Extragalactic Outflows

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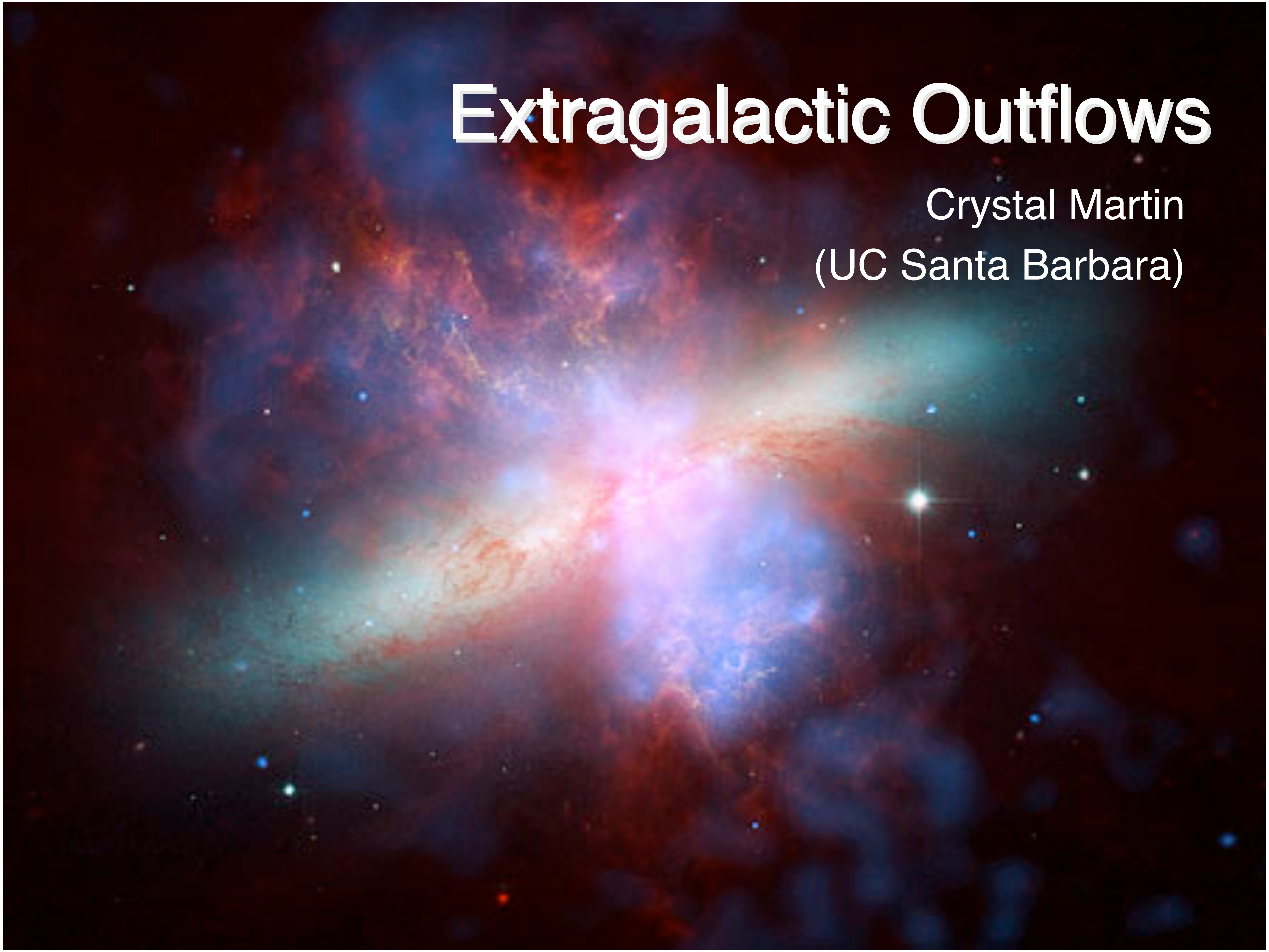


Outline

- UV Pumping of Fluorescent Emission from Outflows

  Collaborators: Alice Shapley & Kathy Kornei (UCLA), Alison Coil (UCSD

- Velocity Dependent Covering Fraction of Outflows

  Collaborators: Nicolas Bouche

- Outflow Properties

  Collaborators: Norman Murray (and above)

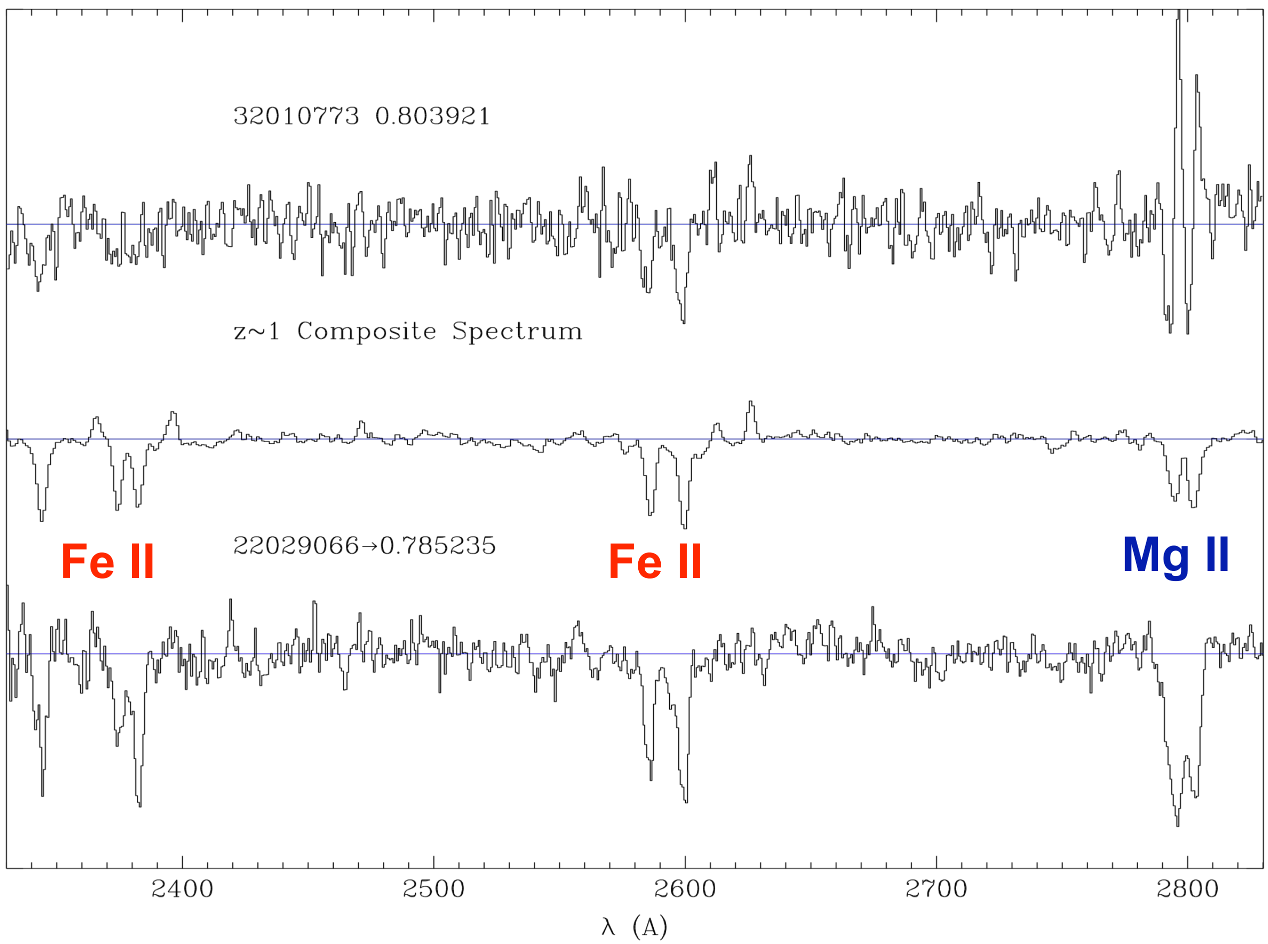
Outflows, Star Formation, and Stellar Mass at 0.6 < z < 1.4

- Blue (Keck) spectra of B < 24 galaxies in DEEP2 fields.
- Resolution of 280 to 440 km/s FWHM, and SNR ~ 10.
- Previous surveys at these redshifts focused on composite spectra (e.g., Weiner + 2009; Rubin + 2010).
- Lower redshift surveys use the optical NaI lines (Sato + 2009; Chen + 2010) rather than near-ultraviolet lines.
- Measure Doppler shifts to 30-40 km/s relative to [OII] emission-line (plus other nebular and stellar features).
- Sensitive to line equivalent widths ~ 100 mA or more.

Part I. UV Pumping of Fluorescent Emission

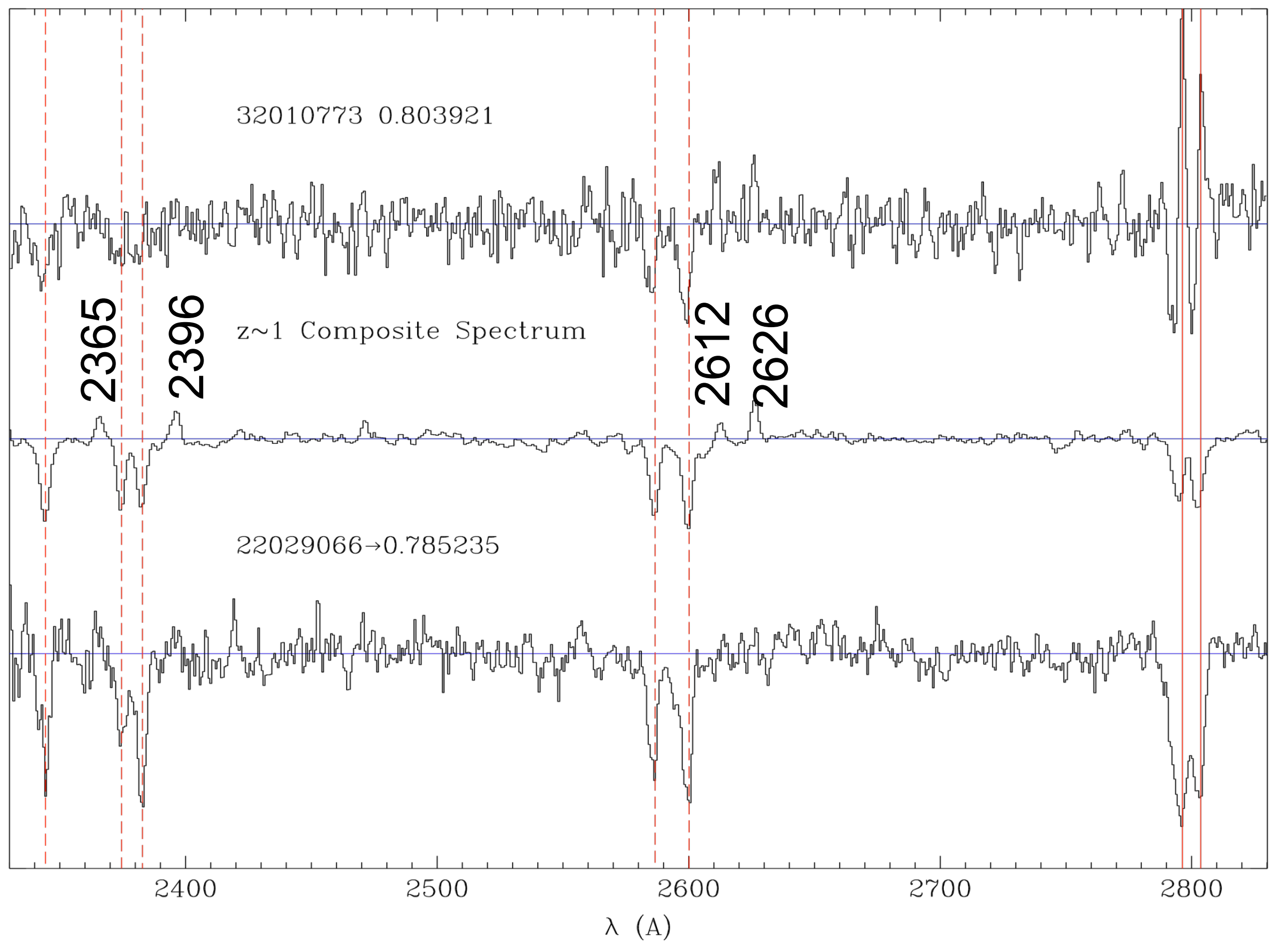
Spectra of z~1 Galaxies

- **Absorption in Fe II and Mg II resonance lines found in nearly all spectra (and composite)**
- **What are the emission lines?**



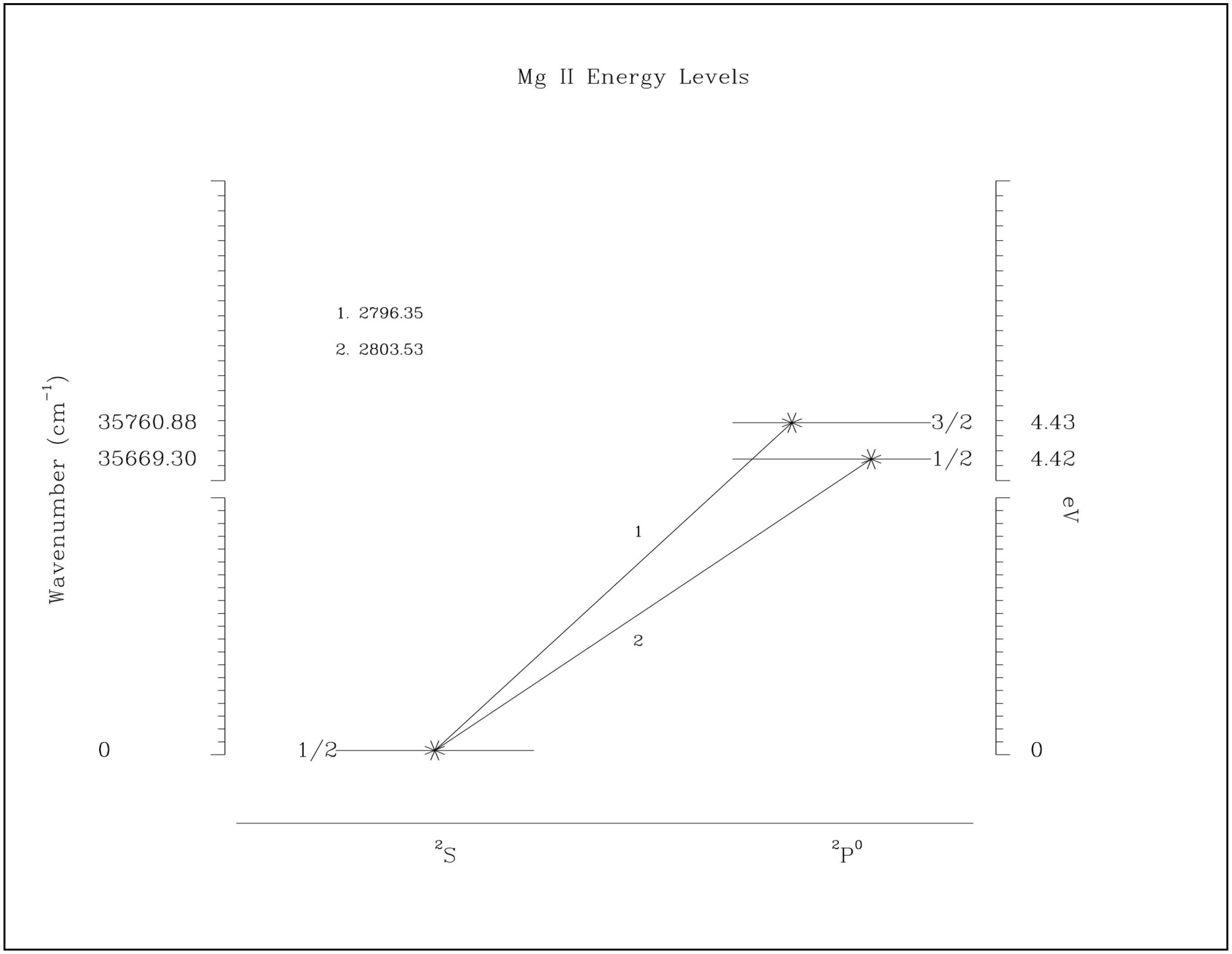
Spectra of z~1 Galaxies

- **Mg II emission found in ~15% (not composite)**
- **Fe II* emission in a few spectra (strong in composite)**
- **Does the emission come from the outflow?**



Energy-Level Diagram for Mg II

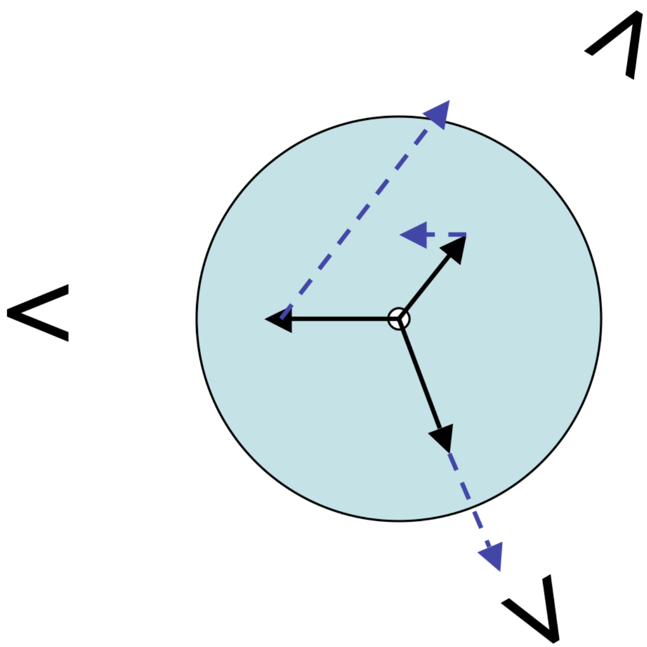
- **Outflow absorbs continuum photons and emits line photons.**



Spherical Outflow:

Mg II Emission vs. Absorption

- Continuum Emission from Point Source



$W_{EM} = W_{ABS}$

- **For every photon removed from the continuum, a line photon is emitted.**
- **An observer on any side of the outflow must see the same spectrum.**
- **The emission equivalent width should be as large as the absorption equivalent width in the same line.**

Various Factors Reduce Emission

- Extended Continuum Source

- **Extended continuum**
- **Dust in the outflow**
- **Break spherical symmetry**

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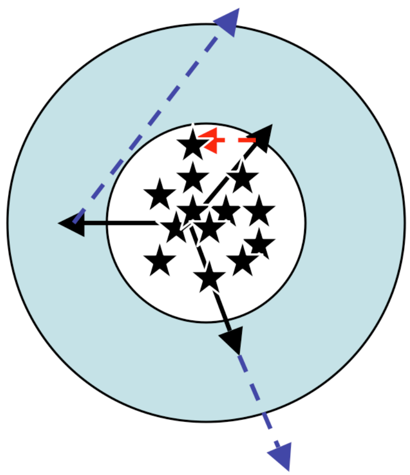
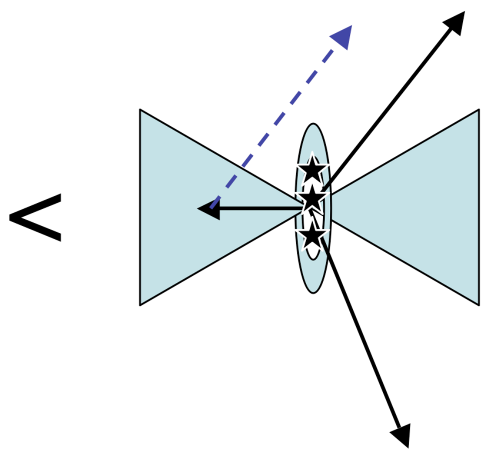


$W_{EM} \leq W_{ABS}$

Viewing Geometry

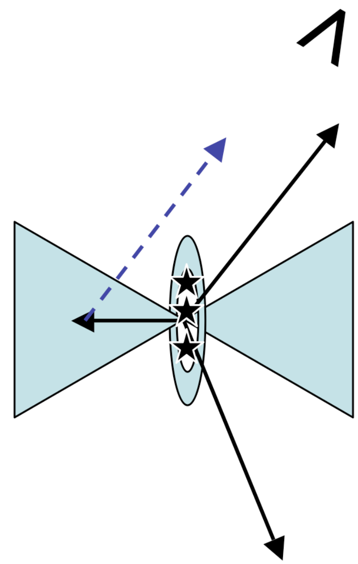
Bipolar Outflow or Streams

- Bipolar Wind Viewed Down the Outflow Axis



$W_{EM} << W_{ABS}$

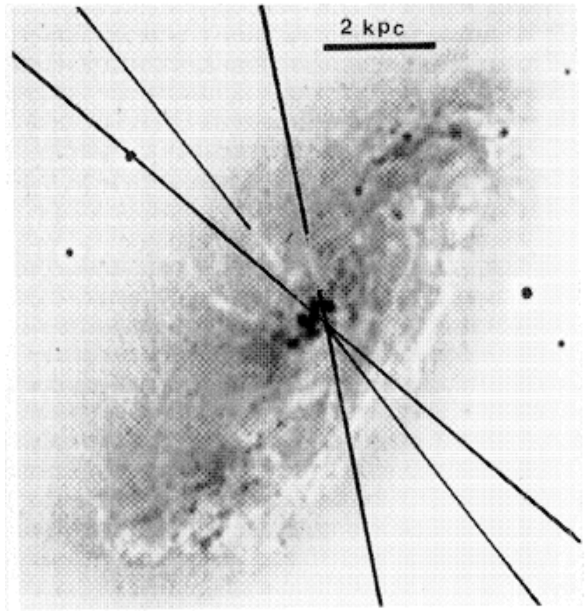
- Bipolar Wind Viewed from the Side

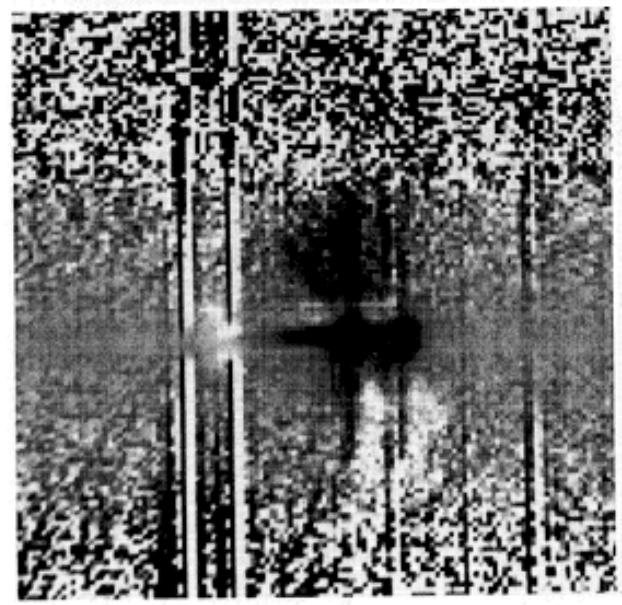


$W_{EM} > W_{ABS}$

Example: Na I Emission

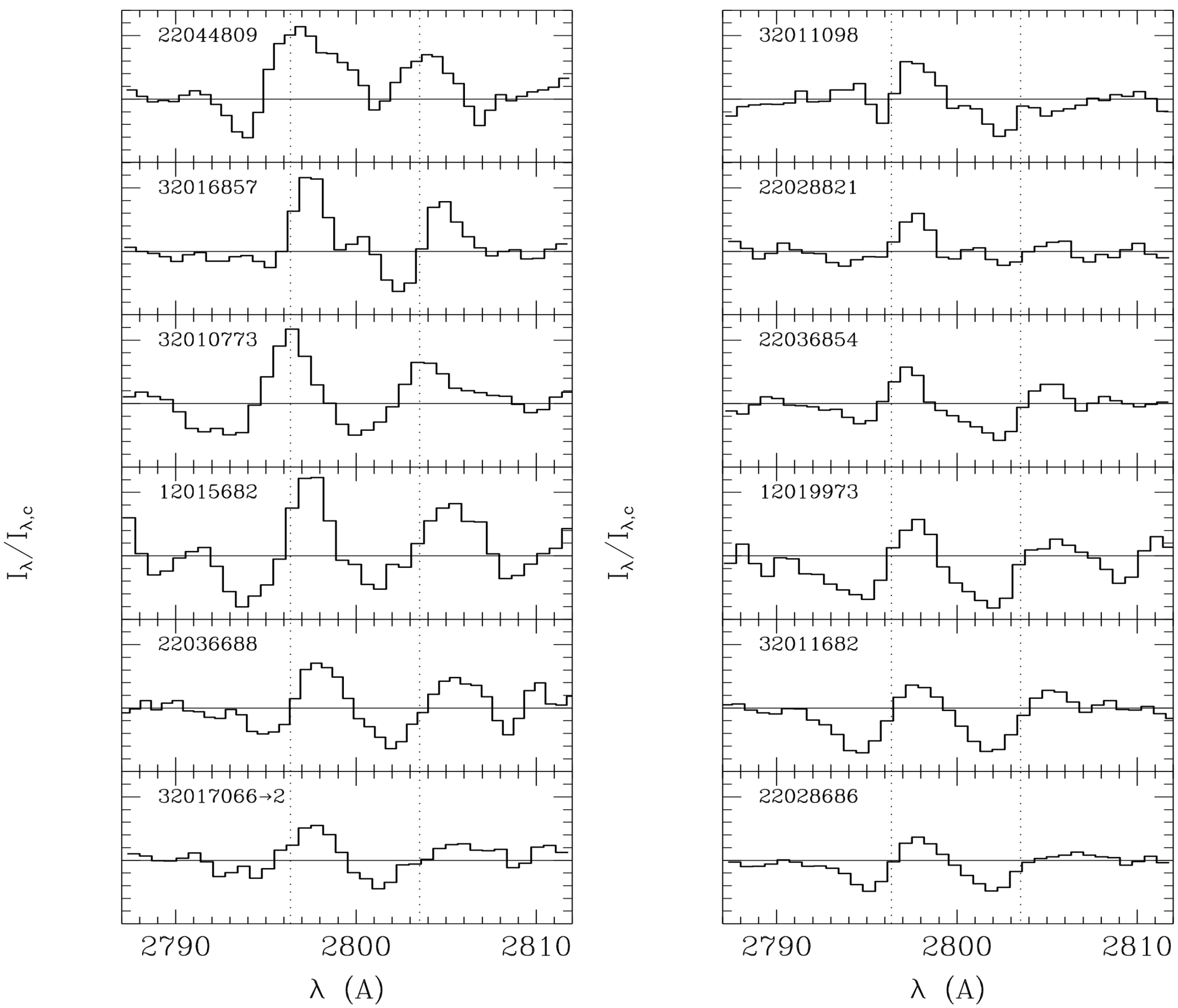
A. C. Phillips 1993 -- NGC 1808





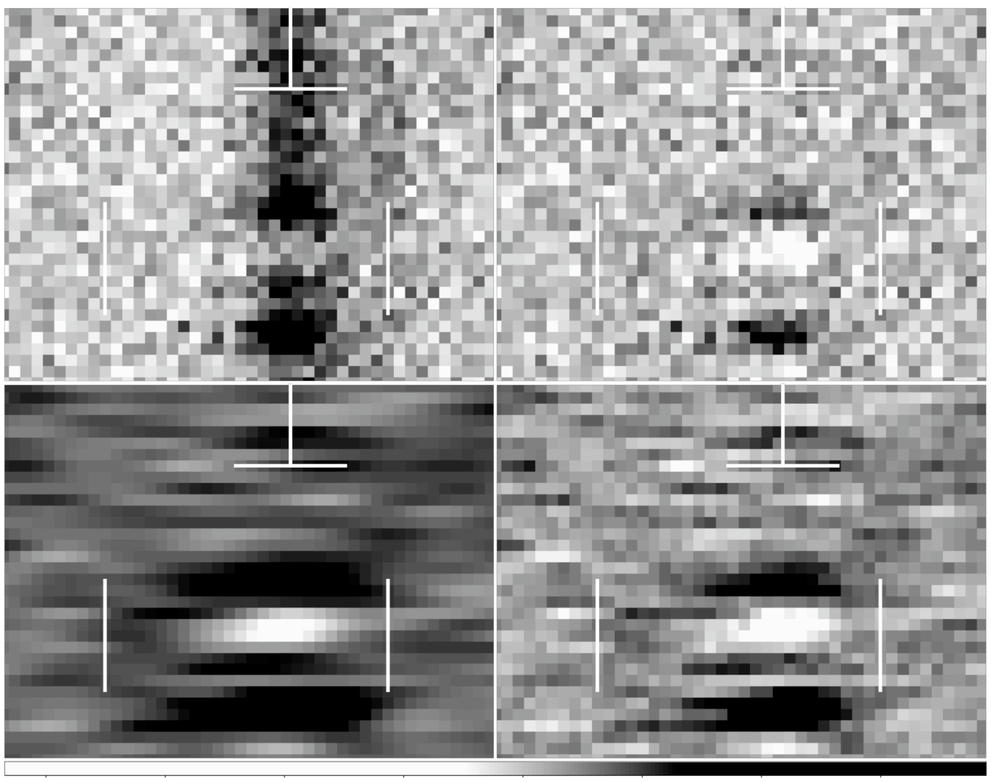
- Dust shielding thought to play a role in the survival of Na I (Martin 2006, Figure 7)
- Grains absorb most emitted Na I photons
- Na I absorption has a component at systemic velocity (v=0) and an outflow component
- The systemic component is stronger in edge-on systems; and its strength is correlated with reddening (Chen + 2010)
- At low inclination, Chen et al find a hint of Na I emission.

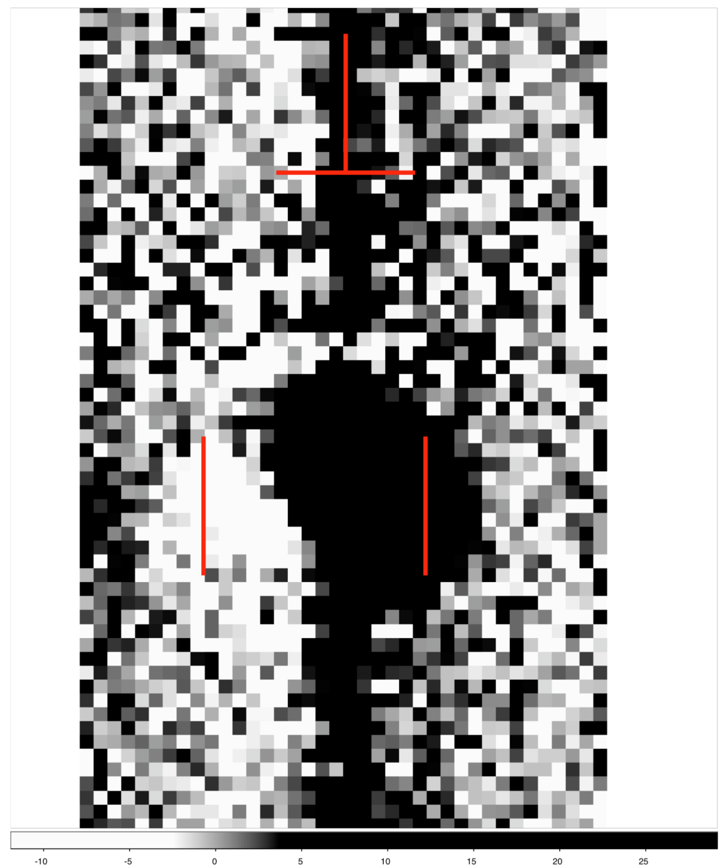
Rare, but find Mg II $W_{em} > W_{abs}$



Detect Extended MgII Emission

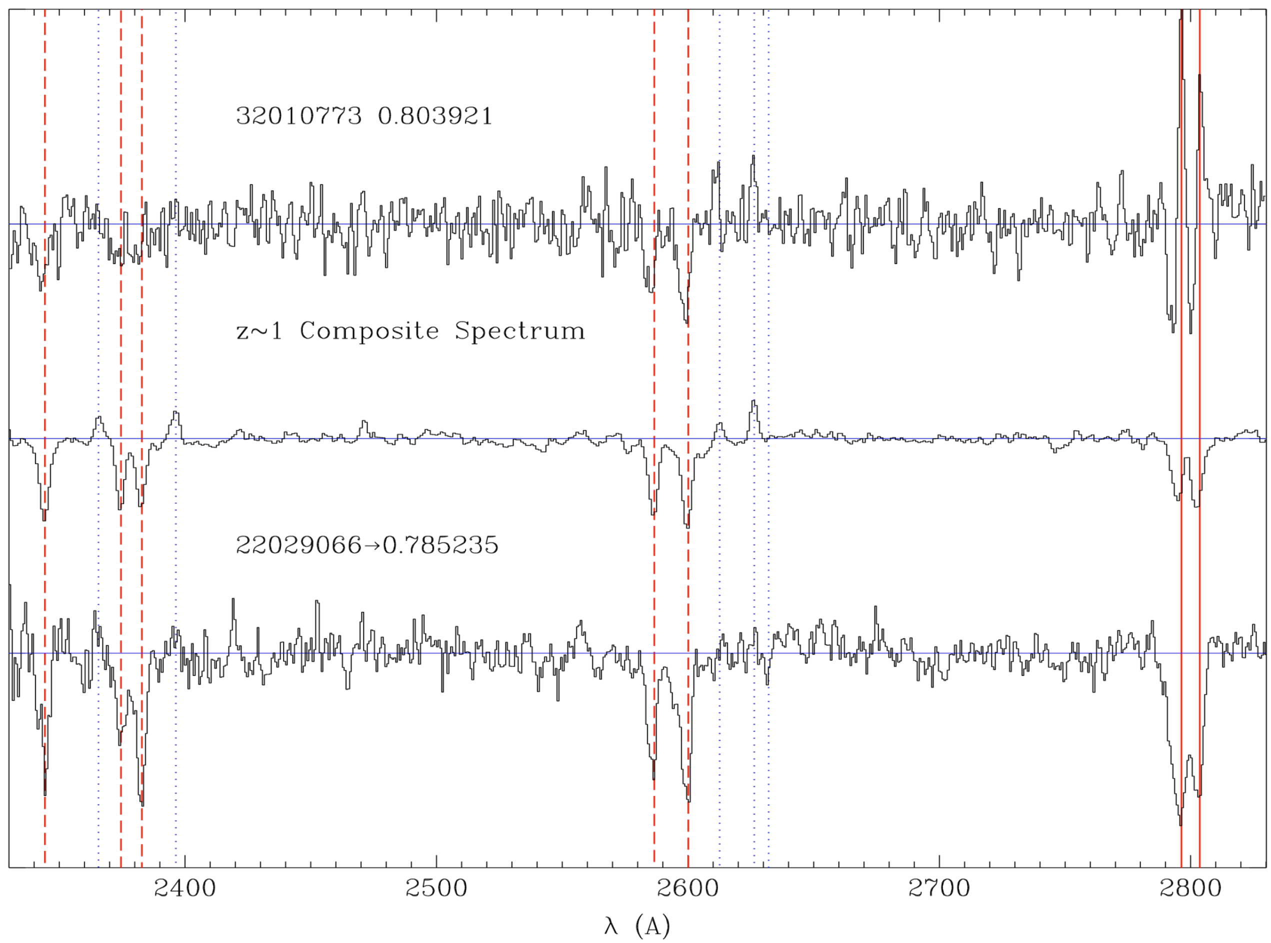
- Spatial extent is at least 3.4” or 27 kpc
- Gas kinematics show the emission is not from the galactic disk.



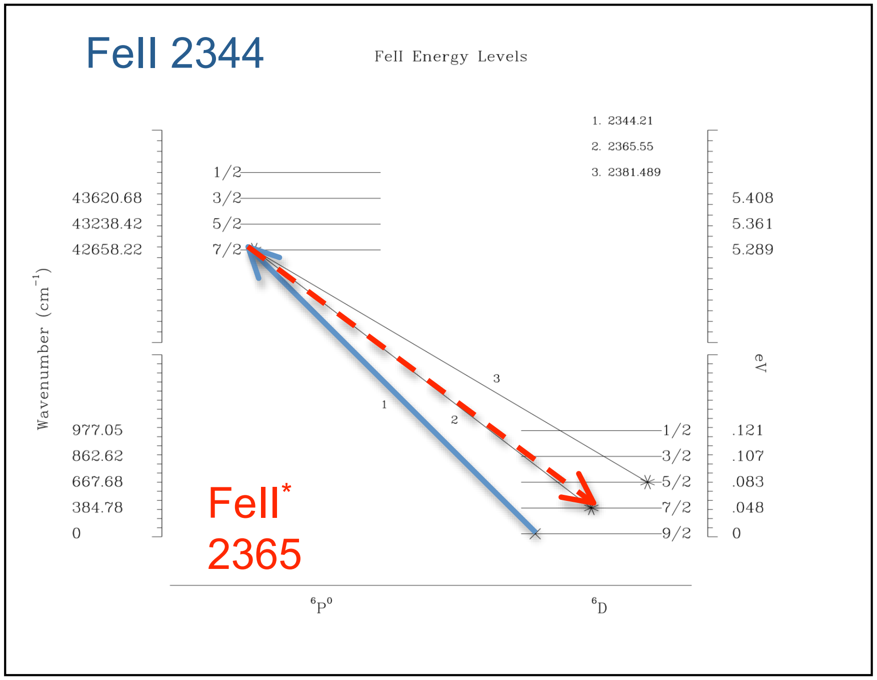


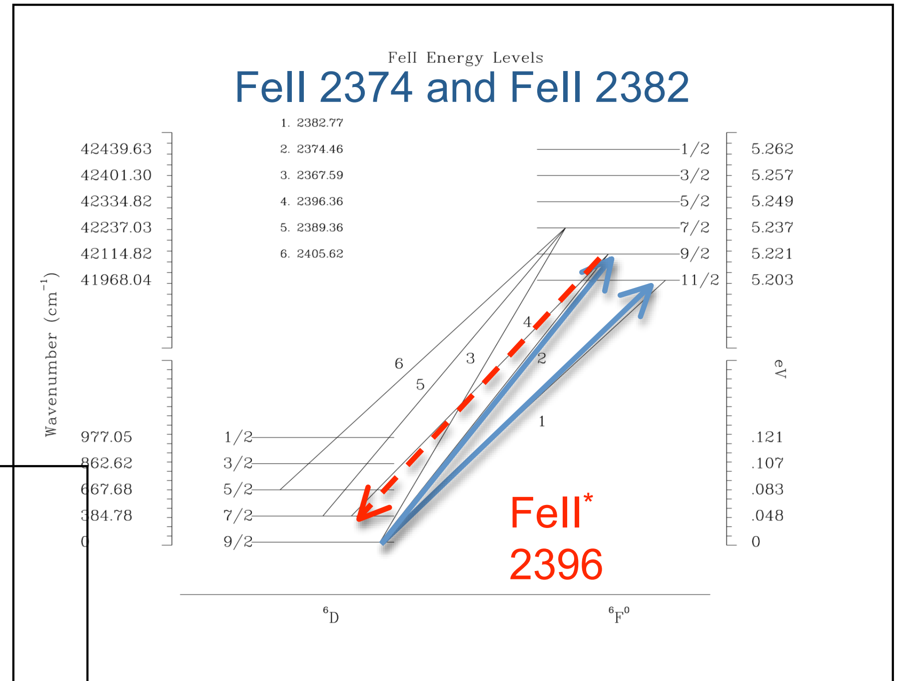
Spectra of z~1 Galaxies

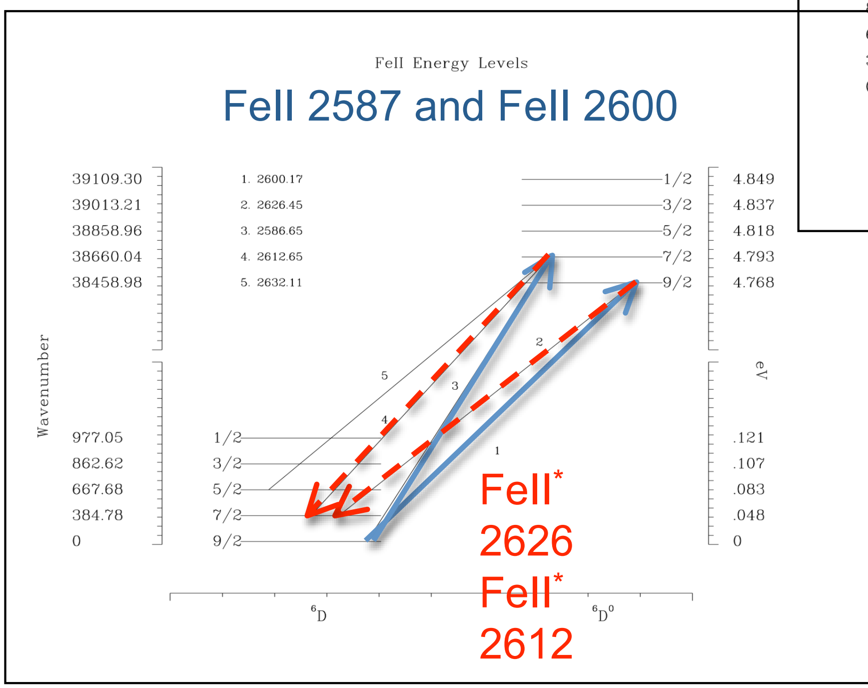
- Where is the Fe II emission that results from the Fe II absorption?
- Partly in the Fe II* emission lines.
- Upper levels of Fe II* transitions are populated by continuum absorption in ground state ions.



Energy-Level Diagrams for Fe II (ΔJ=0,+1,-1)

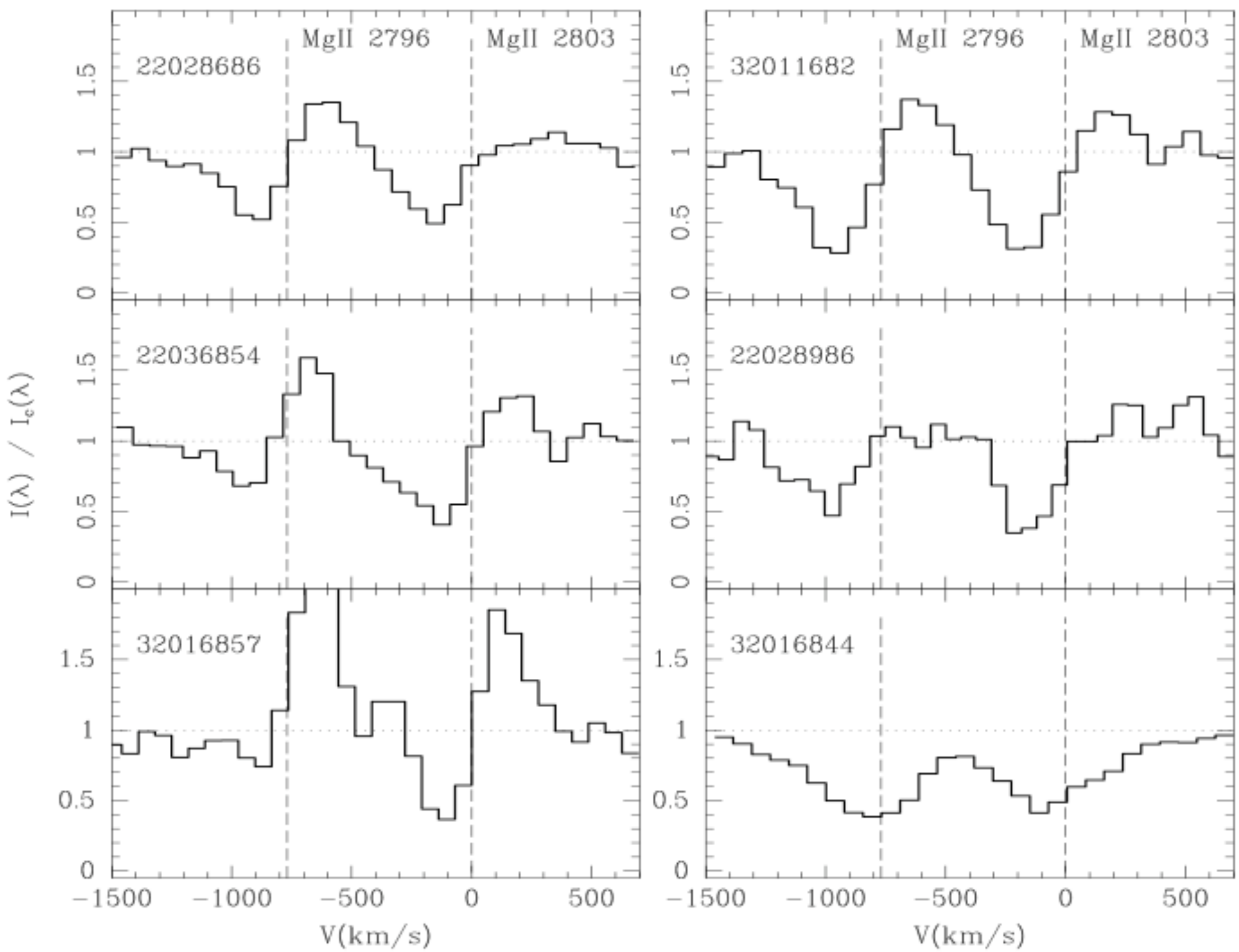






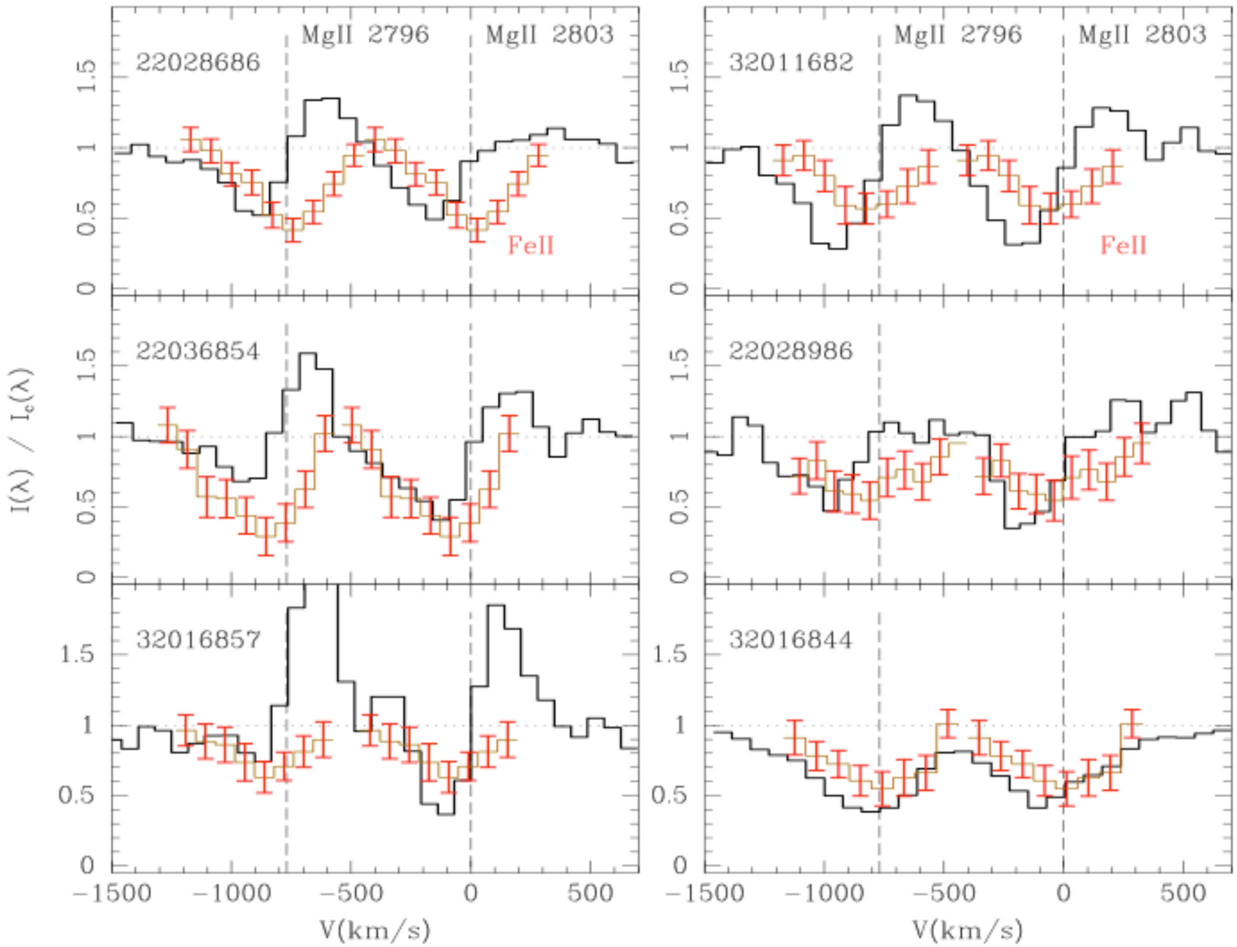
Mg II vs. Fe II Absorption

- **Does the Fe II and Mg II absorption come from the same gas?**

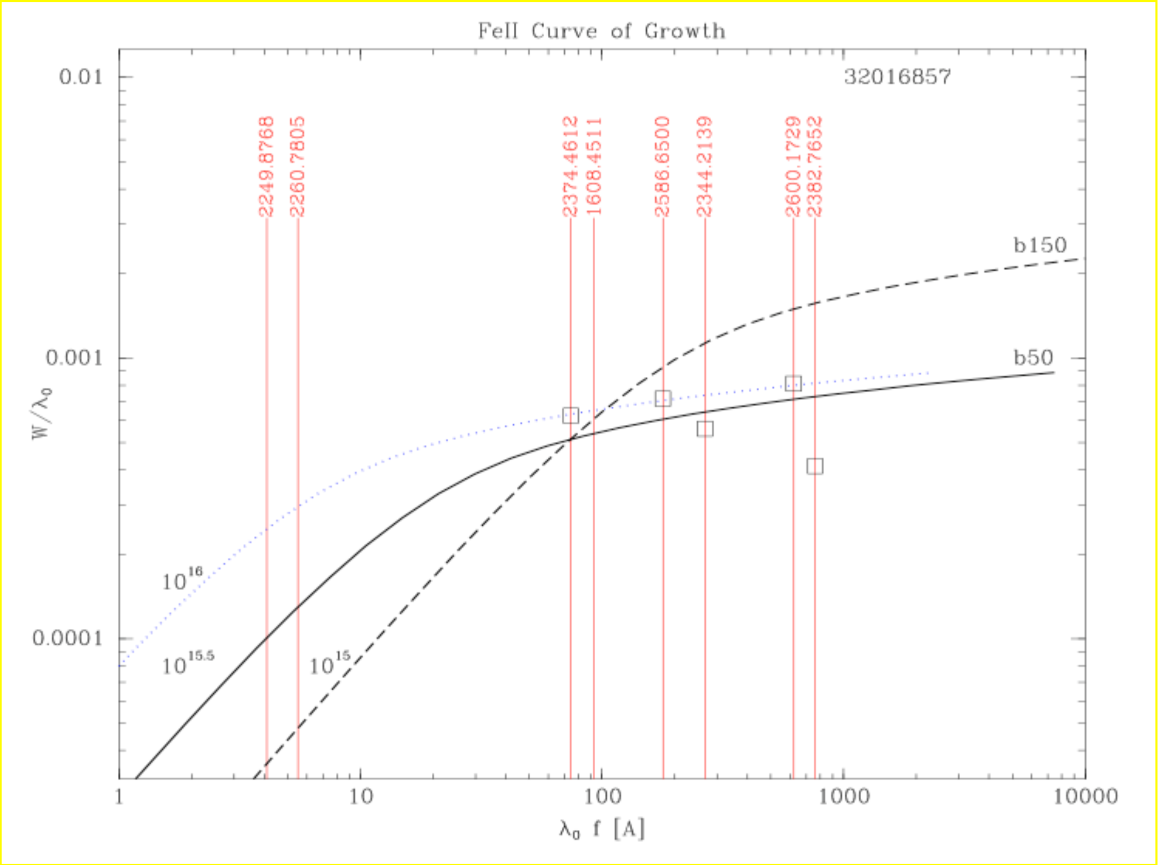


Mg II vs. Fe II Absorption

- **Can hide iron in grains.**
- **Find absence of Mg II absorption at low velocity**



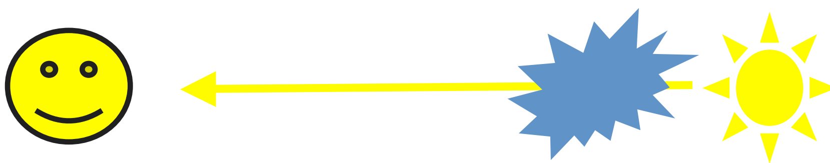
Fe II Curve of Growth



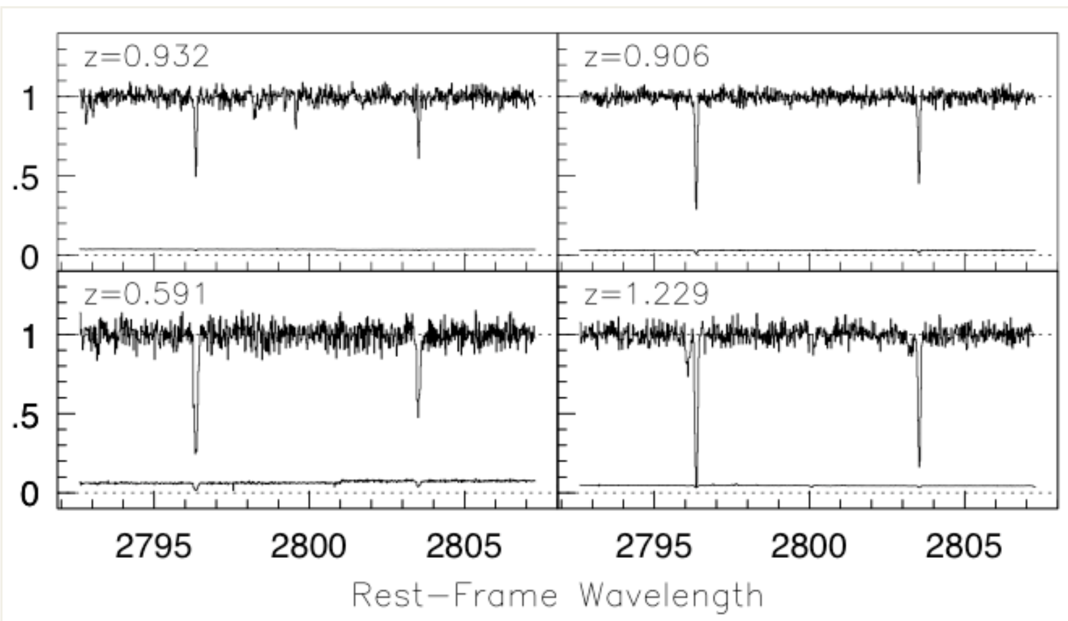
- The oscillator strength of Fe II 2382 is 10 times that of Fe II 2374.
- In some spectra, the 2374 line is stronger than 2382.
- Explain discrepancy by emission filling. The excited electron in $^6F^0$ J=11/2 can only decay radiatively by emission of an 2382 photon.
- Fit N(Fe II) = 10^{16} cm^{-2} and b = 50 km/s
- Compare Fe II* emission EW and absorption EW. Ask me.

The Shape of the Absorption Troughs

- *Martin & Bouche 2009 ApJ, 703, 1394*
- *Optical - Near UV Spectra of z~0.3 Outflows.*
- *Resolution ~ 100 km/s*



Mg II 2796, 2803 Doublet



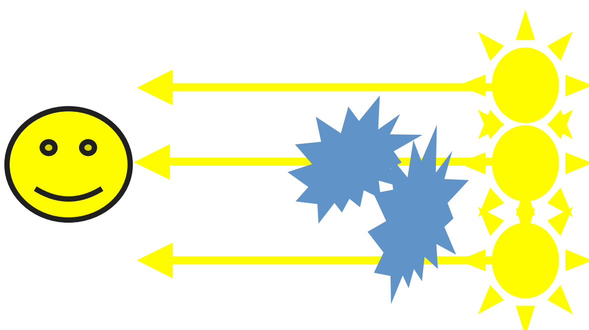
$$I_R(v) = I_0 e^{-\tau_R(v)}$$

$$I_R(v) = I_0 e^{-\tau_B(v)}$$

$$\tau_B = 2\tau_R$$

$$I_B(v) = I_R^2(v)$$

Partial Covering of Continuum Source by Low-Ionization Gas



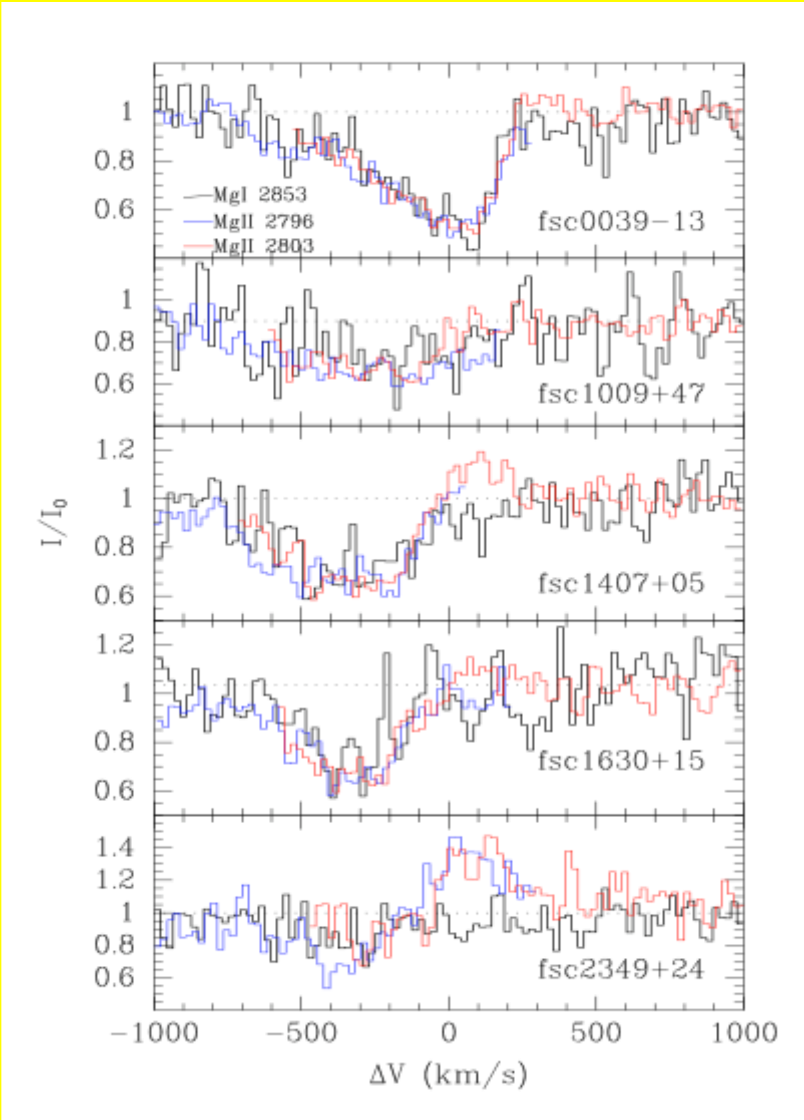
$$I_R(v)/I_0 = 1 - C_f(v) + C_f(v)e^{-\tau_R(v)}$$

$$I_B(v)/I_0 = 1 - C_f(v) + C_f(v)e^{-2\tau_R(v)}$$

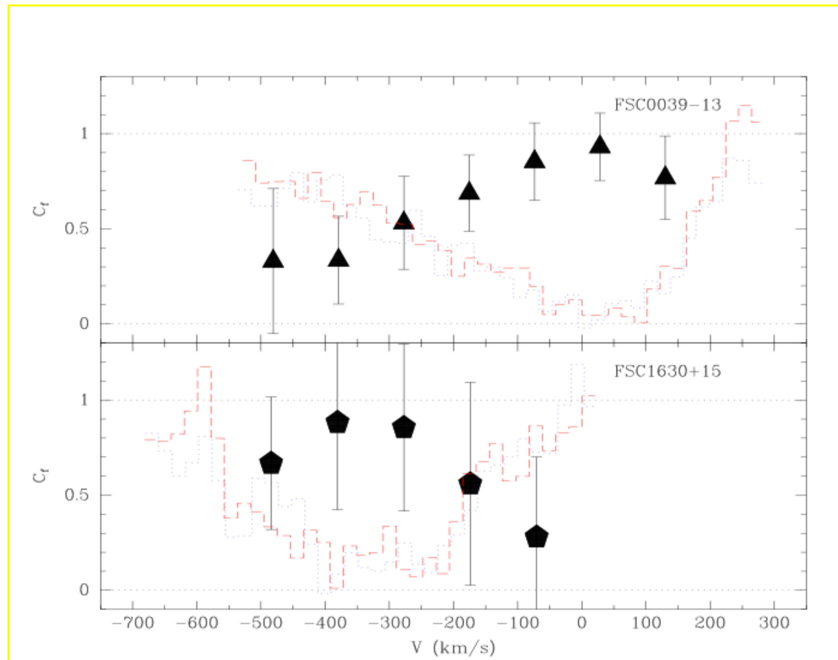
$$C(v) = \frac{I_R^2 - 2I_R + 1}{I_B - 2I_R + 1}$$

$$\tau(v) = ln\left(\frac{C(v)}{I_R(v) + C(v) - 1}\right)$$

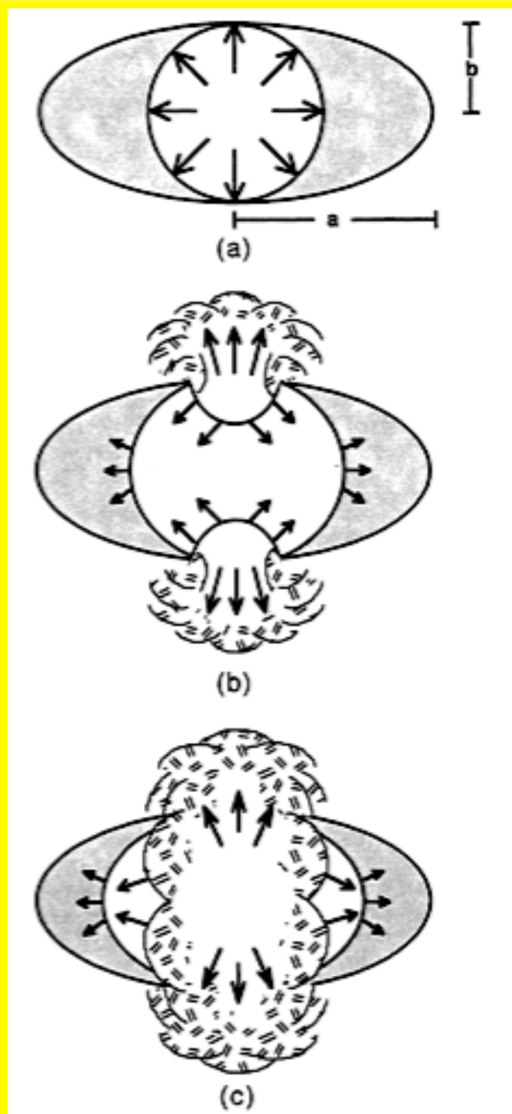
Resolved Absorption Troughs: Variation in Outflow Properties with Velocity



- The absorption troughs in galaxy spectra remain optically thick out to the highest detected velocities.
- Their shape is determined by the gas covering fraction.
- Where the covering fraction of low-ionization gas is low, the absorption trough will be too shallow to detect.

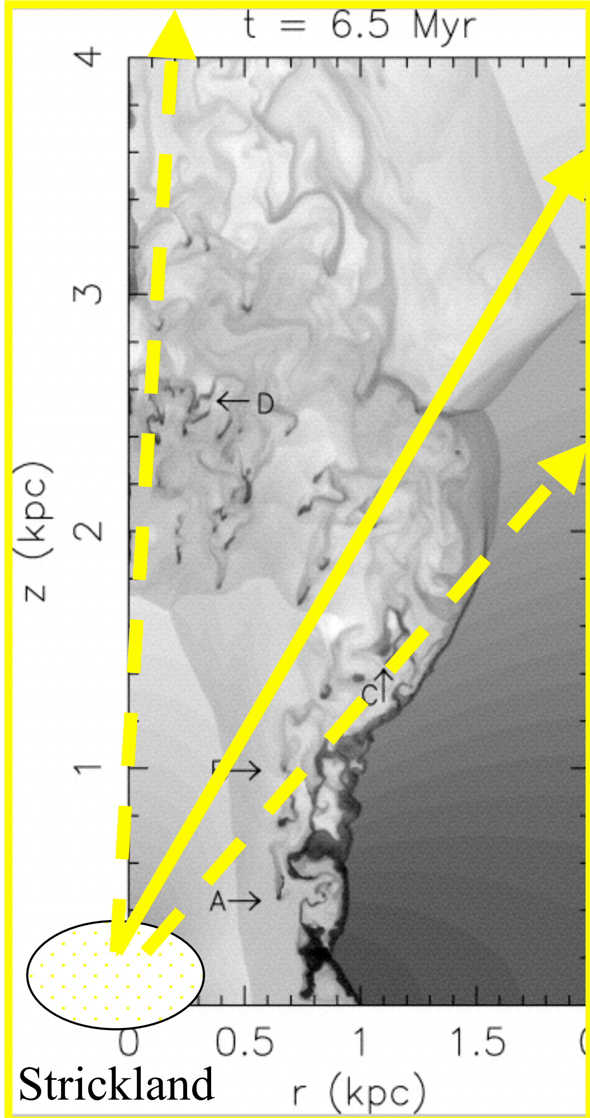


Origin of Low-Ionization Gas in Winds?



MacLow et al. 89; Fujita+09

DeYoung & Heckman 2004



Heckman et al. 2000

Cooper et al. 2009

Need to Constrain Outflow v(r), ρ(r)

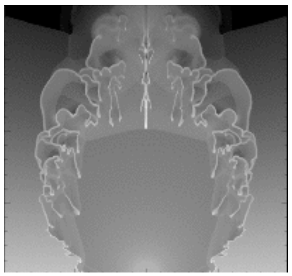
- Outflow kinematics distinguish acceleration mechanisms
- How far do winds propagate?
- How much material do they carry?
- Starburst outflows impact low-ionization gas in circumgalactic medium.

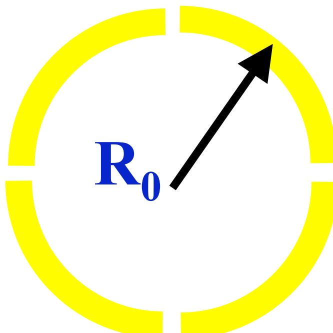
Complete outflow census provided by intervening absorbers.

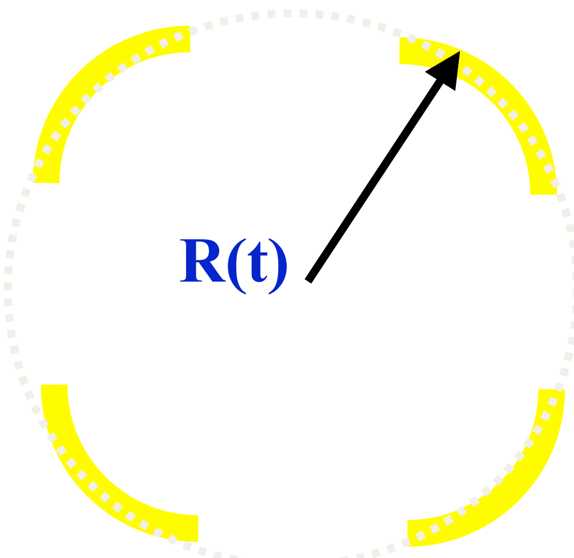
We have d(Number)/dz ~ $n_{gal}\ \sigma_{wind}$.

1. z=0.69 -- (Rubin et al. 2010) -- Mg II detected at b = 7 kpc from starburst galaxy (80 M_o/yr)
2. z~1 -- (Bouche et al. 2007) -- Mg II detected at b = 2 to 54 kpc from starburst galaxies (3-10 M_o/yr)
3. z ~ 3 -- (Steidel et al. 2010) -- Si II detected to b=60 kpc and C IV to b=100 kpc
4. z ~ 3 -- (Martin et al. 2010) -- Size of CIV regions is 150 kpc and v < 200 km/s

Geometrical Interpretation of the Velocity-Dependent Covering Fraction







1. Fragments of uniform N(H) and v_0

- For a spherical outflow geometry, the covering factor of "bricks" is diluted as

$$C_f(R) = C_f(R_0)\,(R_0/R)^2.$$

- Observations require lower C_f at higher v, ***so the higher velocity low-ionization gas is at larger radii.***
- But are shell fragments bricks?

The cold gas clumps expand, but …

Not fast enough to prevent geometrical dilution.

- **Adiabatic Expansion of cool clumps within a hot wind**

$$P_h \propto R^{-2}$$

$$P_h \sim P_c$$

$$P(R_0)[V_c(R_0)]^\gamma = P(R')[V_c(R')]^\gamma$$

$$V_c(R') = \left(\frac{R'}{R_0}\right)^{2/\gamma} V_c(R_0)$$

$$A_c \propto V_c^{2/3} \text{ and } C_f \propto A_c(R)/R^2$$

$$C_f(R')/C_f(R_0) = (R'/R_0)^{-1.2} \text{ for } \gamma = 5/3$$

- $C_f(R') / C_f(R_0) = (R'/R_0)^{-2/3}$

1. We have v increasing with decreasing C_f, and R increasing with decreasing C_f, so v increases with R.
2. Will be challenging to detect gas at highest velocity
3. Difficult to detect material at more than a few times the launch radius (due to dilution).

Scattered Emission Constrains the Wind Density

- Absorption Lines Alone:
  $dM/dt = \Omega\, v\, N\, m\, R_{min}$
  ~ 37 Msun/yr $(R_{min}/1\ \text{kpc})\ (v / 800\ \text{km/s})$

•Optical Depth of Scattered Line:

$\tau = \kappa\, \rho\, v_{th}\, |dv/dr|^{-1}$

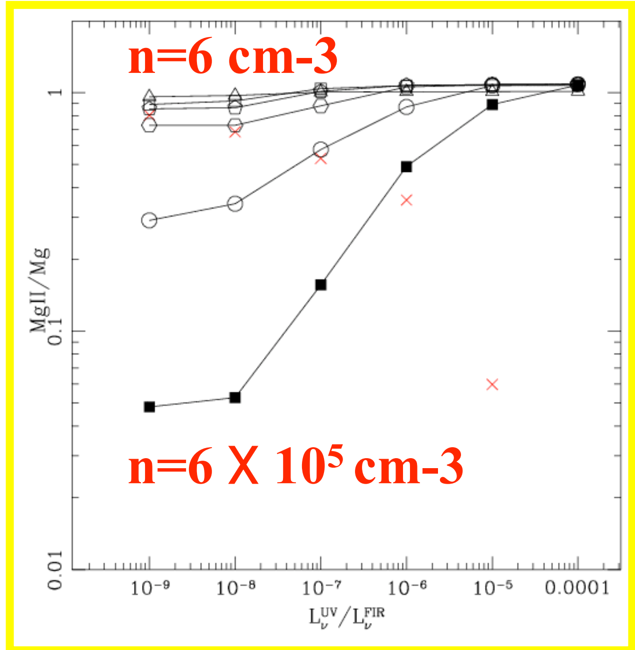
- Measure $r(\tau \sim 1) = 10$ kpc
- $\Delta v = 200$ to 800 km/s
- n(Mg II) ~ $5.6 \times 10^{-9}\ \text{cm}^{-3}$ at b = 10 kpc
- n(H) ~ $1.5 \times 10^{-4}\ \chi^{-1}\ \text{cm}^{-3}$ at b=10 kpc
- Small Ionization correction (Murray + 2007)
- Mass loss rate (in low-ionization gas)

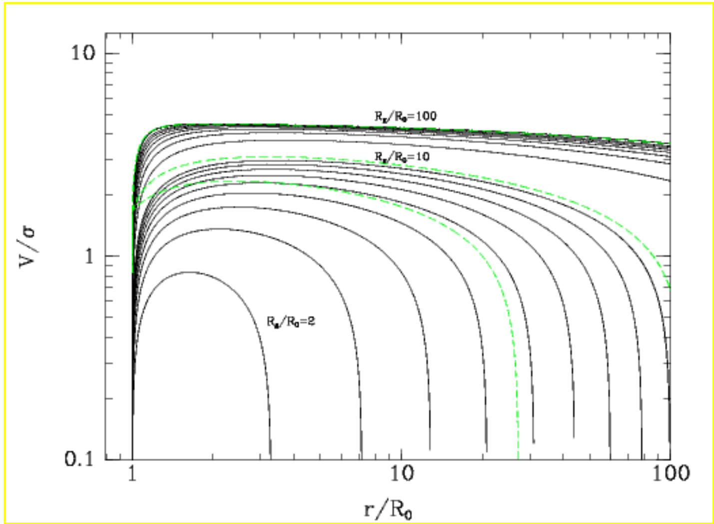
$\rho(r_s) = dM/dt\ /\ \{\Omega(r_s)\, r_s^2\, v(r_s)\}$

$dM/dt \sim 5.3\ M_o/\text{yr}$

- Mass loss rate in low-ionization gas comparable to star formation rate
- Require launch at $R_0 \sim 0.14$ kpc

- Line Profiles (e.g., Castor, Abott, & Klein 1975; Murray & Chiang 1995)





Summary of Low-Ionization Outflows

Evidence for Fluorescent Emission from Outflows:

- **Extended Mg II emission has kinematics that differ from disk**
- **Mg II absorption trough is partially filled in by emission**
- **Fe II absorption trough is partially filled in by emission**
- **Fe II* emission detected (another channel for de-excitation)**

Evidence for Velocity - Dependent Covering Fraction:

- **Covering fraction is lower at larger velocity**
- **Covering fraction is lower at larger radii (spherical geometry)**
- **Absorbing gas at higher velocity lies at larger radii**

Physical Properties of Outflowing Gas

- **Outflow velocity**
- **Column density**
- **Volume density**
- **Mass-loss rate (in low ionization gas)**
- **Launch radius**