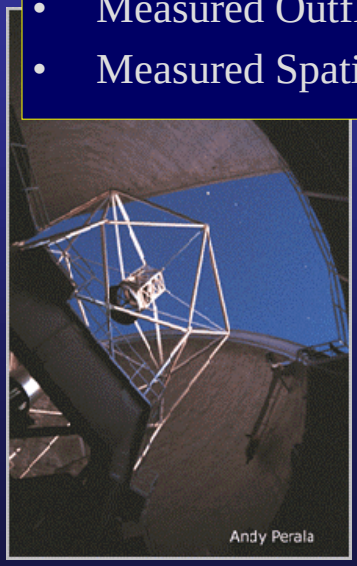
Mapping Galactic Outflows

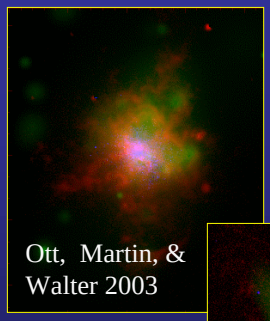
- Measured Outflow Velocity vs Galactic Mass
- Measured Spatial Extent of the Outflow



Collen Schwartz, Taro Sato, Victor Sciortino, Akimi Fujita (UCSB)

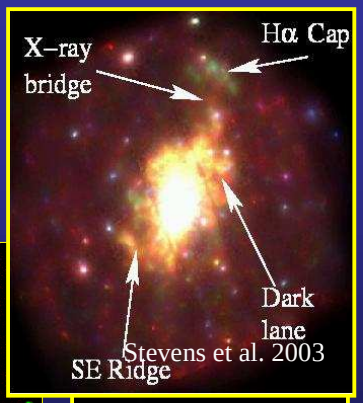
Tim Heckman, Chip Kobulnikcy, Eliot Quartaert, Todd Thompson, Norm Murray

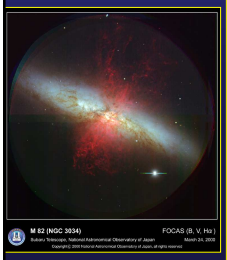
Emission Line Observations ➔ Multiphase Winds

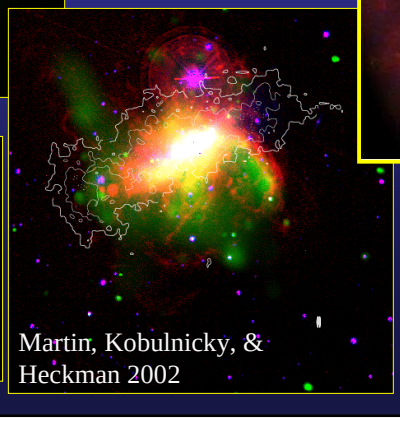


Ott, Martin, & Walter 2003

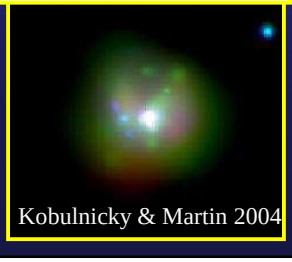
Suchkov 95,96



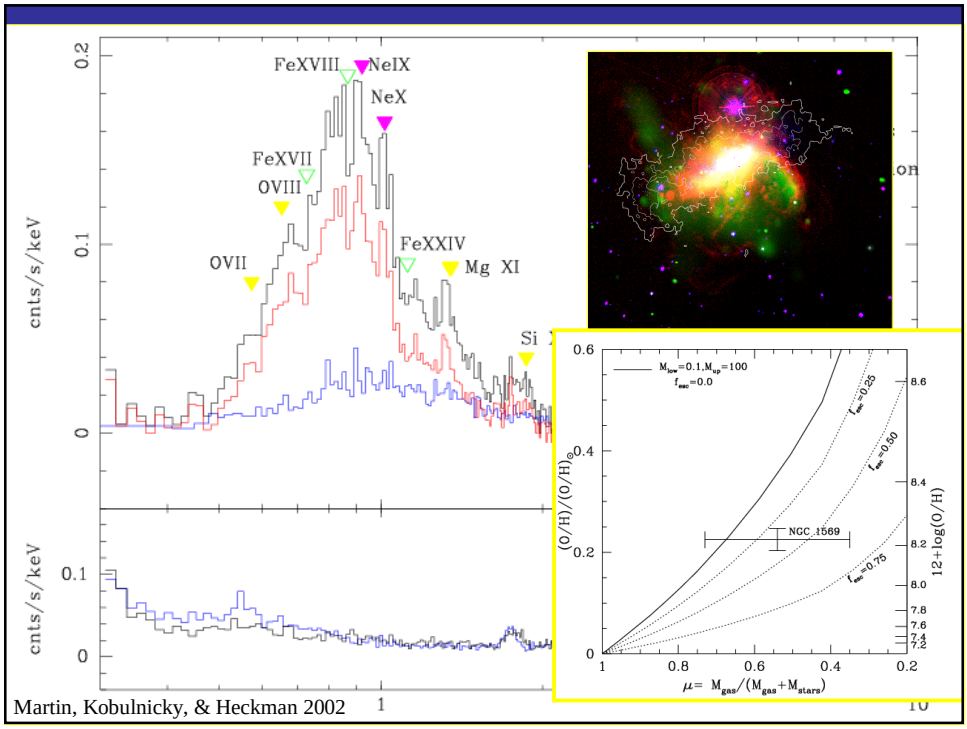




Martin, Kobulnicky, & Heckman 2002

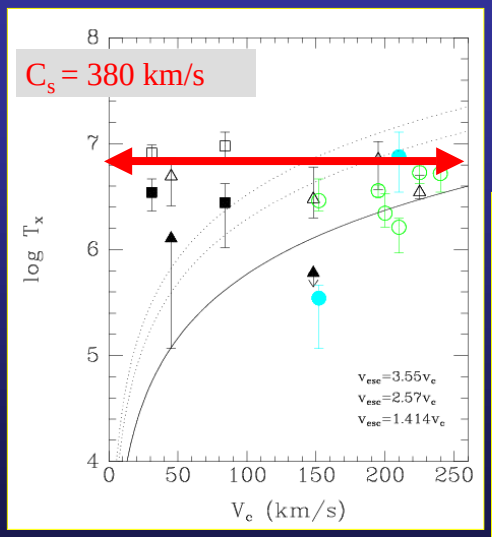


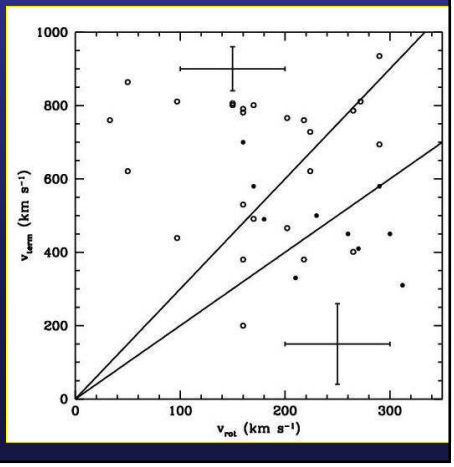
Kobulnicky & Martin 2004



Martin, Kobulnicky, & Heckman 2002

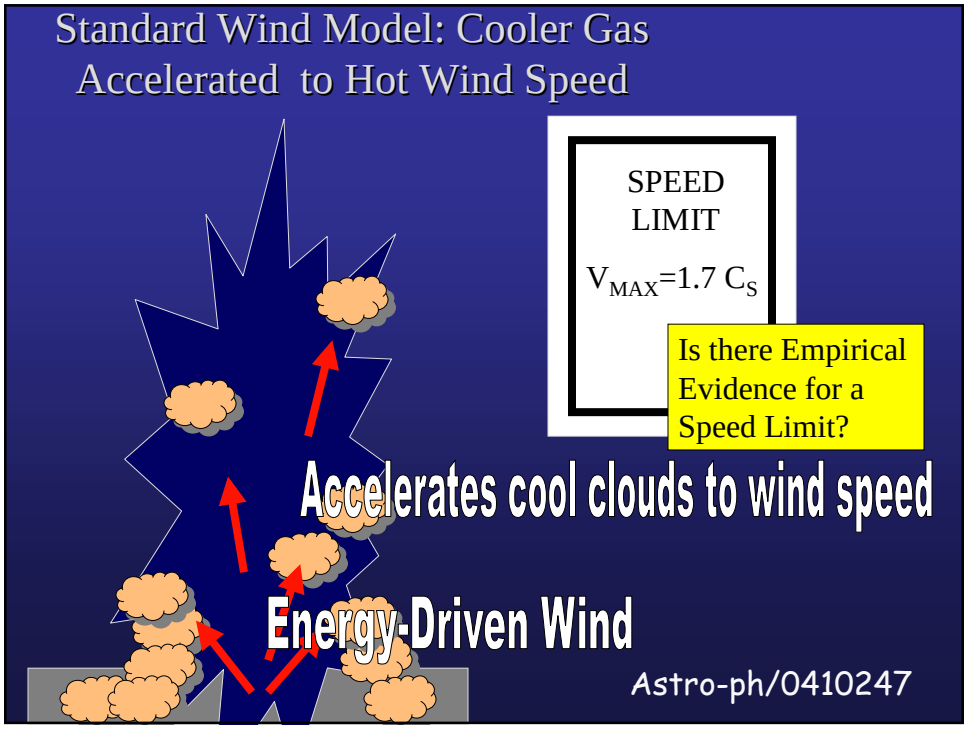
Observe Similar X-Ray Temperatures in all Halos

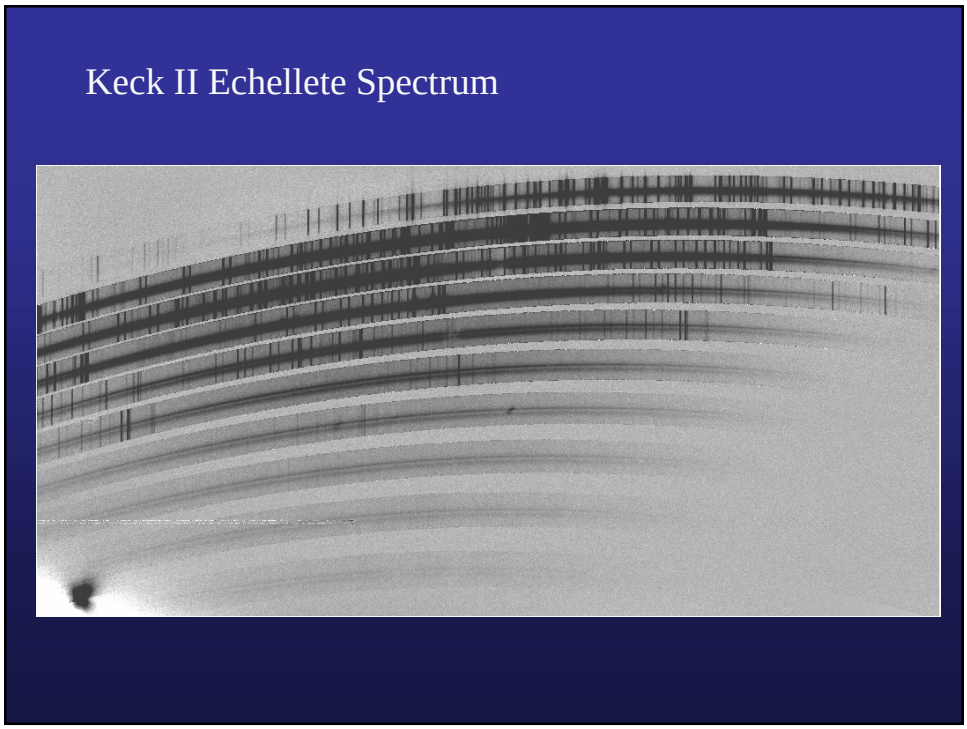


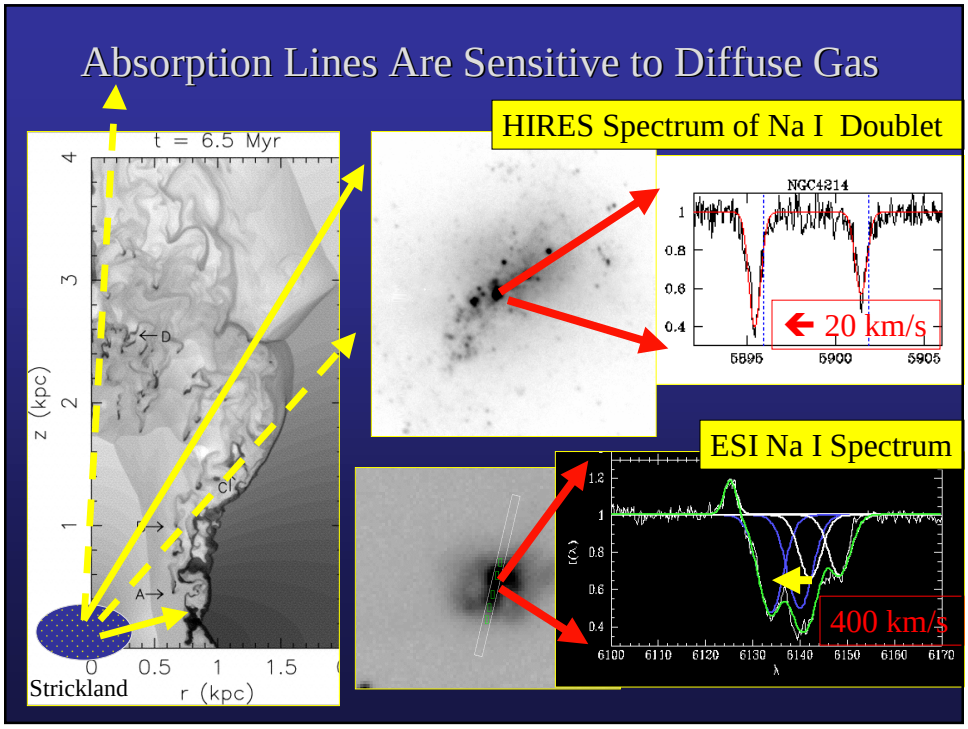


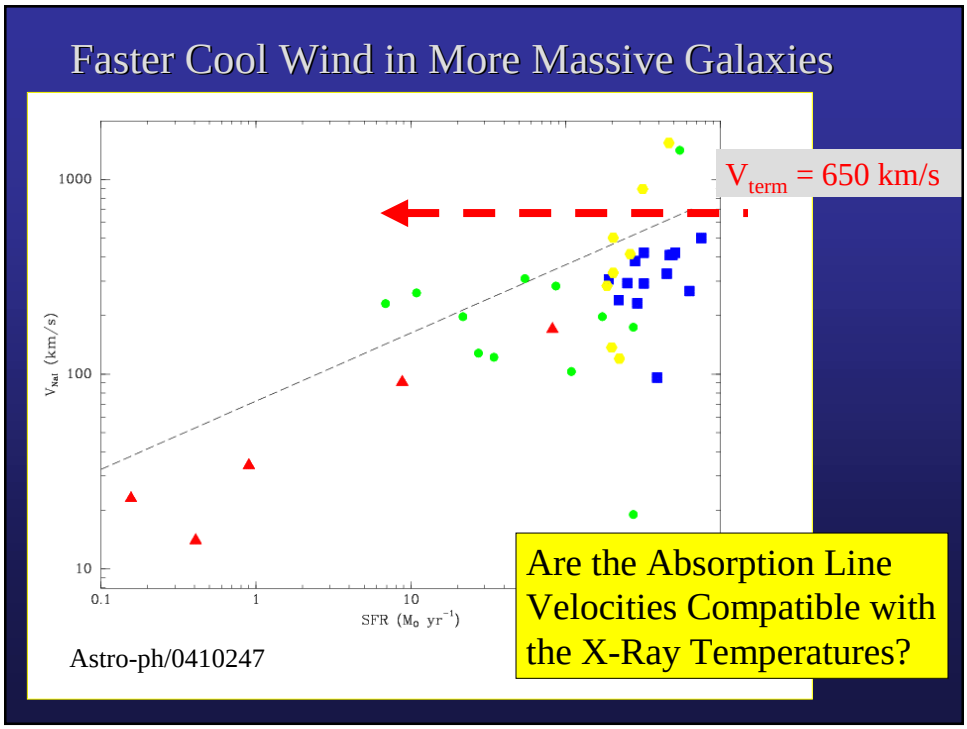
Martin 1999, Martin 2004

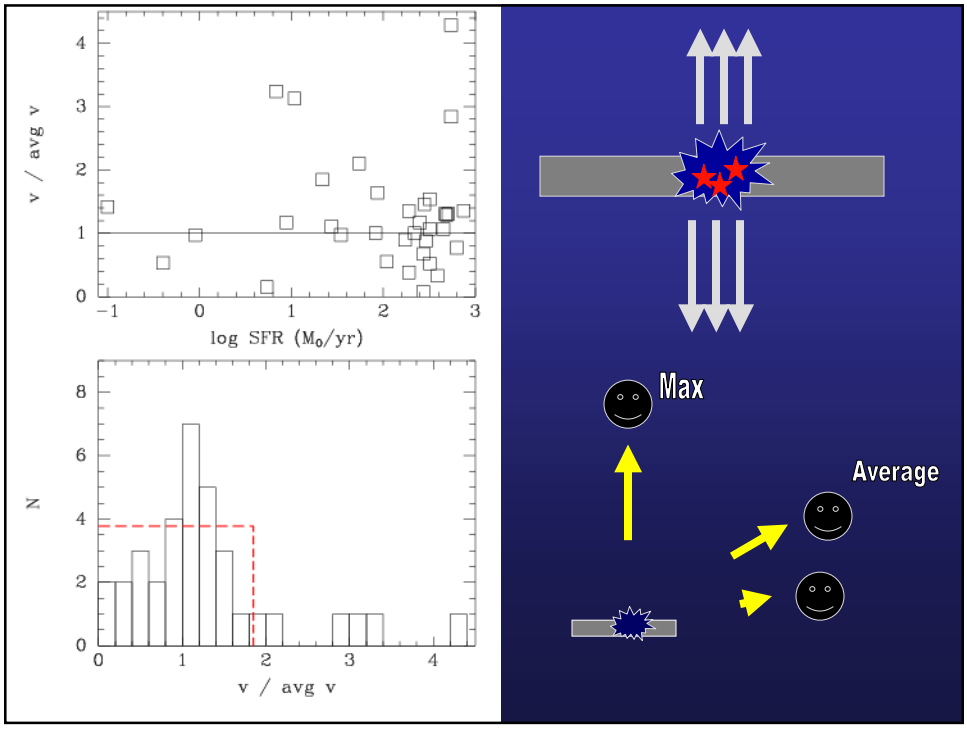
Heckman et al. 2000


Standard Wind Model: Cooler Gas
Accelerated to Hot Wind Speed
SPEED
LIMIT
V_{MAX}=1.7 C_S
Is there Empirical Evidence for a Speed Limit?
Accelerates cool clouds to wind speed
Energy-Driven Wind
Astro-ph/0410247


Keck II Echellete Spectrum


Absorption Lines Are Sensitive to Diffuse Gas
t = 6.5 Myr
z (kpc)
r (kpc)
Strickland
HIRES Spectrum of Na I Doublet
NGC4214
20 km/s
ESI Na I Spectrum
400 km/s

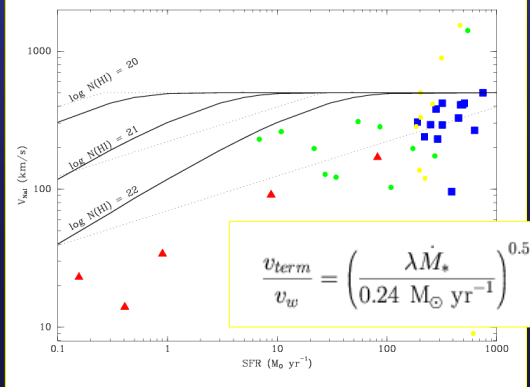

Faster Cool Wind in More Massive Galaxies
V_term = 650 km/s
SFR (M☉ yr⁻¹)
Astro-ph/0410247
Are the Absorption Line Velocities Compatible with the X-Ray Temperatures?



Standard Supernova-Driven Wind Model

$$M_c \frac{dv_c}{dt} = \dot{m}_w (v_w - v_c) \frac{A_c}{\Omega r^2} - \frac{GM(r) M_c}{r^2}$$

$$\frac{dv_c}{dr} = \frac{-2\sigma^2}{v_c r} + \frac{3\dot{p}_w}{4 N_H \mu m_h \Omega} \left(1 - \frac{v_c}{v_w}\right) \frac{1}{v_c r^2}$$

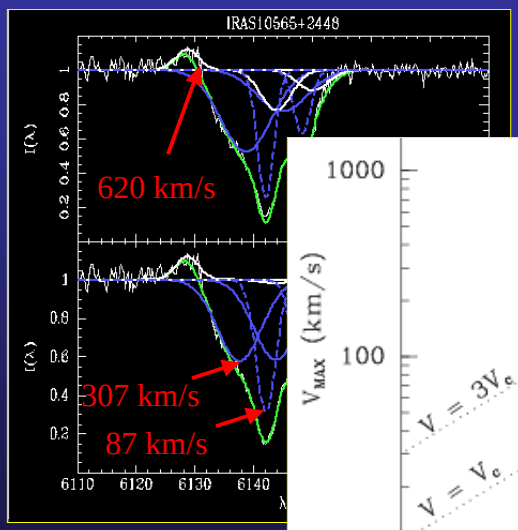


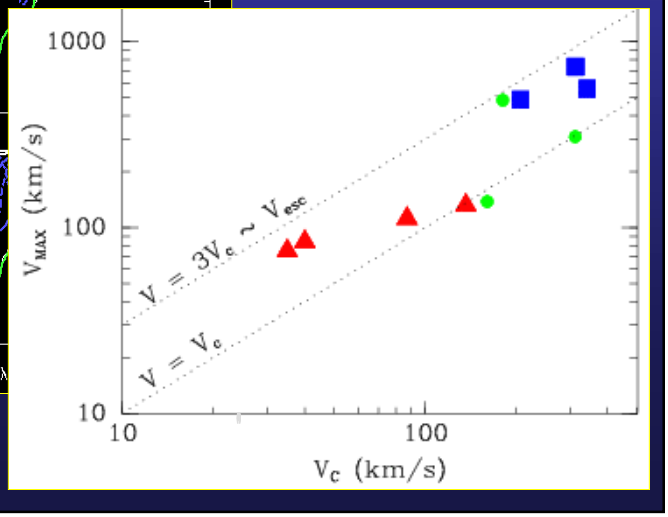
$$v_{term} = \left(\frac{3\dot{p}_w}{2\Omega \rho_c R_0^2}\right)^{1/2}$$

$$v_{term} \propto L_{Bol}^{1/4}$$

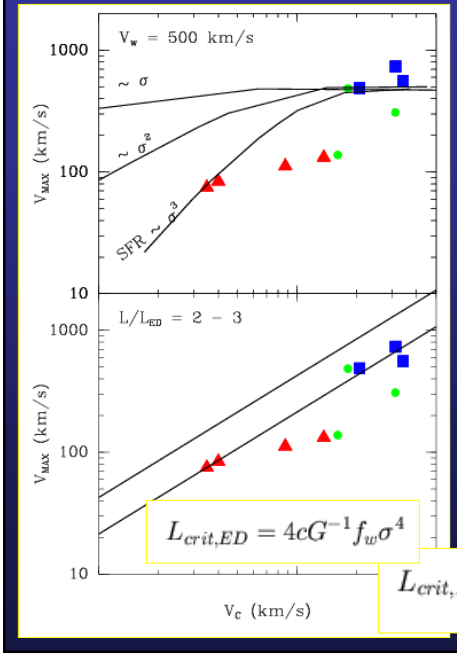
$$\frac{v_{term}}{v_w} = \left(\frac{\lambda \dot{M}_*}{0.24\ \mathrm{M_\odot\ yr^{-1}}}\right)^{0.5} \left(\frac{10^{20}\ \mathrm{cm^{-2}}}{\mu N_H} \frac{200\ \mathrm{pc}}{R_0} \frac{500\ \mathrm{km\ s^{-1}}}{v_w} \frac{\pi}{\Omega}\right)^{0.5}$$

Why Are Terminal Velocities ~ Escape Speed?





Relation of SFR and Luminosity to Halo Mass

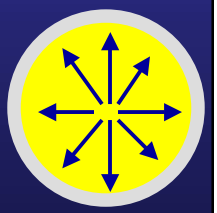


$$SFR \propto f_g M_{tot}/t_{dyn} \propto \sigma^3$$

$$F_{\rm rad} = \frac{M_c}{c}\int \kappa_\nu F_\nu d\nu$$

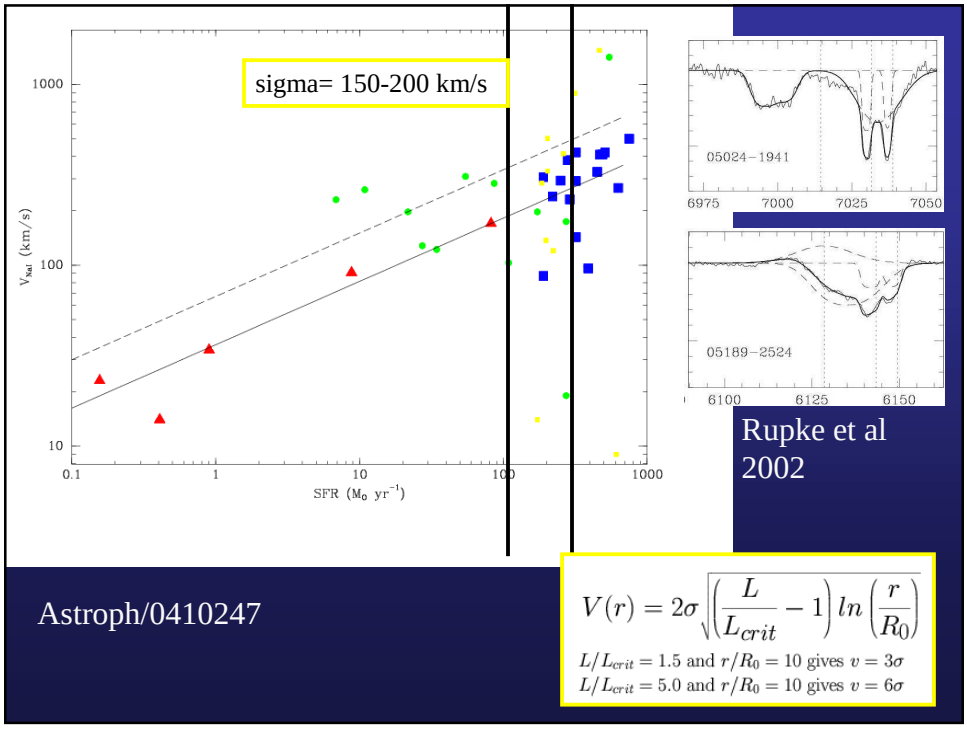
$$F_{rad} = M_c \frac{\kappa}{c}\frac{L}{4\pi r^2} \longrightarrow \frac{L}{c}$$

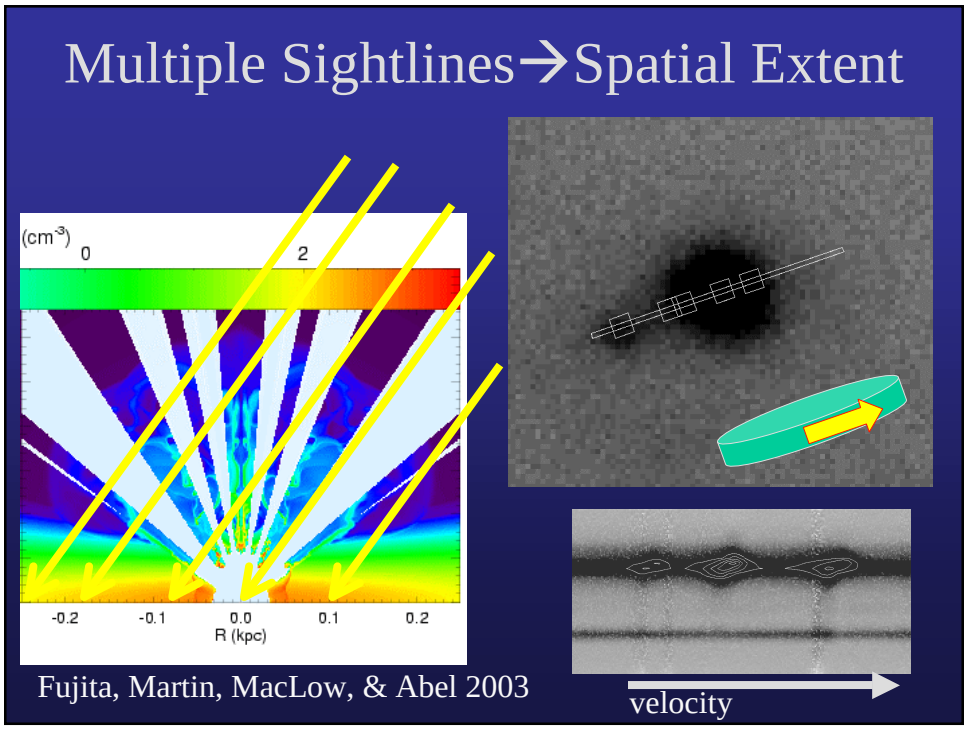
$$\kappa = 600 \text{ cm}^2 \text{ g}^{-1}$$

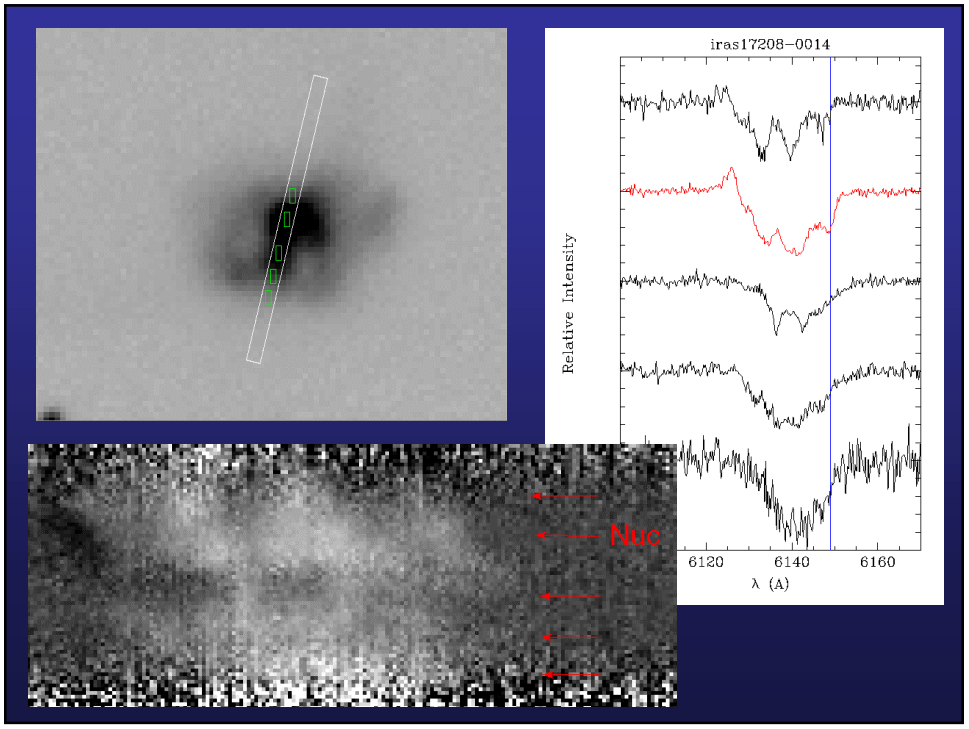


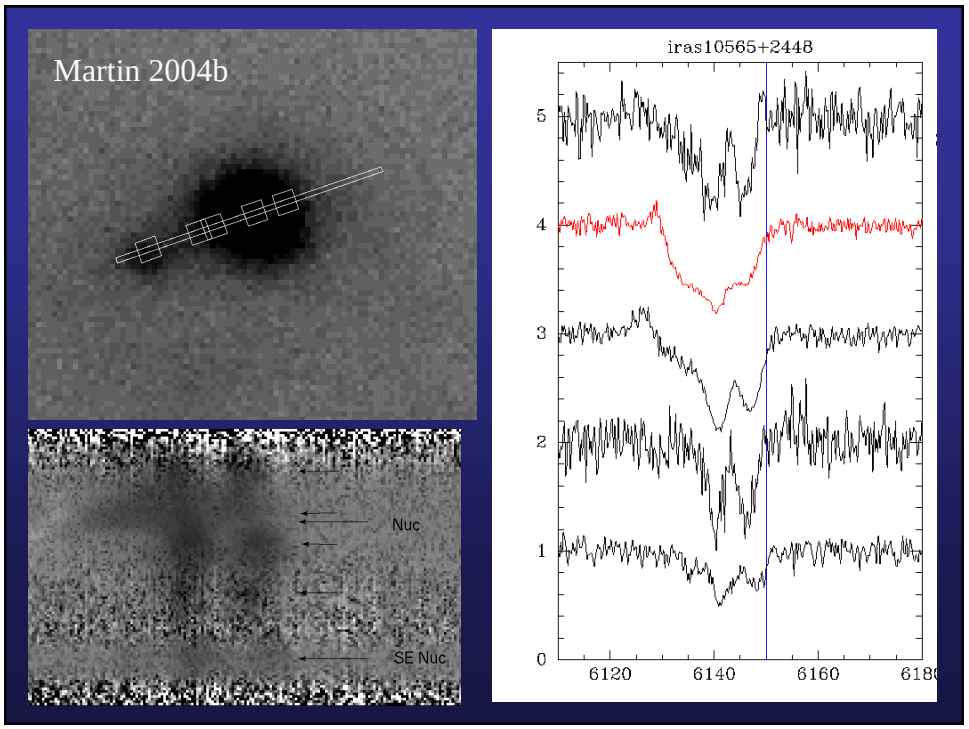
$$L_{crit,ED} = 4cG^{-1} f_w \sigma^4$$

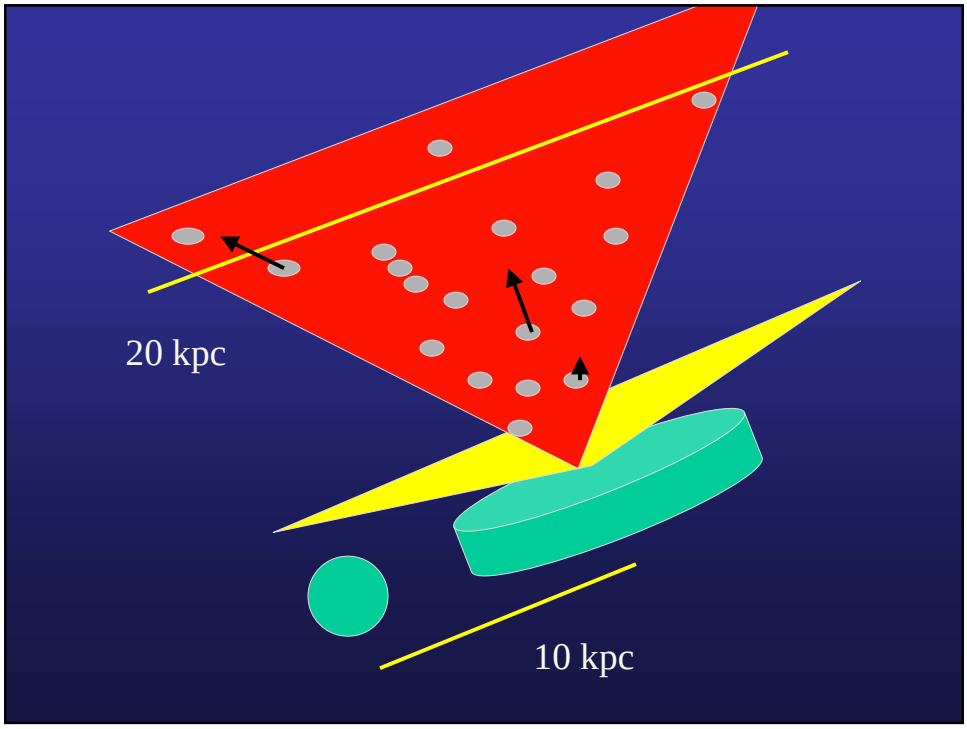
$$L_{crit,ED} = 4.65 \times 10^9 \text{ L}_\odot \left(\frac{\sigma}{150 \text{ km s}^{-1}}\right)^4 \frac{f_w}{0.1}$$


sigma= 150-200 km/s
1000
100
10
V_{sat} (km/s)
0.1
1
10
100
1000
SFR ($M_\odot$ yr^{-1})
05024−1941
6975
7000
7025
7050
05189−2524
6100
6125
6150
Rupke et al 2002
Astroph/0410247
$V(r) = 2\sigma\sqrt{\left(\frac{L}{L_{crit}} - 1\right) ln\left(\frac{r}{R_0}\right)}$
$L/L_{crit} = 1.5$ and $r/R_0 = 10$ gives $v = 3\sigma$
$L/L_{crit} = 5.0$ and $r/R_0 = 10$ gives $v = 6\sigma$


Multiple Sightlines→Spatial Extent
(cm^{-3})
0
2
-0.2
-0.1
0.0
0.1
0.2
R (kpc)
Fujita, Martin, MacLow, & Abel 2003
velocity


iras17208−0014
Relative Intensity
6120
6140
6160
λ (A)
Nuc


Martin 2004b
iras10565+2448
Nuc
SE Nuc
0
1
2
3
4
5
6120
6140
6160



How Much Mass Lost in Cooler Gas?

$$N_H = 4.90\times10^{20}\,\mathrm{cm}^{-2}\left(\frac{N_{NaI}}{10^{14}\,\mathrm{cm}^{-2}}\right)\left(\frac{d_{Na}}{10}\right)\left(\frac{N(Na)}{N(NaI)}\right)$$

$$M_c \sim 4.30\times10^{8}\,\mathrm{M}_\odot\left(\frac{N_{Na}}{10^{14}\,\mathrm{cm}^{-2}}\right)\left(\frac{d_{Na}}{10}\right)\left(\frac{N(Na)}{N(NaI)}\right)\left(\frac{R}{10\,\mathrm{kpc}}\right)^2$$

$$E \sim 6.85\times10^{56}\,\mathrm{ergs}\left(\frac{N_{NaI}}{10^{14}\,\mathrm{cm}^{-2}}\right)\left(\frac{d_{Na}}{10}\right)\left(\frac{N(Na)}{N(NaI)}\right)\left(\frac{R}{10\,\mathrm{kpc}}\right)^2\left(\frac{v}{400\,\mathrm{km/s}}\right)^2$$

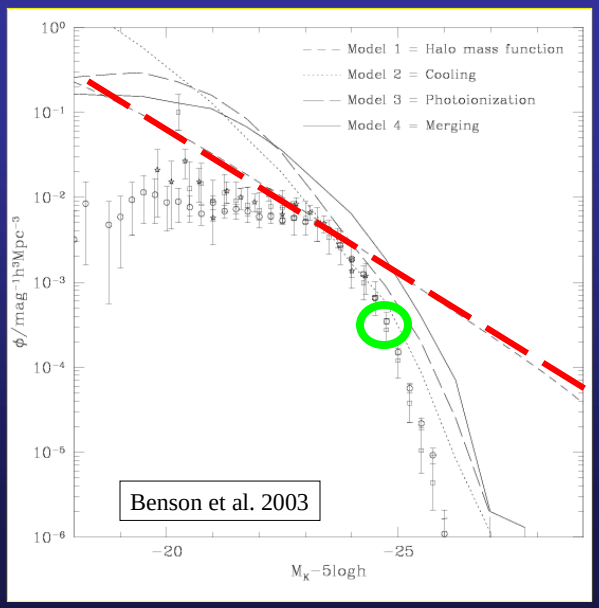
$$\dot{M}_c = 280\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}\left(\frac{N_H}{4.9\times10^{20}\,\mathrm{cm}^{-2}}\right)\left(\frac{R}{10\,\mathrm{kpc}}\right)\left(\frac{v}{400\,\mathrm{km/s}}\right)\left(\frac{\Omega}{4\pi}\right)$$

- Mass flux in the cold wind can be comparable to star formation rate.

Some Implications…

1. Physical Picture of Wind Acceleration
2. Impact on Galaxy Luminosity Function
3. Observability of Winds as Intervening ALS's

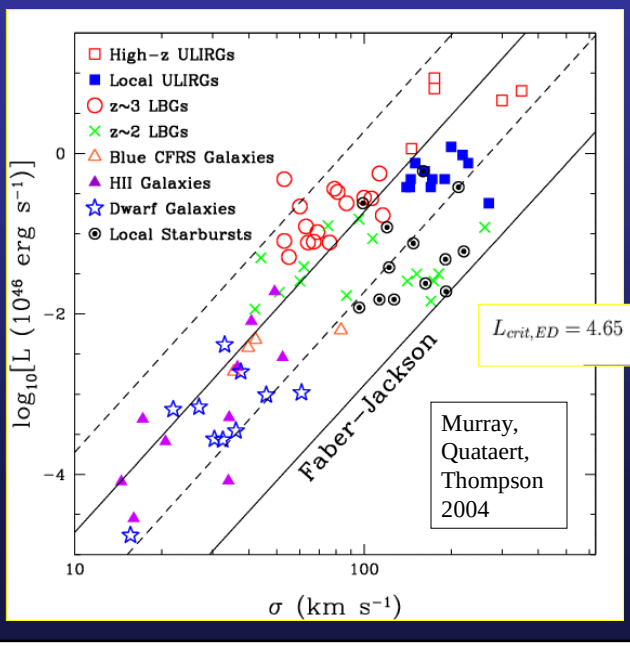
Impact on Galaxy Luminosity Function



The hot outflows are the dominant form of feedback in the dwarf galaxies.

Radiation pressure likely provides an extra kick in the most luminous starbursts.

Does Feedback Limit the Maximum Luminosity?

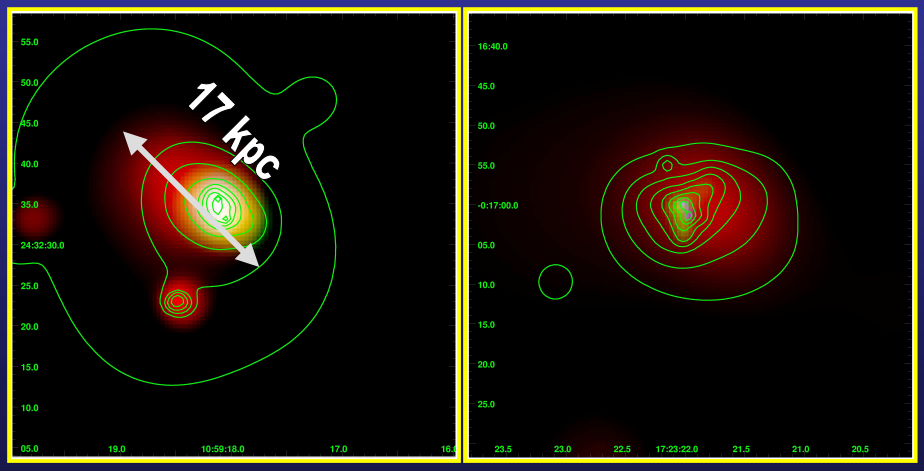


$$L_{crit,ED} = 4.65 \times 10^9\ L_\odot \left(\frac{\sigma}{150\ \mathrm{km\ s^{-1}}}\right)^4 \frac{f_w}{0.1}$$

Murray, Quataert, Thompson 2004

Do ULIGs Have Hot Winds?

IRAS10565+2448 IRAS17208-0014



Images by Victor Sciortino (UCSB Physics)