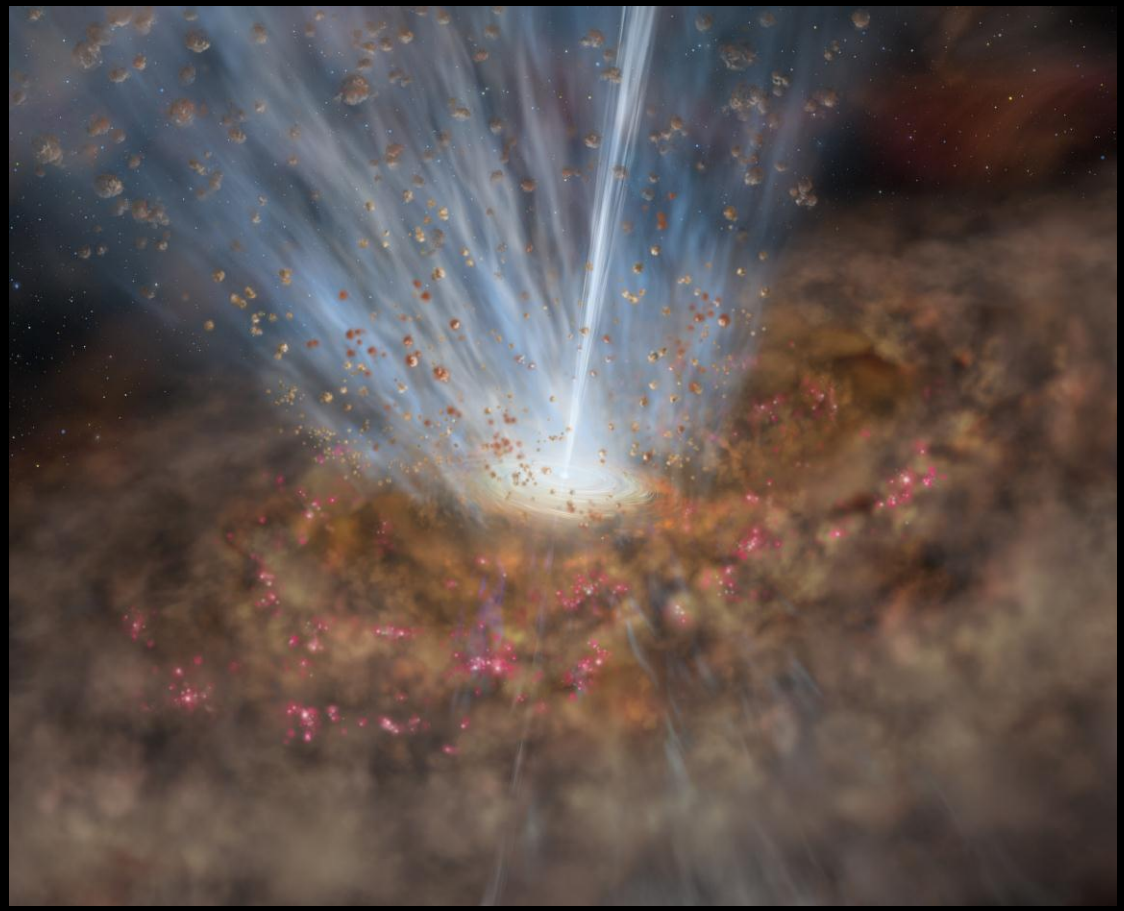
Observational Review of the Outflow Phenomena in Extragalactic Systems

S. Veilleux (U. Maryland)



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

Gemini Press Release

(Rupke & SV 2011)

Two Possible Drivers

- Starbursts:
  - **Mechanical energy / momentum from stellar winds**
  - **Mechanical energy / momentum from supernovae (~10^{51} ergs/SN)**
  - **Radiation pressure**

Scales with *Star Formation Rate*

- Active Galactic Nuclei (AGN)
  (accretion disks around supermassive black holes):
  - **Radiative heating → Compton-heated wind ($T \sim 10^6 - 10^7$ K)**
  - **Radiation pressure**
  - **Magnetic fields in accretion disks → (loosely) collimated jets in (radio-quiet) radio-loud AGN**

Scales roughly with *Mass Accretion Rate / AGN Luminosity*

Three Basic Questions

- **Their Nature**

  What are they? Which conditions trigger them? What powers them (star clusters vs BHs)? Are they nuclear or disk-wide? How energetic are they? What mass, momentum, energy, and metals do they transport? How far?

- **Their Frequency of Occurrence**

  How common were they in the past and are they now? What is their duty cycle? When did they begin to blow?

- **Their Impact**

  How important are they? What impact do they have on the nucleus, bulge, disk, halo, and dark matter distribution of the host galaxy? Are they the dominant source of feedback in galaxy evolution? How do they influence the intergalactic environment? What are their fossil signatures?

Open Issues *(Circa 2005)*

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

Theory:

1. **Modeling the energy source (starburst and 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**

Observables

- **Continuous emission**
  - ***Examples:*** **X-rays (e.g., bremsstrahlung), UV (e.g., scattered light), IR & submm (e.g., thermal), radio (e.g., synchrotron)**
  - **Location may be ambiguous**
  - **No direct kinematic information**
- **Line Emission**
  - ***Examples:*** **Lyα, [O III] 5007 Å, Hα, H_2 2.12 μm, CO mm, HI 21-cm**
  - **Kinematics may be ambiguous (or often unknown for X-ray lines)**
  - **Dependence: ionization, $EM \sim (n_{gas})^2$**
- **Line Absorption**
  - ***Examples:*** **Fe XXVI, N V/O VI, Mg II 2800 Å , Na ID 5896 Å , OH FIR, HI**
  - **Kinematics are in principle unambiguous**
  - **Dependence: ionization, N_{gas} (for unsaturated lines)**

Plan

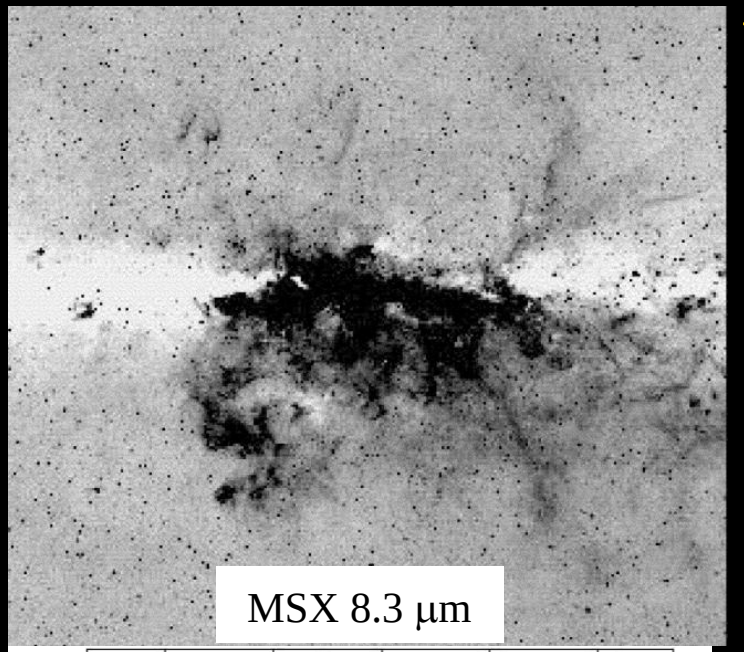
- **Recent results at $\lambda < 1$ μm**
- **Recent results at $\lambda > 1$ μm**
- **Open issues (*circa 2012*)**

Disclaimer

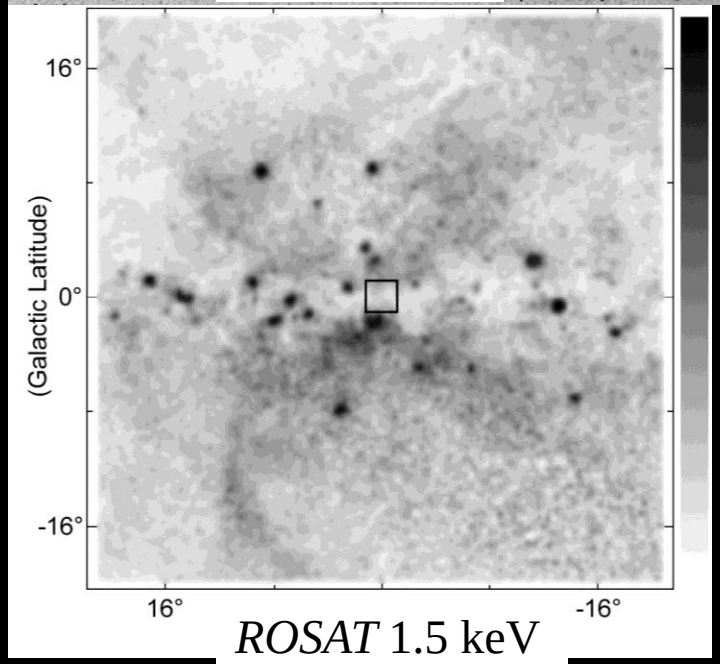
$\lambda <$ 1 μm Material Not Covered Here

- ***X-rays:*** **Spatially unresolved warm absorbers in AGN**
  (e.g., Winter 2010; Winter, SV, et al. 2012; also Tombesi's poster P51)
- ***UV:*** **Spatially unresolved outflows in distant quasars**
  (Arav's talk on Sunday; also Borguet's and Edmonds' posters P3, P9)
- ***Optical:*** **Spatially resolved line-emitting outflows in AGN**
  (Crenshaw's talk on Monday; also Fischer's & Villar-Martin's posters P10, P53)

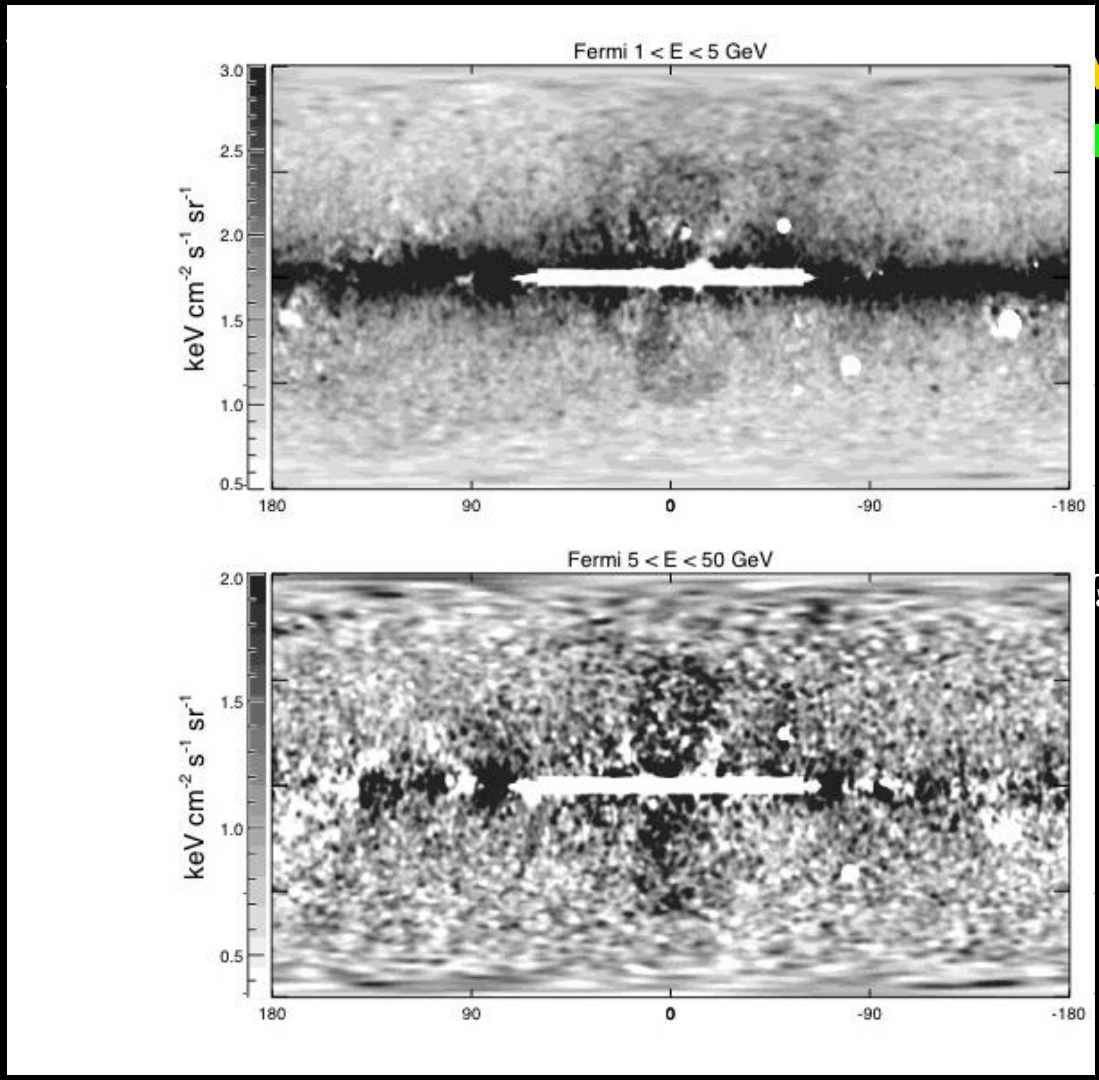
← ~ 3° →



MSX 8.3 μm

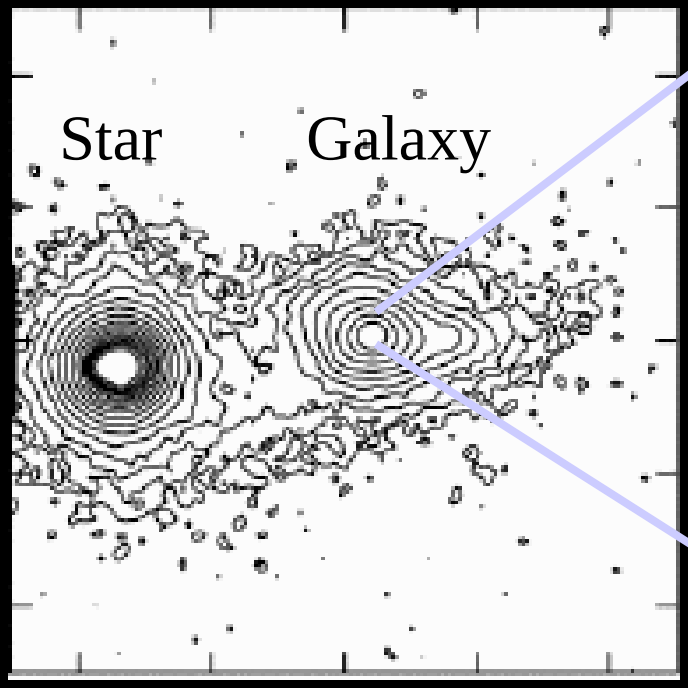


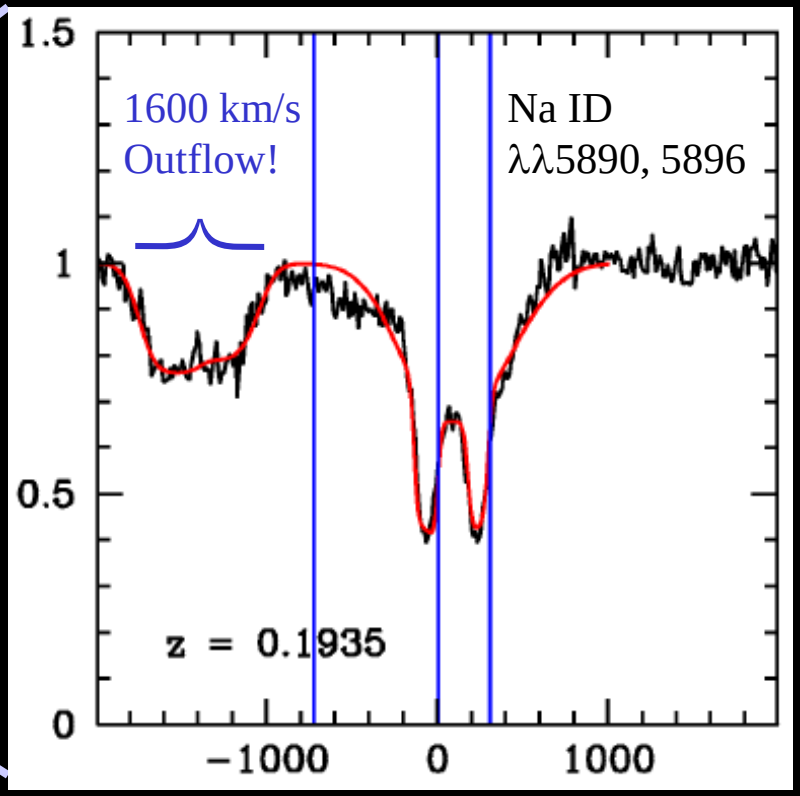
ROSAT 1.5 keV



- **Two large γ-ray bubbles:** ***Su's talk on Sunday***
  - **Fermi-LAT** ***(Su+10; Crocker+11)***
  - **Correlated w/ WMAP "Haze"** ***(Finkbeiner+04)***

Statistics on *Neutral* Galactic Winds @ $z = 0 - 0.5$

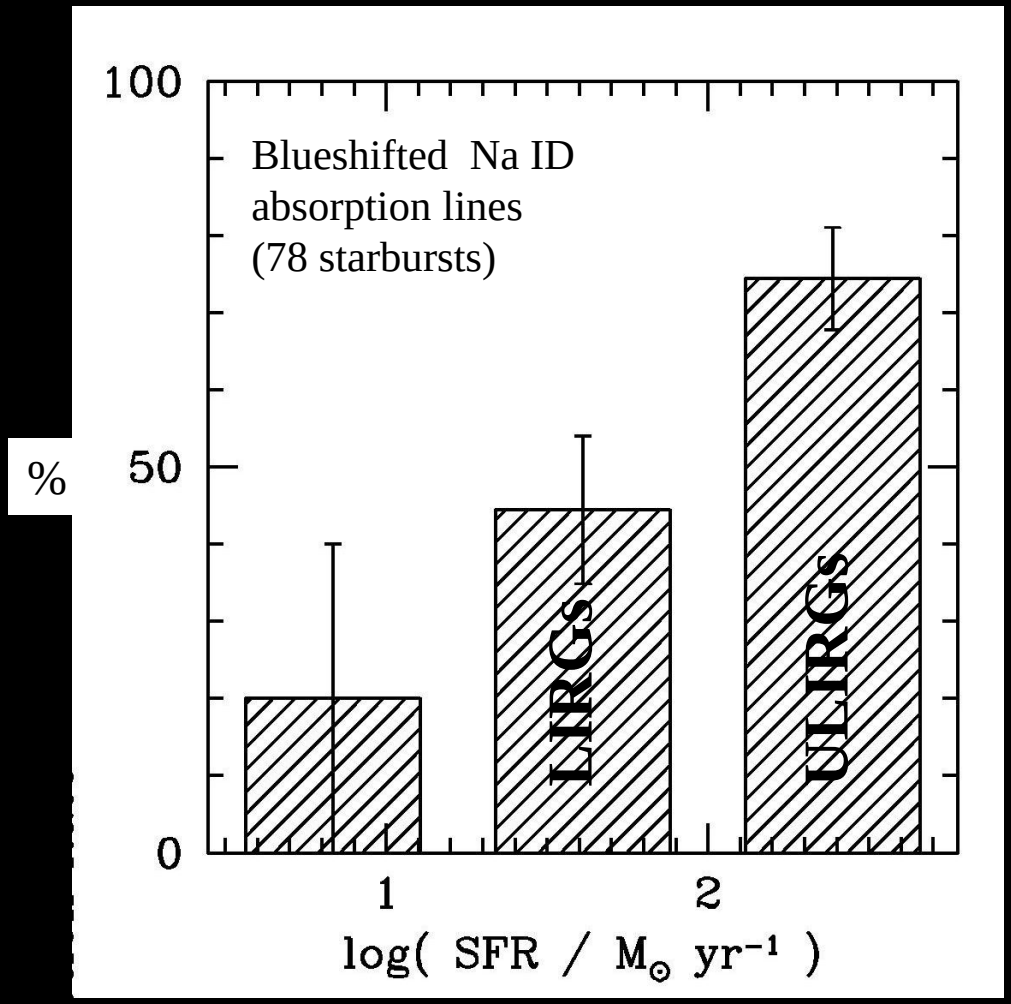




Rupke, SV, & Sanders (2002, 2005abc); Rupke & SV (2005);
AGN: Krug, Rupke, & SV (2010); Winter, SV et al. (in prep)

also Heckman et al. (2001), Martin (2005, 2006), Sato et al. (2009)

Wind Detection Rate in Local Starbursts

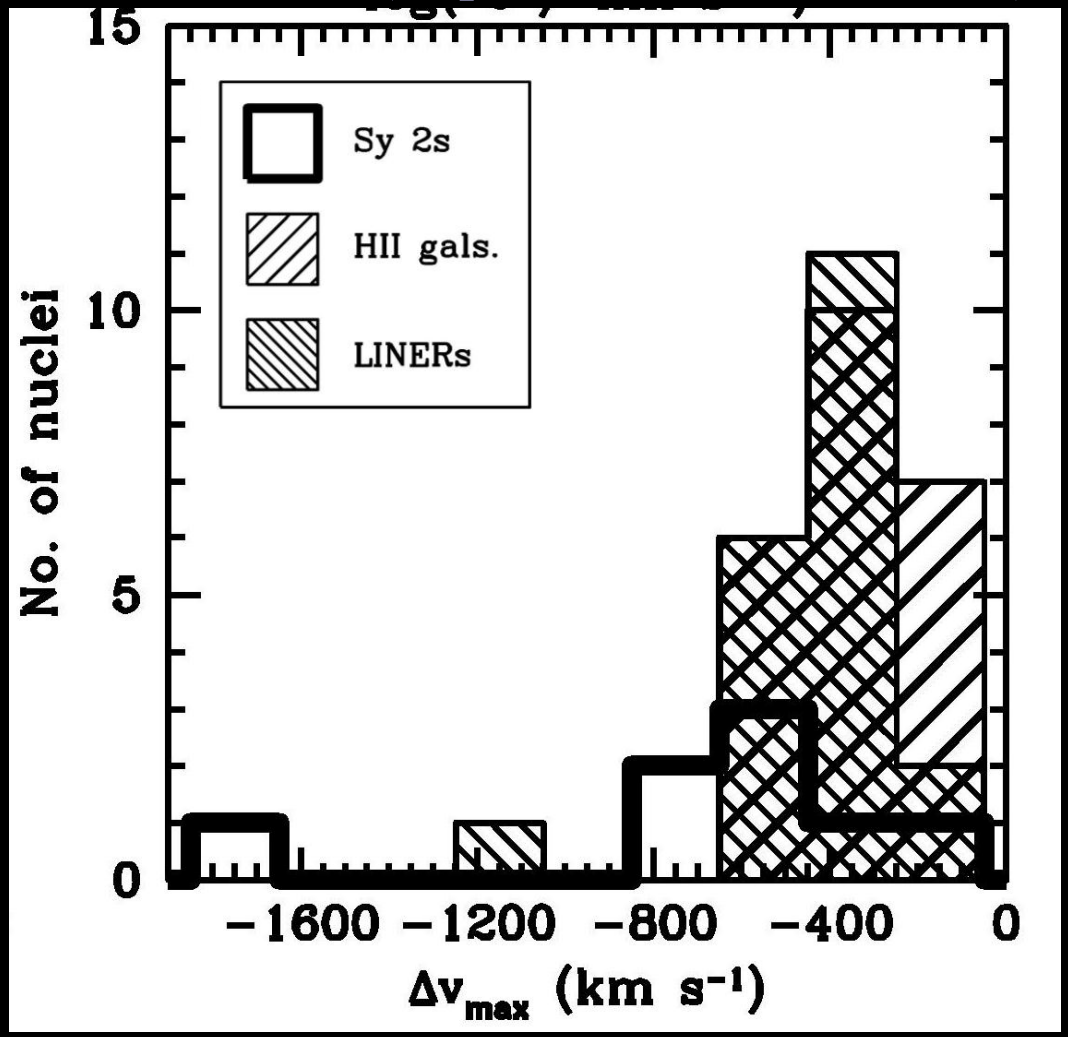


(Rupke+05ab)

All also have SFRD > 0.1 M_{sun} yr^{-1} kpc^{-2}

Outflow Velocities of Neutral Gas

(Rupke+05abc; Martin 05,06)



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

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

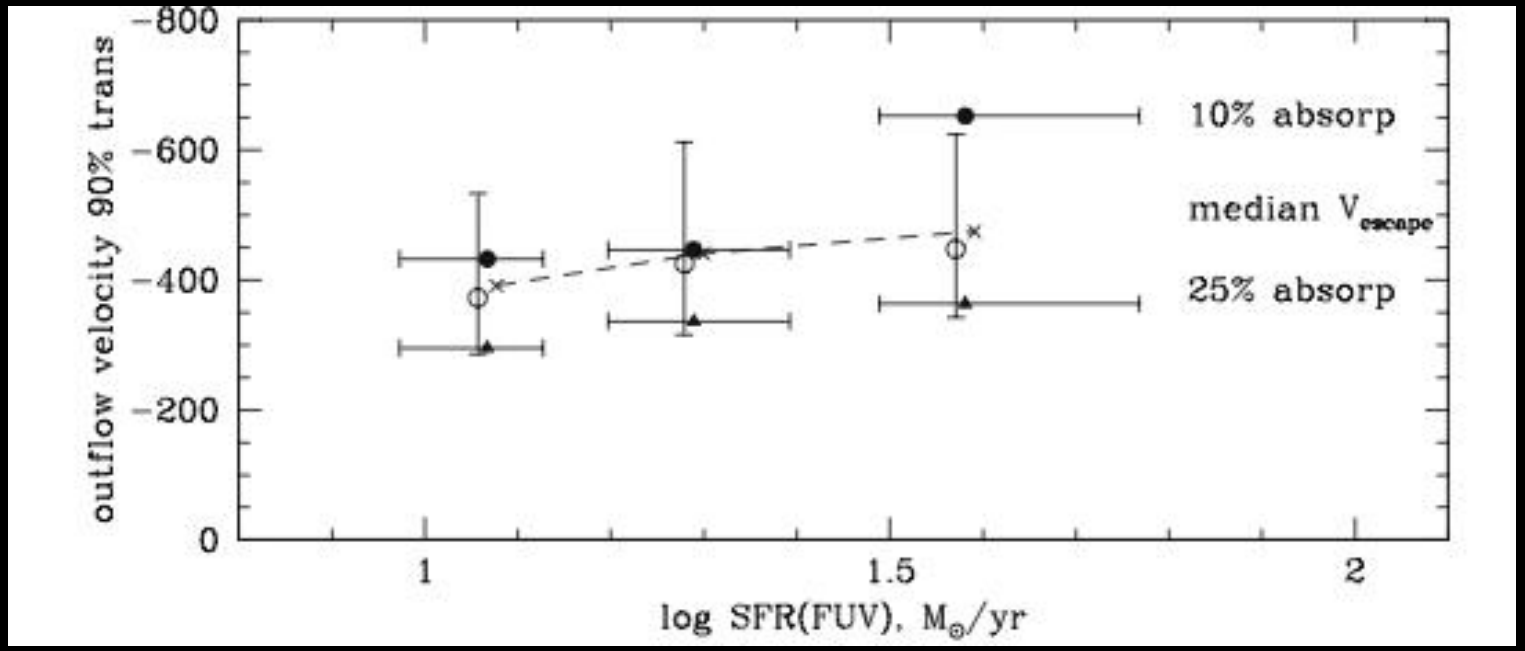
$f_{esc} \sim 5\text{–}20\%$
(if no halo drag)

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

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

Winds are ubiquitous in z ~ 1 – 3 star-forming galaxies

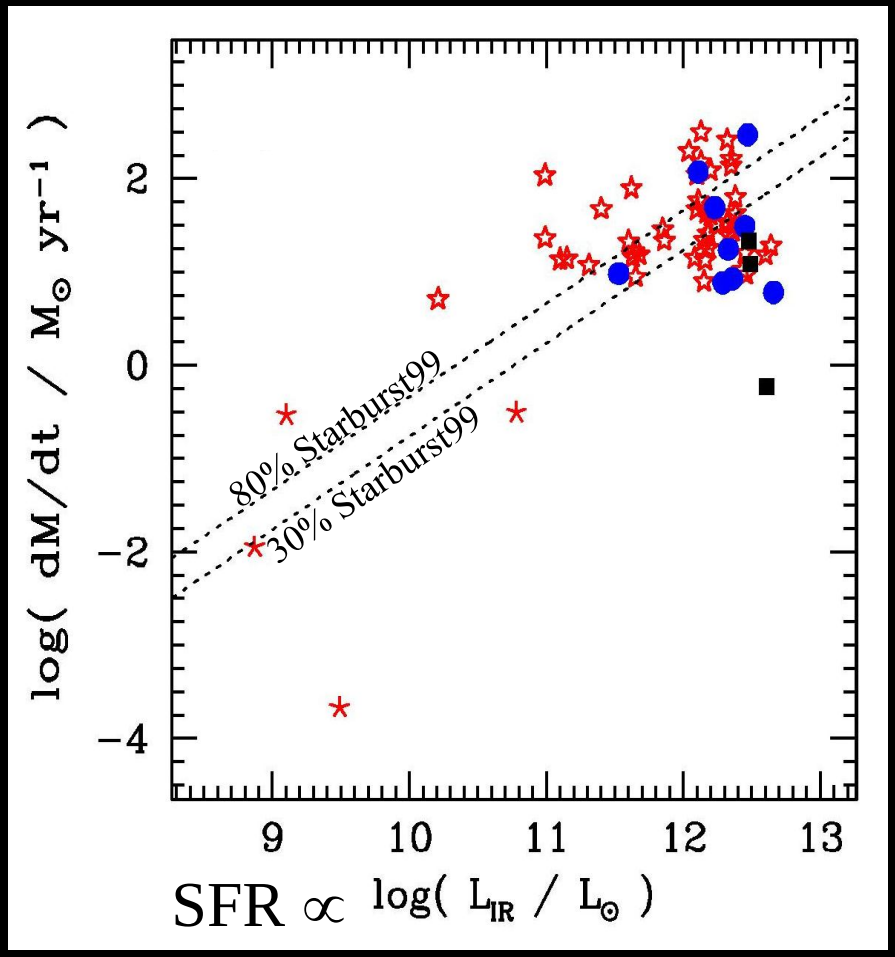
- ***Example*: DEEP2 z ~ 1.4 galaxies, using Mg II λλ2796, 2803 in absorption**
- **All have SFRD > 0.1 M_{sun} yr^{-1} kpc^{-2} *(as in local galaxies)***
- **Wind velocities scale w/ SFR, M_*, V_{escape} (e.g., V_{out} ~ $SFR^{0.3}$ *as in local galaxies)***

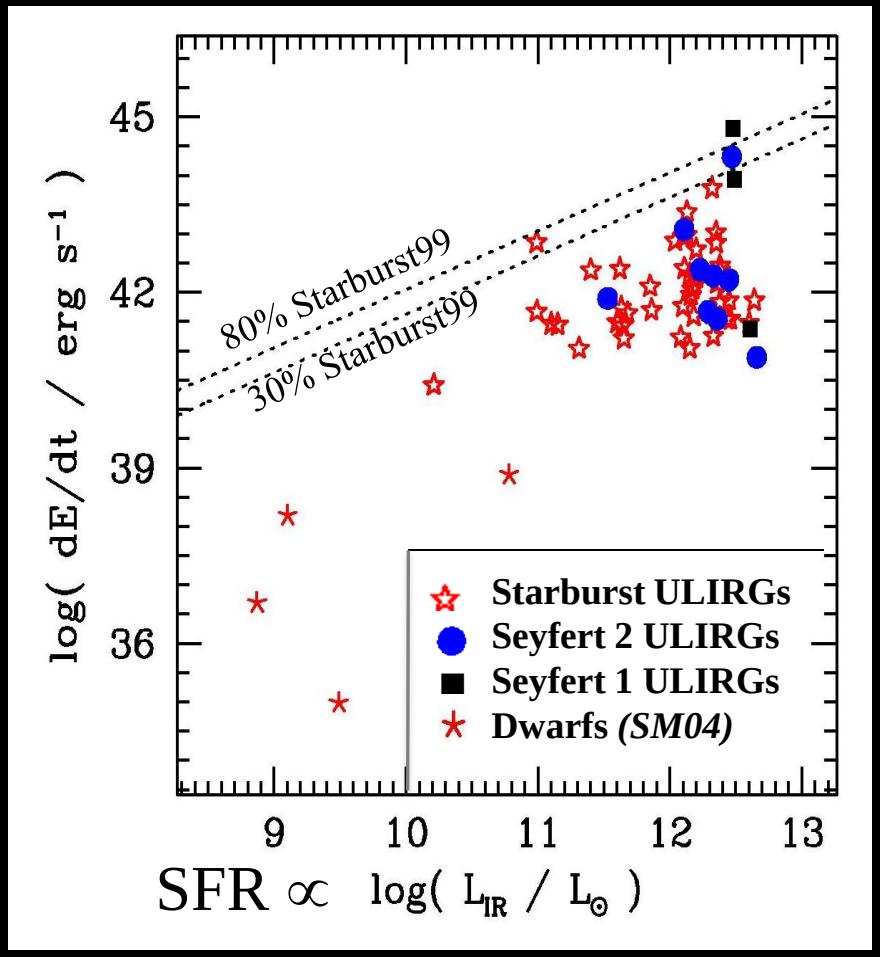


(Weiner+09)

Local winds have a profound effect on the hosts

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



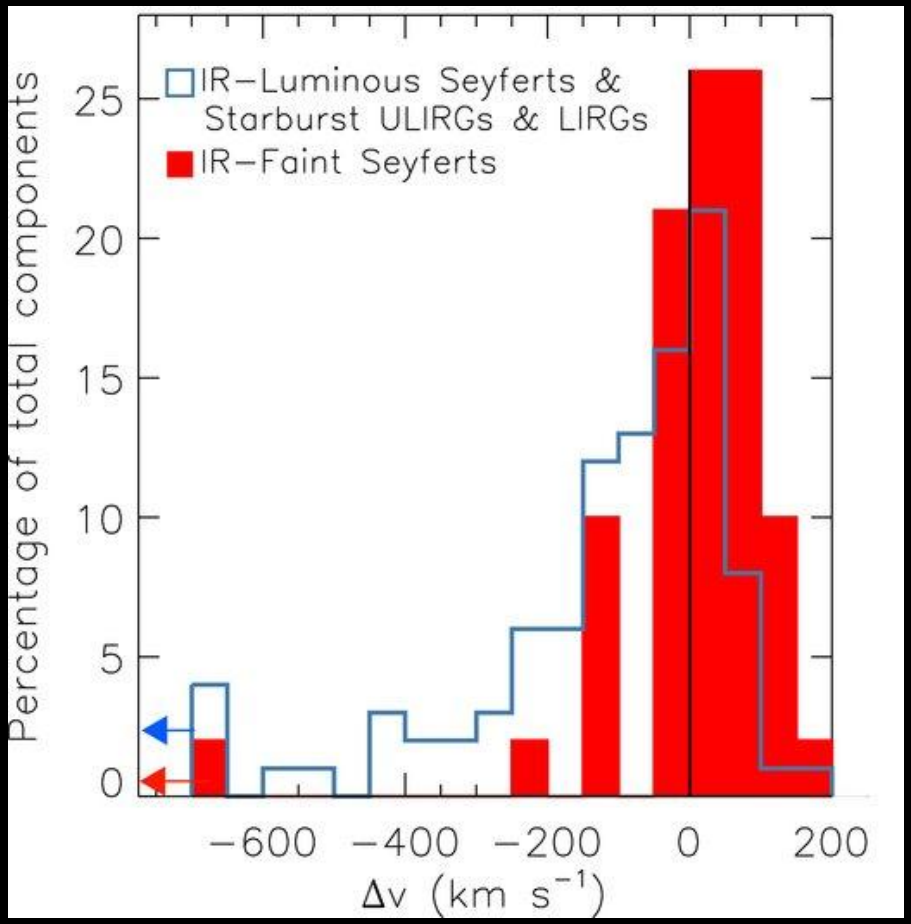


(Rupke+05abc)

IR-Faint "Pure" Seyferts

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

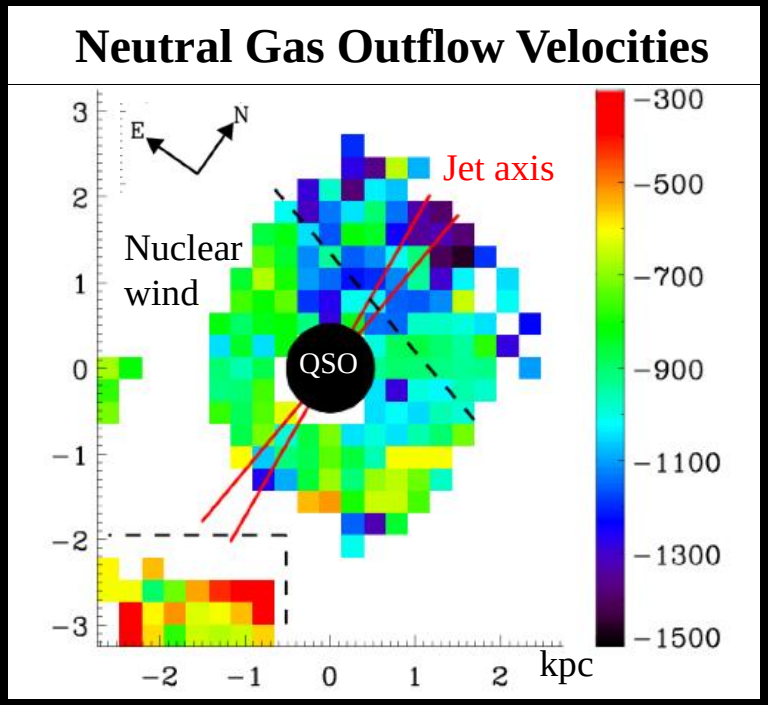
IR-faint AGN have fewer and weaker winds than IR-bright AGN

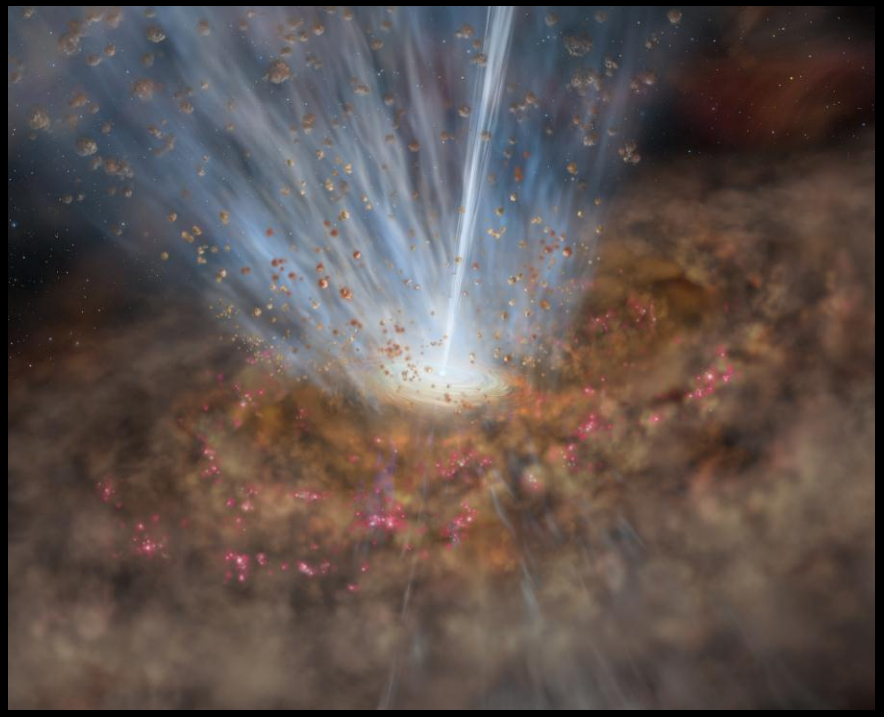


(biases? Being revisited on the BAT AGN: ***Winter, SV+12, in*** *prep*)

Powerful Wind in IR-Bright Quasar Mrk 231

(Rupke & SV 2011)





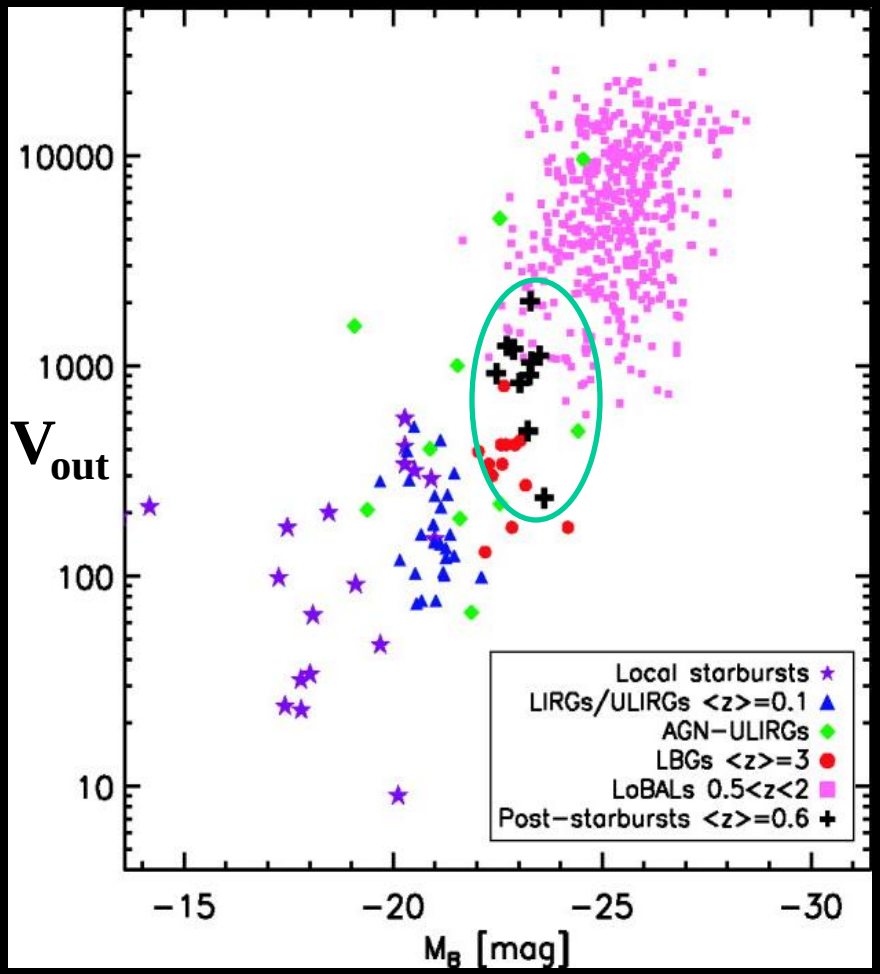
Gemini Press Release

- **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 ~ 1% L_{AGN}**

(Rupke's talk on Tuesday)

Luminous Post-Starburst Galaxies at z ~ 0.6

(Tremonti+07)

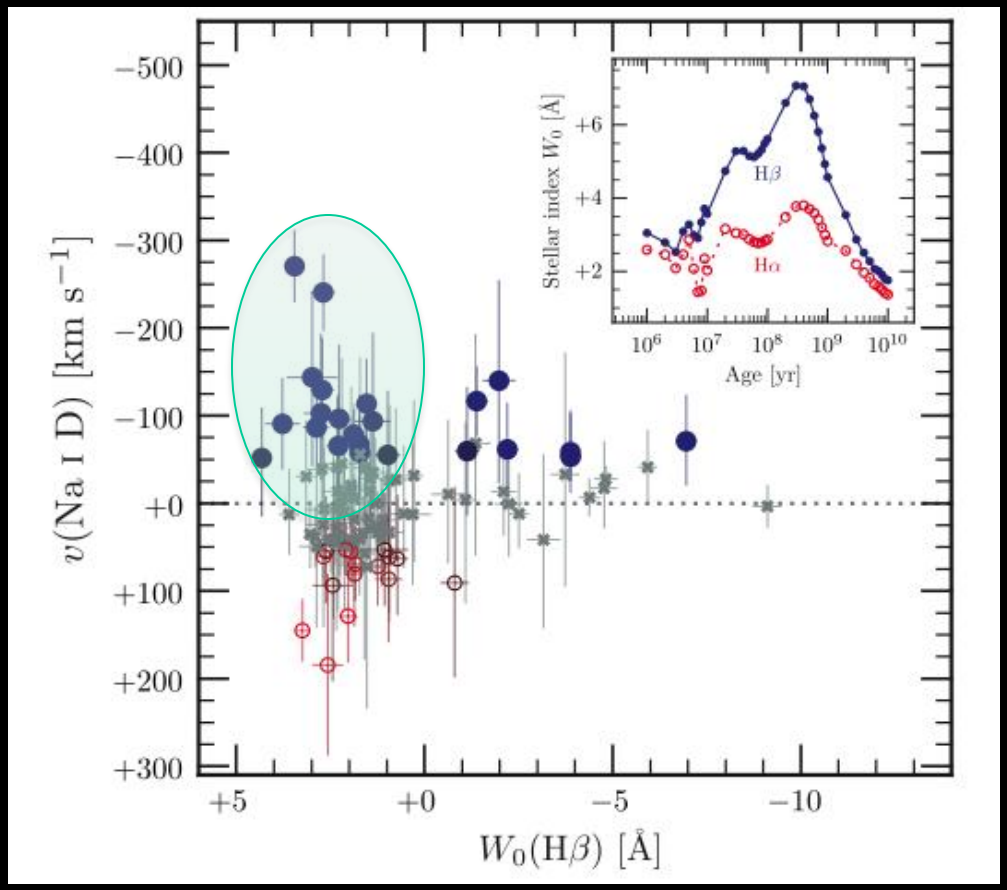


- **Sample:** 14 massive K+A galaxies from SDSS with $M_* \sim 10^{11}\ M_{sun}$
- **Results:** Winds in 10 systems with $V_{wind} \sim 490 – 2020$ km s^{-1}
- **Possible interpretation:** Fossil AGN winds launched ~100 Myr ago during peak of activity?

Wind Relics in More Typical Post-Starburst Galaxies

(Sato+09; Coil, Weiner+11)

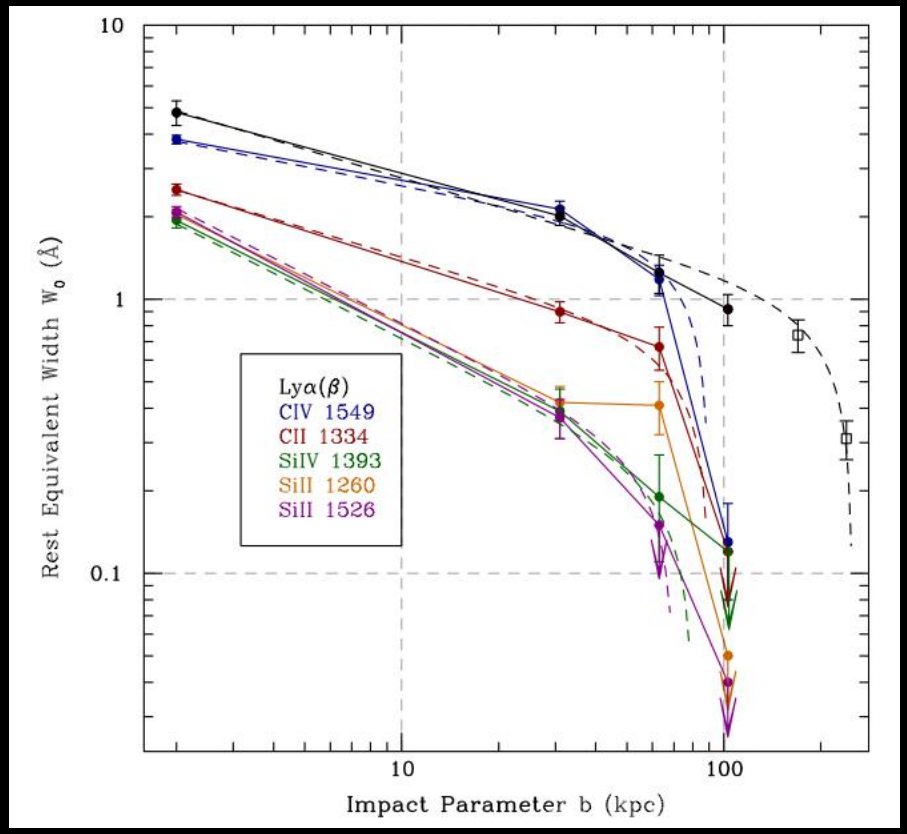
- **Fewer detections of outflows at 0.1 < z < 0.9**
- **V_{out} ~ 100 – 400 km s^{-1}**
- **Outflow outlives the starburst, but no need for AGN driver**



Circumgalactic Medium: Size of Winds?

2 < z < 3

(Steidel+10: 500 close angular pairs)

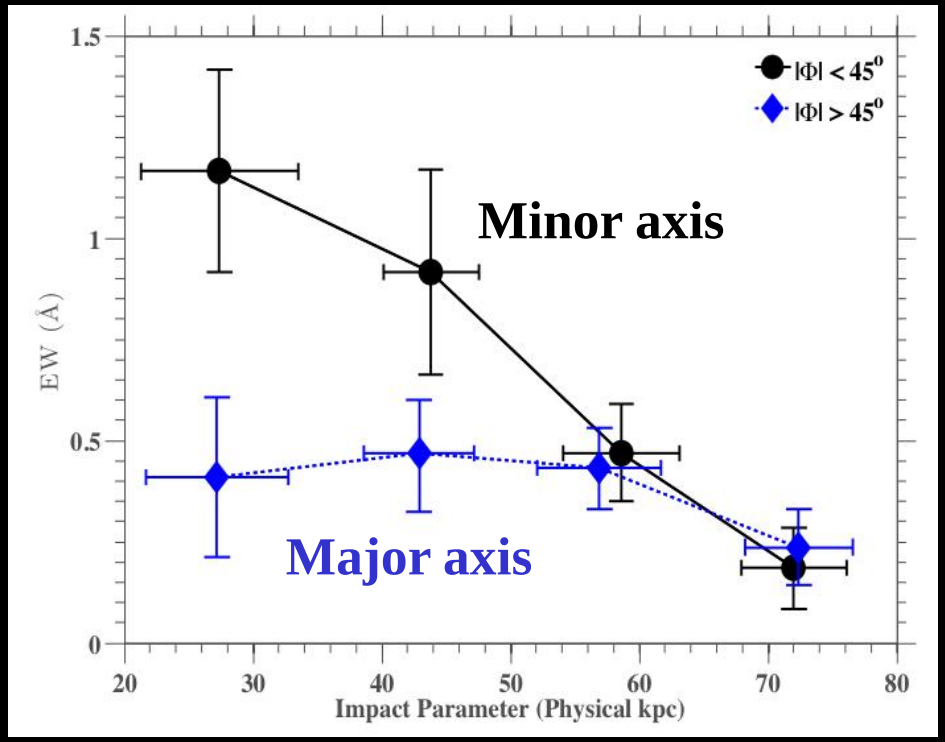


- Kinematics are *not* consistent with cool infalling material
- Outflow velocity increases monotonically with distance from host: $V_{max} \sim 800$ km s^{-1}
- $M_{CGM} \sim 3 \times 10^{10} M_{sun}$
- $dM_{CGM}/dt \sim 200\ M_{sun}\ yr^{-1}$

Circumgalactic Medium: Size of Winds?

0.5 < z < 0.9

(Bordoloi+11, zCOSMOS: ~4000 galaxies using 5000 background galaxies)



Strong azimuthal dependence of EW(Mg II) within 50 kpc of inclined disks

→ **Strongly bipolar outflows aligned along disk rotation axis?**

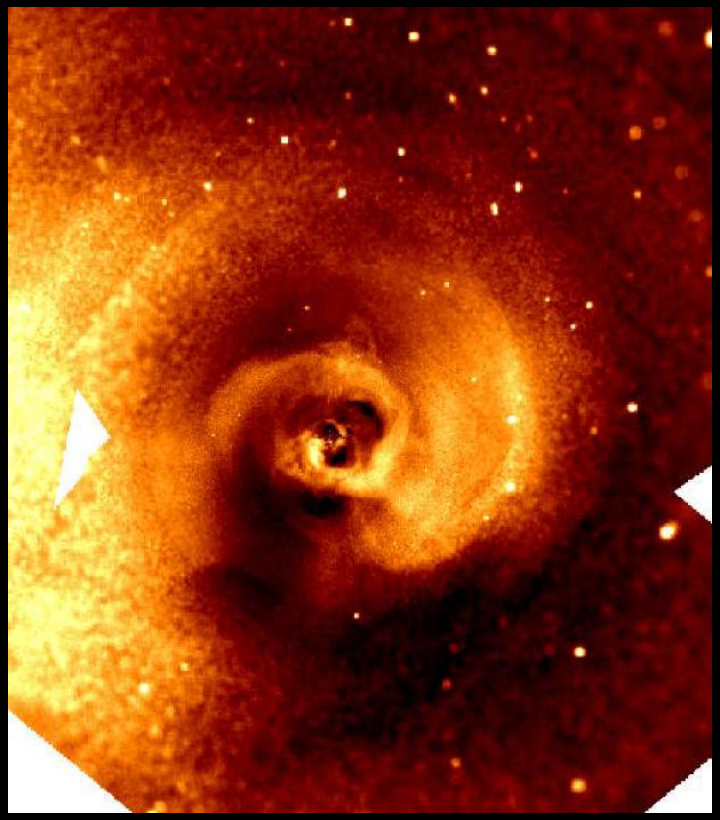
Plan

- **Recent results at $\lambda < 1$ μm**
- **Recent results at $\lambda > 1$ μm**
- **Open issues (*circa 2012*)**

Disclaimer

λ > 1 μm Material Not Covered Here

- **Powerful jets from radio galaxies affect thermodynamics of ICM in galaxy clusters** ***(Rupen's talk on Monday; Russell's talk on Tuesday; also Holt's poster P18)***



Perseus Cluster

X-rays

(Fabian+11)

~100 kpc

Disclaimer

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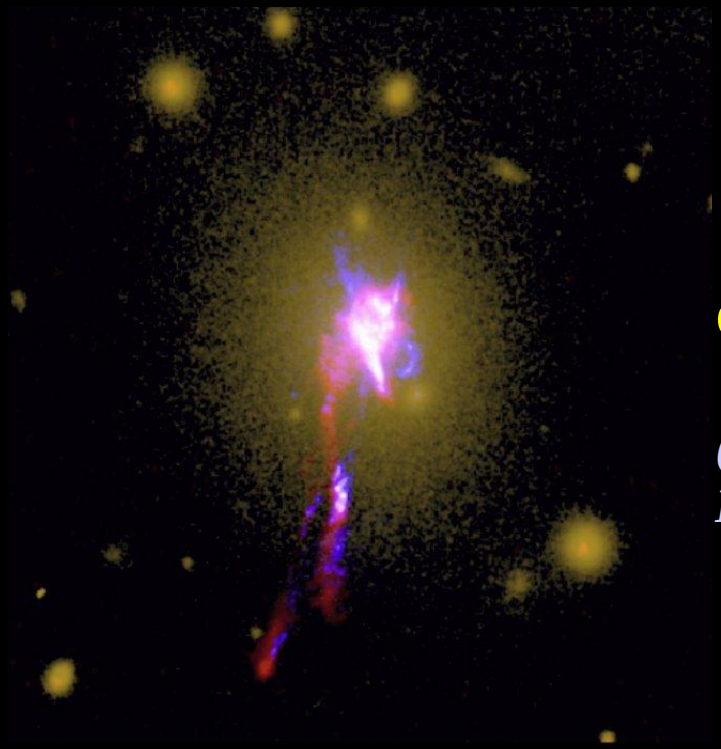
- **Powerful jets from radio galaxies affect thermodynamics of ICM in galaxy clusters** ***(Rupen's talk on Monday; Russell's talk on Tuesday; also Holt's poster P18)***



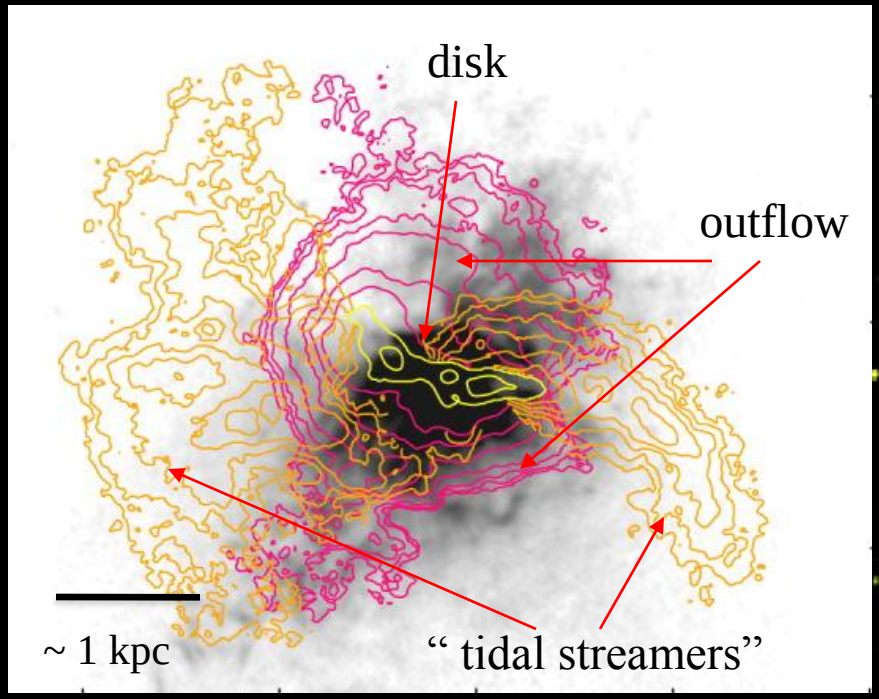
Abell 1795

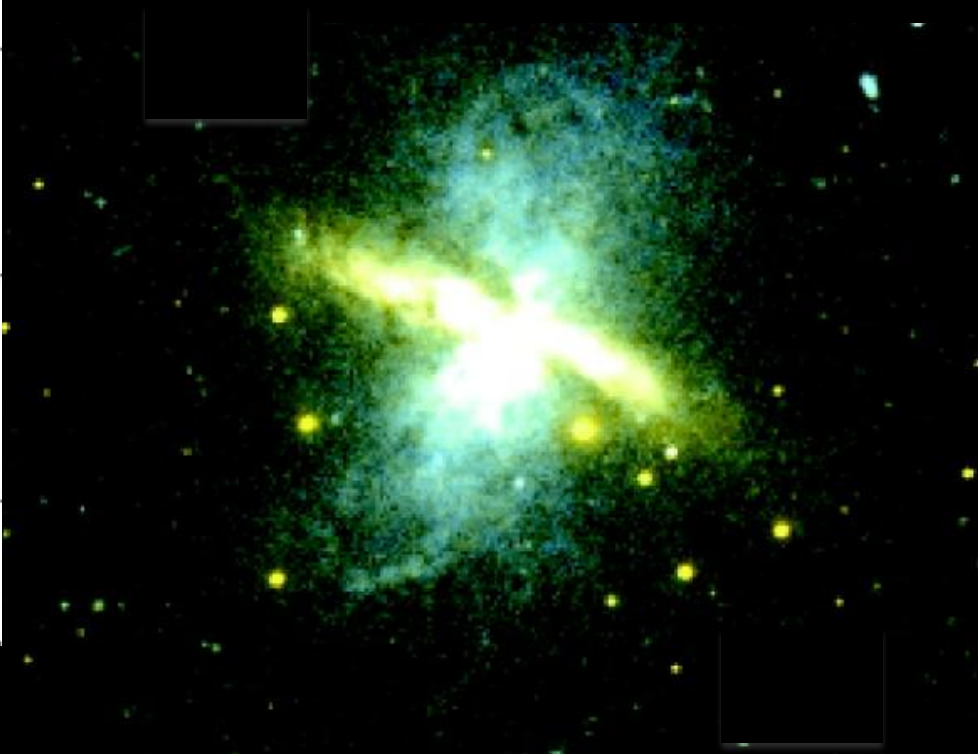
Old stars Hα FUV

(McDonald+SV 2009; McDonald, SV+10, 11ab, 12)

~50 kpc

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





Cold Molecular Gas (~3.6”)

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

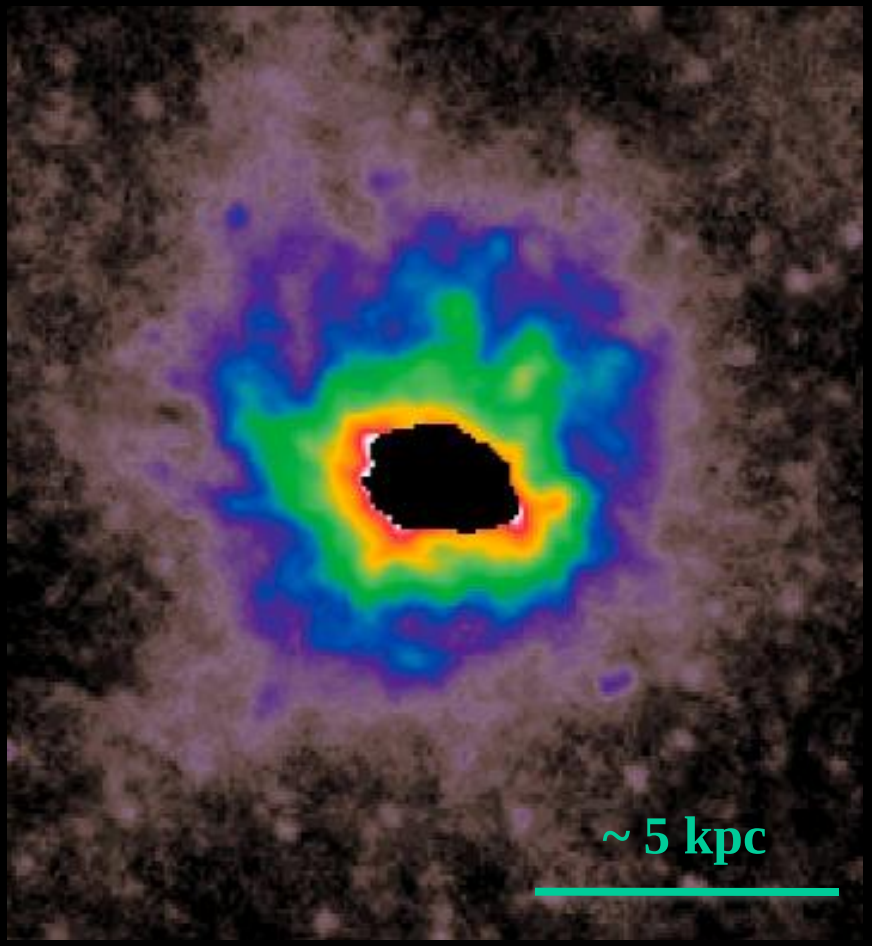
Dust Scattering

(GALEX: Hoopes et al. 2005)

Dust Outflows of M82

Warm Dust (PAH 8 μm)

(Spitzer: Engelbracht et al. 2006)

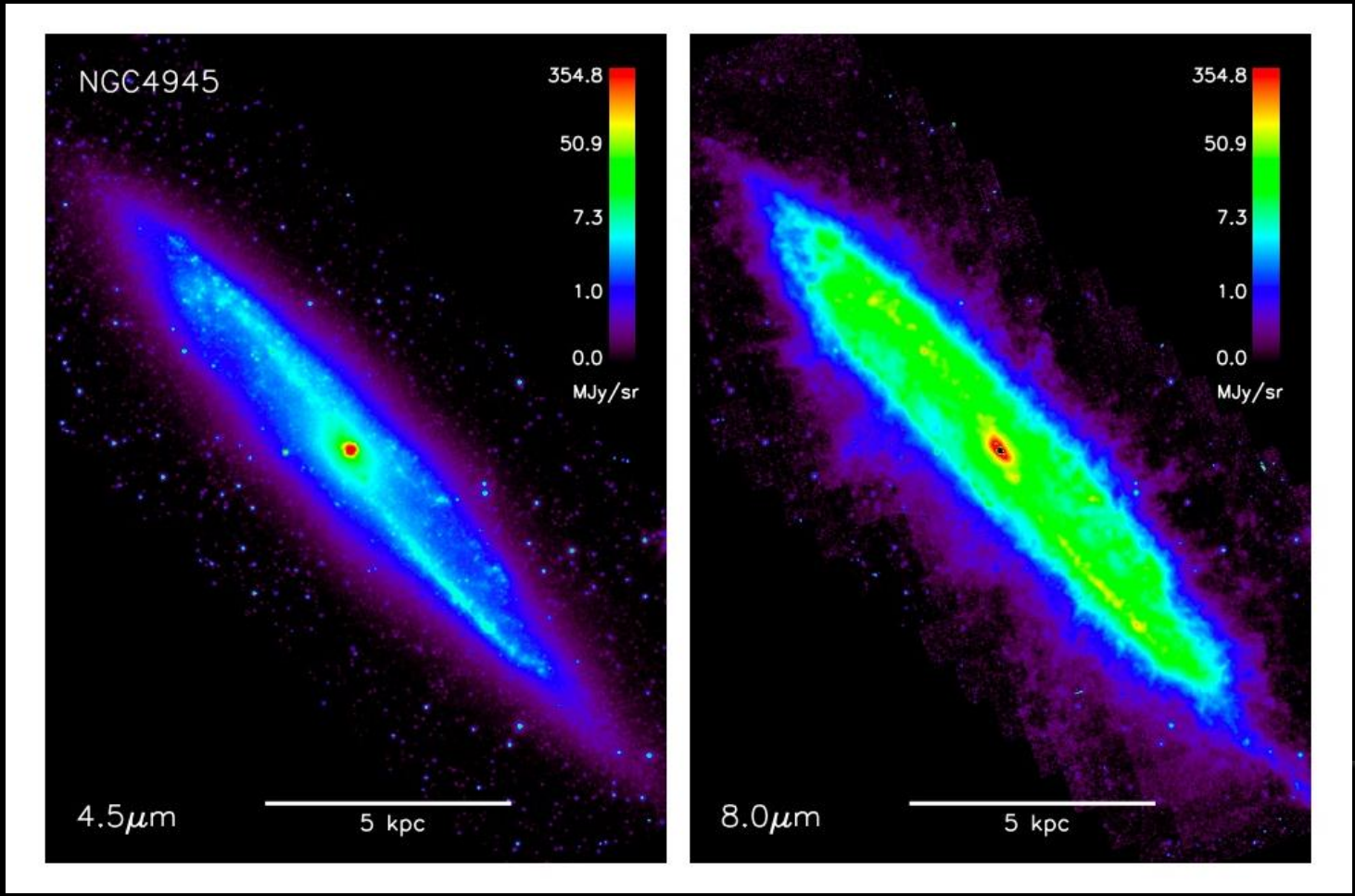


Cold Dust (250 μm)

(Herschel: Roussel et al. 2010)

Dust Outflows in Nearby Galaxies

(McCormick, SV, & Rupke 2012 in prep)

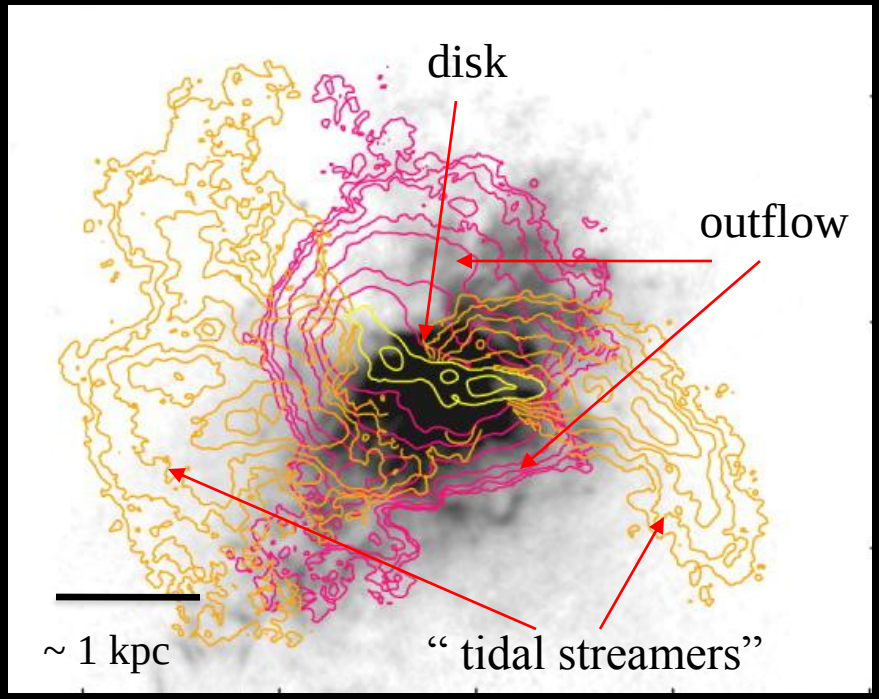


Stars

Warm Dust (PAH 8 μm)

Molecular Outflows of M82

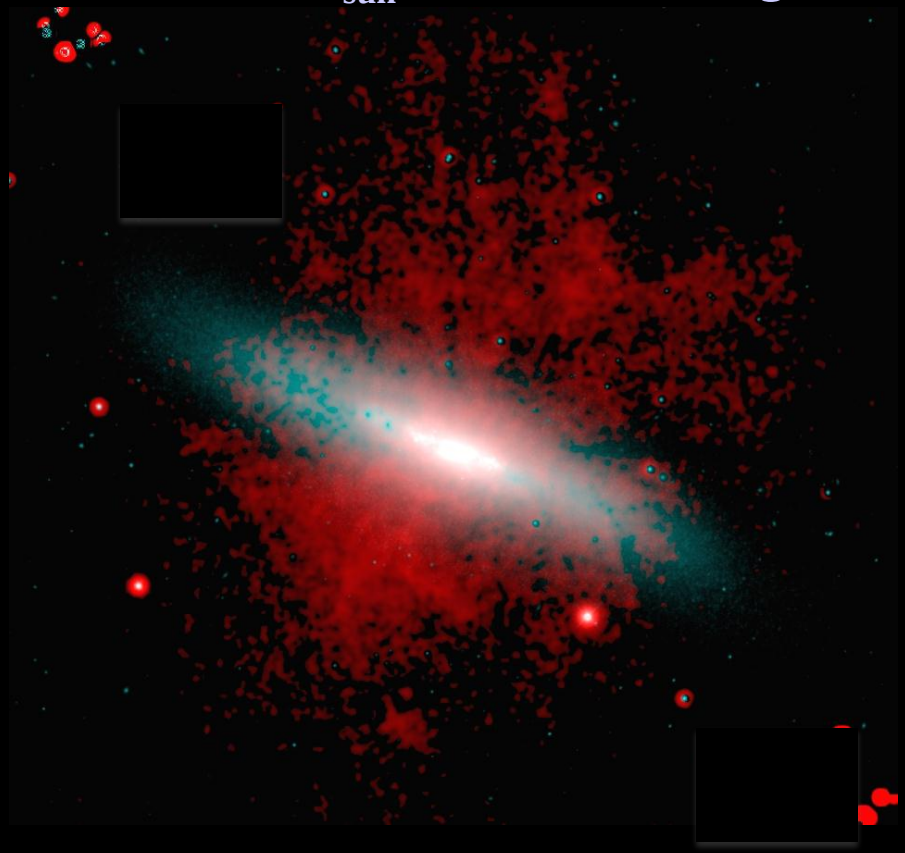
$M \sim 3 \times 10^8\ M_{sun}$ $E \sim 1 \times 10^{55}$ ergs



Cold Molecular Gas (~3.6”)

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

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

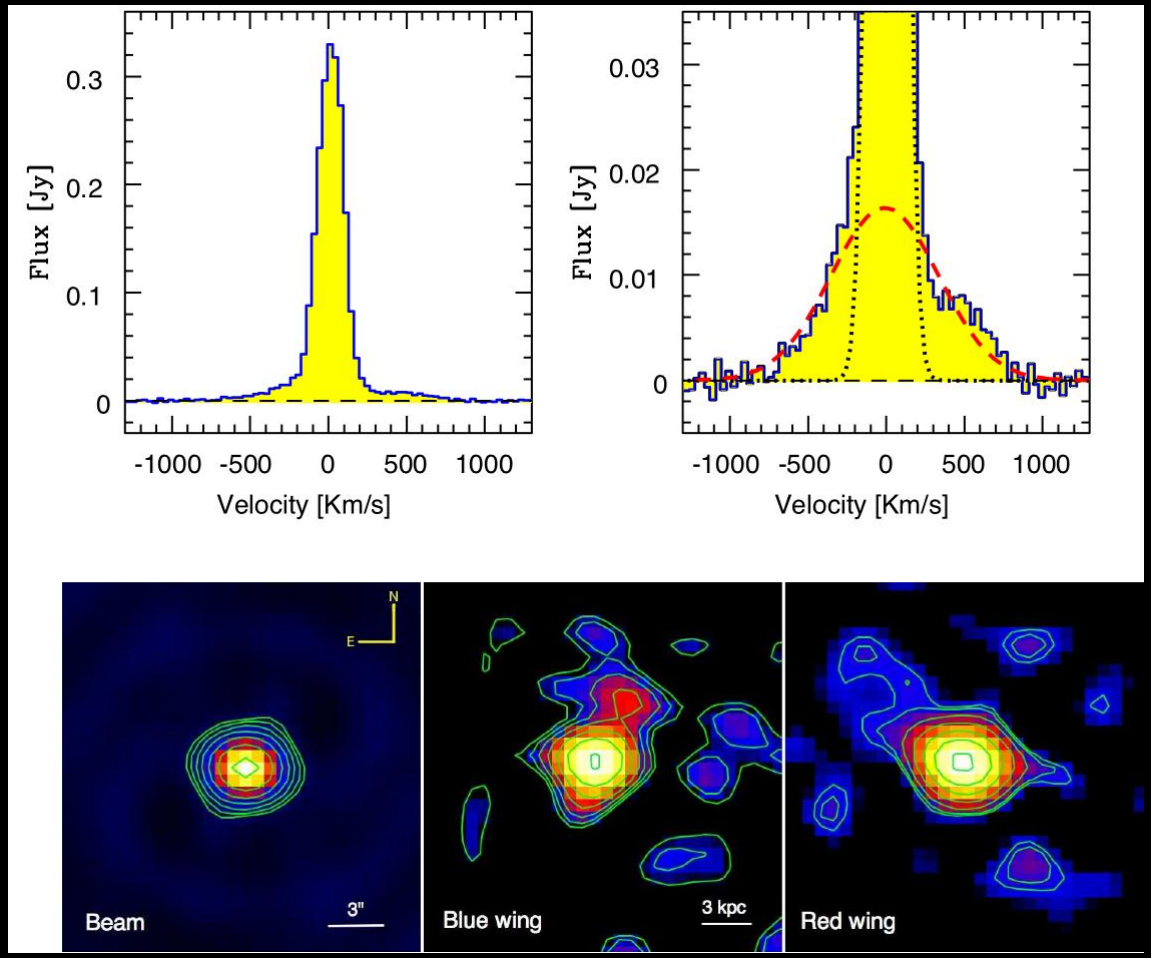


Warm Molecular Gas (~4”)

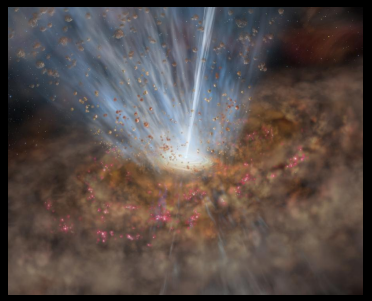
(H_2 2.12 um: SV, Rupke, & Swaters ’09)

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}**



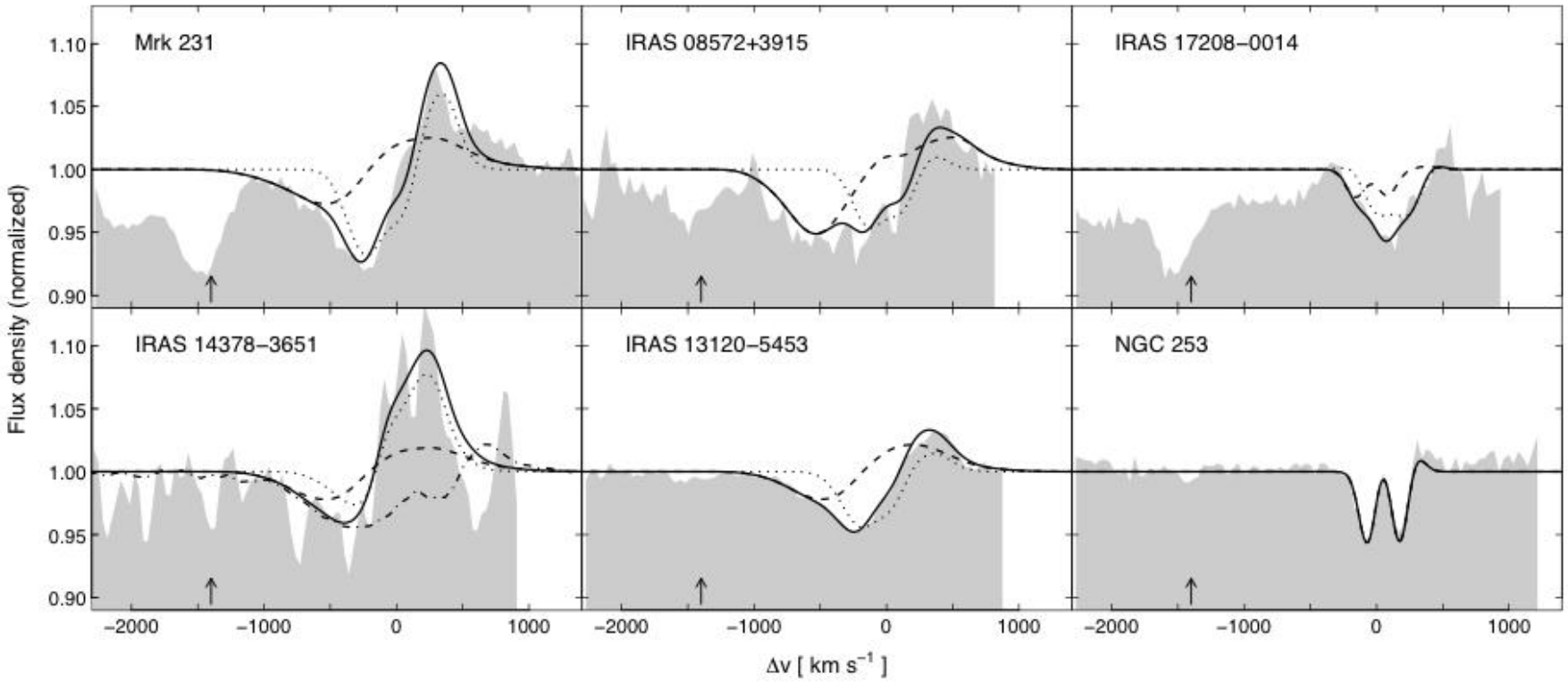
(Na I: Rupke & SV 2011)

(also NGC 1266: Alatalo et al. 2011;Alatalo's talk on Tuesday)

Massive Molecular Outflows in ULIRGs

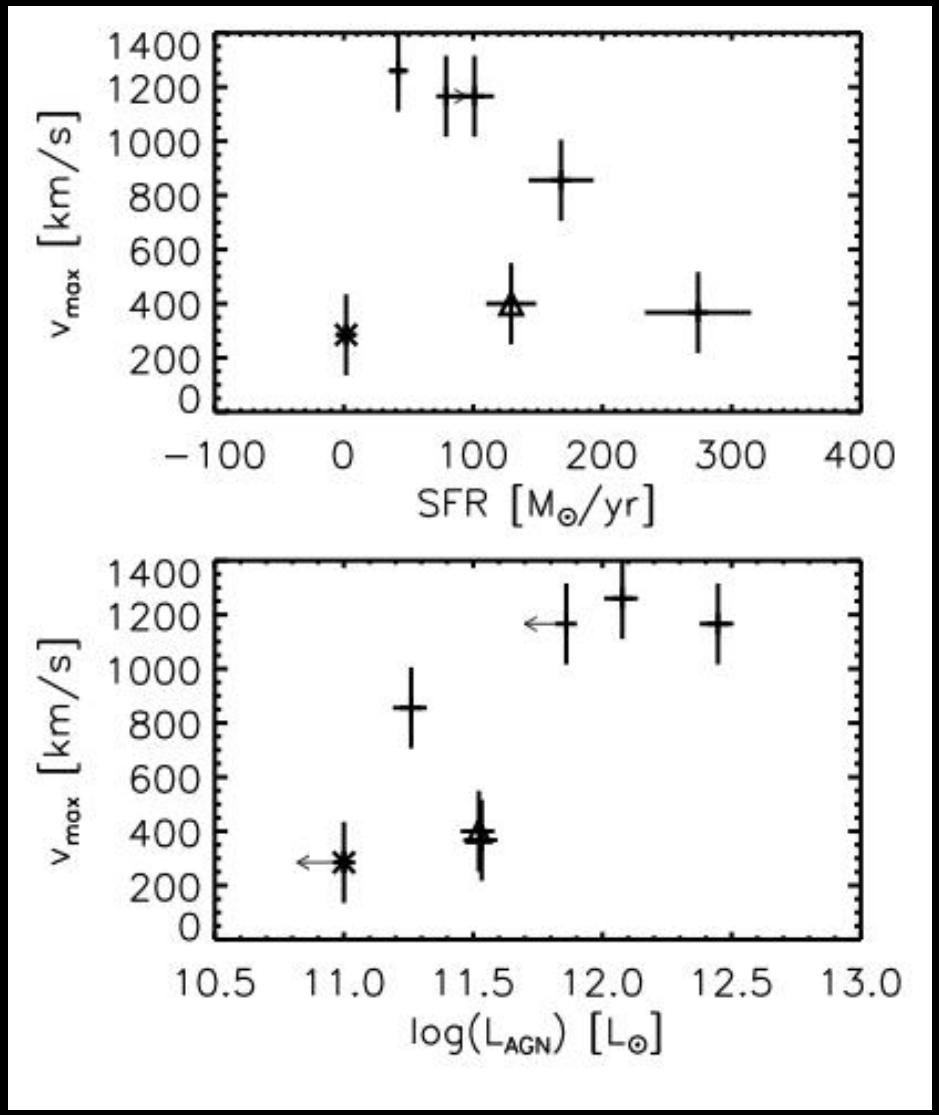
(SHINING: Sturm, Gonzalez-Alfonso, SV, et al. 2011)

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



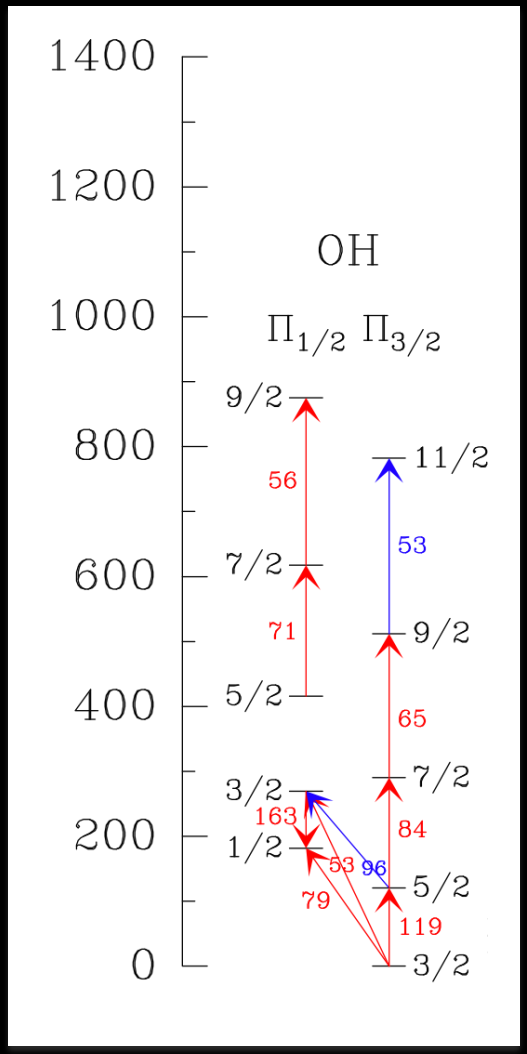
Powerful Quasar-driven Winds?

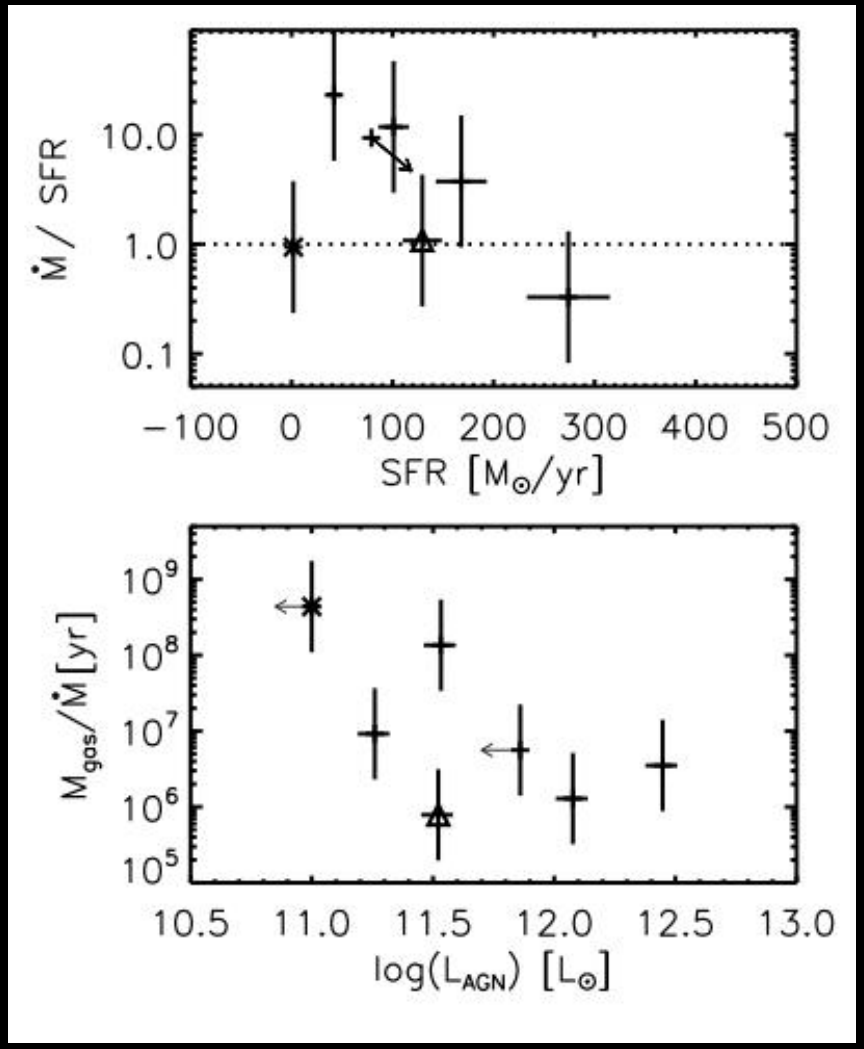
(Sturm et al. 2011)



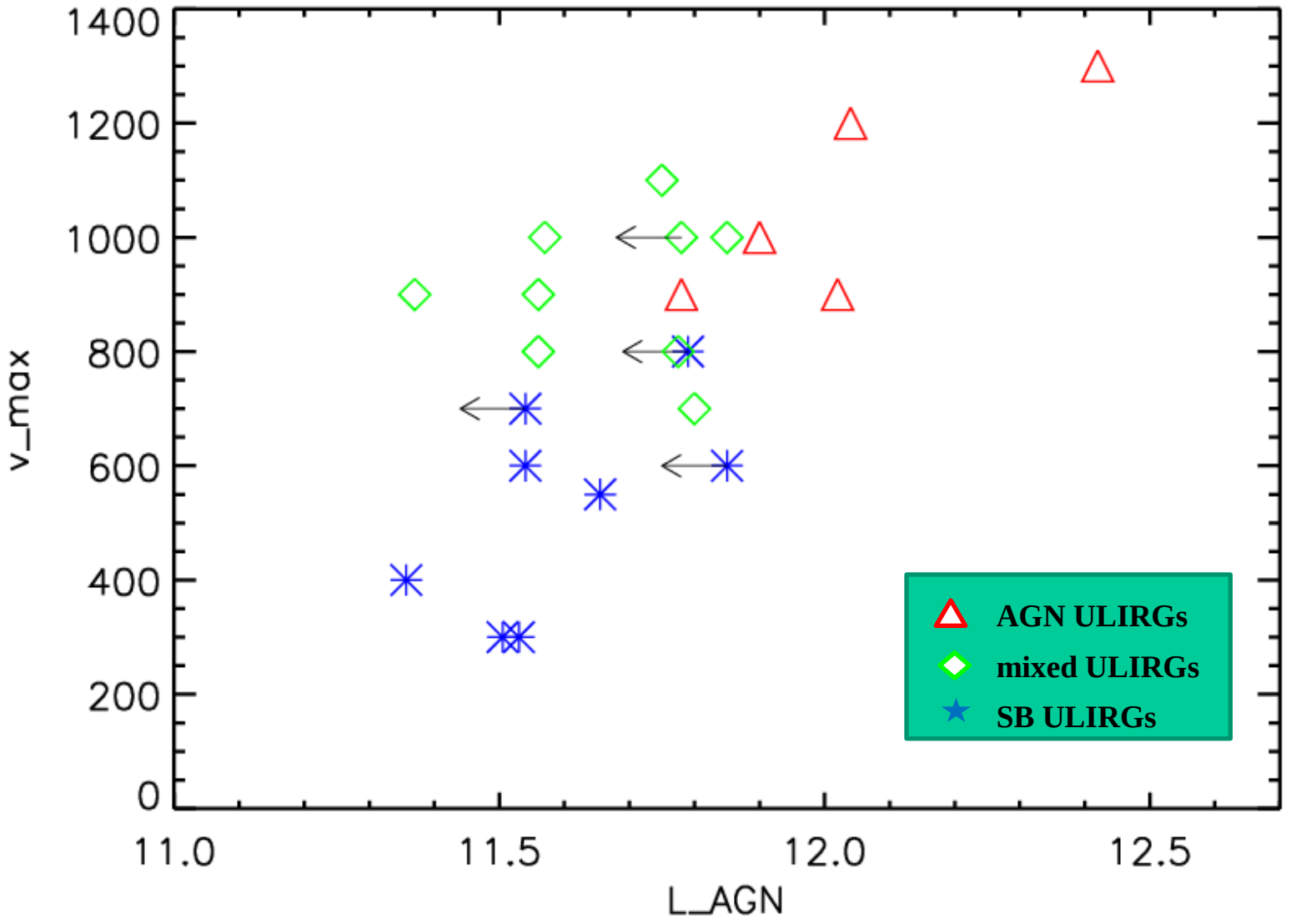
Powerful Quasar-driven Winds?

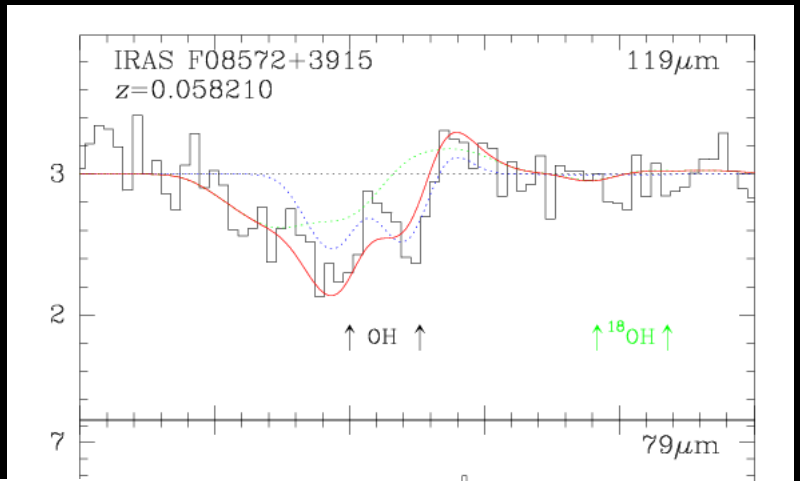
(Sturm, Gonzalez-Alfonso, SV, et al. 2011)



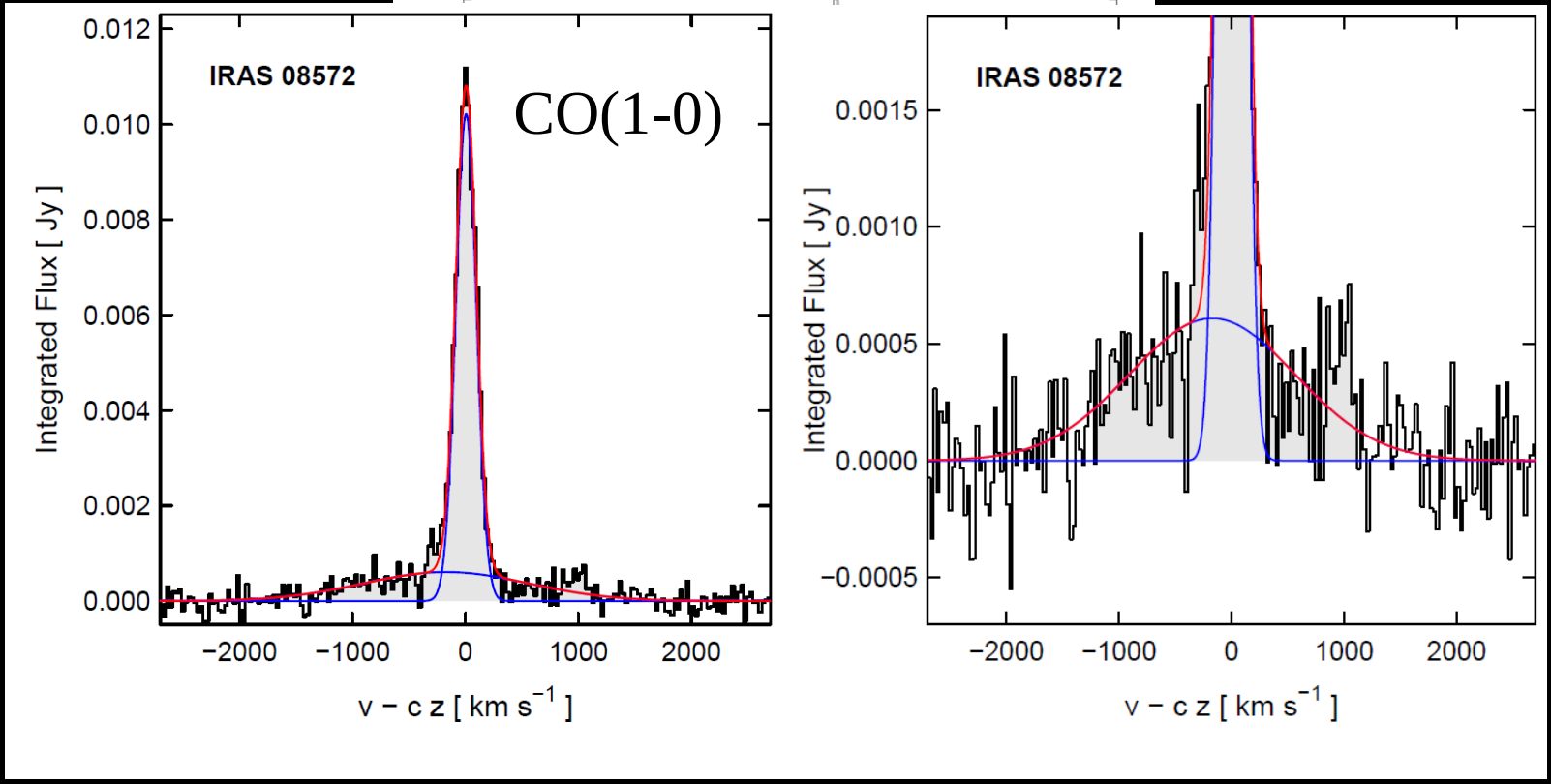


2012 Update


1400
1200
1000
800
600
400
200
0
v_max
11.0
11.5
12.0
12.5
L_AGN
AGN ULIRGs
mixed ULIRGs
SB ULIRGs

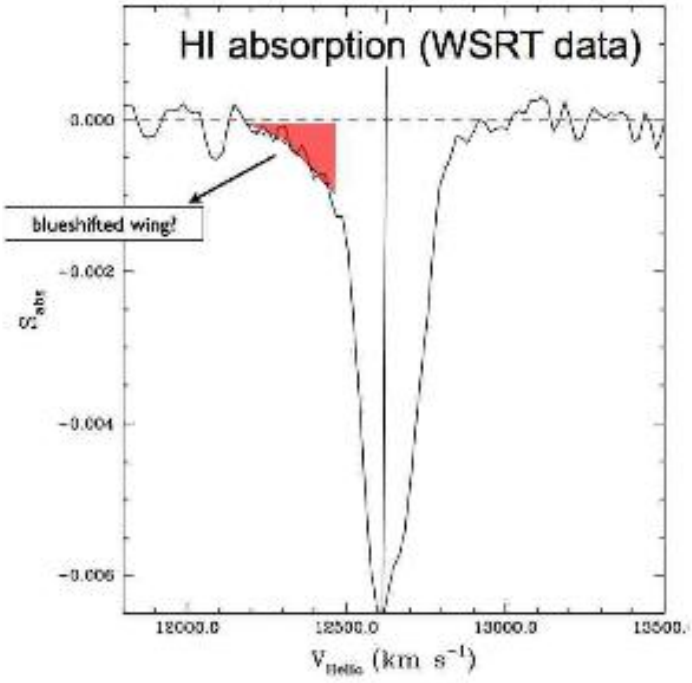

IRAS F08572+3915
z=0.058210
119μm
79μm
OH
18OH

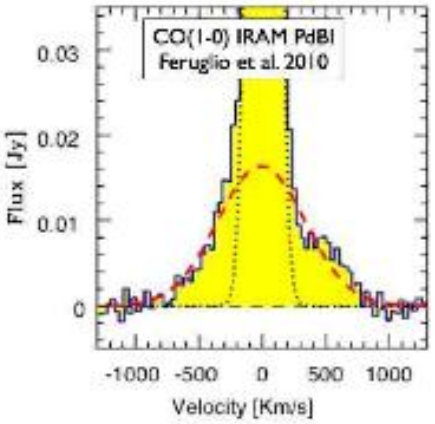
Sturm+2012


IRAS 08572
CO(1-0)
Integrated Flux [Jy]
v − c z [km s−1]
IRAS 08572
Integrated Flux [Jy]
v − c z [km s−1]

HI 21-cm Outflow in Mrk 231?

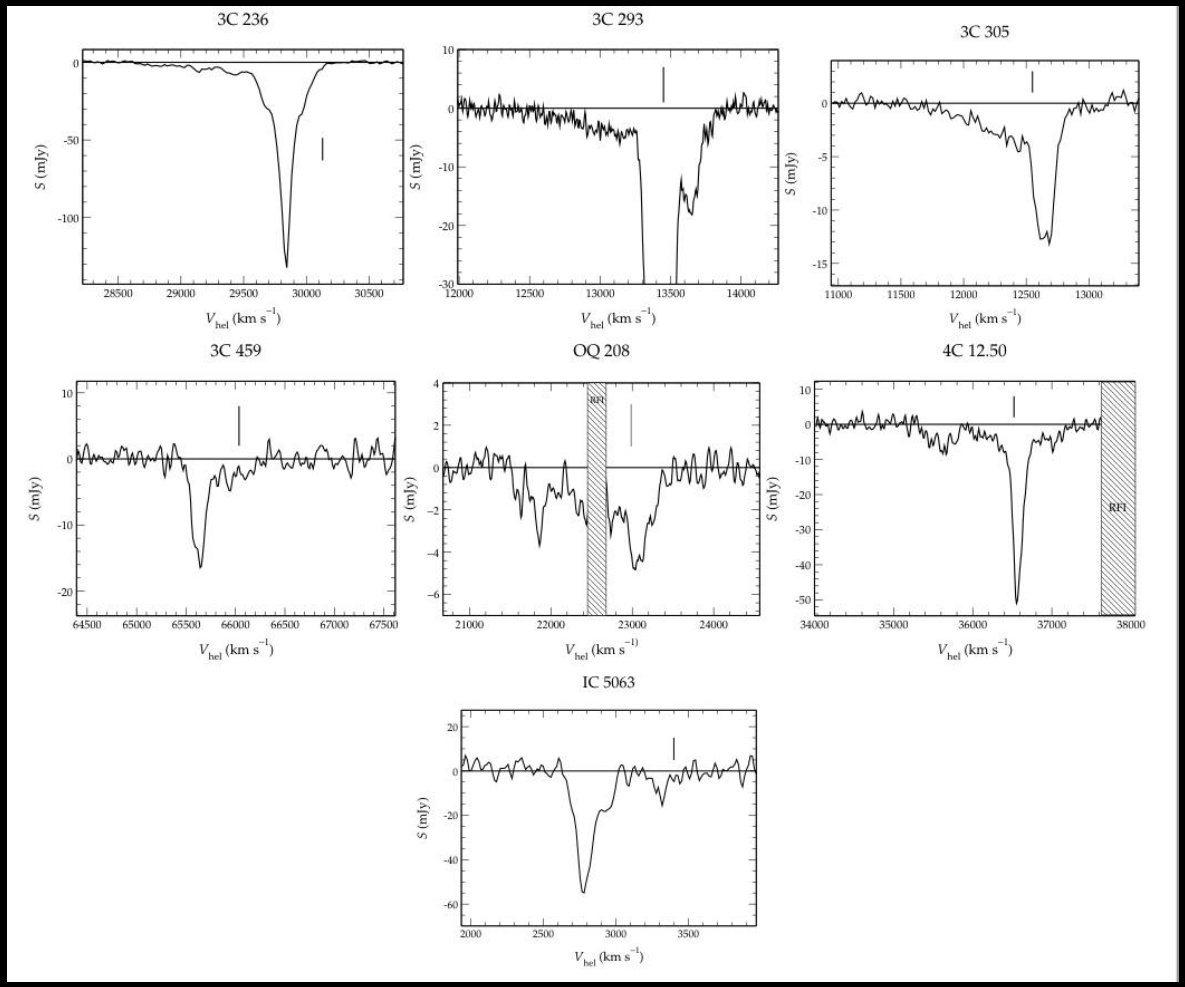
(Morganti 2011)





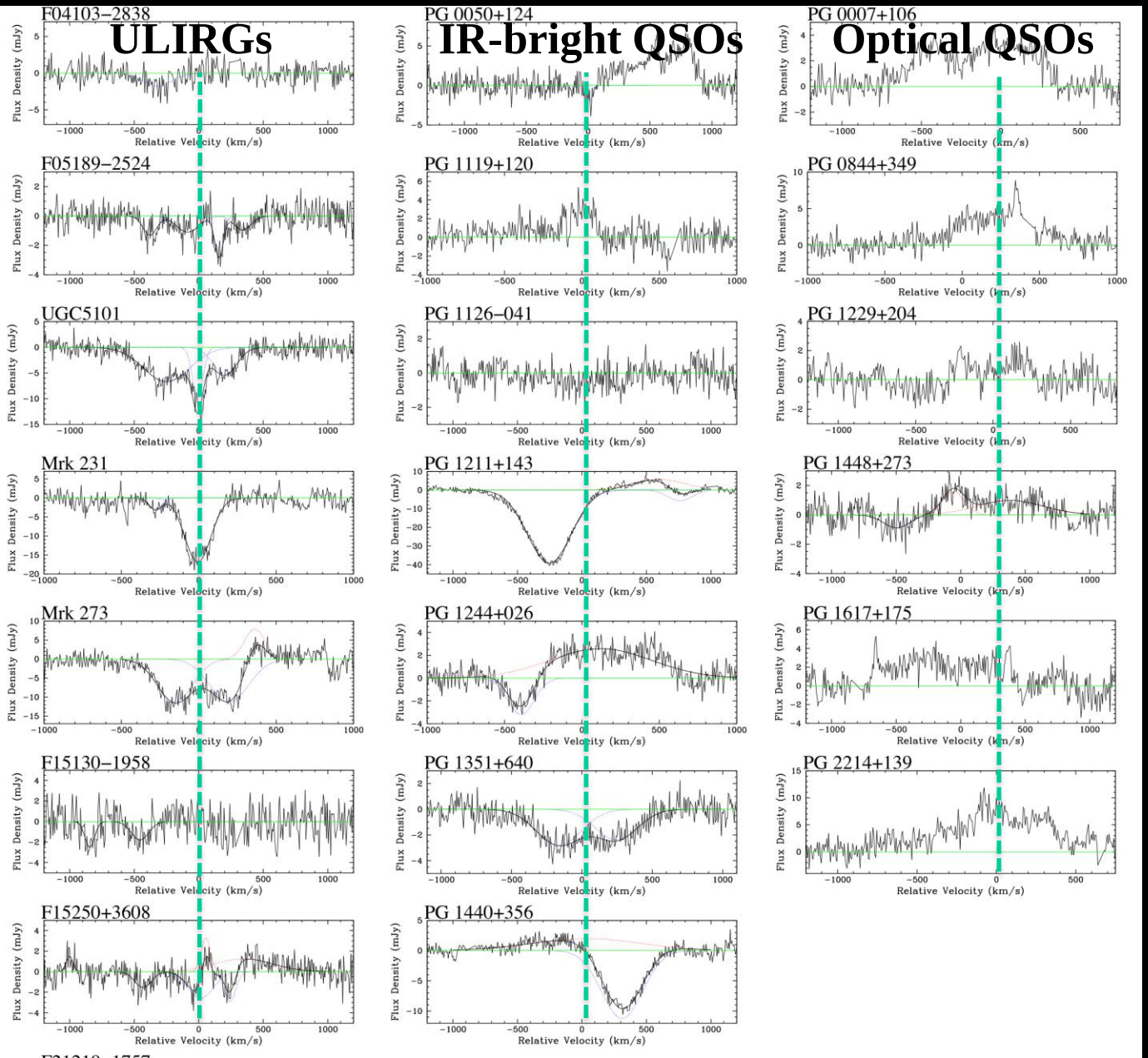
HI 21-cm Outflows in Radio Galaxies

(Morganti, Tadhunter, & Osterloo 2005)



- V_{out} → 1000 km s^{-1}
- dM/dt → 50 M_{sun} yr^{-1}

HI 21-cm Outflows in ULIRGs & Quasars?



GBT Results

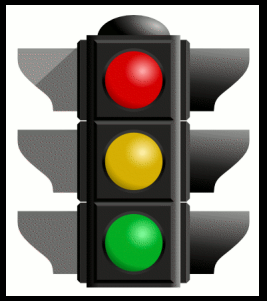
(Teng, SV, & Baker 2012 in prep.; see Teng's poster P50)

(Not shown are new Arecibo HI 21-cm data on U/LIRGs by Zauderer+12 in prep.)

Plan

- **Recent results at $\lambda < 1$ μm**
- **Recent results at $\lambda > 1$ μm**
- **Open issues (*circa 2012*)**

Open Issues *(Circa 2012)*



Stalled
Slow
Fast

1. **Hot wind fluid**
   best cases so far: M82, MW?, NGC 1569??
2. **Entrained neutral / molecular gas & dust**
   new: NIR, Spitzer, Herschel + IRAM (+ ALMA), GBT (+ JVLA)
   Signatures of massive winds
3. **Zone of influence & escape efficiency**
   ironically, current best constraints are at high redshifts
   on-going HST / COS programs will soon provide better local constraints
4. **Efficiency**
   contingent on #2 and #3 above; perhaps #1 is not relevant
5. **Wind/ISM interface & magnetic fields**
   our best hope: the Milky Way wind where 1" ~ 50 light-days?
6. **Positive feedback**
   best cases so far: shock-induced star-formation in disks of M82 and NGC 3079 and in hosts of radio galaxies
7. **Galactic winds in the distant universe**
   dependences on M_*, SFR, SFRD similar to those seen in local winds
   winds present in post-starbursts → relic signature of AGN blowout?