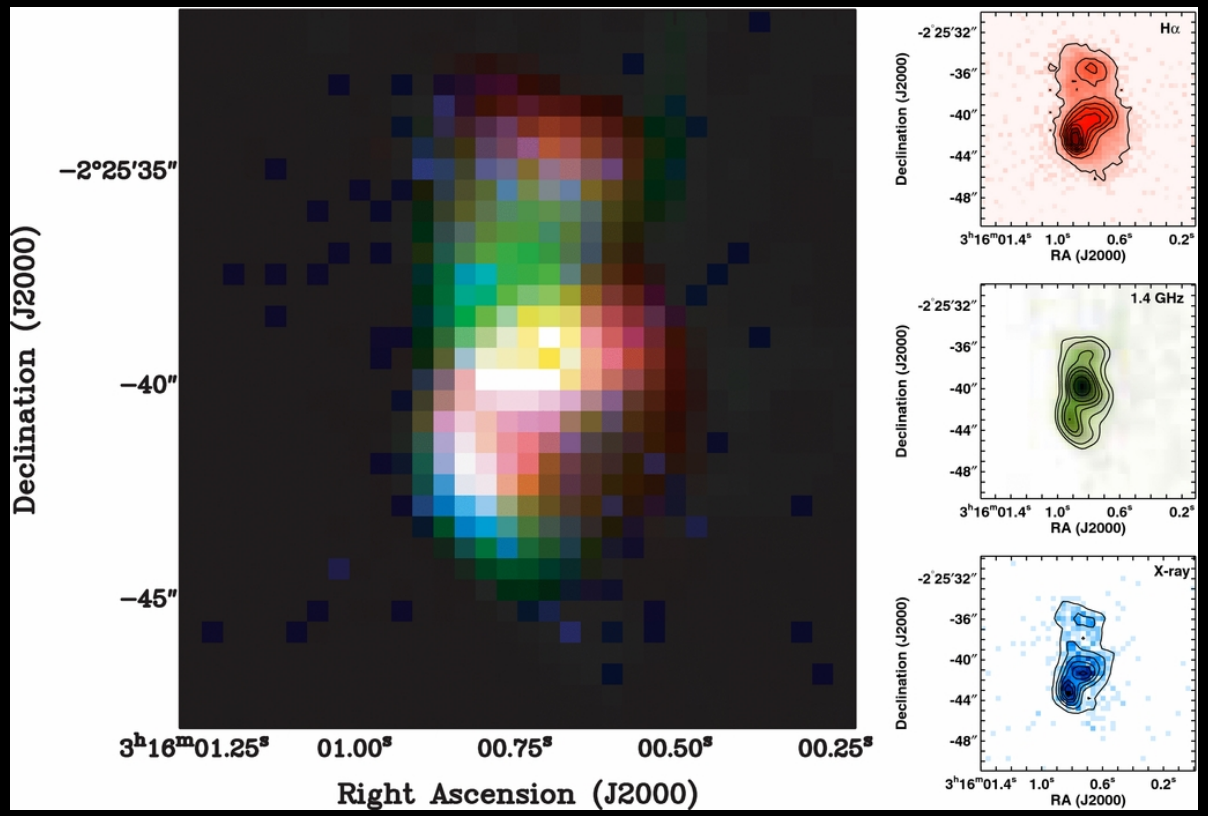


- **Host: non-interacting S0 field galaxy**
- **Nuclear disk**
  - $\Sigma(H_2) \sim 2.7 \times 10^4\ M_{sun}\ pc^{-2}$
  - $SFR \sim 0.5\text{-}2\ M_{sun}\ yr^{-1}$ (?)
  - $SFR / \Sigma(H_2) \sim$ Kennicutt-Schmidt law (?)
- **Molecular Outflow**
  - $V_{out} \sim 177\ km\ s^{-1}$
  - $dM/dt \sim 13\ M_{sun}\ yr^{-1} >> SFR$
  - τ(depletion) $\leq$ 85 Myr

Jet-driven Outflow in NGC 1266?

(Alatalo et al. 2011)



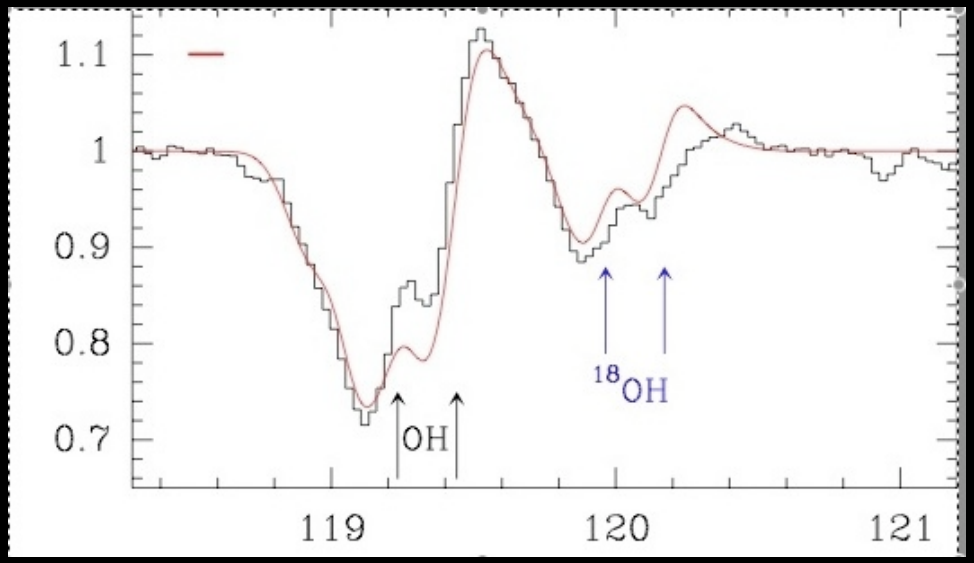


Similar to outflows in radio galaxies *(e.g., Morganti+03, 04, 05) (?)*

Massive Molecular Outflows in ULIRGs

(SHINING: Fischer et al. 2010)

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



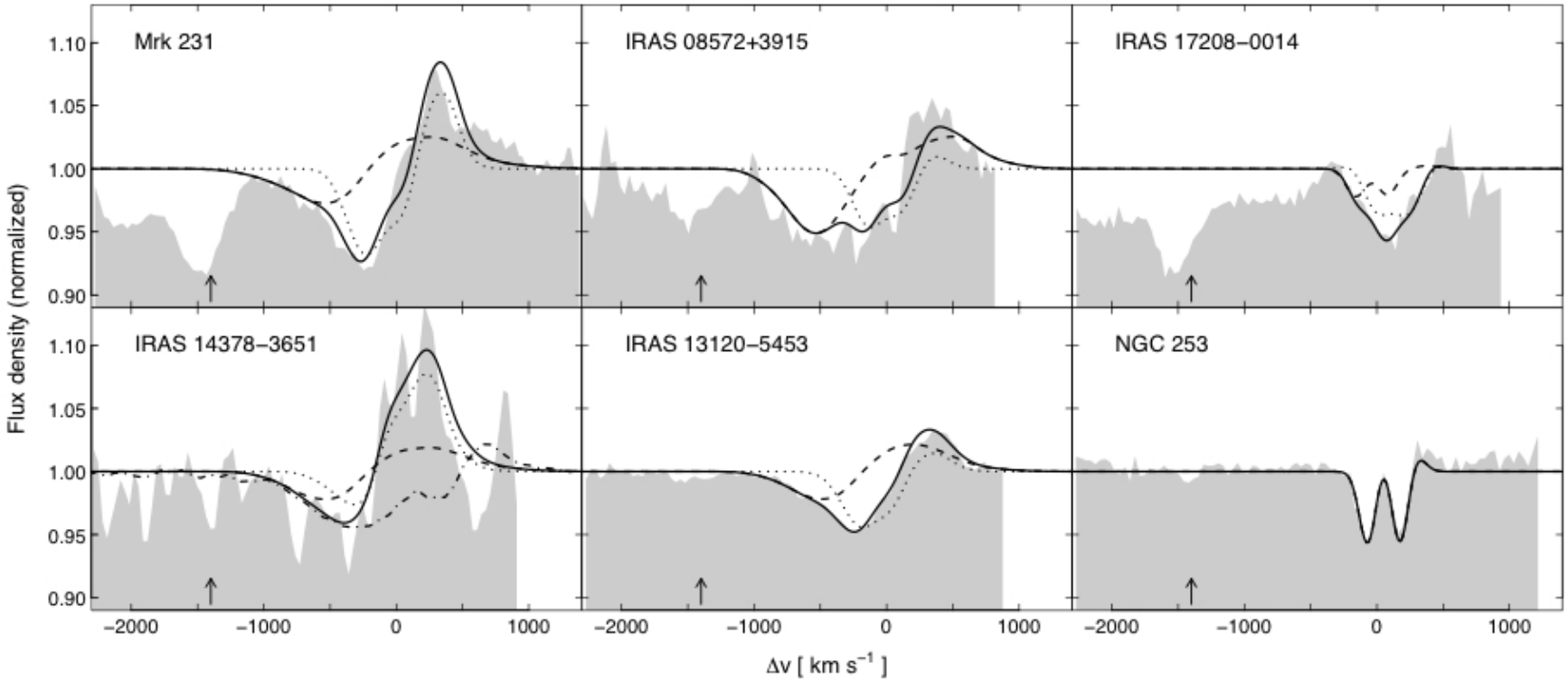
Mrk 231

- **Molecular Outflow**
  - V_{out} → *1400 km s^{-1}*
  - **M > 7 x 10^{7} M$_{sun}$ yr^{-1}**
  - **E > 10^{56} ergs**
  - **dE/dt > 1% L$_{IR}$**

Massive Molecular Outflows in ULIRGs

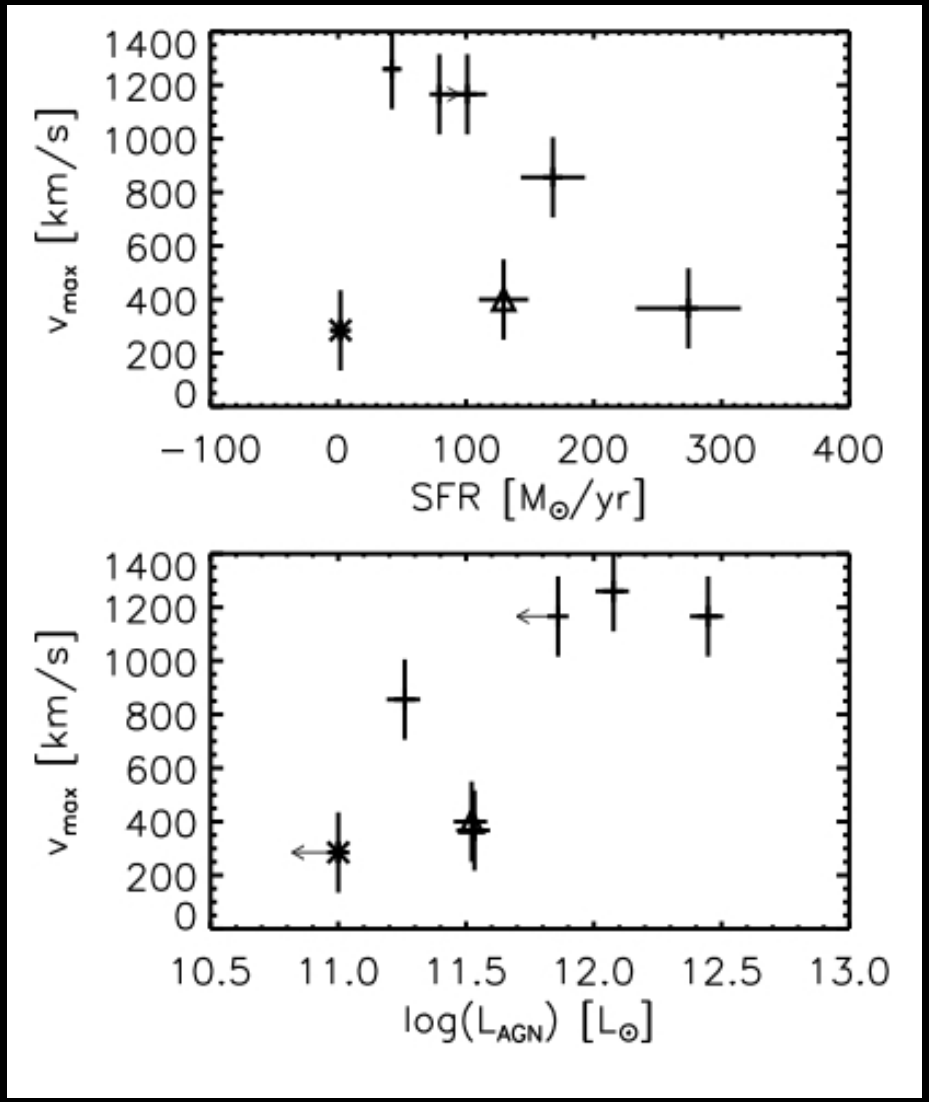
(SHINING: Sturm et al. 2011)

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



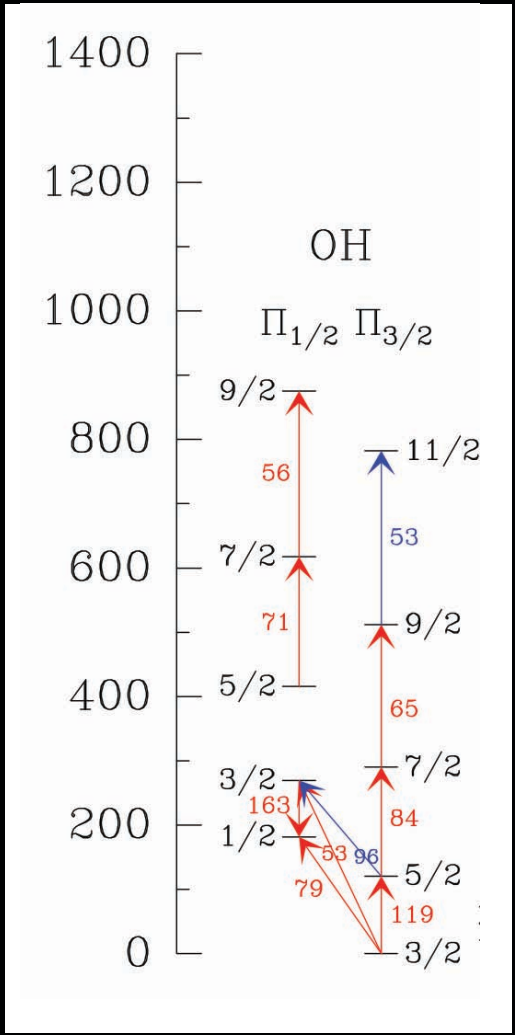
Powerful Quasar-driven Winds?

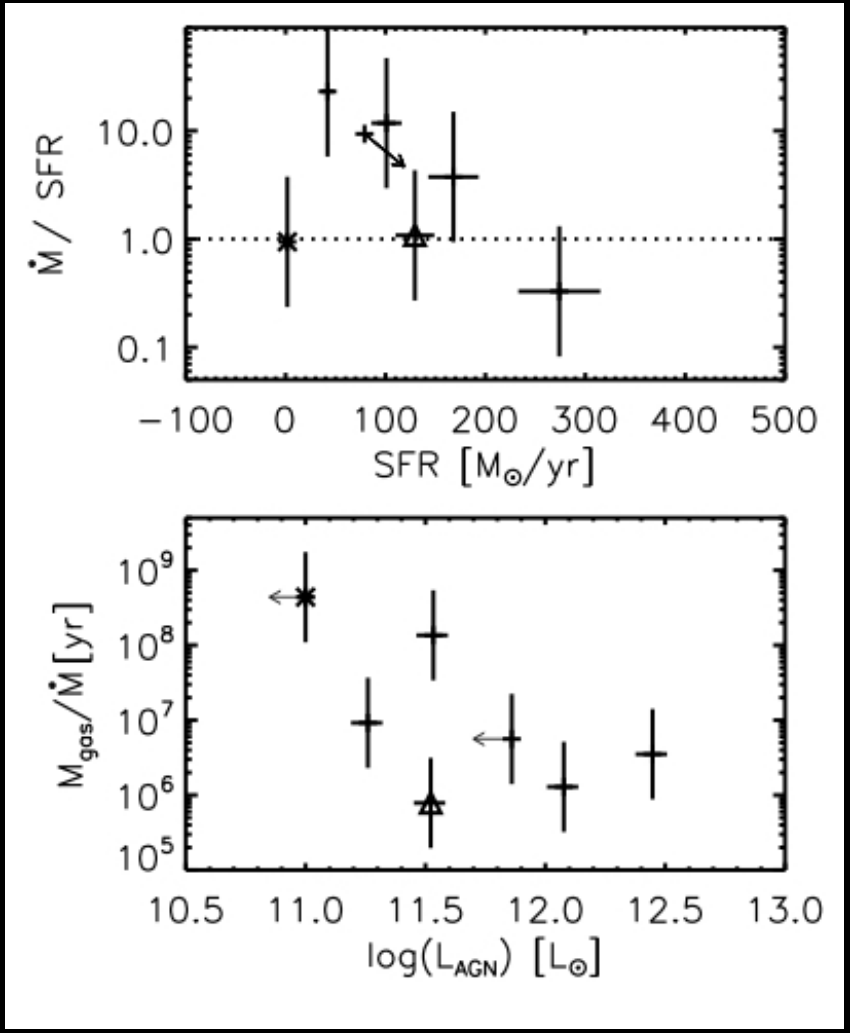
(Sturm et al. 2011)



Powerful Quasar-driven Winds?

(Sturm et al. 2011)





Summary & Prospects

- **Galactic-scale winds with masses ~ 10^6 – 10^8 M_{sun} and kinetic energies ~ 10^{56} – 10^{58} ergs are detected in nearly all ULIRGs**
- **The nearest quasar known, Mrk 231, hosts a powerful wide-angle *neutral* outflow:**
  - **V_{out} → 1100 km sec^{-1}**
  - **> 2-3 kpc**
  - **dM/dt > 2.5 x SFR**

  → Quasar-driven wind
- **Powerful *molecular* winds are detected in ~70% of ULIRGs so far**
  - **Tentative kinematic / dynamical trends with L_{AGN} suggest an AGN origin**
- **Prospects:**
  - **Neutral + ionized winds: IFUs on 8m-class telescopes**
  - **Molecular winds: *Herschel*, ALMA**
  - **Ionized winds: HST/COS + *Chandra*: 400 ksec on Mrk 231**