Kinematics of Circumgalactic Gas
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Background Beacons
3D Galaxy Orientations
Feedback in Low Mass Galaxies
Observations of Outflowing Gas

1. Galaxy spectra
   - Detect cool, outflowing gas within a few kpc of galaxies.
   - Defines scaling relations with galaxy properties.

2. Raise questions such as
   - Total mass flux?
   - Spatial extent?
   - Ejected or recycled?

3. CGM sightlines help.
Quasars Probing Galactic Inflow

$z \approx 0.2$

Mg II 2796, 2803 at 3200-3380 A
Minor Axis Sightlines: No Net Corotation

- **Left:** Stacking 50 quasar sightlines through the halos of 50 galaxies of log $M^*/M_0 = 10.0$.

- ELTs: Multiple sightlines per galaxy!
Quasars Probing Galactic Outflow?

(a)

(b)

(c)
Mg II Absorption Strength Depends on Azimuthal Angle

• Strong minor axis Mg II absorption (as seen previously); does it imply disturbed by galactic winds?

• Strong major axis Mg II absorbers (new); previous studies lacked sightlines at $b < 40$ kpc. These ALS are related to disks but are not thin disks.

Symbol size (and color) indicate absorption strength.
Minor Axis Excess Absorption

- Average equivalent width declines with impact parameter.
- Most ‘excess absorption’ is detected in minor axis sightlines.
- We can show that this is a kinematic disturbance.

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![Graph showing Minor Axis Excess Absorption](image)

- Data from Chen et al. 2010; Nielsen et al. 2013
- Clusters around major and minor axes
- Color indicates Doppler shift sign relative to Galactic Rotation

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Minor Axis (kpc) vs. b (kpc)
Confirm that Strong Absorbers Have Large Velocity Spread

We want to understand how outflows increase the absorption.

\[ \Delta V \text{ (km/s)} \]

\[ W_{r, 2796} (\text{A}) \]

Conical Outflow Model
Motivated by Outflow Properties Measured from Galaxy Spectra

Cone opening angle $\theta = 30-45^\circ$

Radial outflow speed $\approx \text{few } \times 100 \text{ km/s}$
Determine 3D Orientation of Galactic Disks

• Rotation curves are not enough.

• Which side of the disk is tipped towards the observer?

• Spiral arms are generally trailing.
  • Resolving spiral arms determines ‘disk flip,’ or sign of disk inclination.

Ho & CLM 2018b
Measured 3D Orientation of Galactic Disks
Minor-Axis Sightlines with Strong Mg II: Example with No Disk Component

\[ R = 141 \text{ kpc}, \text{ so sightline misses disk.} \]
Minor-Axis Sightlines with Strong Mg II: Example with Possible Disk Component

R = 33 kpc, so not surprising that sightline intersects disk.

\[ x_0 = -12.0 \text{ kpc} \]
\[ y_0 = 30.95 \text{ kpc} \]
\[ z_0 = -23.3 \text{ kpc} \]

\[ J153546+391931 \]

\[ \theta \sim 45^\circ \]

Is line wing part of outflow?

Correlation with SF Activity?

Timescales: $t_{\text{flow}} \sim r_{\text{los}} / v_{\text{wind}}$

- **J095424+093648** ($r_{\text{min}} = 89$ kpc)
  - @1000 km/s, $t_{\text{flow}} = 87$ Myr
  - @ 100 km/s, $t_{\text{flow}} = 870$ Myr
- **J153546+391931** ($r_{\text{min}} = 22$ kpc)
  - @1000 km/s, $t_{\text{flow}} = 22$ Myr
  - @ 100 km/s, $t_{\text{flow}} = 220$ Myr

*Do the host galaxies have elevated SFRS?*
Population Statistics

\[
\frac{W}{c} < 50 \text{kpc} \quad \text{(Å)}
\]

\[
\langle W_\rho \rangle < 50 \text{kpc} \quad \text{(Å)}
\]

\[
W_{\text{FeII}}^{2600} + W_{\text{FeII}}^{2382}
\]

\[
W_{\text{MgII}}^{2796} + W_{\text{MgII}}^{2803}
\]

Lan & Mo 2018

Heckman+2017

Log \( W_{\text{CV}} \) [mÅ] vs \( \rho / R_{\text{vir}} \)

\[
\log W_{\text{CV}} = (-0.416 \pm 0.336) \rho / R_{\text{vir}} + (2.880 \pm 0.302) \\
\log W_{\text{CV}} = (-1.969 \pm 0.620) \rho / R_{\text{vir}} + (2.813 \pm 0.396)
\]
Yes, but they are within 1.5 sigma of the SFR main sequence.
Need to Link Models and Observables

- Mass loading in starburst region vs. significant mass entrainment from CGM
  - High-resolution spectra → component velocities and column densities
  - Estimates for mass flux depend on assumptions about the flow.

Schneider+ 2019

Cloud moving outward

Gronke & Oh 2019
Outflow – CGM Interaction

Vs = 800 km/s
11.6 kpc

Devine+1999; Lehnert + 1999
Feedback in Low-Mass Galaxies

CLM+2002

Chisholm+2017

SBS 1415+437
IZw 18

$\log M_{\odot}/SFR_{\odot}$

$\log M_{\odot} (M_{\odot})$

Chisholm+2017
Ionized-gas detected 1.4 kpc above star-forming regions.

Echelle spectrum resolves near and far sides of expanding shell. Tick marks are separated by 46 km/s.

Shell extending 1 kpc V ~ 34 km/s
KCWI continuum, Hβ nebula (white contours), and He II nebula (cyan contours).
Summary & Outlook

• Impact of winds on CGM directly observed! Excess Mg II absorption in minor-axis sightlines is well established.
• The value of spatially resolved galactic rotation and morphology has previously been underestimated.
  • Need to explore the nature of the line broadening observationally and theoretically.
  • Demonstrated stacking 50 sightlines, but ELTs will provide access to multiple sightlines per galaxy.

• Challenging to find evidence for very high mass loading (> 20) in low mass galaxies. Stay tuned!
  • KCWI study of highest sSFR dwarfs at d < 60 Mpc
  • COS Legacy Archive Spectroscopic Study (Berg, PI + )