AGN Feedback: The Cold Gas Phase

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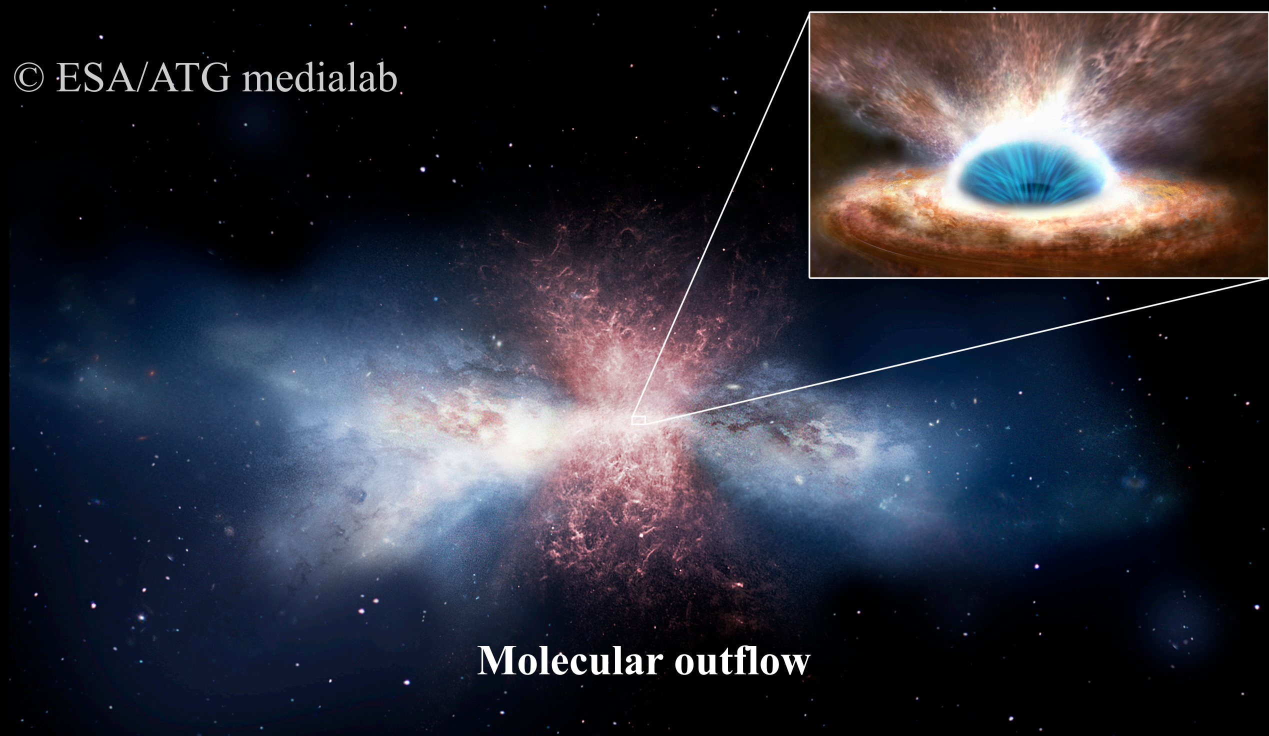


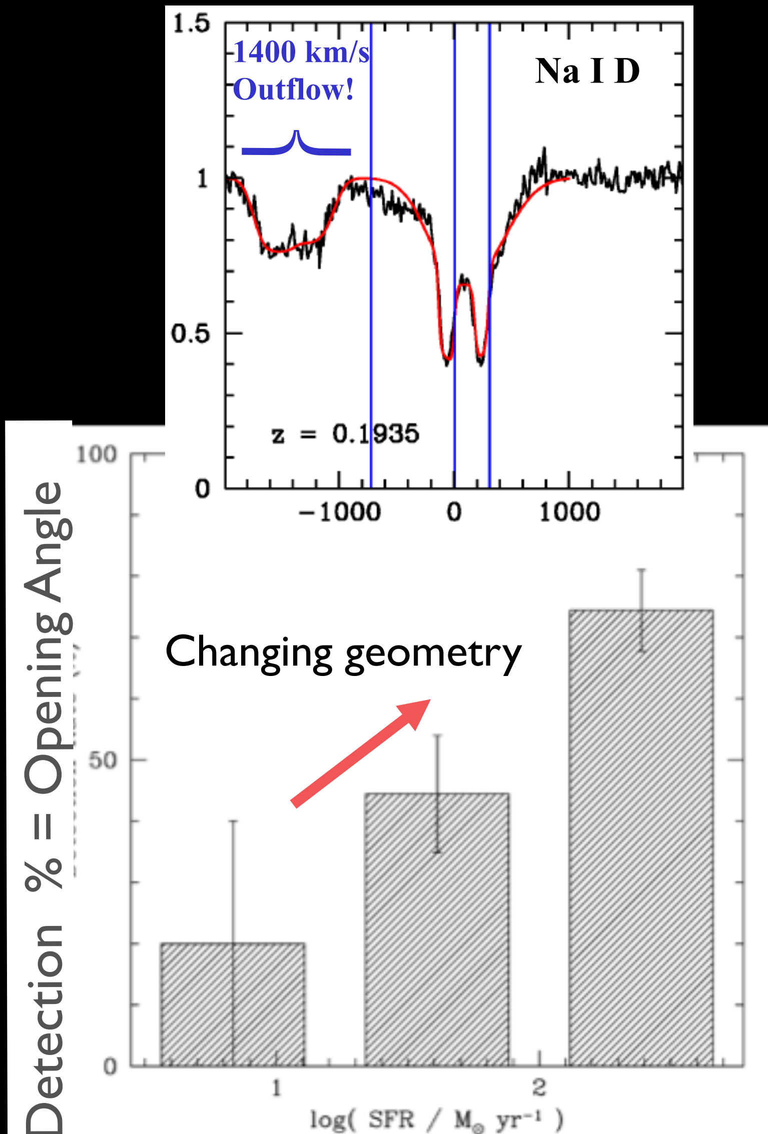
(based on *Tombesi, Meléndez, SV, et al. 2015, Nature*)

Why Focus on the Cold Gas and Dust?

- **Largely unexplored, until "recently" (≥ 2005 ARAA)**
- **Cold gas + dust = raw material for new stars**
- **Often is the energetically dominant phase of galactic winds**
- **Trends with AGN luminosities suggest that we are finally seeing quasar feedback in action.**

NEUTRAL-GAS OUTFLOWS IN (U)LIRGS *(CIRCA 2010)*

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



- **Detection rate:**
  - **~25% when *SFR* ~ 10 M_{sun} yr^{-1}**
  - **~75% when *SFR* > 100 M_{sun} yr^{-1}**

  (Rupke, SV, & Sanders 2005a, b)
- $V_{out} \sim SFR^{0.2\text{-}0.3}$ *(also Σ_{SFR})*
  ***p*-driven winds:** $\sim SFR^{0.25}$ *(e.g., Murray+05)*
- $V_{out} \sim V_{circ}^{\ 0.8 \pm 0.2}$ *(also V_{escape}* **and** *M*)*
- η = *(dM/dt) / SFR ~ 0.5 – 5*

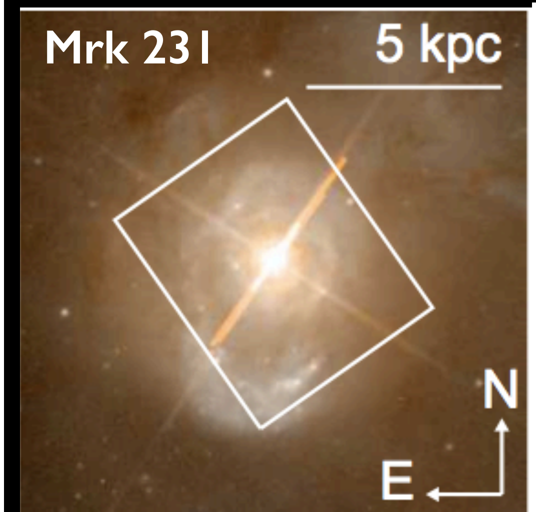
  ~ σ^{-1} ??? *(e.g., Murray+05; Oppenheimer+10)*
- f_{esc} *~ 5–20%* (if no halo drag)

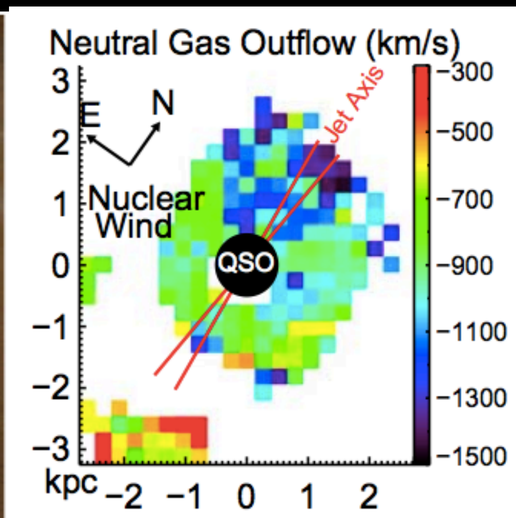
  → **pollute CGM** *(e.g., Steidel+10; Tumlinson+11; Stocke+13; Werk+13, 14…)*

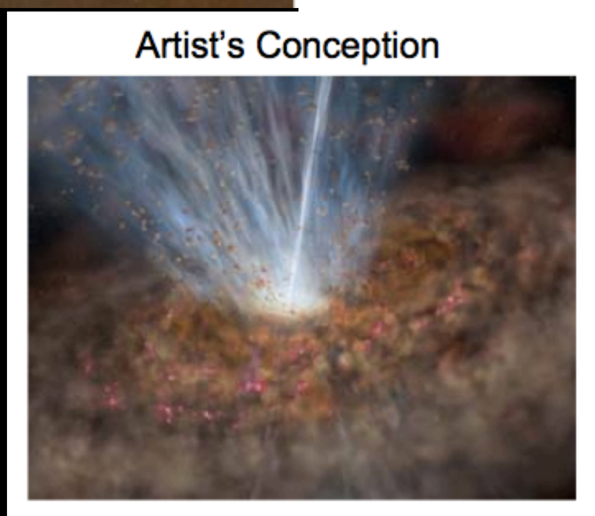
NEUTRAL-GAS OUTFLOWS IN (U)LIRGS *(CIRCA 2015)*

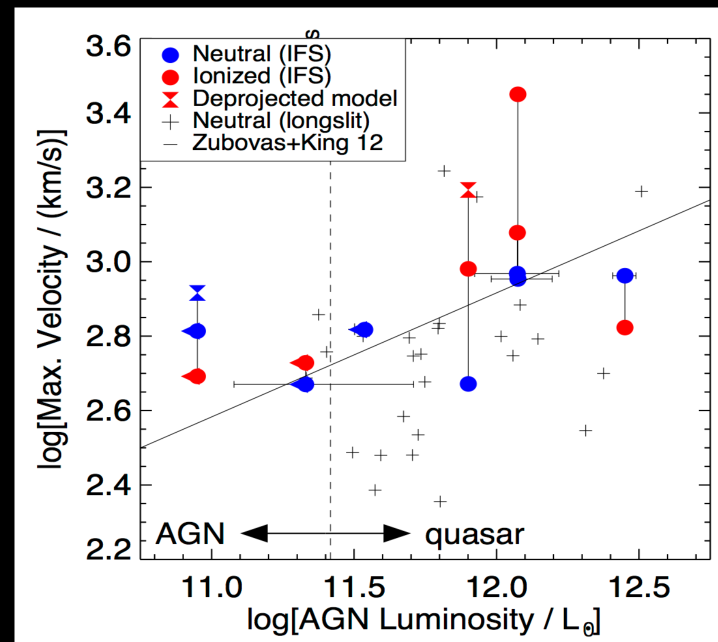
(Rupke & SV 11, 13a, 13b, 15; Rupke+15)

IFS of neutral-gas outflows … … driven by quasars









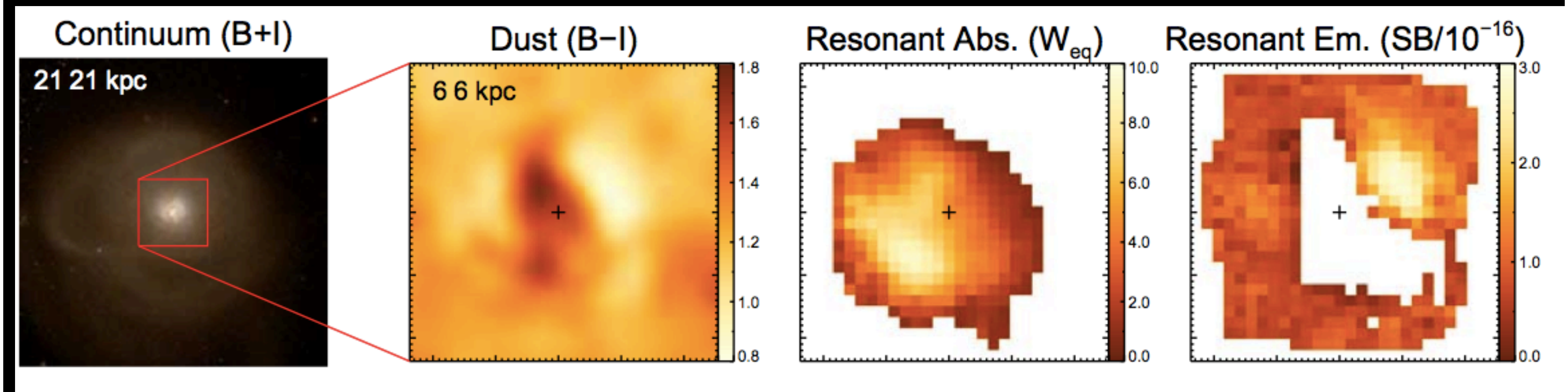
- $dM/dt \geq (0.5 - 5.0)\ SFR$
- $L_{mech} \geq dE_{SB}/dt \sim (0.2 - \text{few})\%\ L_{BOL}$ (AGN)
- $dp\,/\,dt \geq 5\ L_{SB}\,/\,c$ but $\geq 2\ L_{IR}\,/\,c$

  → AGN driving is important

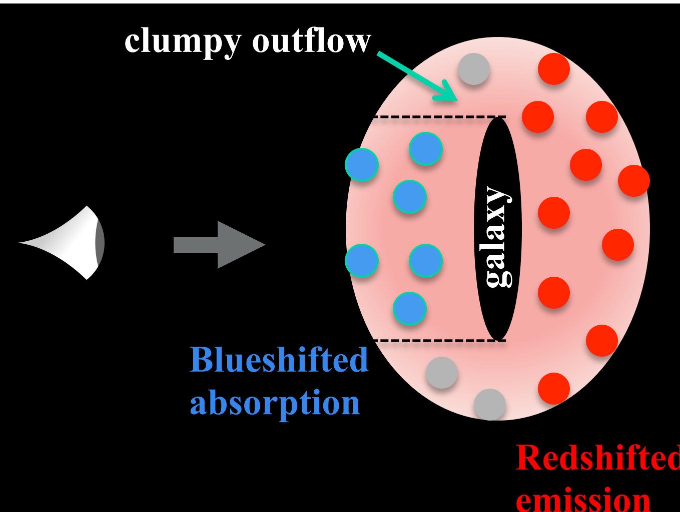
Sizes of Outflows from Resonant Na I ***Emission***

(Rupke & SV 2015)

Type-2 Quasar / ULIRG F05189-2524



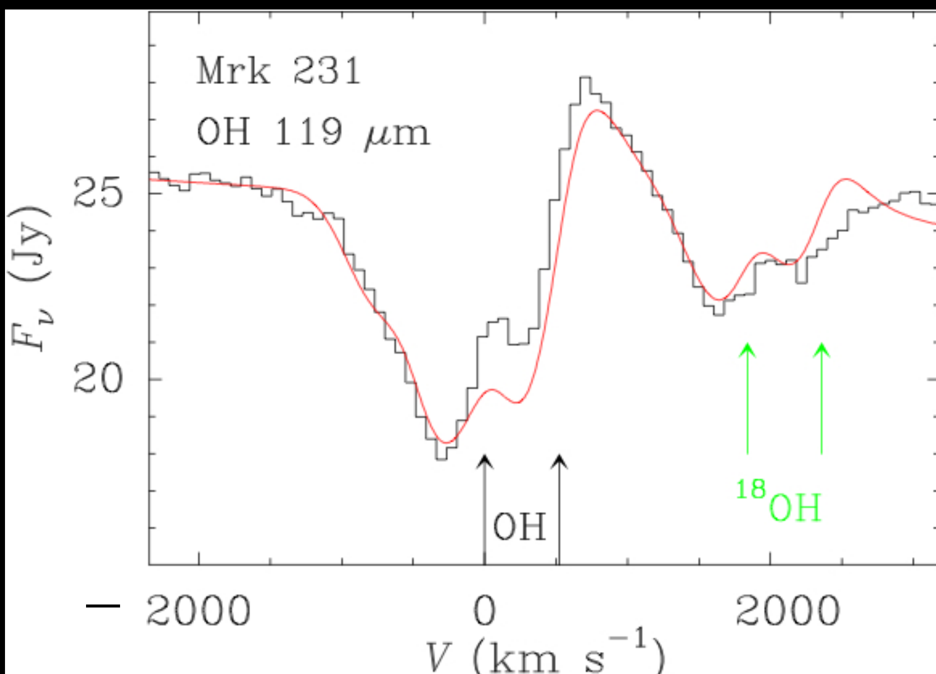
- **Complementary to Na I D absorption**
  (no need for background galaxy emission)
- **Provide new constraints on sizes of *local* winds**
  (cf. 100+ kpc Ly α halos; ***e.g., Steidel+ 2011; Matsuda+ 2012; Hayes+ 2013…)***

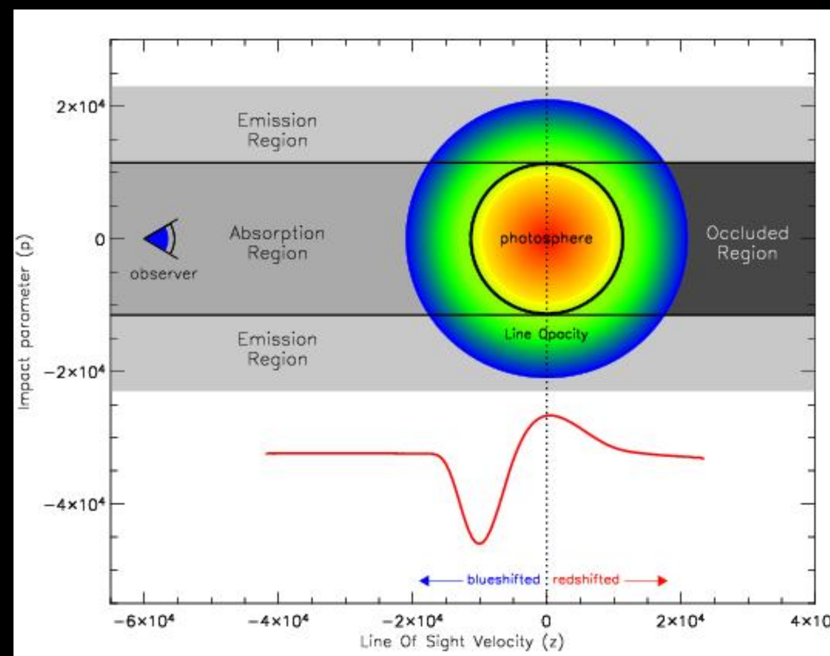


Massive Molecular Outflows in (U)LIRGs

(Fischer+2010; Sturm+ 2011; Gonzalez-Alfonso+2012ab; SV, Melendez+2013…)

- **Herschel/PACS spectra: OH 65 / 79 / 119 um spectra**
- **P-Cygni profiles!**
- **Outflow: $|V_{out}|$ in excess of 1000 km s^{-1}**





Massive Molecular Winds in 43 (U)LIRGs

(Fischer+2010; Sturm+ 2011; Gonzalez-Alfonso+2012ab; SV, Melendez+2013…)

- **OH 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}
- **Winds with v_{50}(abs) < -50 km s^{-1} are detected in 70% of the 37 objects with OH 119 µm detection**

  ➔ Wide-angle geometry (~145^o)
- **Infall with v_{50}(abs) > +50 km s^{-1} is detected in only 4 objects**

  ➔ Rare or disky / filamentary geometry?
- **$|V_{out}|$ increases with L_{AGN} but not M_* or SFR (over ~1 dex)**
- **dM / dt ~ 100 – 1000 M_{sun} yr^{-1} ~ (0.3 – 20) *SFR*** **(7 objects)**
- **dp / dt ~ (1 – 30) L_{AGN} / c** **(7 objects)**
- **$\tau_{depletion}$ ~ M_{gas} / (dM/dt) ~ 10^7 – 10^8 yrs** **(7 objects)**

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

Spectral Imaging of Molecular Winds in ULIRGs

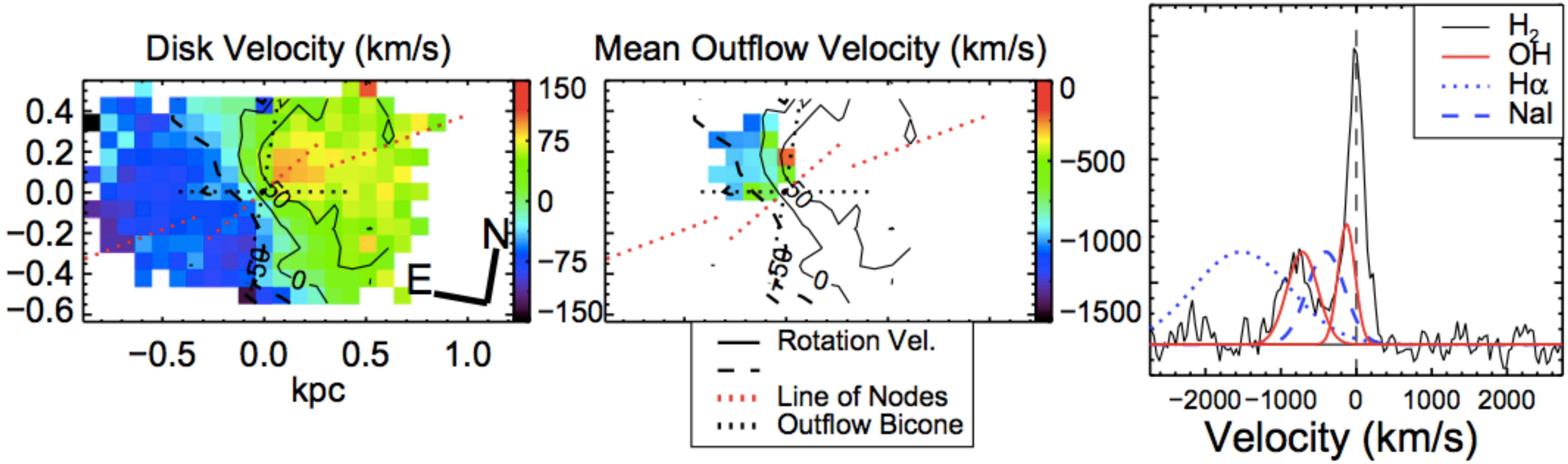
(H_2 2.12 μm as a *tracer* of the cold molecular gas)

(Rupke & SV 2013b)

* <u>Instrument</u>: Keck OSIRIS IFU + AO + Laser (resolution ~ 0.09” ~ 100 pc)
* <u>Results</u>: v(H_2) ~ v(OH); H_2 wind size ~ 400 pc; H_2 opening angle = 100 ± 10 deg

→ *consistent with Sturm+11*

Buried QSO: F08572+3915 NW



$T(H_2 \text{ wind}) = 2400$ K > T(disk) = 1500 K

Summary & TMT

- **Summary: Local (U)LIRGs and AGN**
  - **Statistics: ~70% of local ULIRGs have OH winds ($\Theta \sim 145^o$)**
    <10% among BAT AGN with lower L_{AGN}
  - **Kinematic trend with L_{AGN} suggests that the AGN is playing a dominant role in local galaxies when $L_{AGN} \geq 10^{11.8 \pm 0.3}$ L_{sun}**
  - **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 [ALMA]**
  - **Na I D line emission → improved constraints on wind sizes / energetics**
- **TMT = "Near-IR ALMA" [IRIS – IFU: ~0.8 – 2.5 μm]**
  - **Census from z ~ 0.4 to ~ 3 (Na I D) → 7+ (UV low-ionization metal lines, H_2 Lyman-Werner band, CO A-X bandhead)**
  - **Θ ~ 0.01" and FOV ~ 1" @ z ~ 0.4 → 0.05 and 5 kpc**
    @ z ~ 3.0 → 0.08 and 8 kpc
    @ z ~ 7.0 → 0.05 and 5 kpc