An Observational Perspective on Galactic Winds and the Circumgalactic Medium

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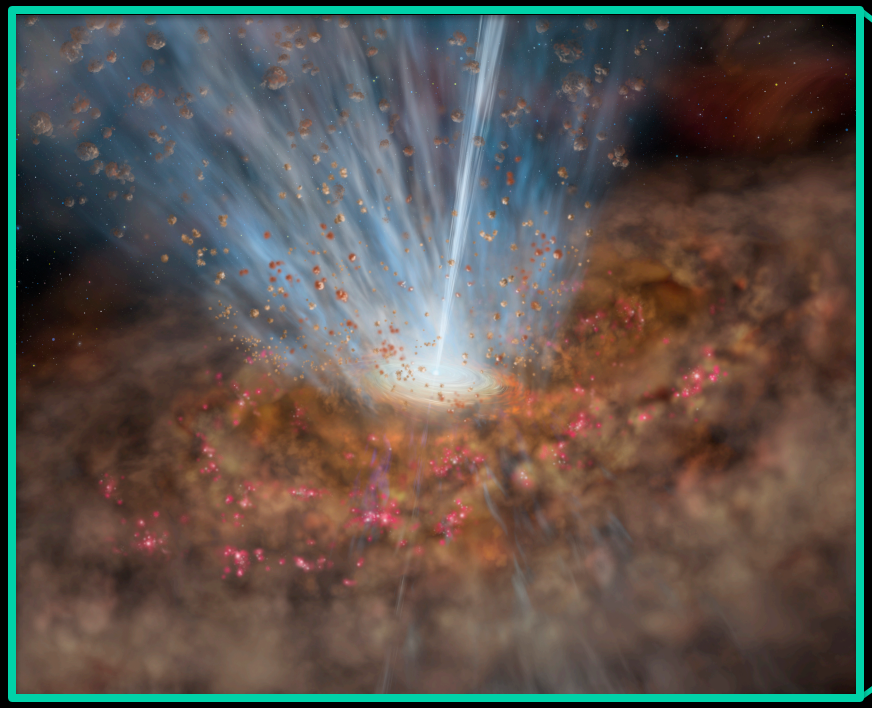
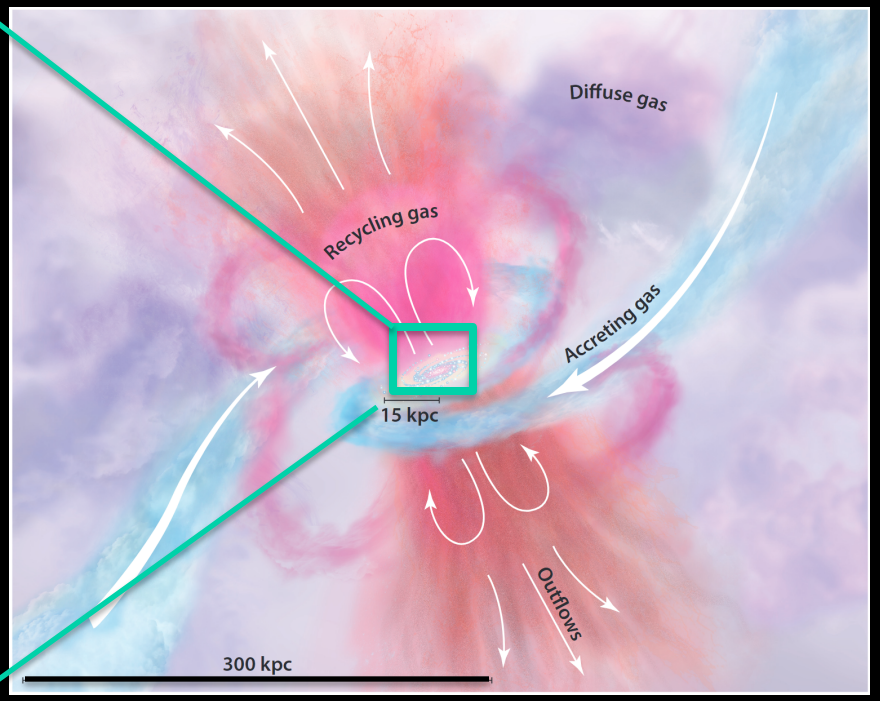




Galaxy scale

(based on *Rupke & SV 2011*)

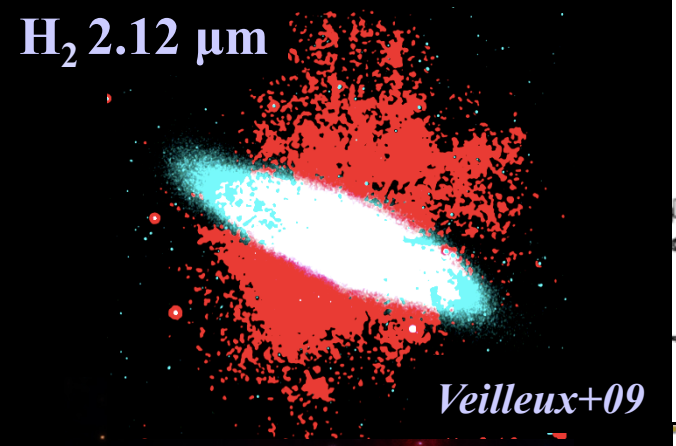
CGM scale

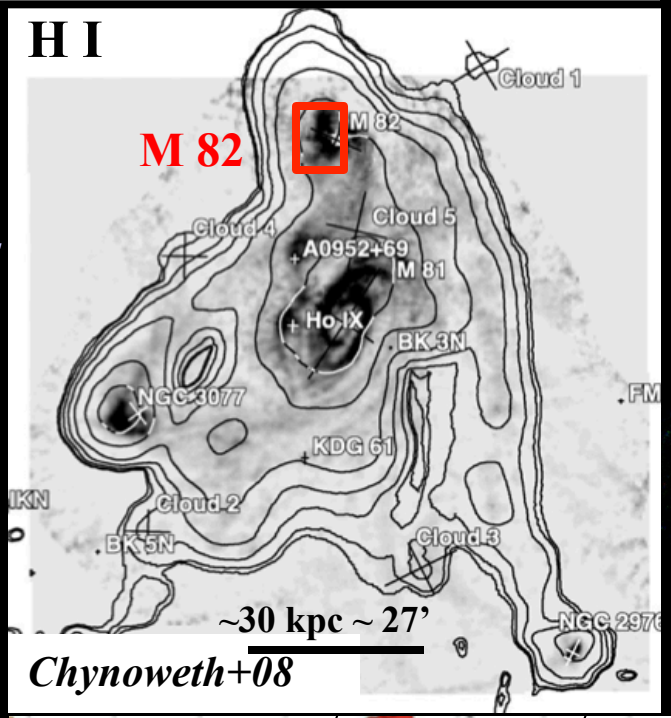
(Tumlinson+17)

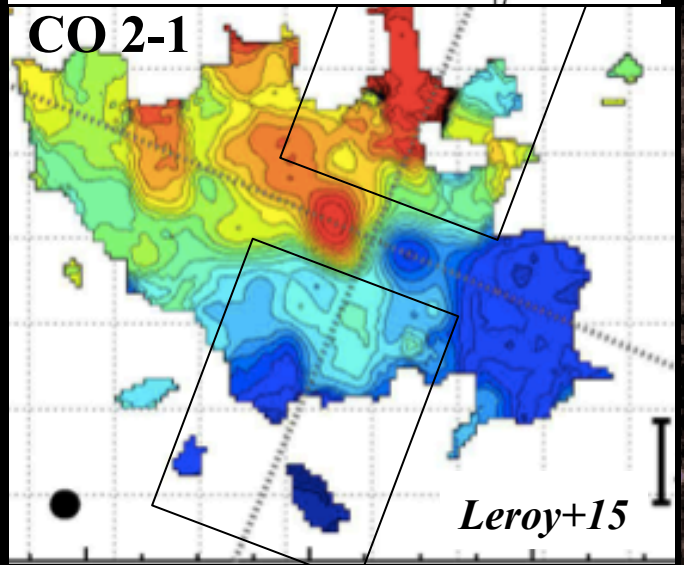
Plan

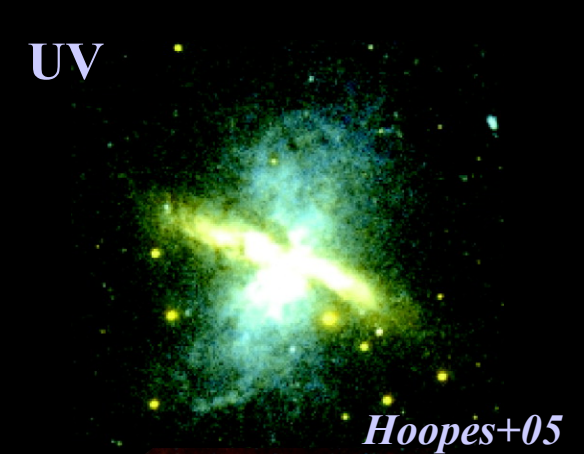
- Galaxy scale: Multiphase outflows at $z \leq 0.5$
- CGM scale: New constraints at $z = 2 - 5$
- Future: *JWST*
- Summary

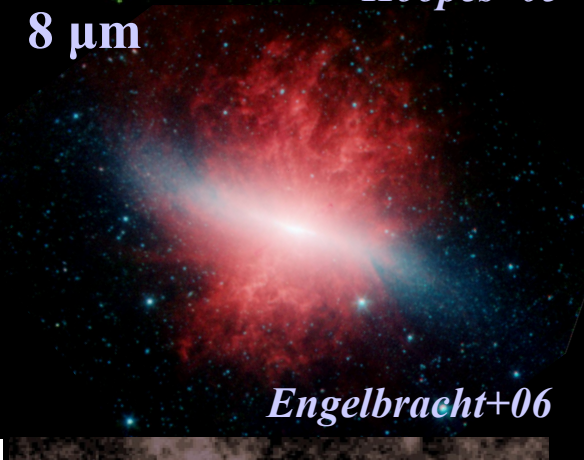
M82: Nearest Starburst
Starburst-driven Wind

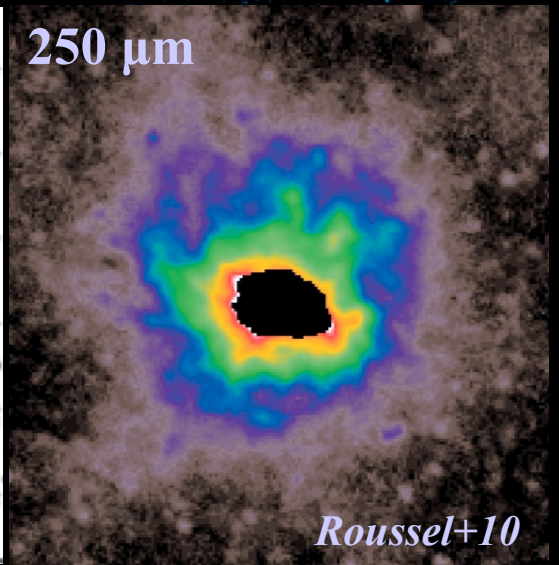




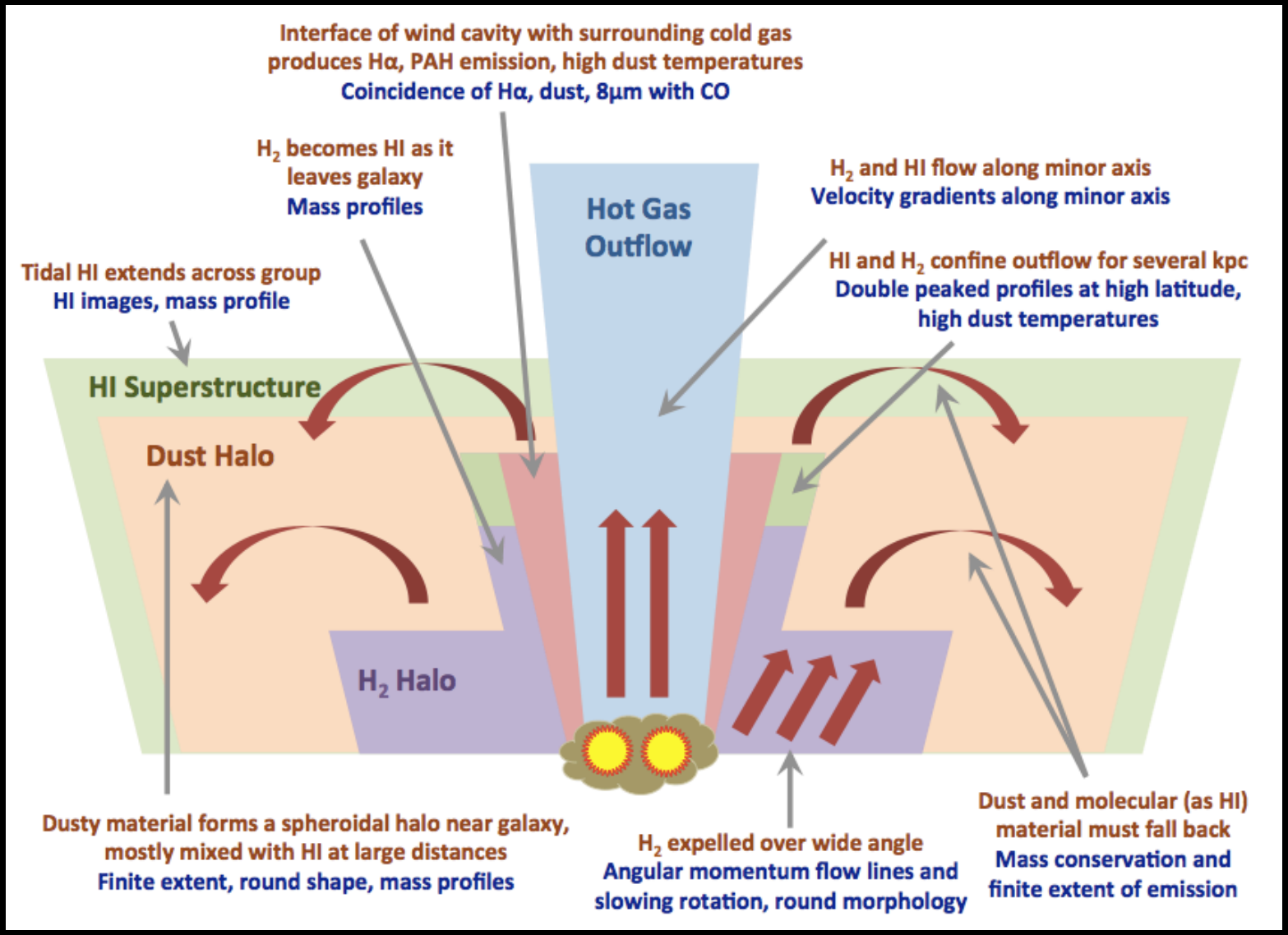








Multiphase Outflow of M82 ($\Sigma_{SFR} > 1\ M_{sun}\ yr^{-1}\ kpc^{-2}$)

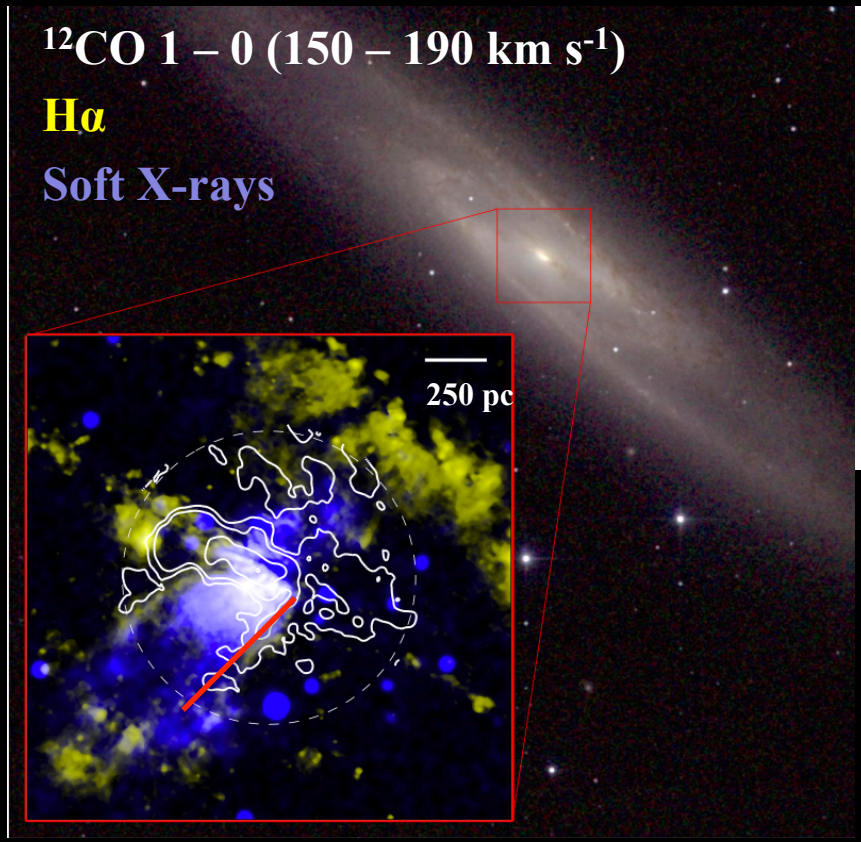


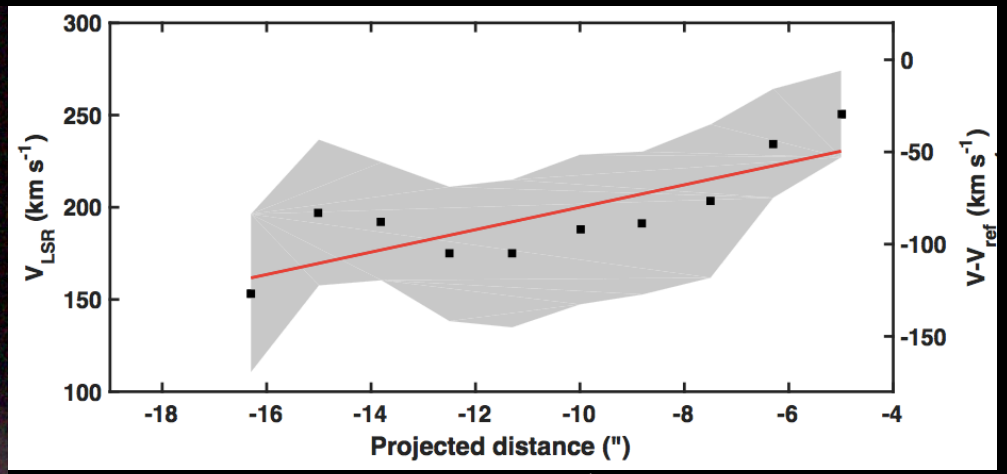
(Leroy + 15; also Martini+18)

Molecular Outflow in NGC 253

($\Sigma_{SFR} > 1\ M_{sun}\ yr^{-1}\ kpc^{-2}$)

Bolatto, Warren, Leroy, Walter, SV, et al. (2013)
Walter, Bolatto, Leroy, SV, et al. (2017)

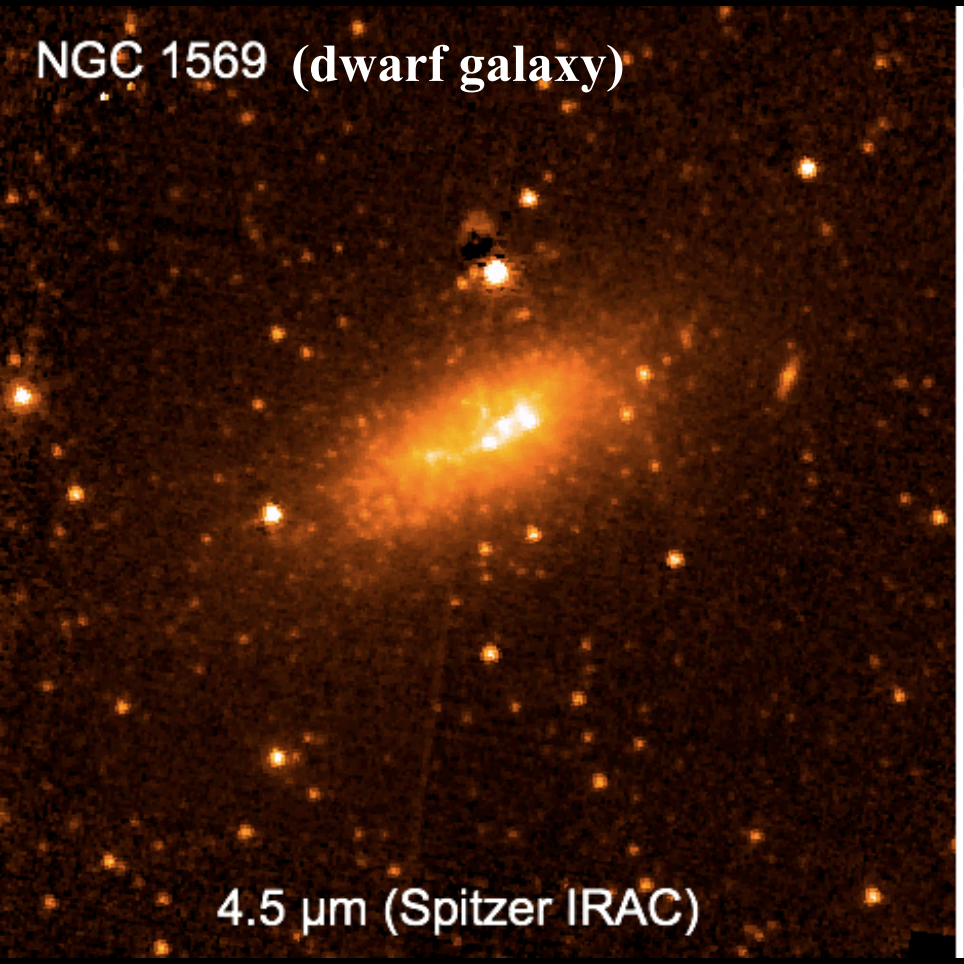




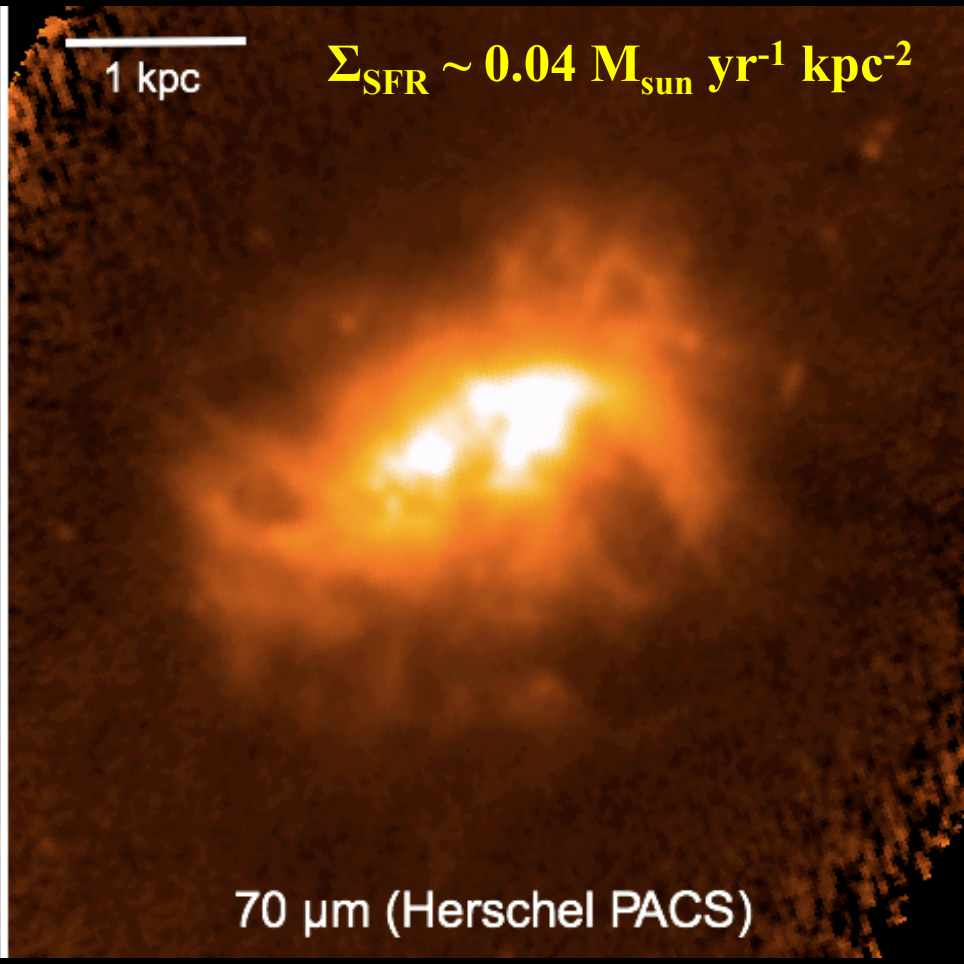
- $dM/dt \sim 3 – 9\ M_{sun}\ yr^{-1}$
- $\eta = dM/dt\ /\ SFR = 1 – 3$
  (H_2/CO ~ 0.1 x Galactic value)
- *Dense* gas is entrained in the outflow (HCN, HCO^+, CS, and CN → ~10^4 cm^{-3})
- Properties of outflowing gas are similar to those in the central starburst disk
- $dV/dr \sim +1$ km s^{-1} pc^{-1} → accelerating (?)

Cool Dust around Galaxies with $\Sigma_{SFR} < 1\ M_{sun}\ yr^{-1}\ kpc^{-2}$

(Herschel: Meléndez, SV et al. 2015; McCormick, SV, et al. 2018)



Stars

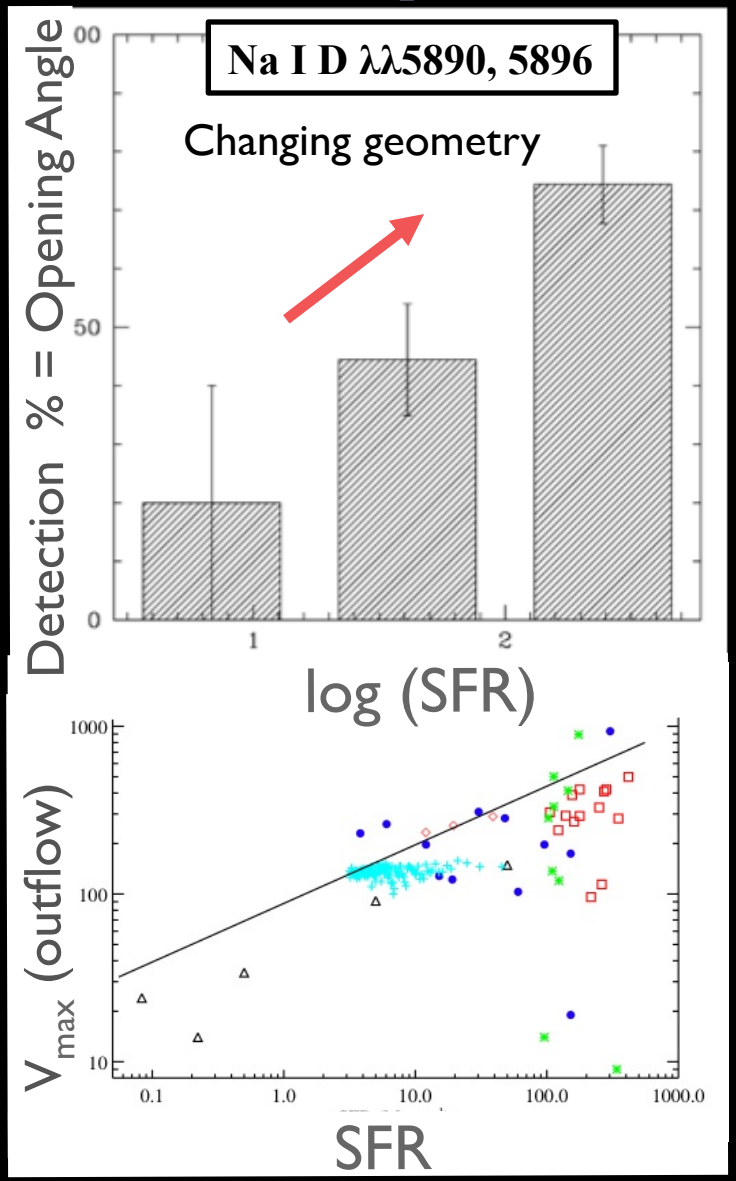


Cool Dust

(>50% lies outside stellar disk)

Cool Winds in z < 0.5 Star-Forming Galaxies

(Heckman+00; Rupke, SV,+02,05ab; Martin 05,06,+12; Chen+10; Rubin+14…)

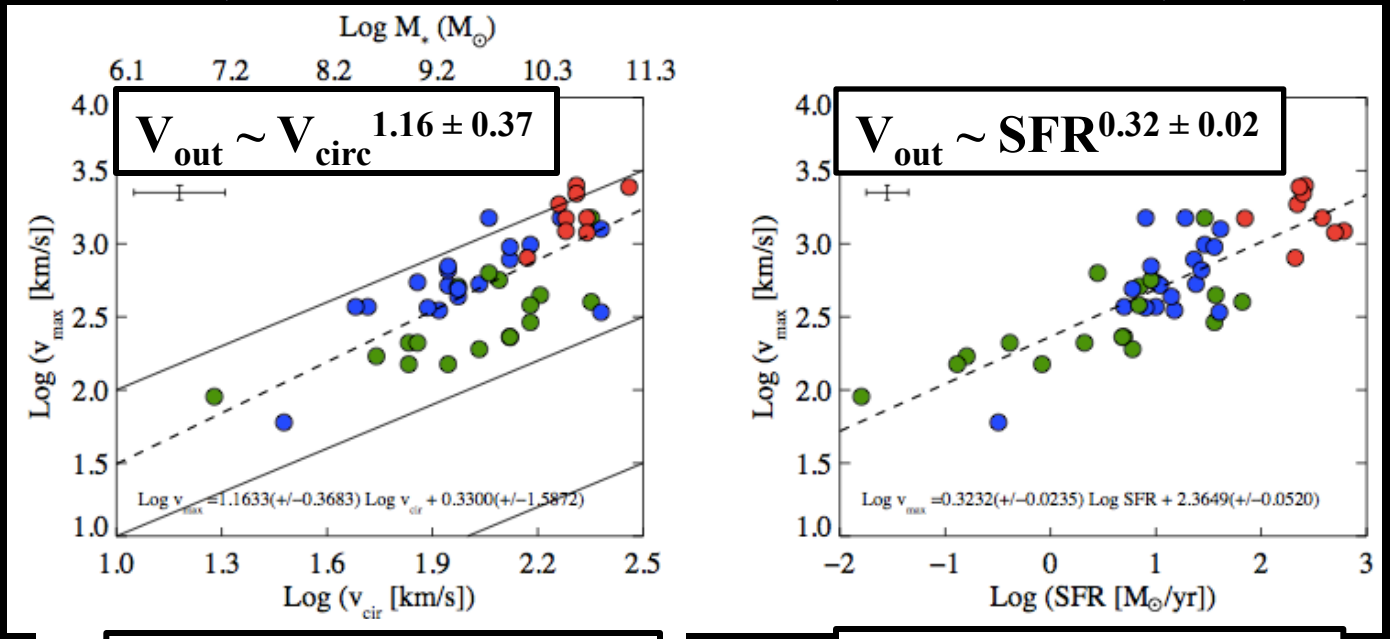


Optical/NUV absorption lines

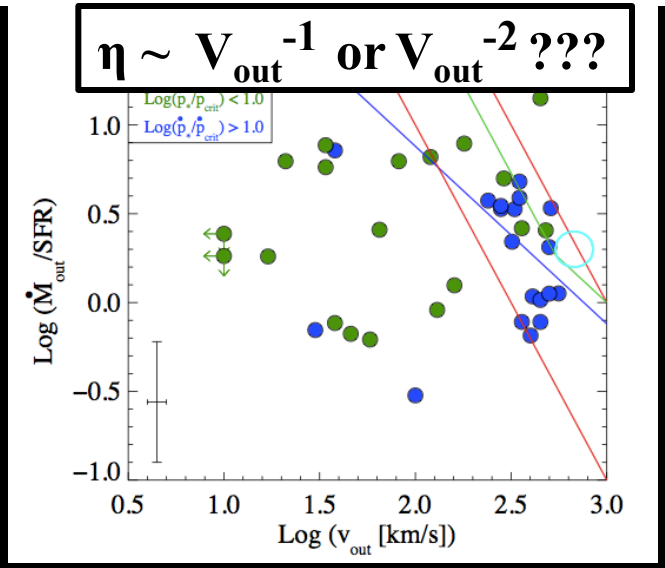
- **Detection rate:**
  ~20% when SFR_{IR} ~ 10 M_{sun} yr^{-1}
  ~75% when SFR_{IR} > 100 M_{sun} yr^{-1}
  (Rupke, SV, & Sanders 2005a, b)
- **$V_{out} \sim SFR^{0.2\text{-}0.3}$ (also Σ_{SFR})**
  p-driven winds: $\sim SFR^{0.25}$ *(e.g., Murray+05)*
- **$V_{out} \sim V_{circ}^{\ 0.8\pm 0.2}$ (also V_{escape} and M^*)**
- **$R \sim 0.1 - 5$ kpc**
- **$\eta = (dM/dt) / SFR \sim 0.5 - 5$**
  $\sim V_{out}^{-1}$ (p-driven) or V_{out}^{-2} (E-driven) ???
- **$f_{esc} \sim 5$–20%** (if no halo drag)
  → **pollute galaxy outskirts (CGM)**

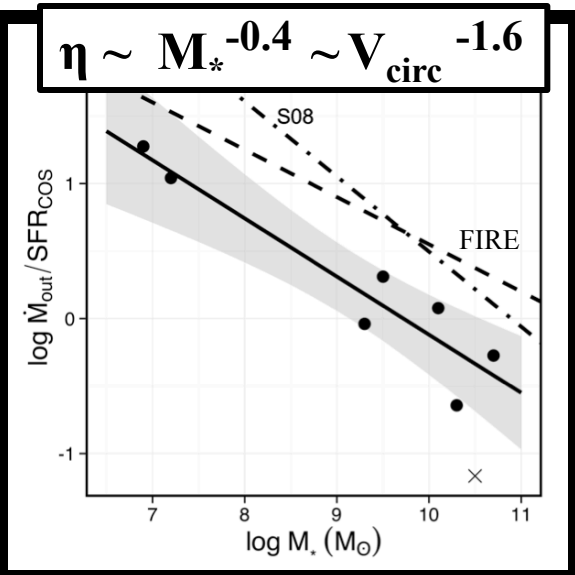
Warm Winds in $z < 0.5$ Star-Forming Galaxies

(Heckman+15; Heckman & Borthakur 16; Chisholm+15, 16, 17ab…)

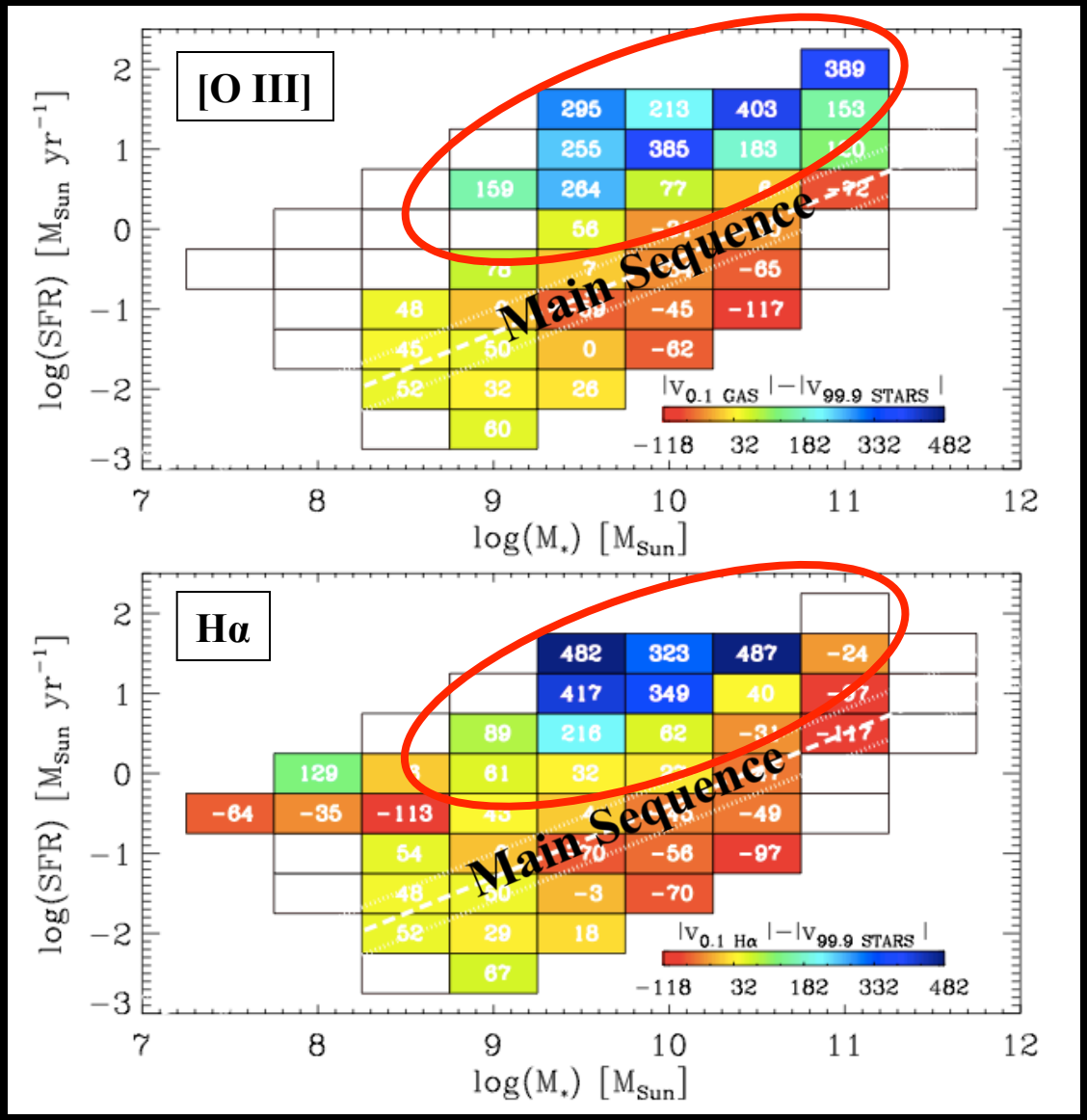


FUV abs'n lines





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

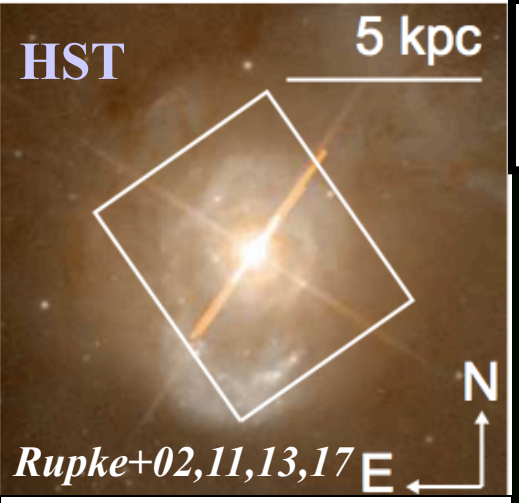


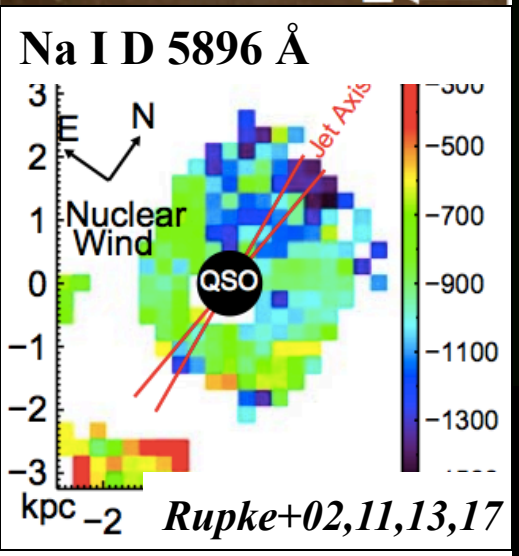
Optical emission lines

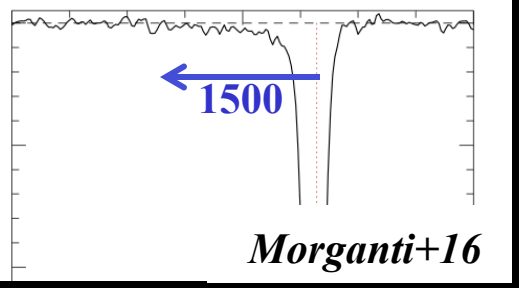
- V_{out} scale with *SFR*, and SFR / SFR_{MS}

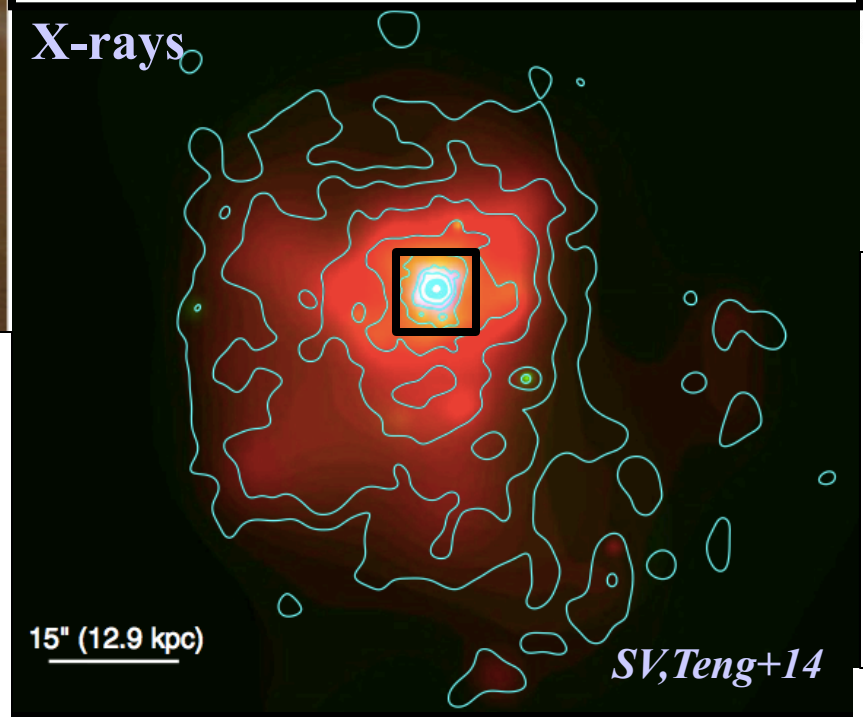
(Cicone+16)

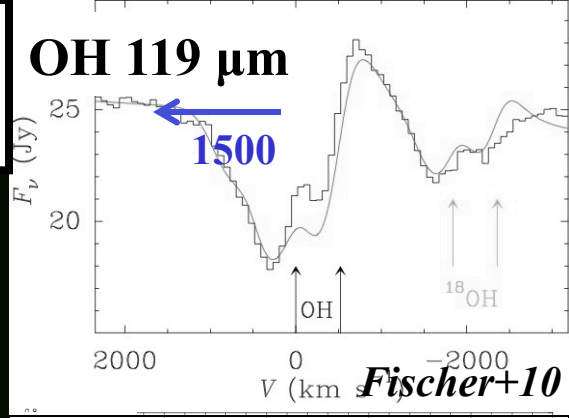
Mrk 231: Nearest Quasar
Quasar Feedback in Action

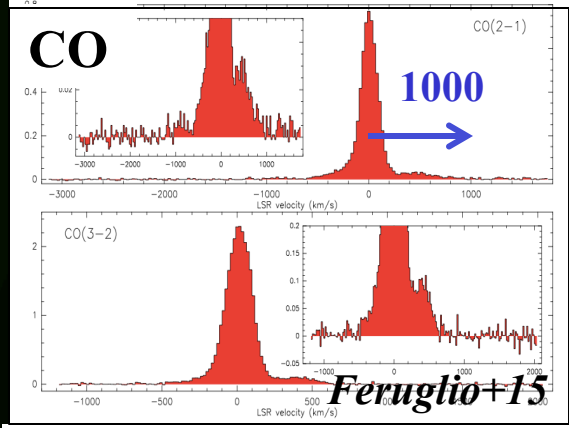


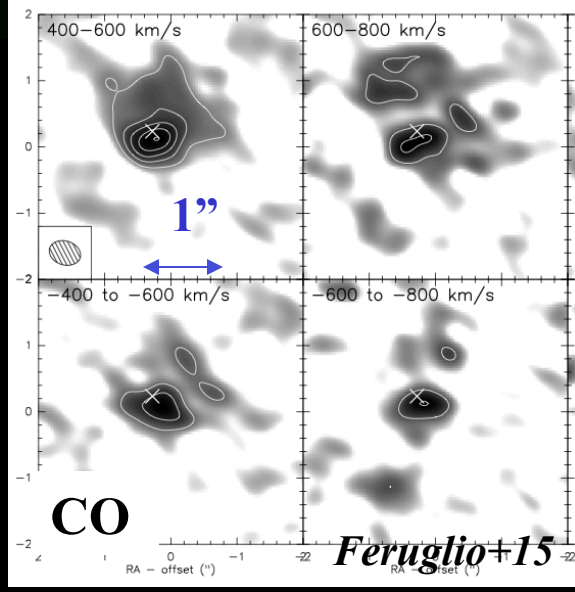












- *Lesson learned at z ~ 0:* cool gas often is the energetically dominant gas phase of galactic winds in gas-rich systems

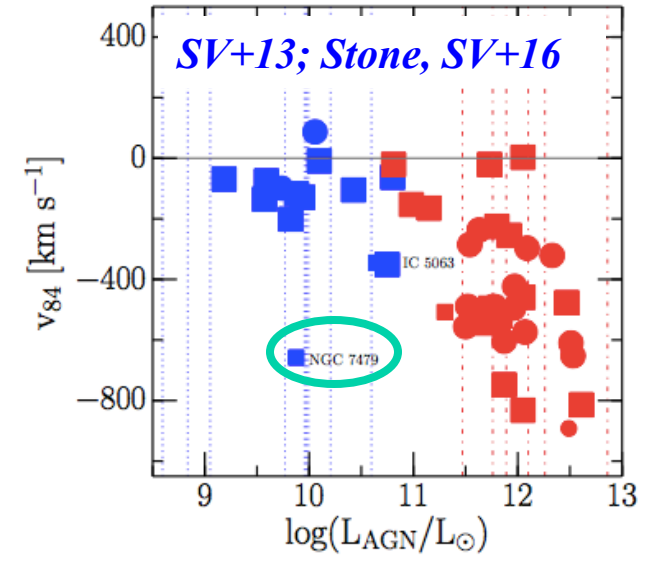
Molecular Outflows in U/LIRGs & IR Quasars

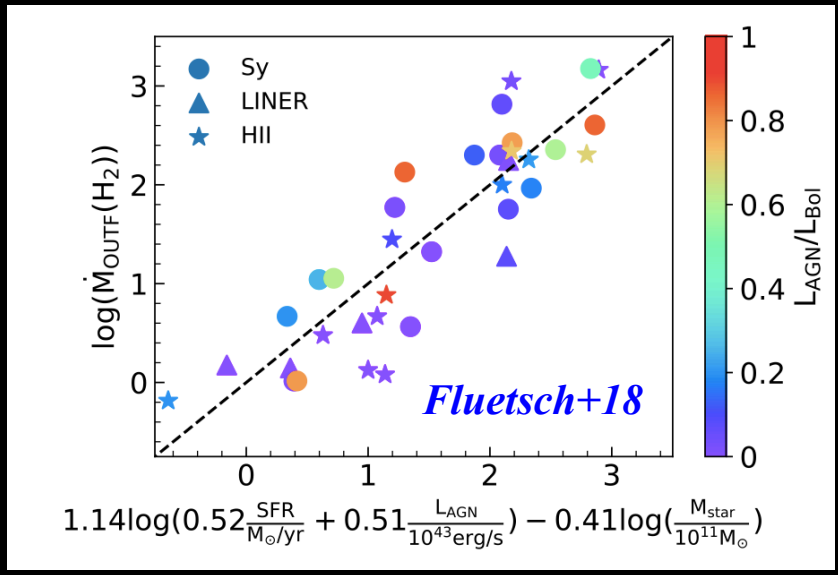
- **Statistics**: ~70% of local U/LIRGs have molecular winds (Θ ~145°) [SV+13]
- **Outflow velocities**: $\langle v_{50} \rangle$, $\langle v_{84} \rangle$, $\langle v_{max} \rangle$ ~ -200, -500, -925 km s^{-1} [feed CGM]
- **Energetics**: Size ~ 0.1 – few kpc [sometimes up to 10+ kpc; SV, Bolatto+17]

  $dM/dt \sim 10 - 1000\ M_{sun}\ yr^{-1}$ [$t_{depl} < 10^8$ yrs (ULIRGs)]

  $dp/dt = (0.1 - 20)\ L_{IR}/c$ [the most extreme outflows are E-driven]

  $dE/dt < 2\%\ L_{IR}$ [plenty of energy from the central SB + AGN]
- **Trends with SFR and AGN luminosities**: suggest that we are seeing *combined* starburst + quasar feedback in action



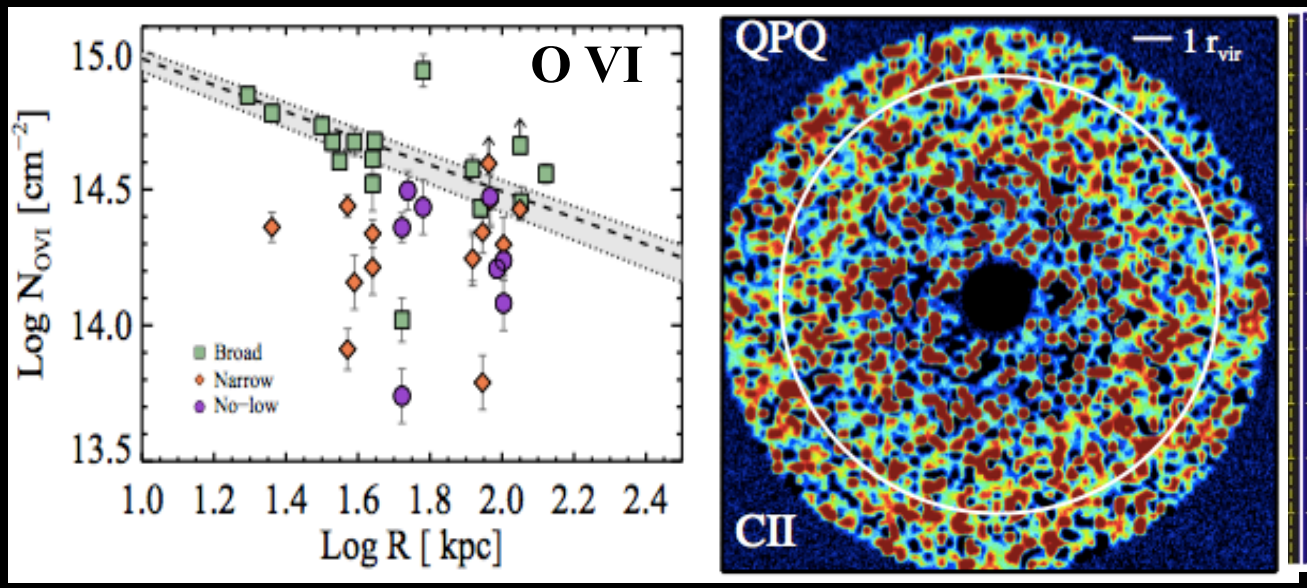


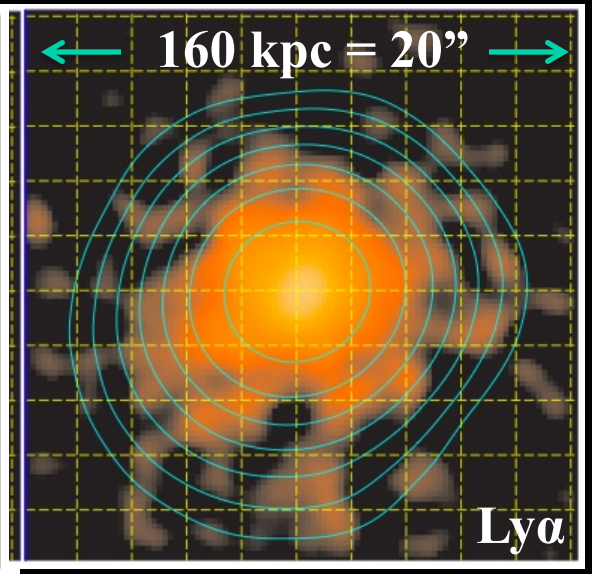
Plan

- Galaxy scale: Multiphase outflows at $z \leq 0.5$
- **CGM scale: New constraints at $z = 2 - 5$**
- Future: *JWST*
- Summary

Circumgalactic Medium (CGM): Near & Far

- Ubiquitous, large (~100+ kpc), metal-enriched, dusty halos around galaxies
- May contain more metals and dust than galaxies themselves
- May be the cumulative effect of CGM enrichment by outflows





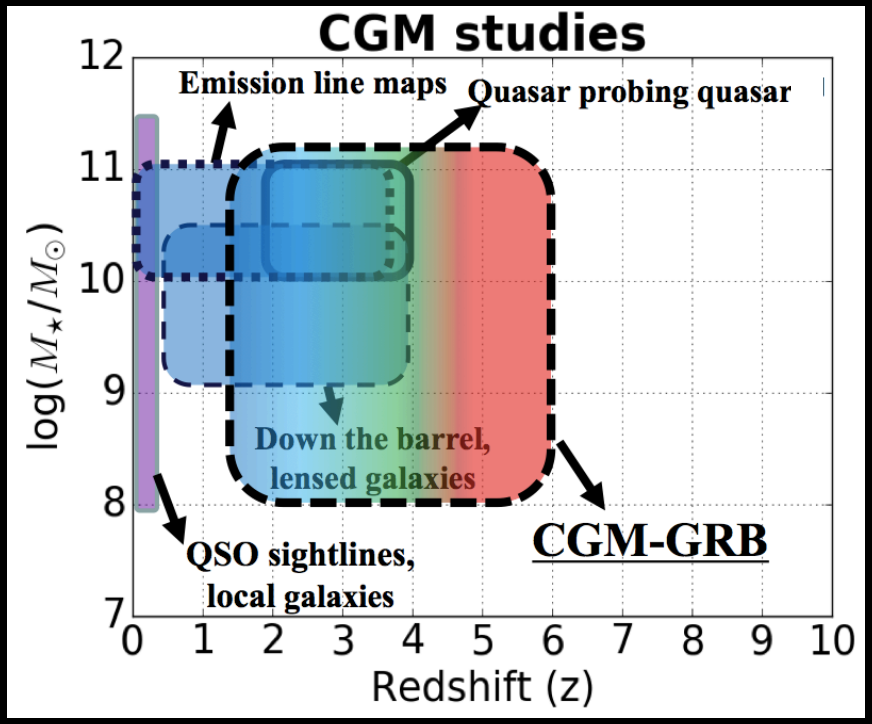
(Tumlinson+11,17; Werk+13, 14, 16; Peeples+14; Ford+16; Bordoloi +17…)

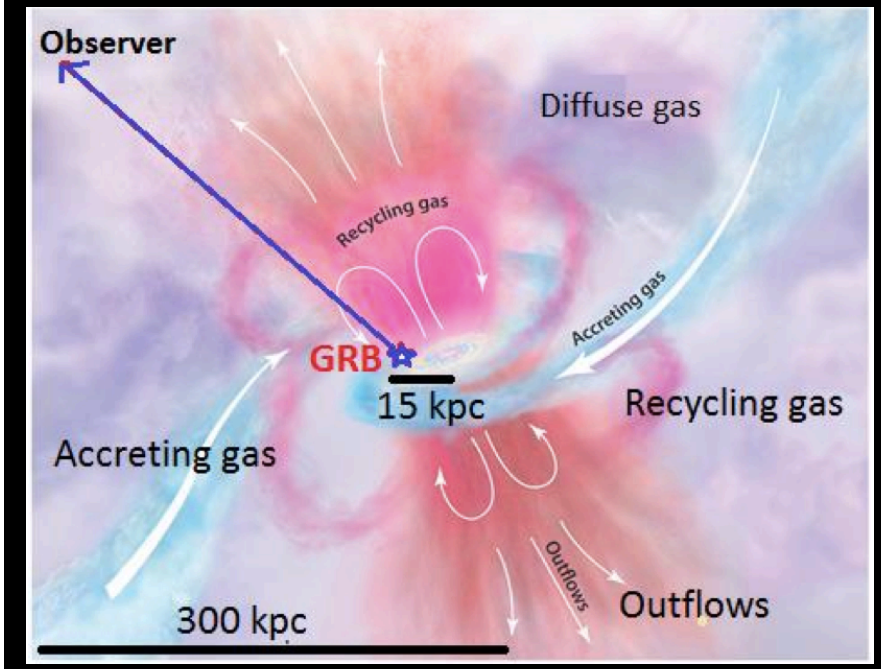
(e.g., Steidel+10; Prochaska+14; Lau+15)

(Steidel+11; Matsuda+12; Hayes+13; Borisova+16)

CGM at z = 2 - 5
Composition, Kinematics, Ionization?

PhD Thesis: Pradip Gatkine (UMD)
Co-I: A. Cucchiara (UVI)





(e.g., Fox+08)

CGM at z = 2 - 5
Composition, Kinematics, Ionization?

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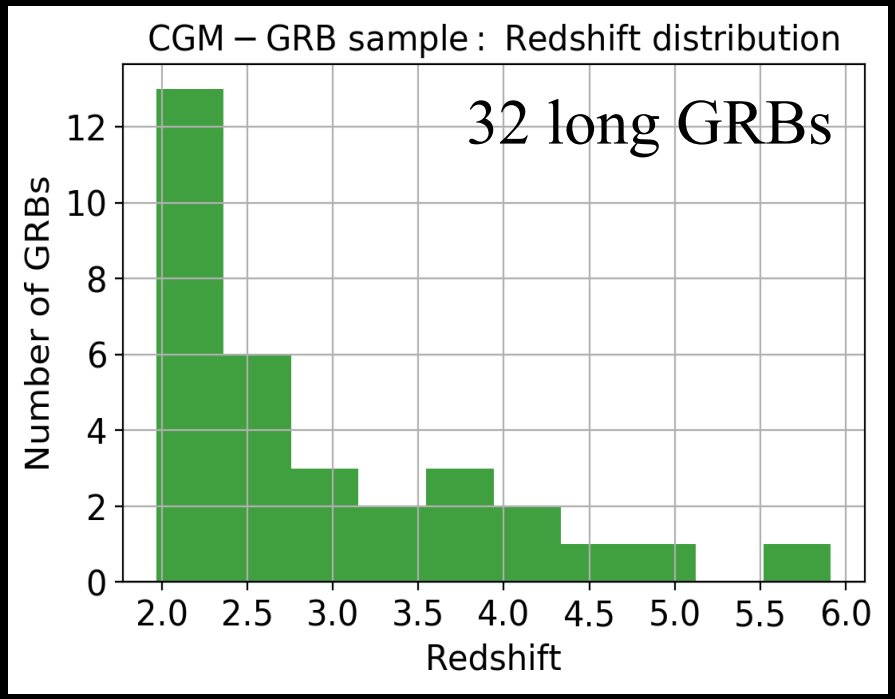
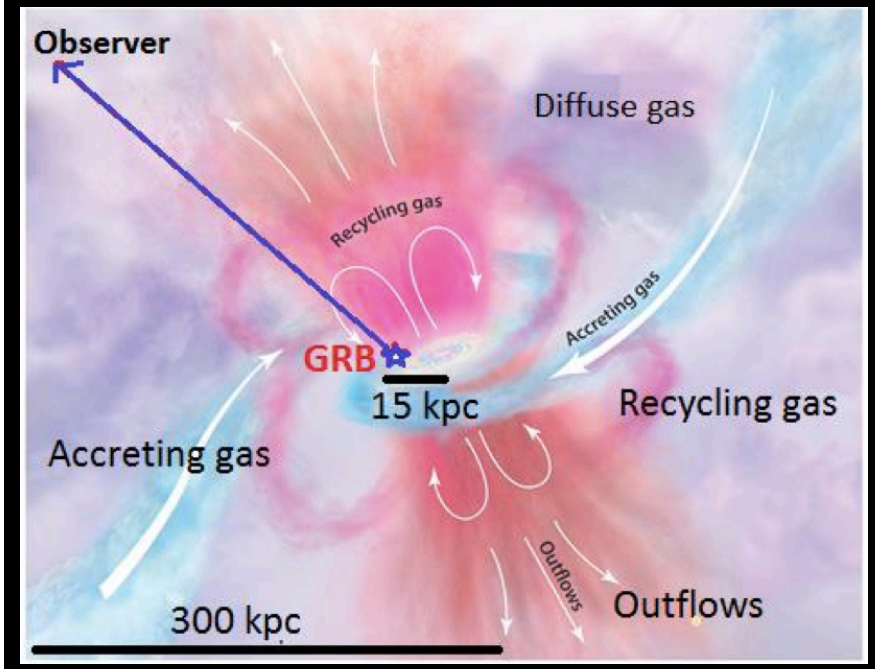
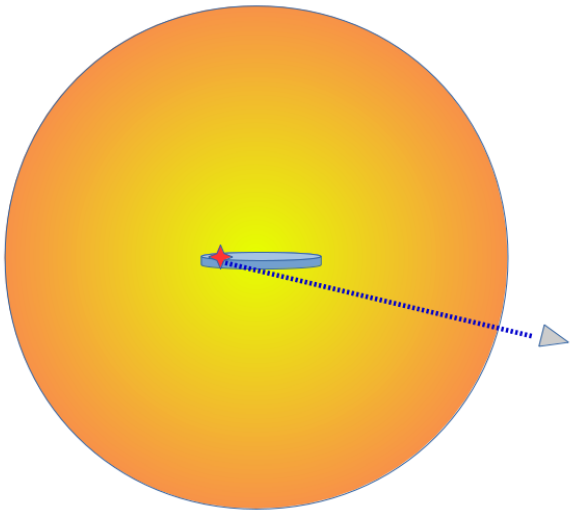
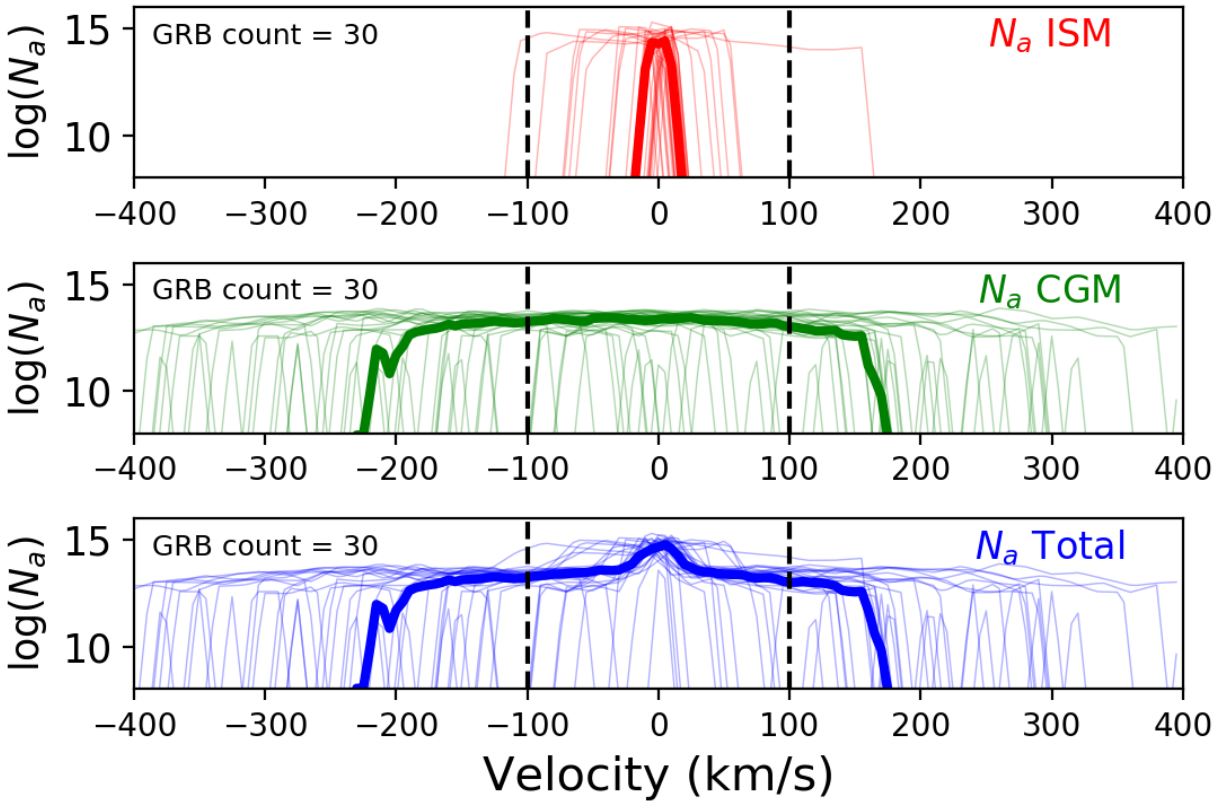




Expectations

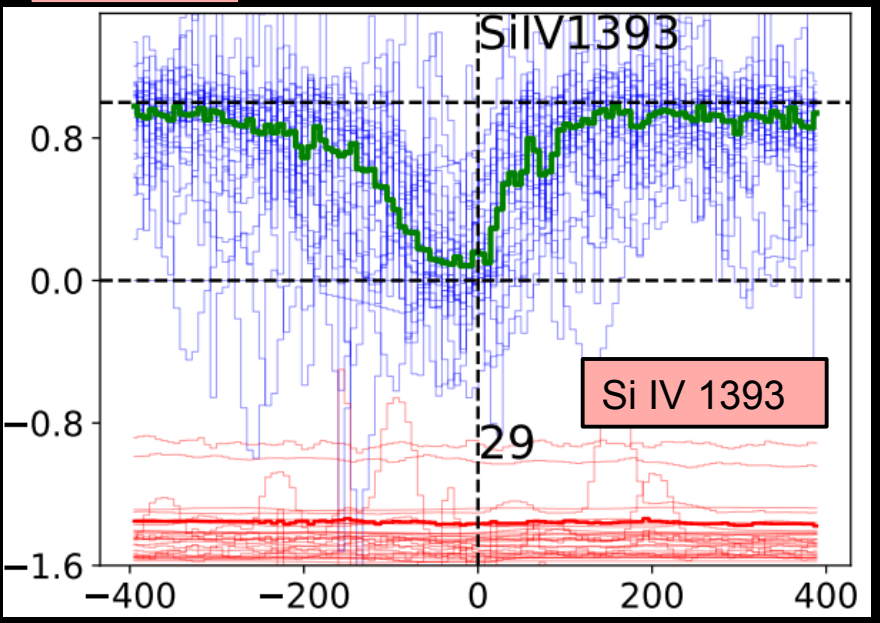
GRB toy model: MW-like

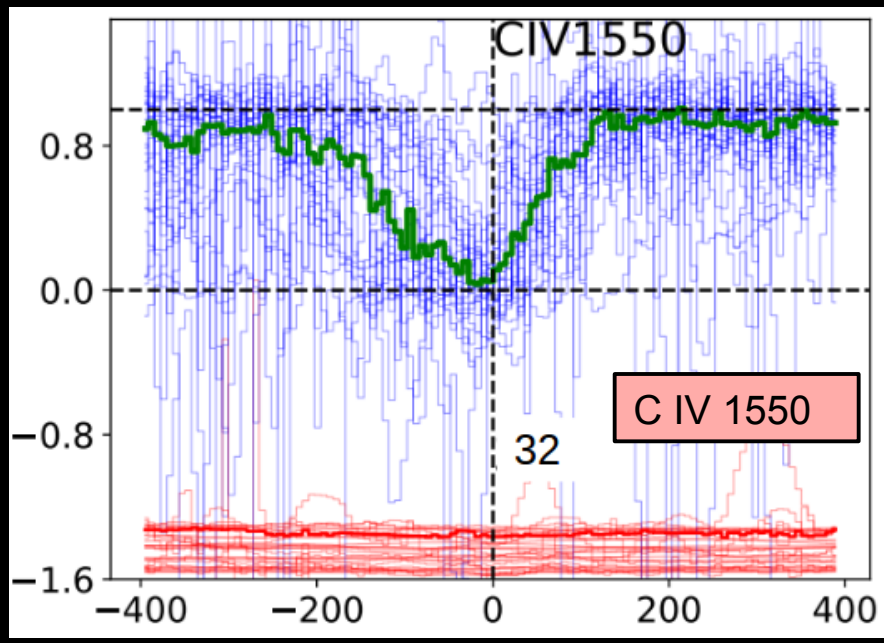




Galaxy radius: 15 kpc
Galaxy height: 1 kpc
Flat velocity: 220 km/s
CGM extent: 150 kpc (conservative estimate)
Vol. filling fraction: 70%
ISM density: 10 cm^{-3} (to emphasize ISM)
CGM density: 0.0005 cm^{-3}
CGM dispersion cloud velocity: 150 km/s
CGM cloud extent: 0.5 kpc (for each absorbing cloud)

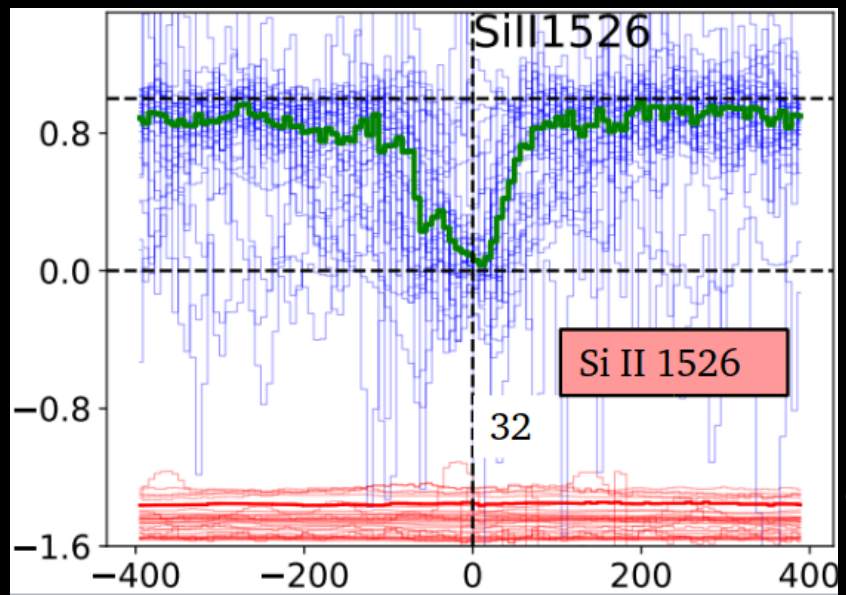
High-ions



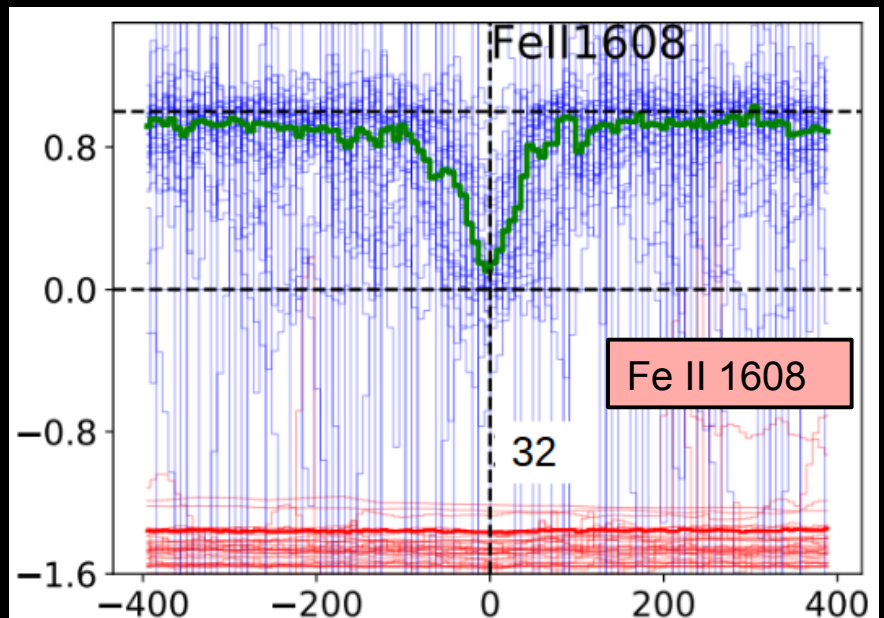


CGM is already largely in place at z ~ 2 – 5
High-ions and low-ions trace different kinematics

low-ions



(e.g., Fox+08)



Plan

- Galaxy scale: Multiphase outflows at $z \leq 0.5$
- CGM scale: New constraints at $z = 2 - 5$
- **Future: *JWST***
- Summary

Approved Director's Discretionary Early Release Science Program

IMAGING SPECTROSCOPY OF QUASAR HOSTS WITH JWST

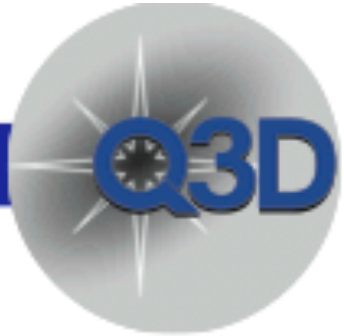
ANALYZED WITH A POWERFUL NEW PSF DECOMPOSITION AND SPECTRAL ANALYSIS PACKAGE

Dominika Wylezalek (PI)

S. Veilleux (Co-PI)
N. Zakamska (Co-PI)
D. Rupke (Co-I)
A. Sun (Co-I)
J. Barrera-Ballesteros (Co-I)
N. Luetzgendorf (Co-I)
N. Nesvadba (Co-I)
R. Alexandroff
H.-W. Chen
M. Garcia Marin
J. Greene
K. Hainline
F. Hamann
T. Heckman
S. Johnson
G. Liu
D. Lutz
V. Mainieri
R. Maiolino
P. Ogle
E. Sturm

27.6 hrs with NIRSPEC + MIRI IFU

Q3D: SUMMARY



Science Goals:

- **3 powerful quasars ("poster child" sources) with z = 0.4, 1.6, 2.9**
- **Study multiple phases of the quasar-driven winds and quasar nebulae (ionized + molecular gas phases, shocks, SFR)**
- **Impact of quasar feedback on the host galaxy**

→ **Scientific dataset of broad interest**

→ **Pathfinder for *JWST* science investigations in IFU mode**

Science-Enabling Data Products:

- **PSF Decomposition and Analysis Tool for high dynamic range IFU observations (*IFSFIT; Rupke, Gultekin, & SV '17*)**

→ **Powerful new data analysis tool that will enable frontier science for a wide swath of astrophysical research**

Summary: New Results

- **Cool gas often is the energetically dominant phase of galactic winds in gas-rich systems**
- **Ubiquitous (>70%) cool gas outflows in nearby U/LIRGs – IR QSOs**
  - **Velocity:** $\langle v_{50} \rangle \sim 200$ km s^{-1} $\langle v_{max} \rangle \sim -1000$ km s^{-1} **[feed CGM]**
  - $R \sim 0.1$ – few kpc **[sometimes up to 10+ kpc]**
  - $dM/dt \sim 10 - \underline{1000}\ M_{sun}$ yr^{-1} **[$t_{depl} < 10^8$ yrs (ULIRGs)]**
  - $dp/dt = (0.1 - \underline{20})\ L_{IR}/c$ **[the most extreme outflows are E-driven]**
  - $dE/dt < 2\%\ L_{IR}$ **[plenty of energy from the central SB + AGN]**
- **New constraints on the CGM at z ~ 2 - 5 using GRBs**
  - **Today's CGM was already largely in place at z ~ 2 – 5**
  - **Blue asymmetric C IV and Si IV → CGM-scale ionized winds?**
- **Future: *JWST DD ERS program + IFSFIT 2.0***