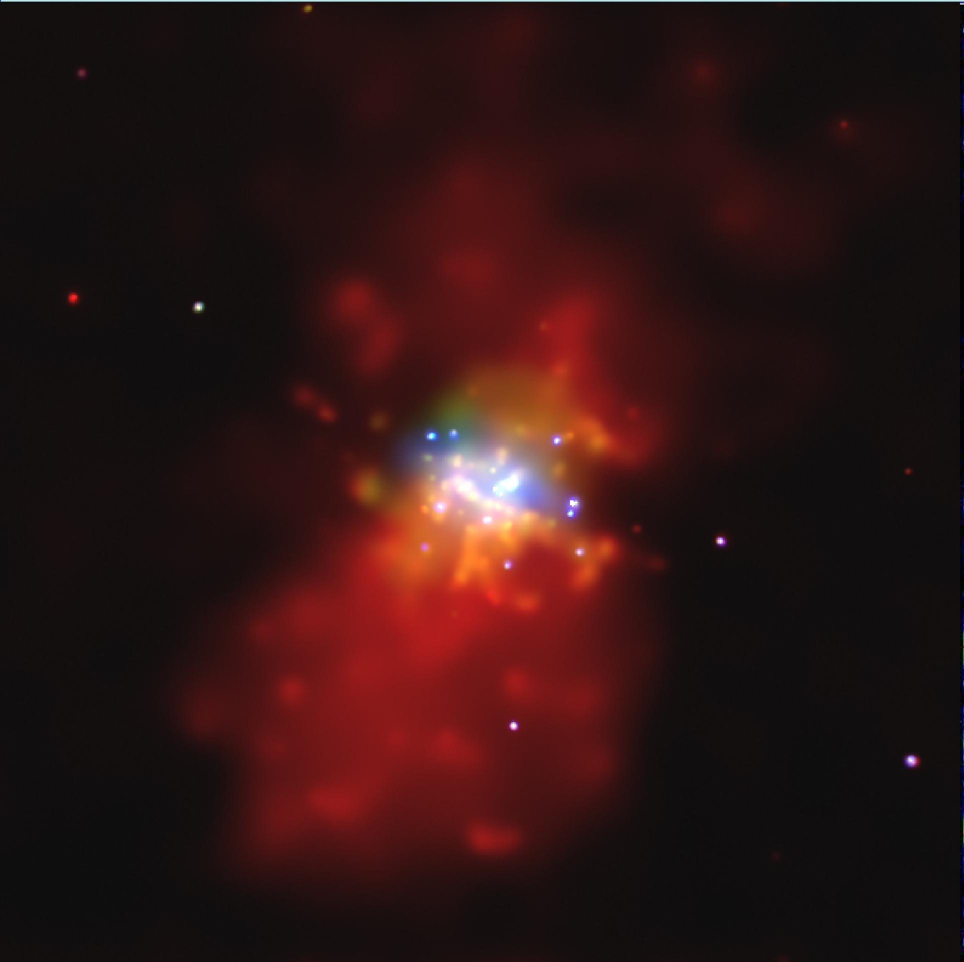
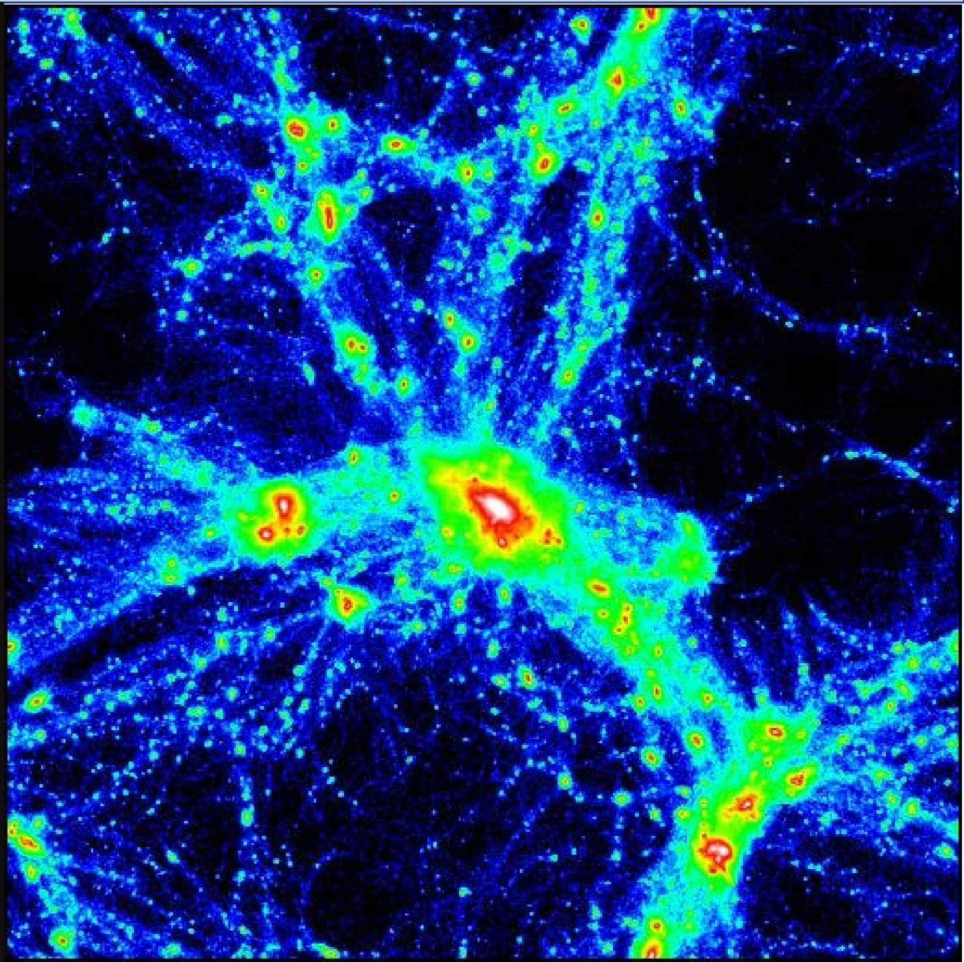
GALACTIC WINDS: Physics, Phenomenology, and Implications





Talk Outline

Part 1: Introduction

a) Motivation

b) Wind physics

c) A tour of a multi-phase wind

Part 2: Systematics of observed winds

a) Empirical results

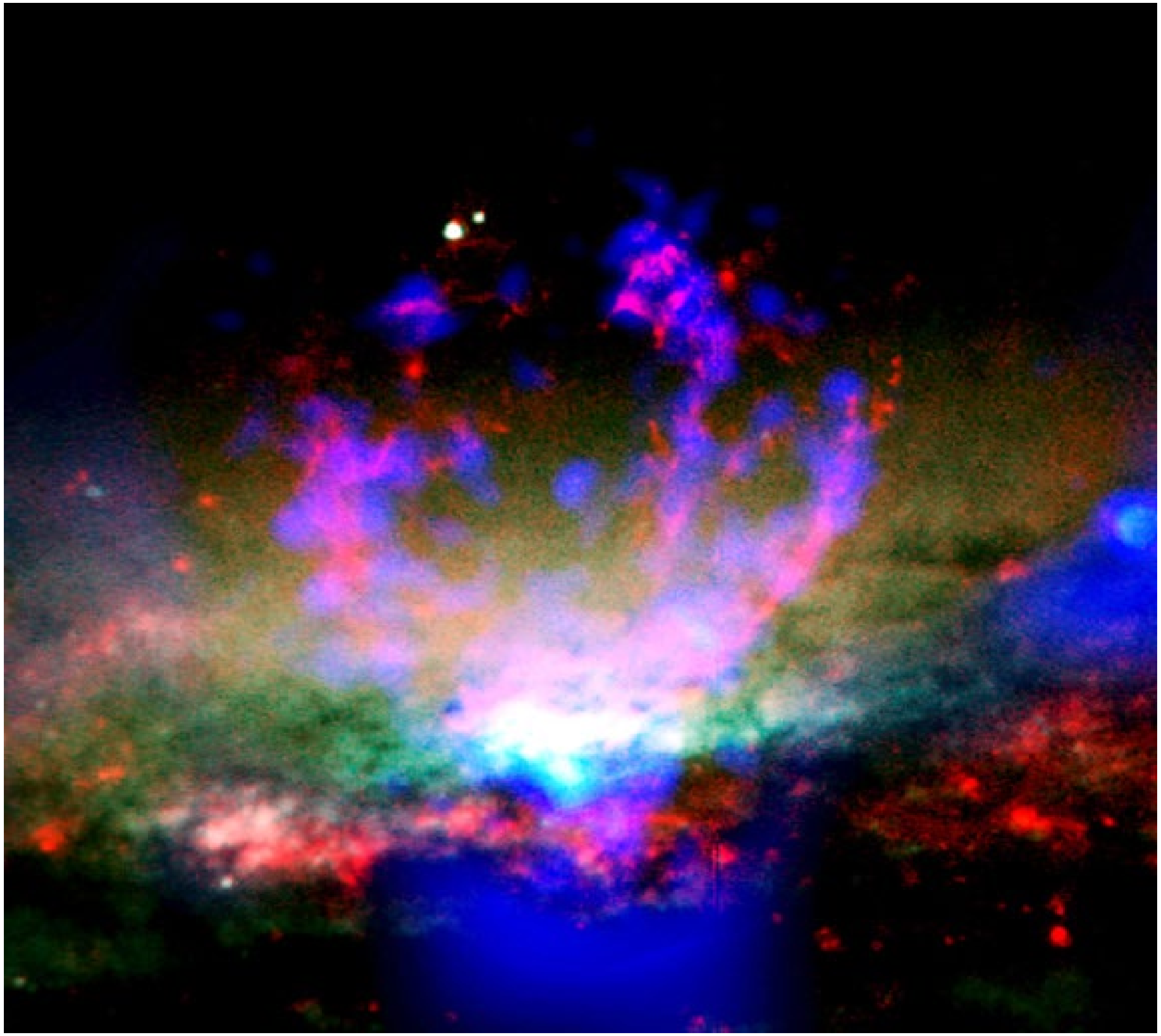
b) Physics & implications for models

Part 3: Implications for chemical evolution

Part 4: Winds and the circum-galactic medium

Part 5: Summary

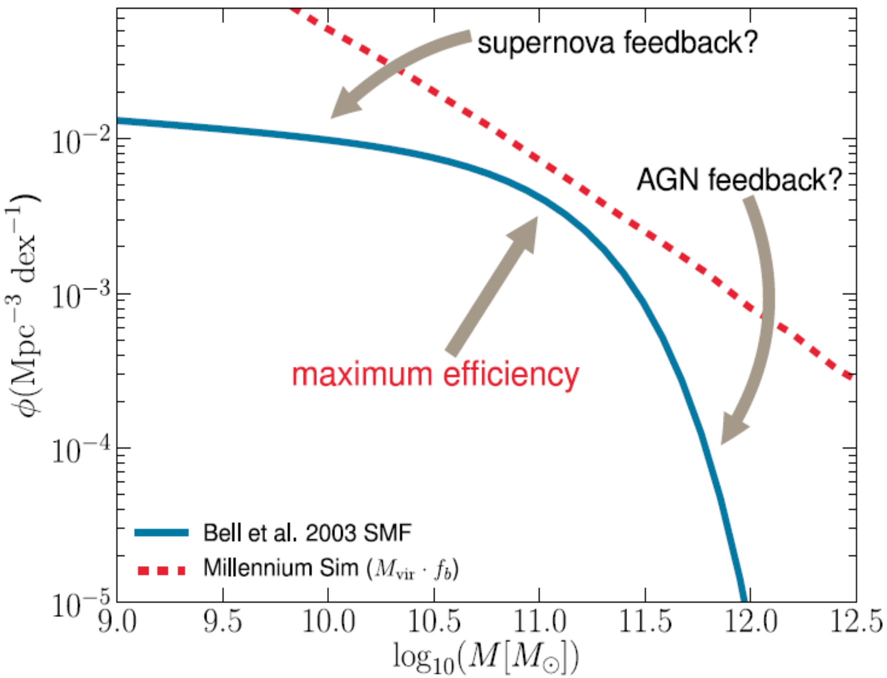
Part 1a: Motivation: Why are galactic winds important?

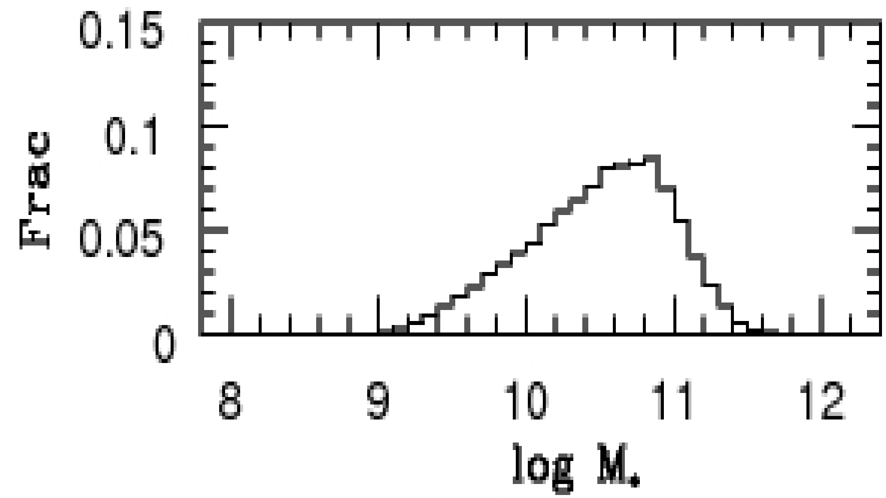


The current paradigm

- Galaxies grow primarily by accretion from the cosmic web
- (Some) of the newly acquired gas is converted into stars
- **'Feedback'** from massive stars and (active galactic nuclei) influences these processes
- ***Winds driven by massive stars are key***
- ***Cosmological simulations treat these using prescriptions ('sub-grid physics')***
- ***Observational input is vital***
- ***Many questions remain***

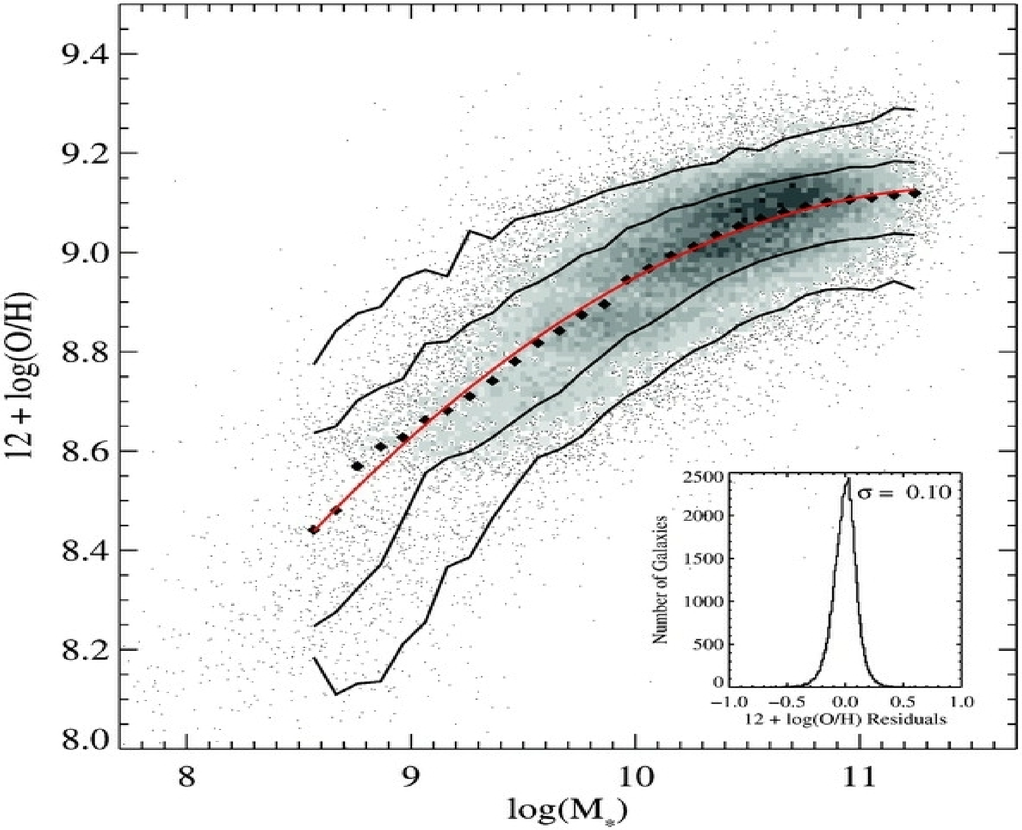
Example: Why do galaxies have a characteristic stellar mass?





- Unlike dark matter, galaxies have a characteristic baryonic mass scale: Why?
- Need to suppress the conversion of gas to stars in both low- and high-mass dark matter halos

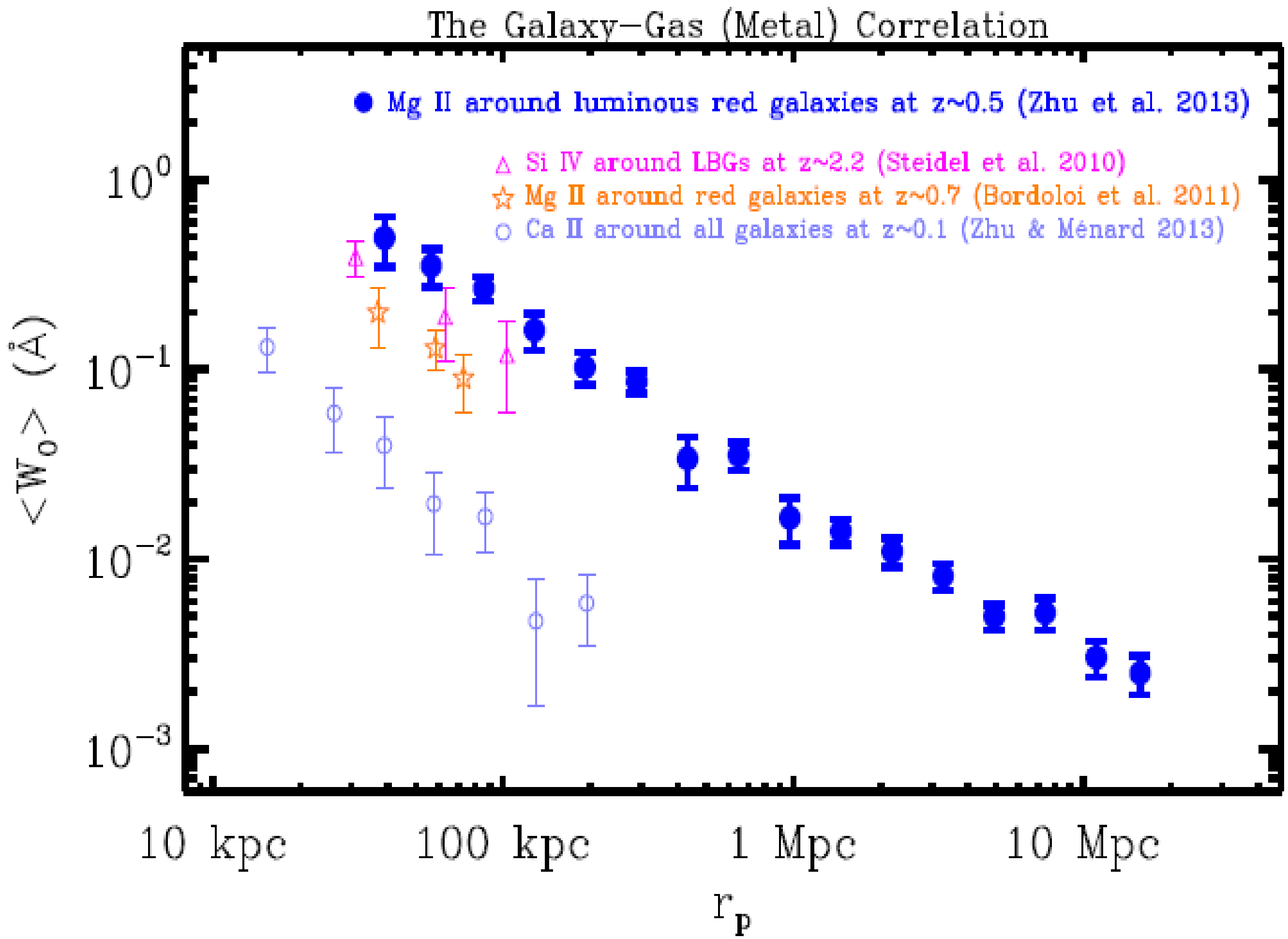
Example: **Why do galaxies have a strong correlation between metallicity and mass?**



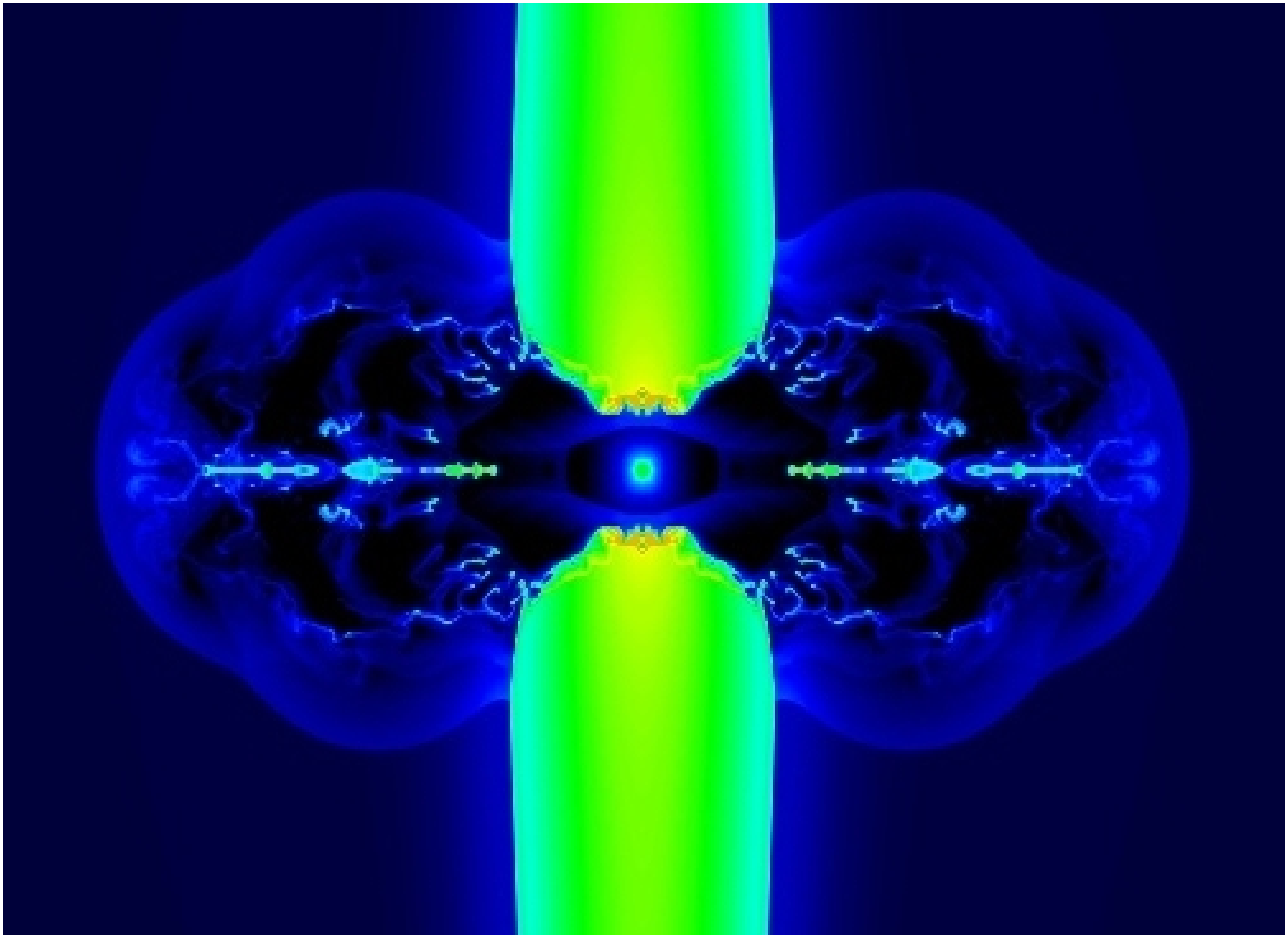
- Selective loss of metals expelled by supernovae from the shallow potential wells of low-mass galaxies?

  Tremonti et al.

Example: How do metals get far outside galaxies?



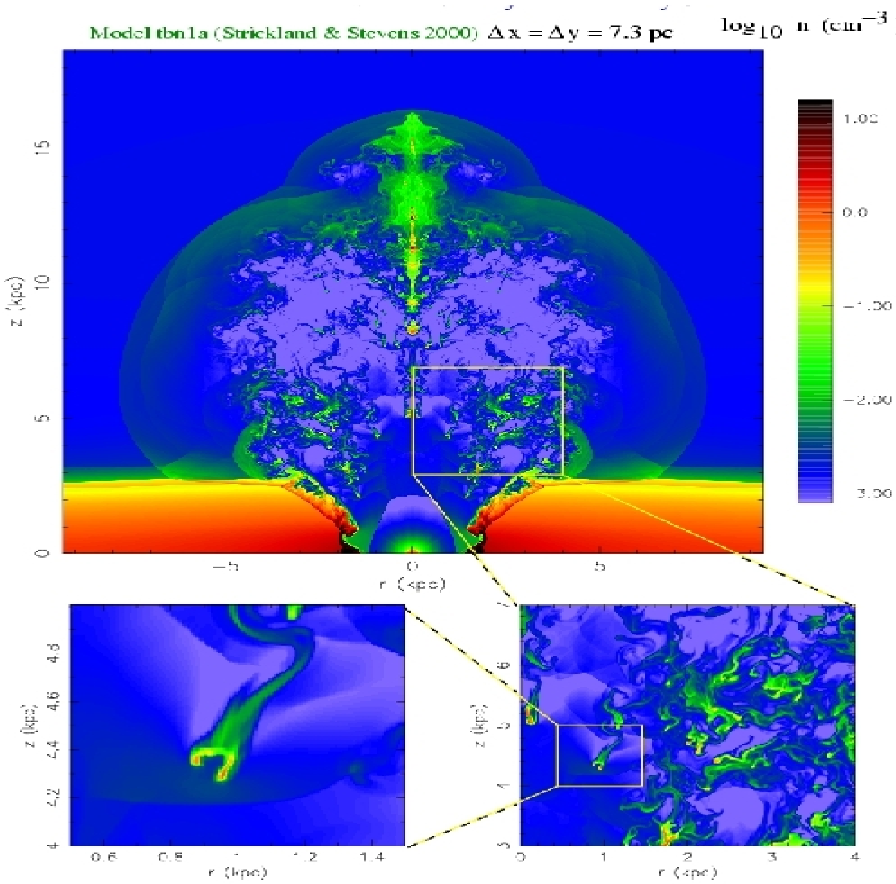
Part 1b: Wind Physics



Wind Creation

- For every solar mass of stars formed get ~1.6 x 10^{49} ergs of KE delivered by supernovae and stellar winds (~10^{-5} c^2)
- "Inefficient", but potential well-depth of MW-type galaxy is ~10^{-6} c^2
- Thermalize stellar ejecta and produce hot gas with T ~ 10^8 (α/β) K
- Here α is thermalization efficiency and β is the "poisoning factor"
  (β ≡ 1 for pure stellar ejecta).
- P >> surroundings: Expansion along the disk minor axis and blow-out into the halo to form wide-angle bipolar wind
- Adiabatic expansion leads to a wind with v_{term} ~ 2800 $(\alpha/\beta)^{1/2}$ km/s
- KE flux = 7 x 10^{41} α SFR erg/s
- Momentum flux of wind ~ 5 x10^{33} $(\alpha\beta)^{1/2}$ SFR dynes
- Metallicity = 1 + 5/β times solar

Blow-Out Into the Halo



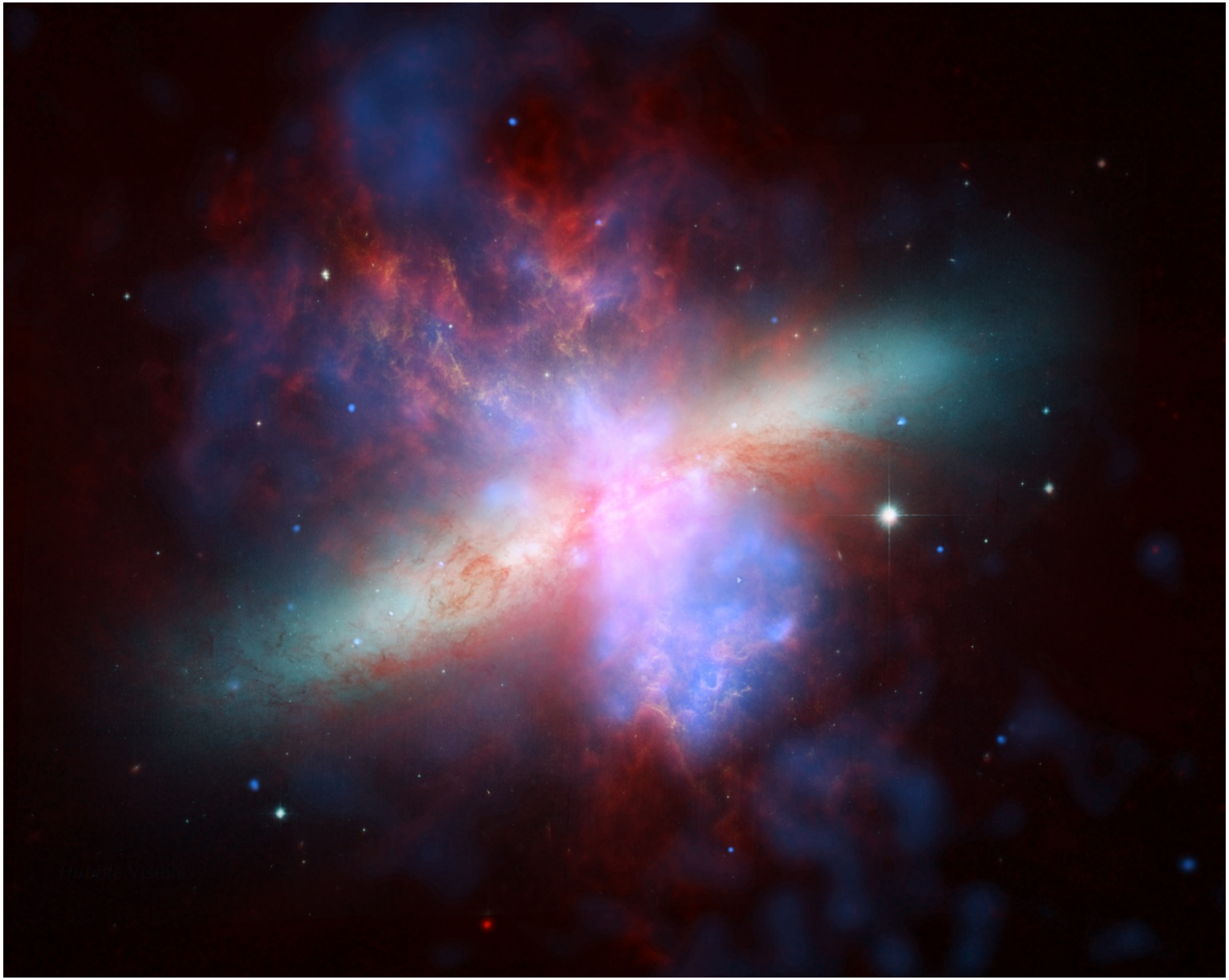
- Most of the halo volume is occupied by the very energetic and tenuous "WIND FLUID"
- Most of the emission and absorption comes from denser material interacting with the wind fluid

Wind vs. Outflow

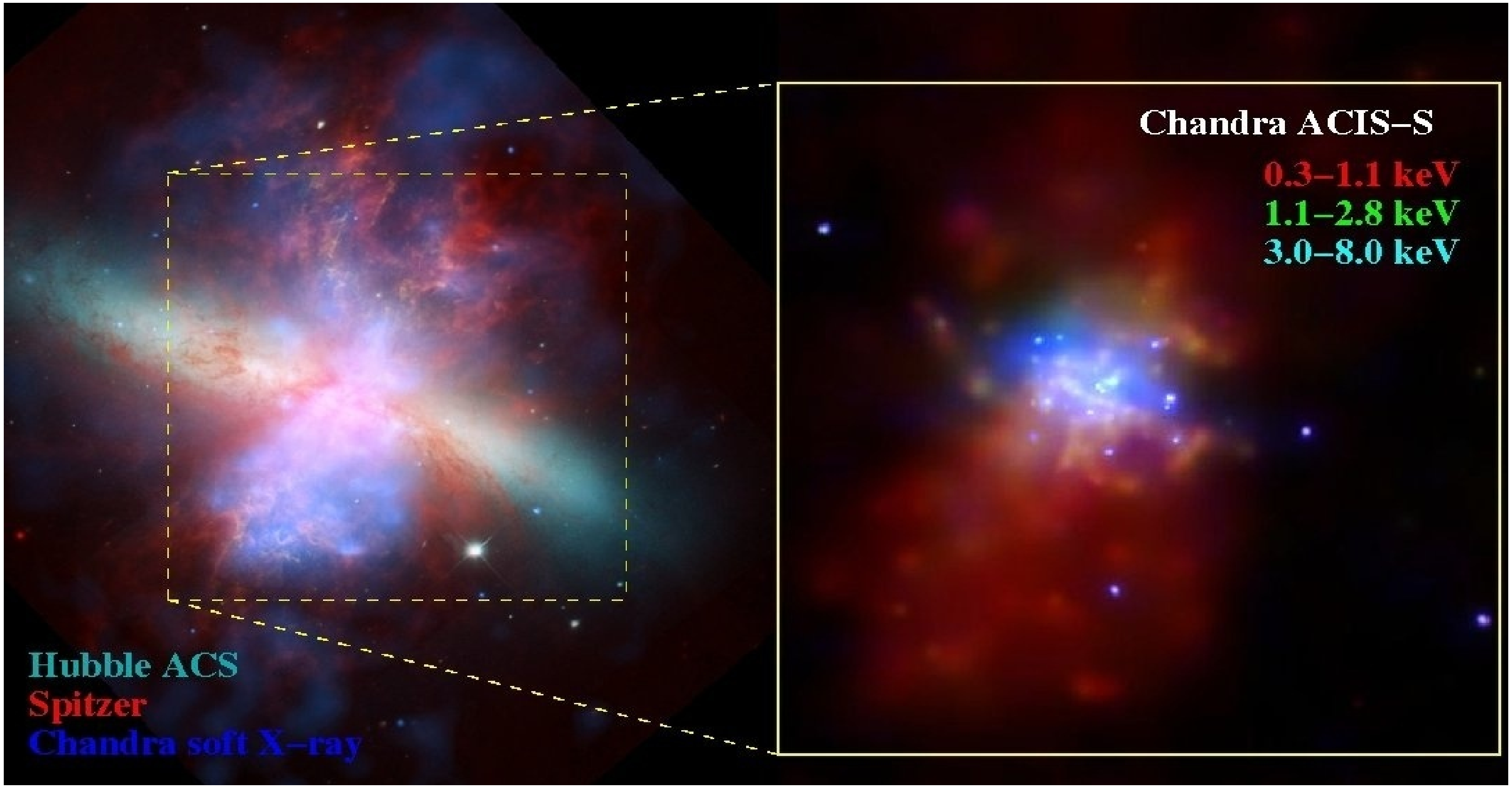
- The wind fluid is the prime mover. It carries most of the outflowing kinetic energy and much of the heavy elements
- The “outflow”, heated and accelerated by the wind fluid (and radiation), is the interstellar and circum-galactic medium of the galaxy
- The impact of the wind fluid on this material will influence the evolution of the galaxy
- ***Both the “wind” and “outflow” are important, but in different ways***


Not the wind

Part 1c: A Guided Tour



The Wind Fluid in M82



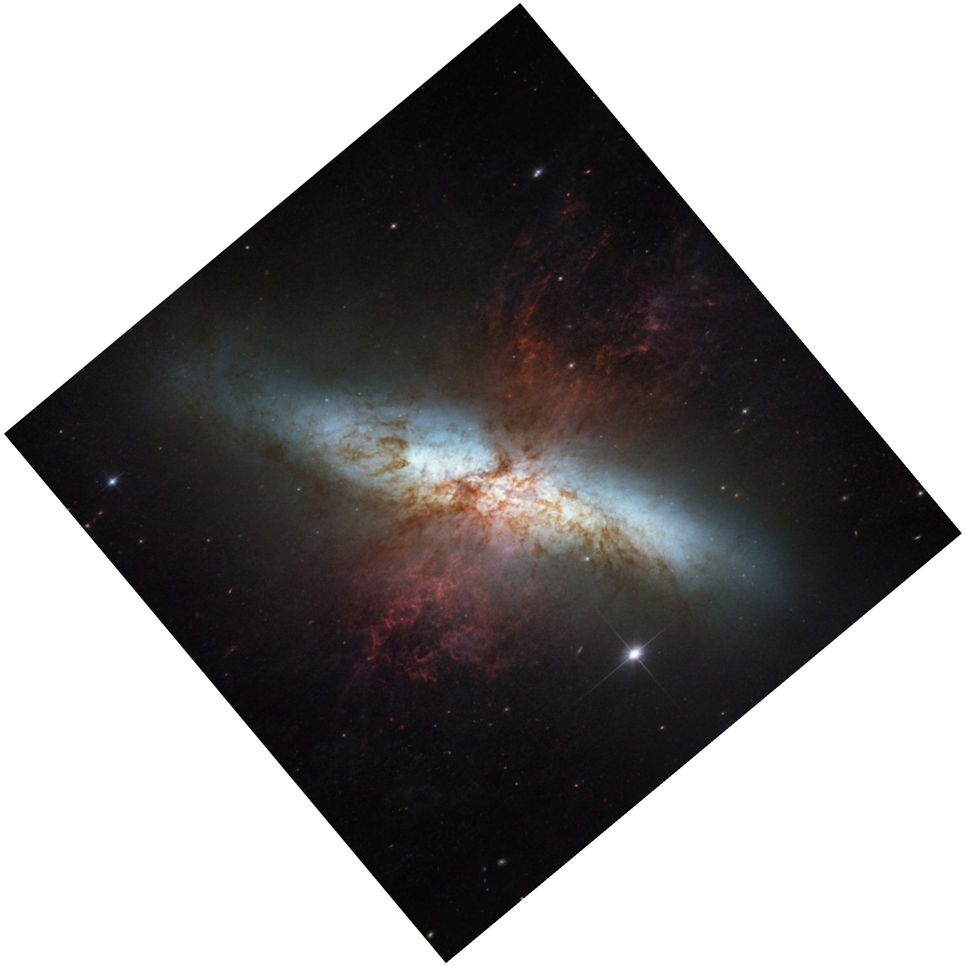
- H- & He-like Fe lines at 6.9 & 6.7 keV: very hot gas (T ~ 60 million K) inside the starburst: implied wind velocity ~ 2000 km/s
- Detected in ***hard*** X-rays in the central region (adiabatic expansion & cooling causes it to disappear further out)

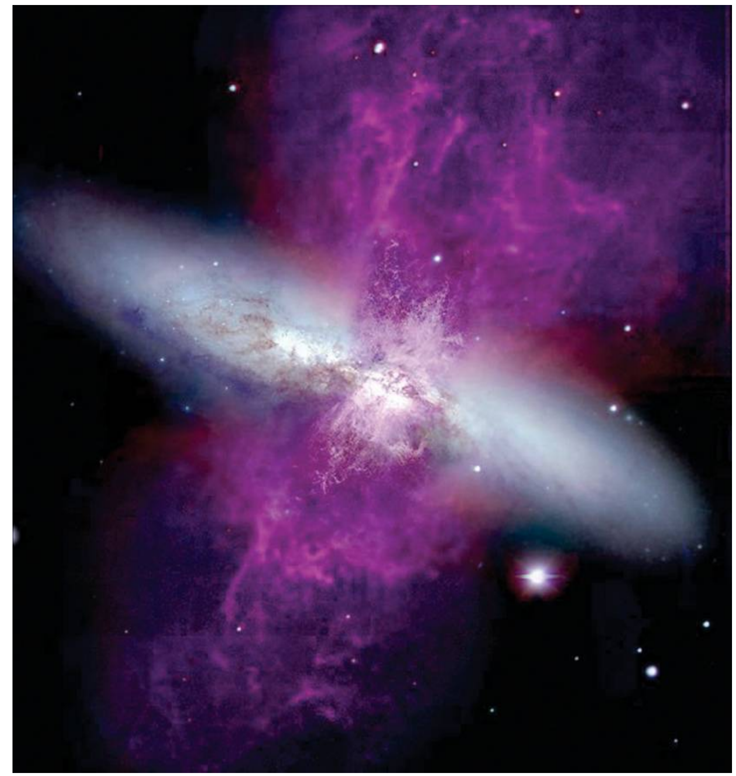
Hot Outflow (*soft* X-rays)

T ~ 3 to 10 million K. Wind-driven shocks?

Clumpy (not volume-filling)

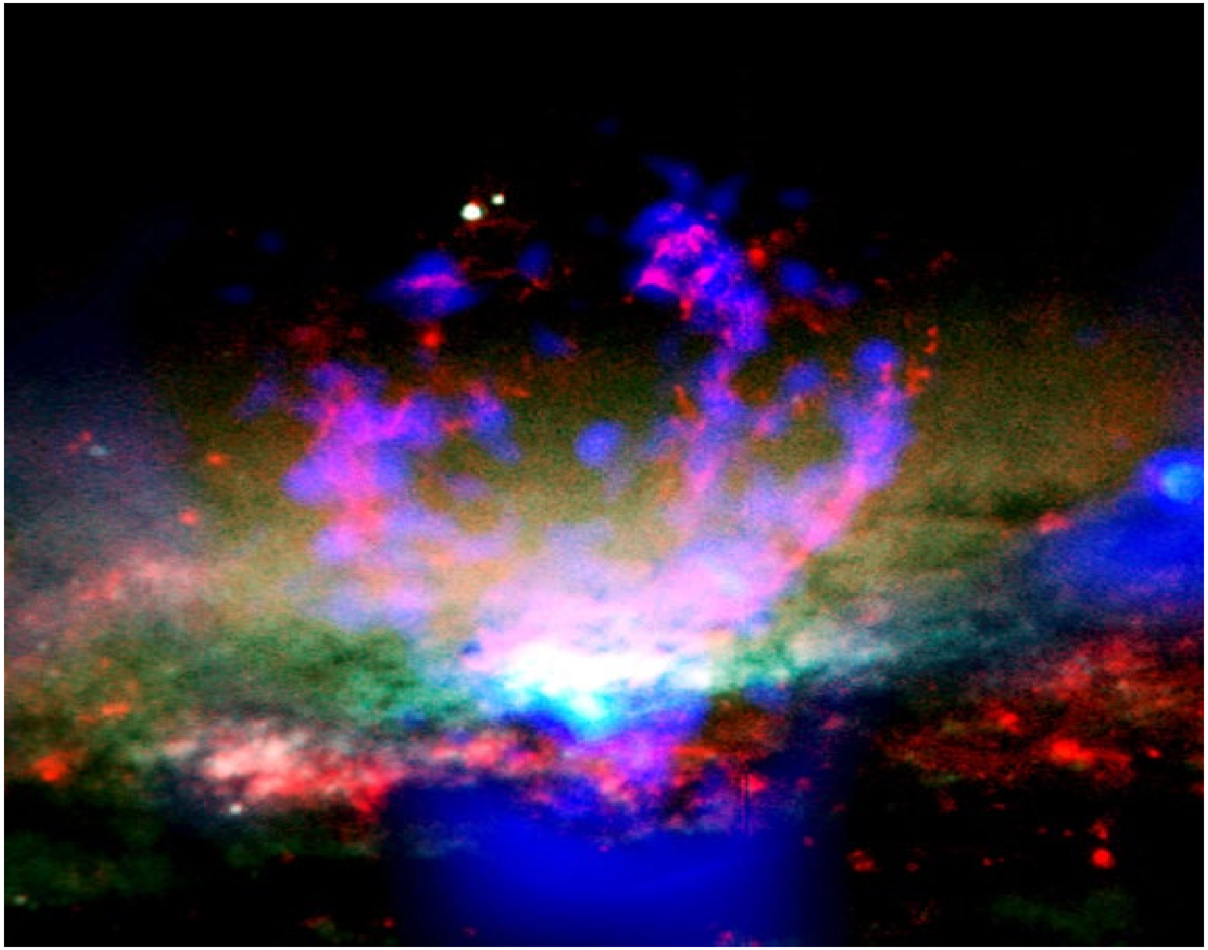
Warm Ionized Outflow





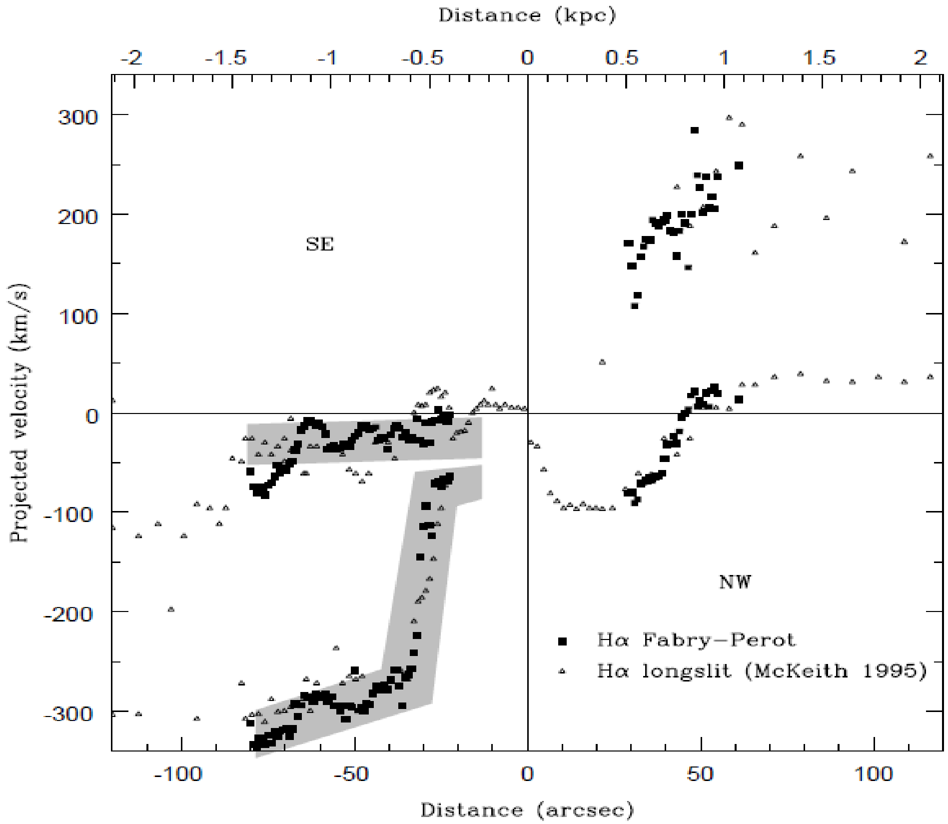
Dense,clumpy material that is shock-heated and accelerated by the wind fluid and radiation

The Warm-Hot Interface



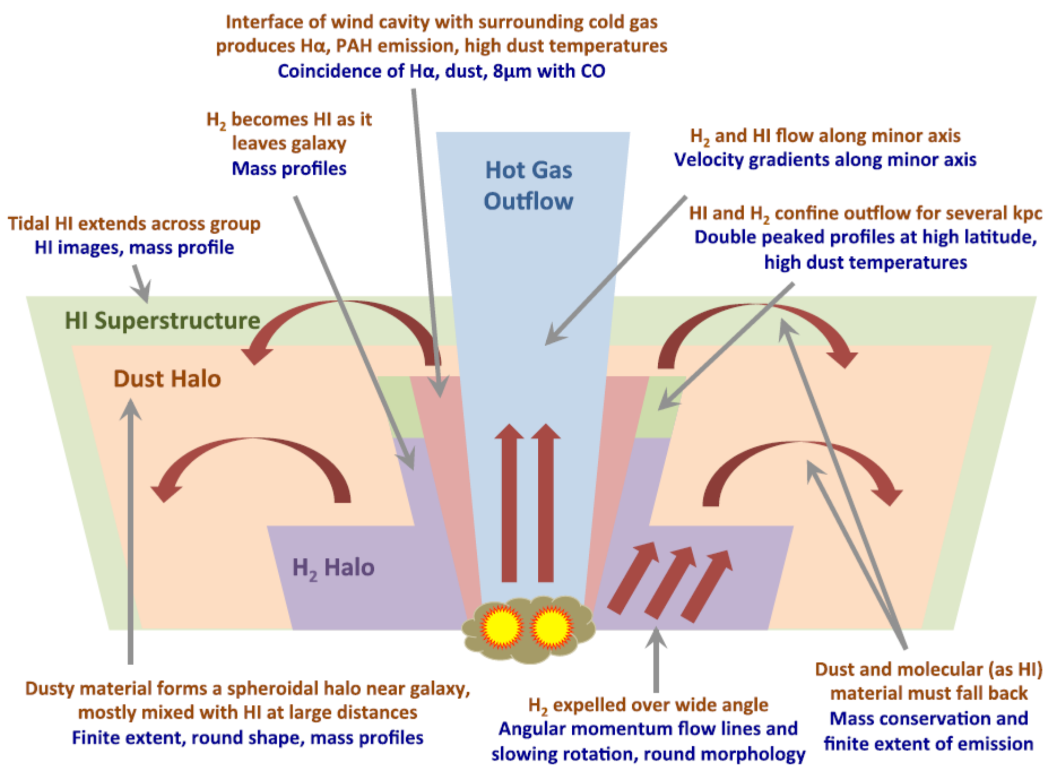
Close relationship between soft X-rays and optical emission-lines. Surface of a cavity filled with the wind fluid (Cecil et al.)

Kinematics: flow along the surface of a hollow bi-cone surrounding the wind fluid



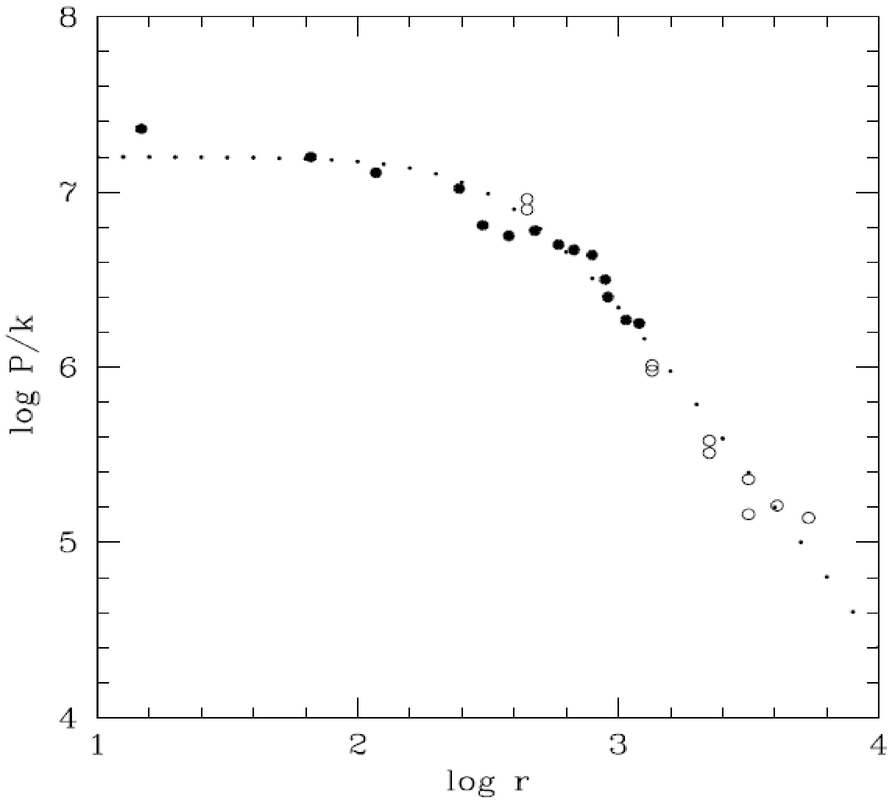
- Rapid acceleration of entrained material to de-projected outflow speed of 600 km/s
- Shopbell & Bland-Hawthorne

Dusty Molecular & Atomic Phases



- Large mass flux in fountain flow (~ 100 km/s)
- Leroy et al. (2015)

The *wind fluid's* momentum flux as traced with the outflow



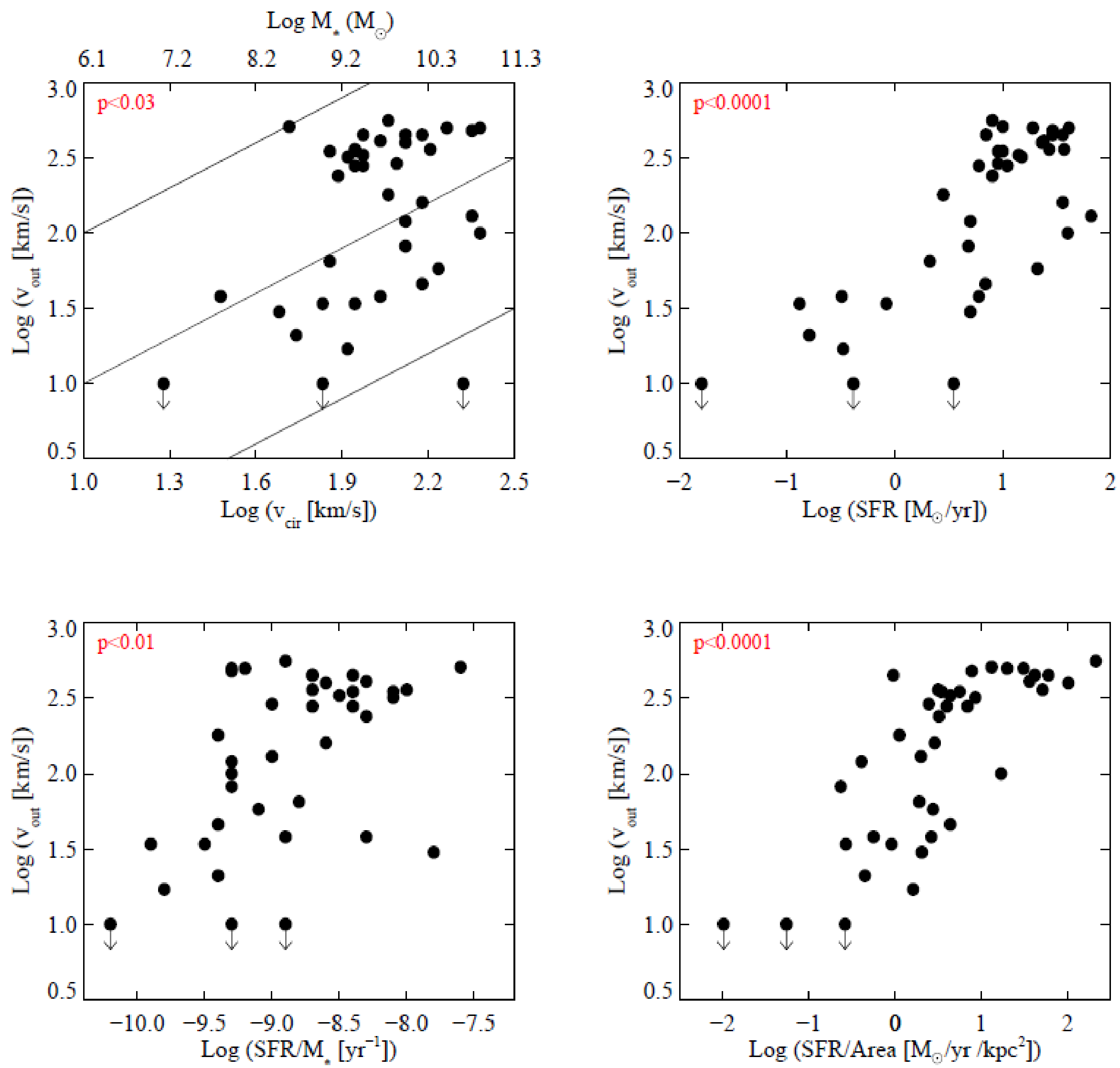
M 82: Data vs. Model

The radial pressure profile from optical emission-lines & soft X-rays measures the wind fluid's ram pressure

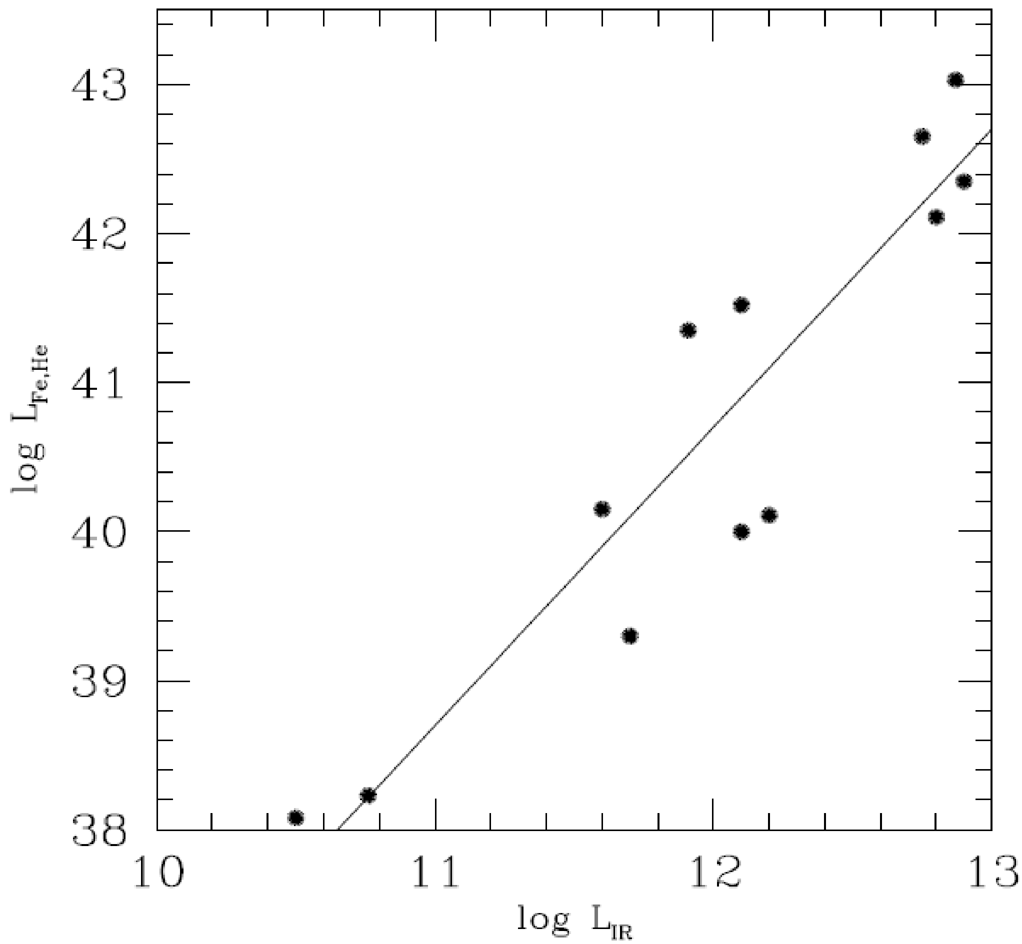
Summary of Part 1

- Galactic winds are believed to play critical roles in the evolution of galaxies and the inter-galactic medium
- Winds are driven by the thermalized ejecta of massive stars (‘wind fluid’ T ~ 10^8K)
- The wind fluid interacts with ambient gas, leading to most of the observational signatures of outflows
- Winds are multi-phase, and this can only be fully observed in the relatively local universe

Part 2: Wind Systematics

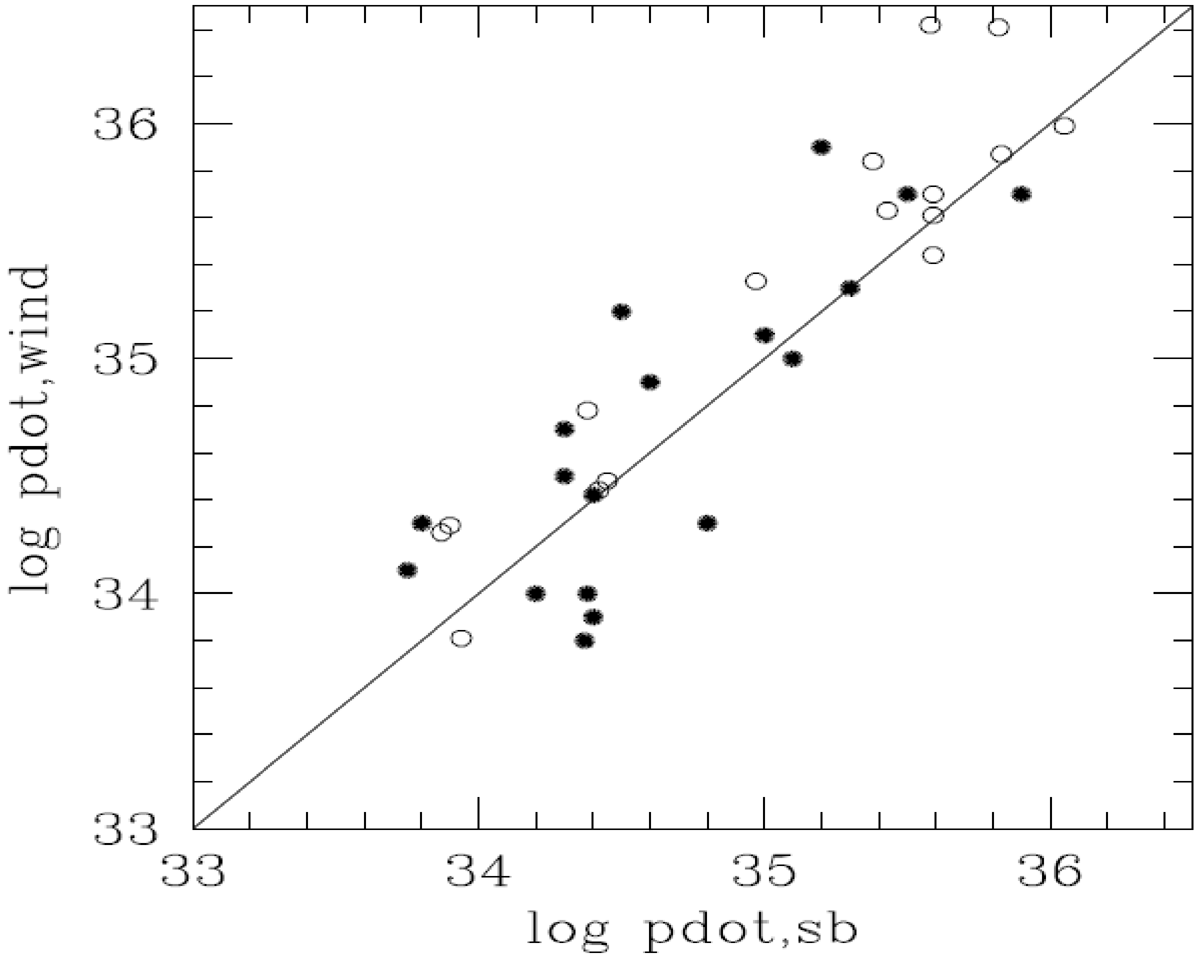


Systematics of the Wind Fluid



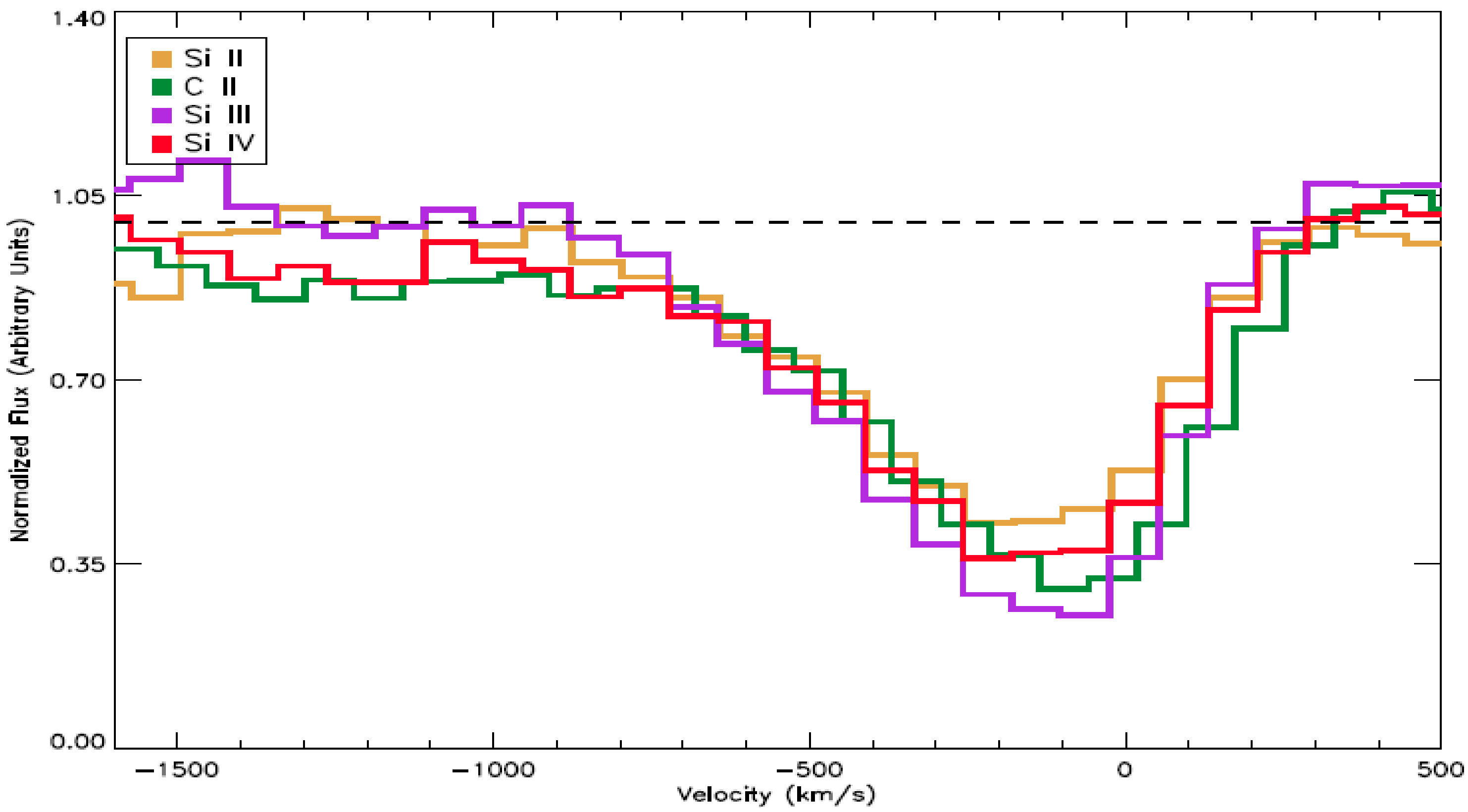
- Probe emission with He-like Fe line (6.7 keV)
- Data agree with simple scaling: SFR^2/r_*

Momentum Flux of Wind Fluid



- X-ray (hollow) and optical (solid) measures
- Momentum flux ~ starburst injection rate

Systematics of the Outflow

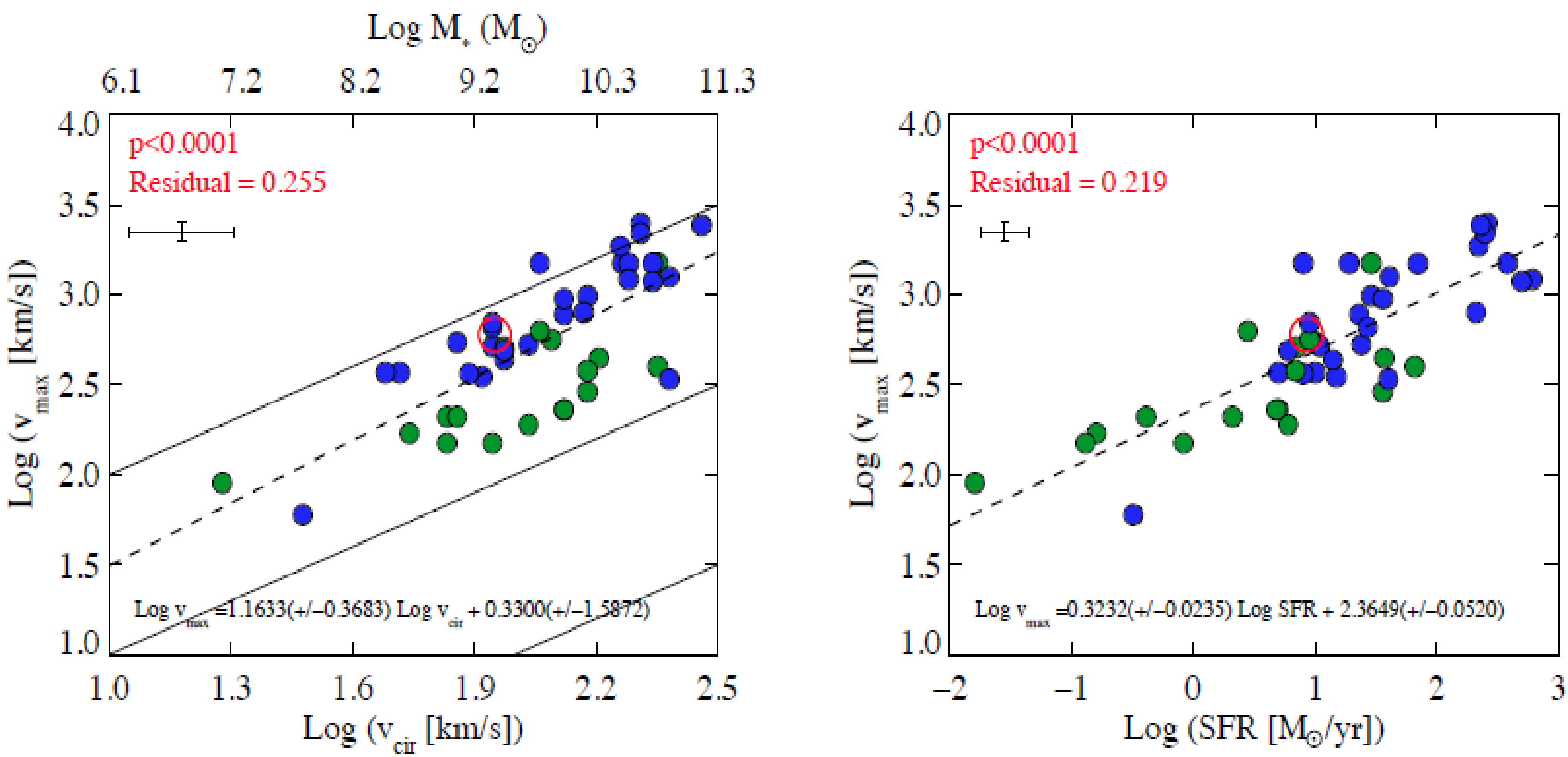


- The warm phase of the outflow can also be probed in absorption against the starburst in the rest-UV
- The most-available probe beyond the local universe

Systematics at Low-Redshift: Heckman & Borthakur+15,16

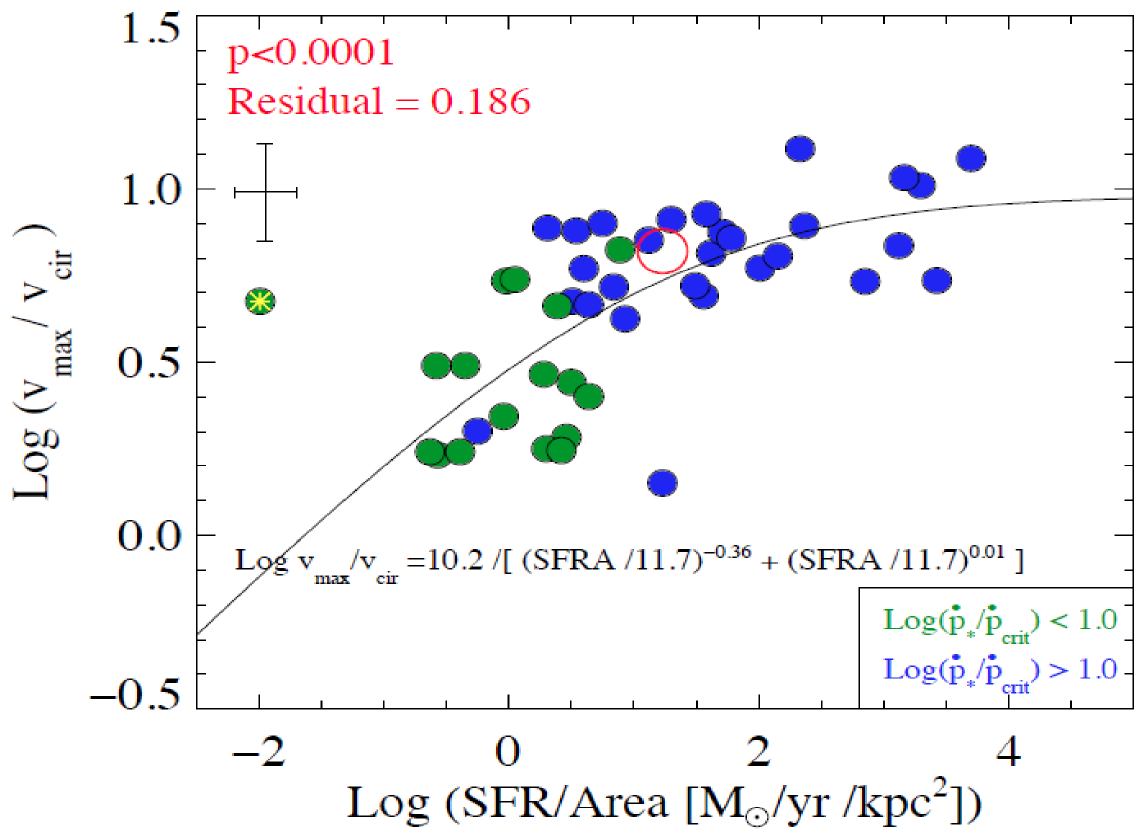
- A sample of 48 low-z starburst galaxies
- Ultraviolet spectroscopy (FUSE + HST): Apertures cover entire starburst
- Goal: determine how the most basic properties of the outflows correlate with those of the starburst galaxy
- ***Goal: Use these results to inform 'sub-grid physics' in models and simulations and to better understand winds***

Results on outflow velocites



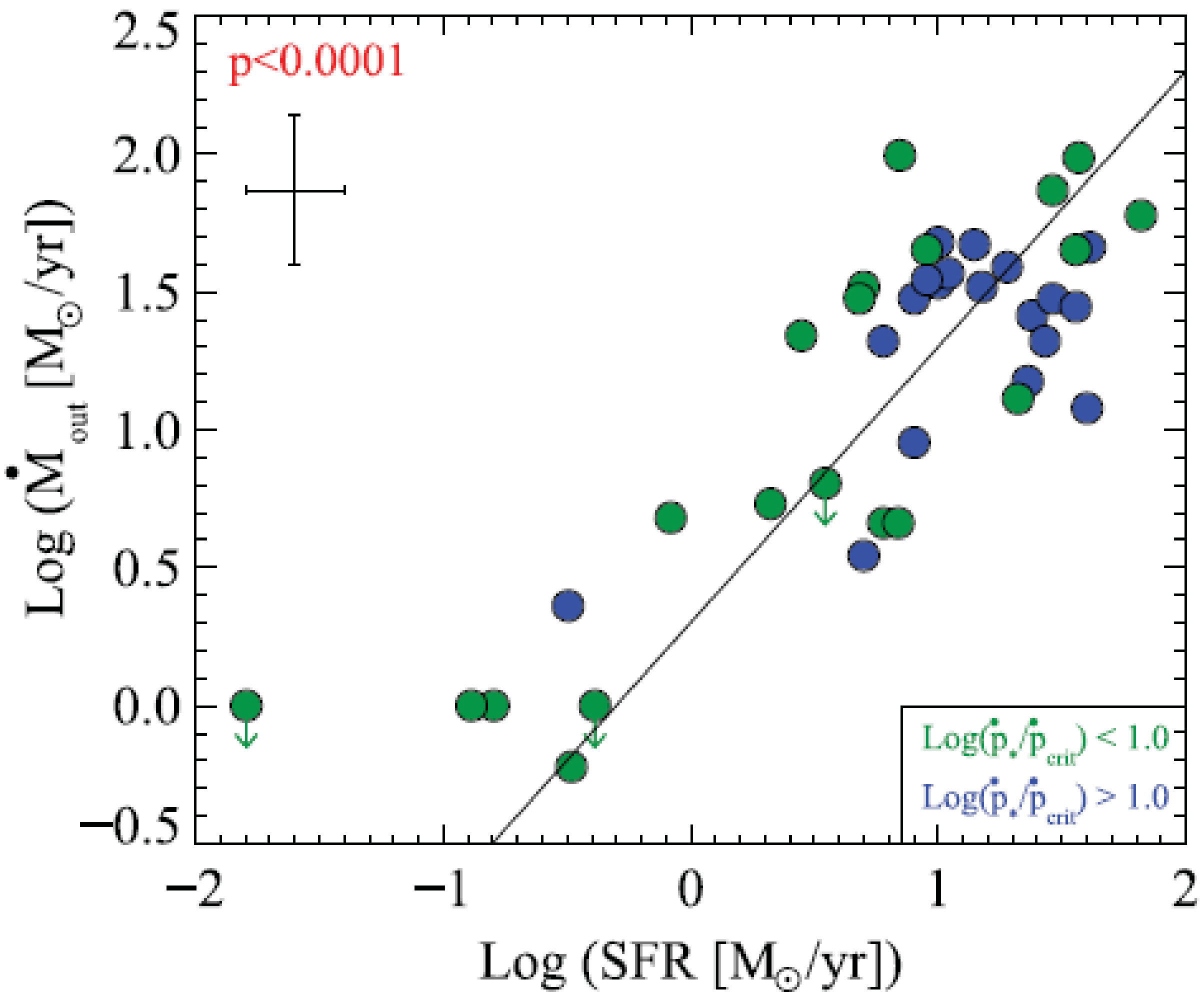
- Strong correlations with v_{cir},M_*,SFR
- M 82 (red circle) is typical

Normalized Outflow Velocity



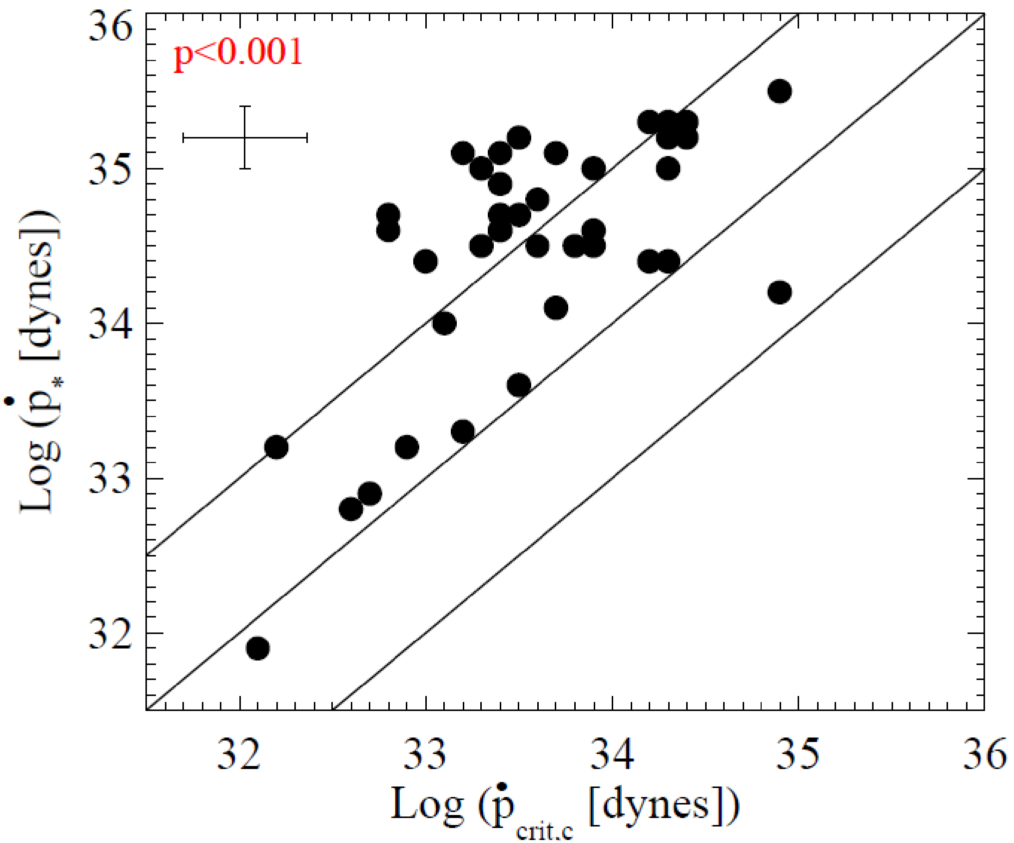
- The ratio of outflow velocity to galaxy circular velocity depends strongly on SFR/Area
- In strong outflows v_{max} = 5 to 10 v_{cir} ($>v_{esc}$)

Mass Outflow Rates



- The outflow rate is ~few times SFR

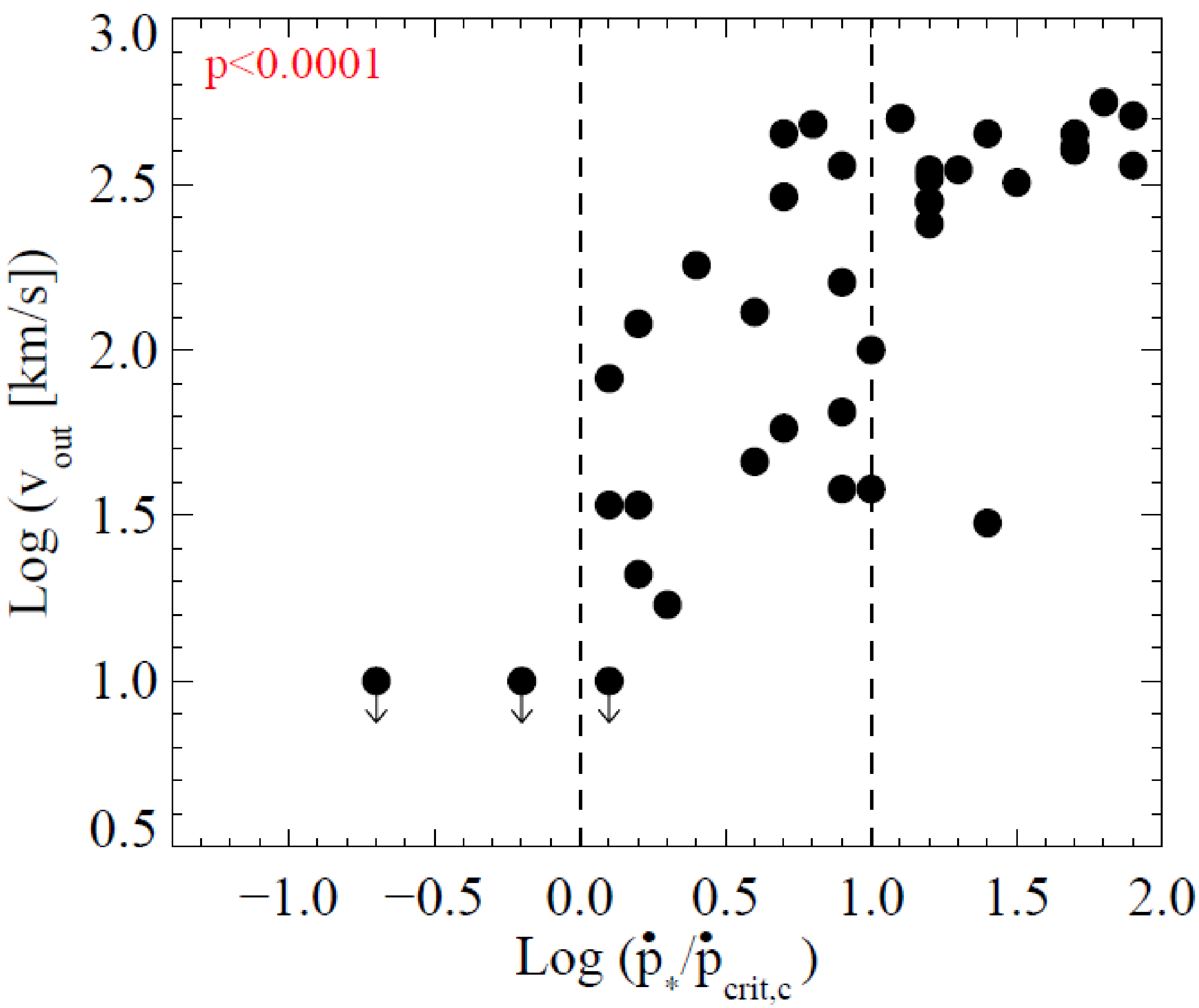
What's the Physics?



$$\dot{p}_{crit,c} = 4\pi\beta r_* N_c < m > v_{cir}^2$$

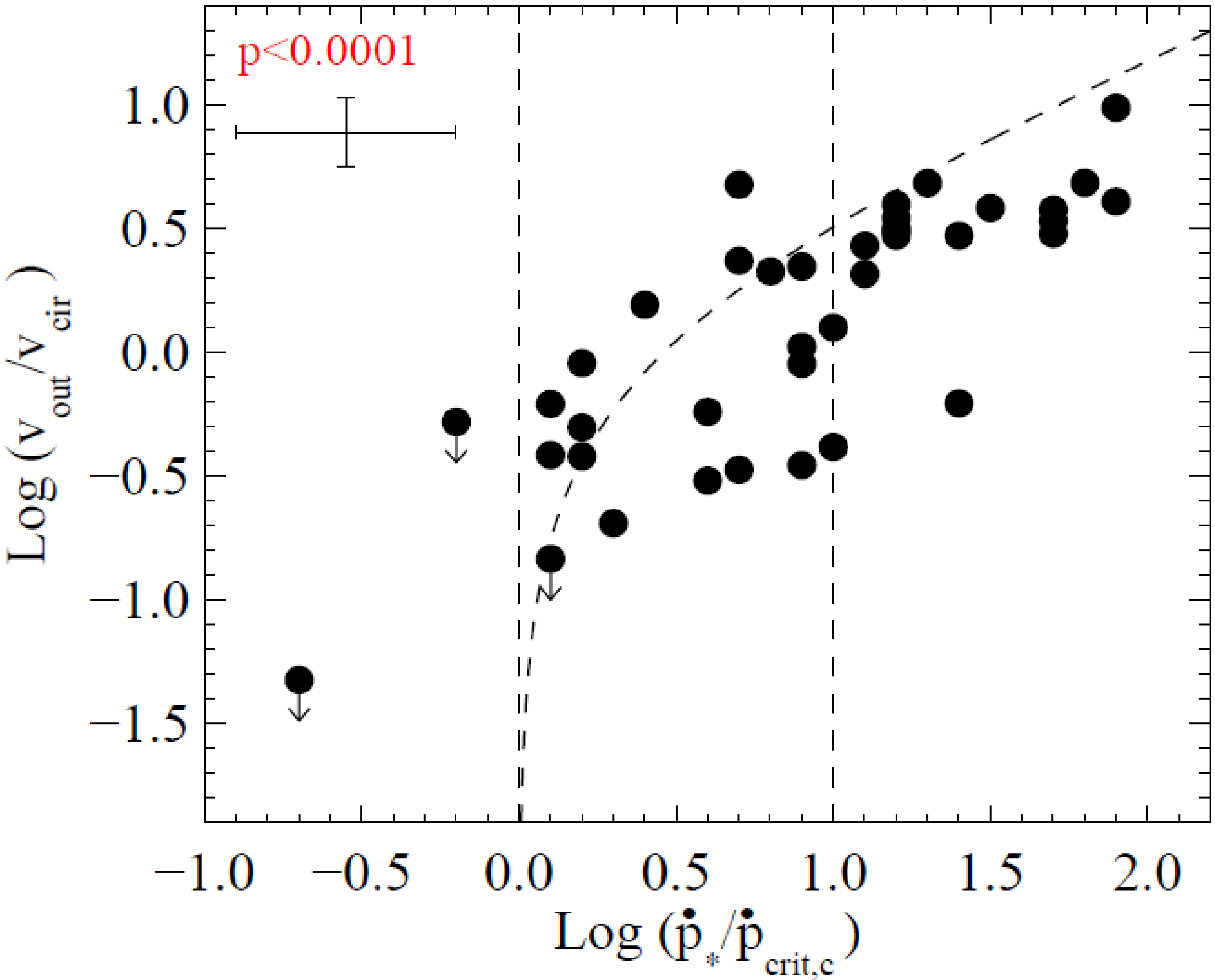
Consider a simple model of a population of 'clouds' being accelerated by a combination of wind-fluid + radiation pressure (outwards) and gravity (inwards)

Resulting Outflow Regimes



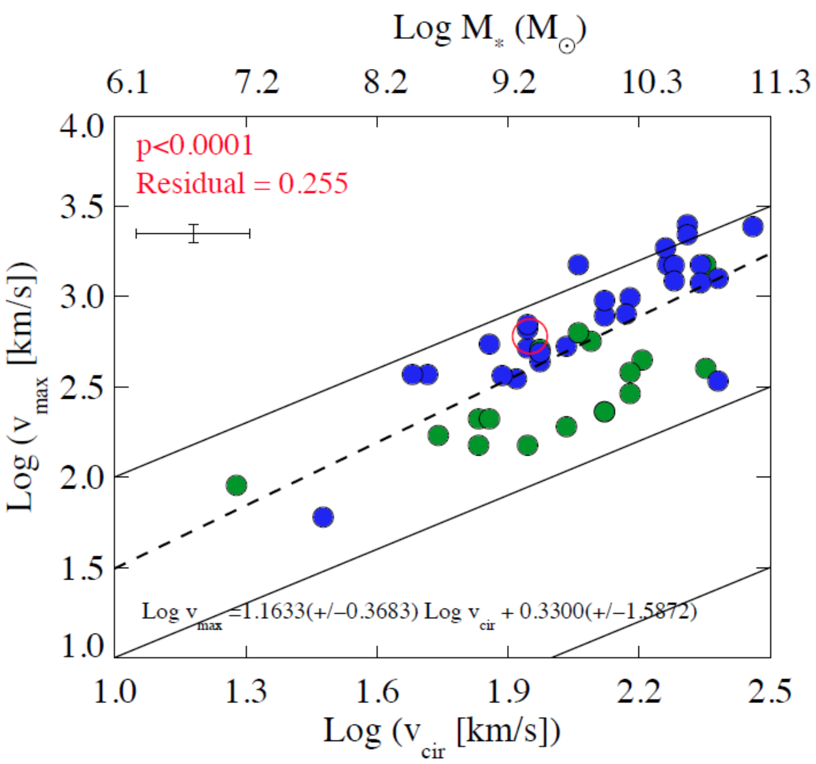
- No outflow, weak outflow, strong outflow

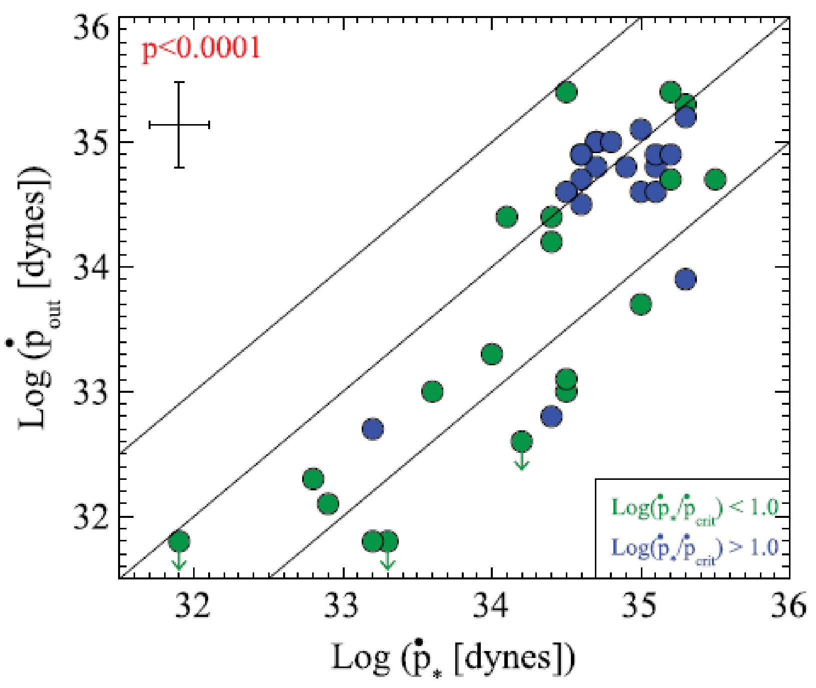
Outflow Velocity: Model vs. Data



A satisfactory match for such a simple model

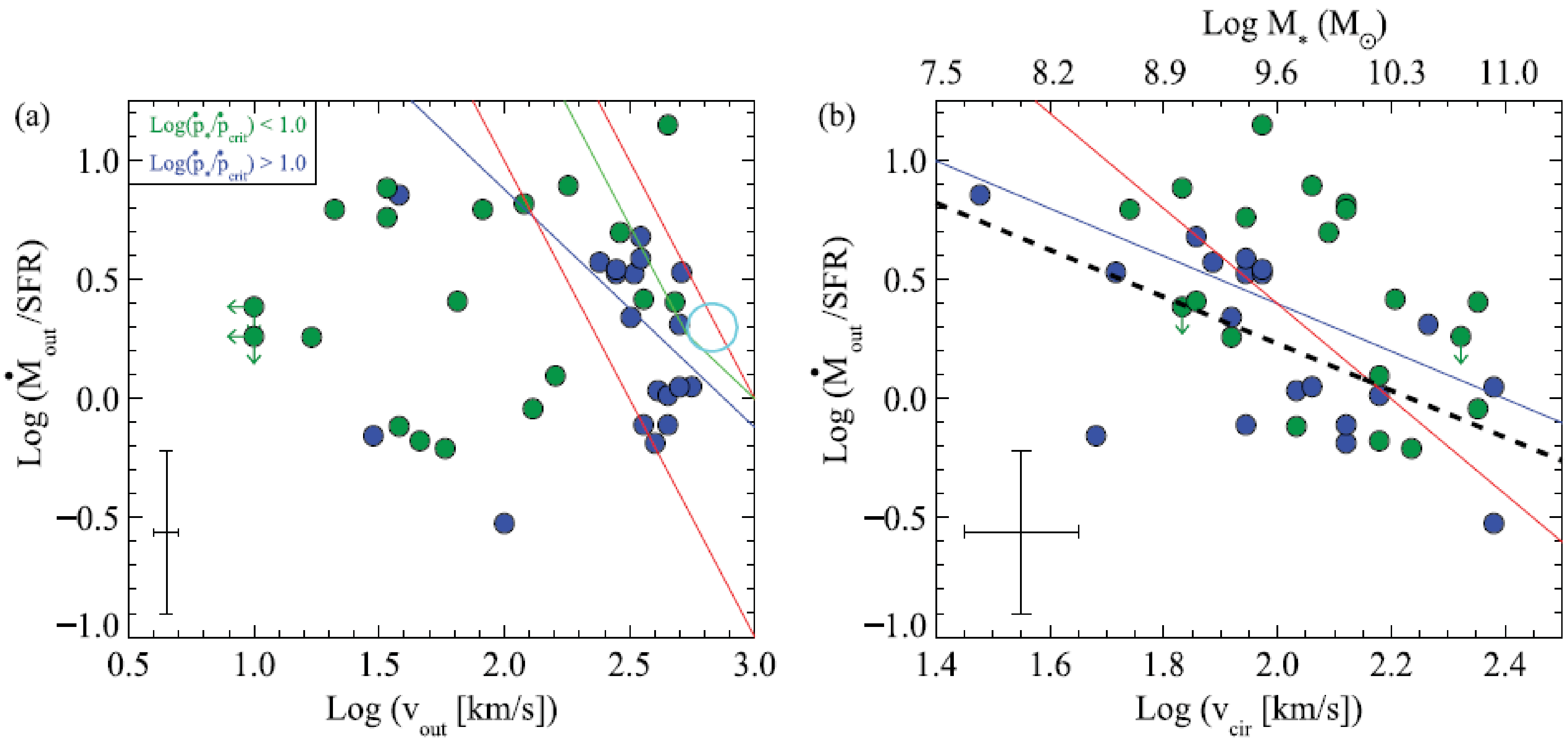
Implications for Sub-Grid Physics





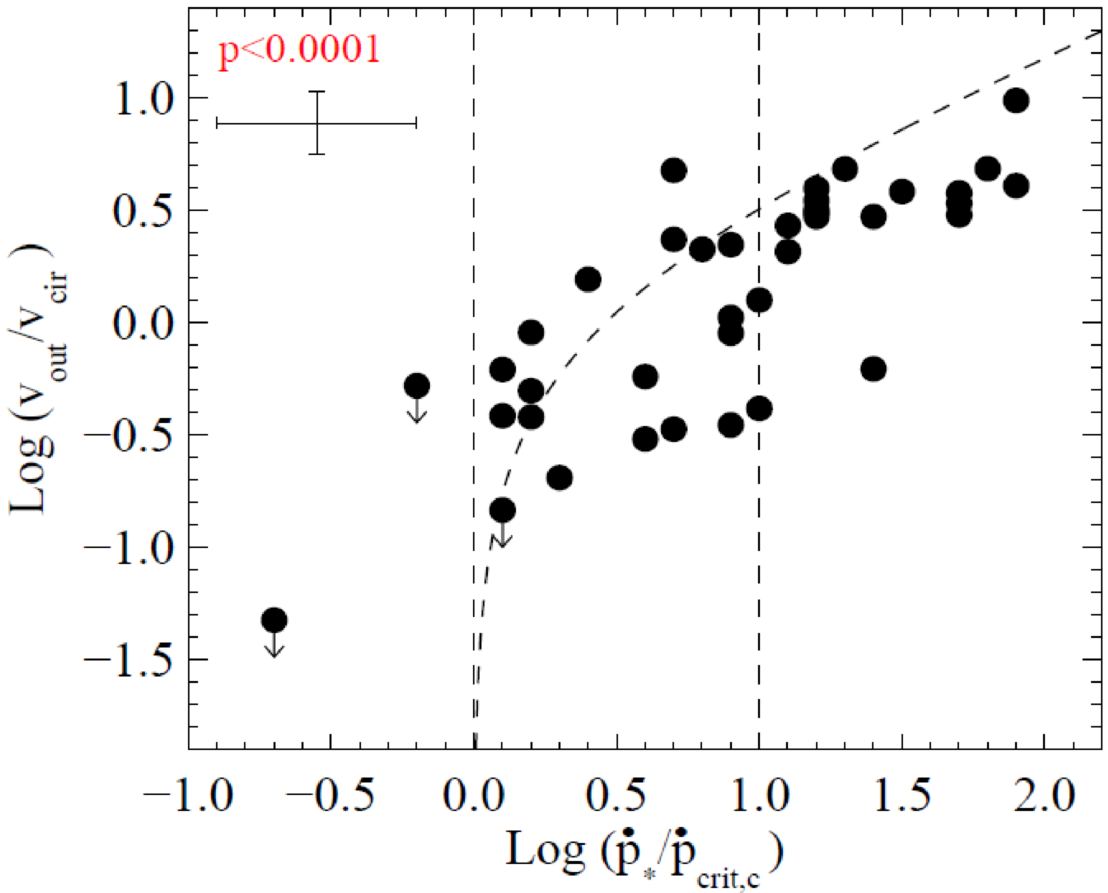
- Only strong winds obey simple scaling of v_{out} with v_{cir}
- Only strong winds carry the supplied momentum flux

Implications for Sub-Grid Physics



- Only strong winds obey prescriptions for “mass-loading” term (outflow rate/SFR)

The Evolving Role of Winds



> On "SF Main Sequence": Currently no/weak winds, to weak winds (z ~ 0.5), to strong winds (z > 1)

> Ratio of outward/inward forces α SFR/$r_* v_c^2$

> At fixed mass, SFR α $(1 + z)^{2.5}$ and r_* v_c^2 independent of z

Summary of Part 2

- The outflows traced by absorption-lines can be understood using a model of a population of momentum-driven clouds
- Key: The ratio of the starburst momentum flux to the critical value needed to overcome gravity
- When this is large, outflows carry most of the momentum flux supplied by the starburst
- And carry mass outward at a rate similar to the SFR, and faster than the escape velocity
- Standard sub-grid prescriptions only work in the "strong wind" regime

Part 3: The Chemical Evolution of Galaxies

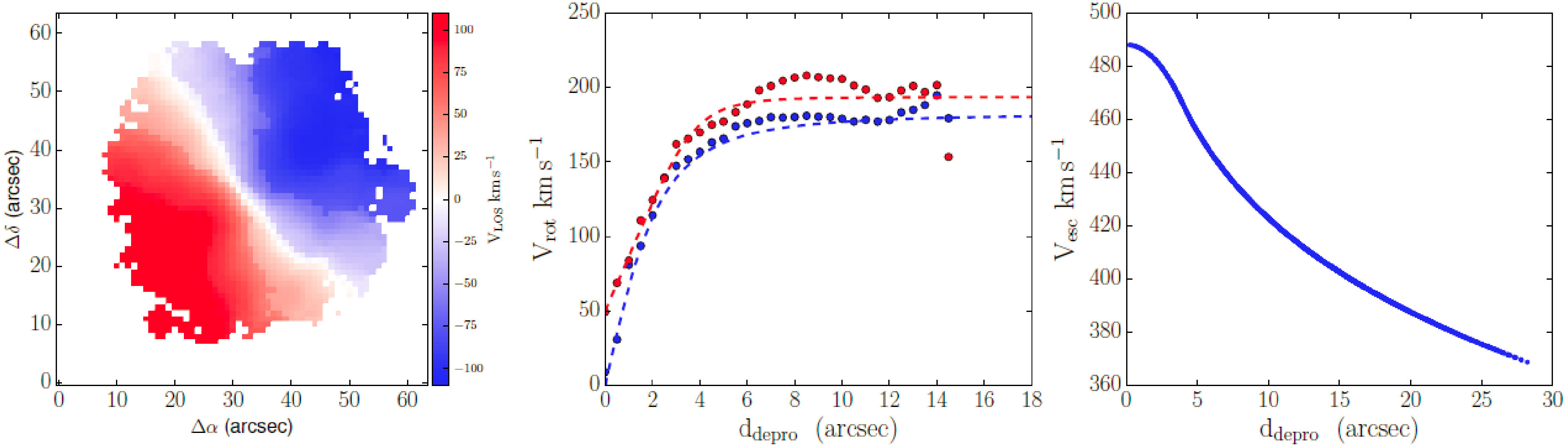
> In the simple "Closed Box" model for chemical evolution, the ISM metallicity depends only on the gas mass fraction μ:

$Z = y \ln 1/\mu$, where y is the "yield" (metal mass returned relative to mass of long-lived stars)

> Complication: the box is not closed. Winds can carry metal-enriched gas out. More efficient in shallow potential wells ("leaky box")

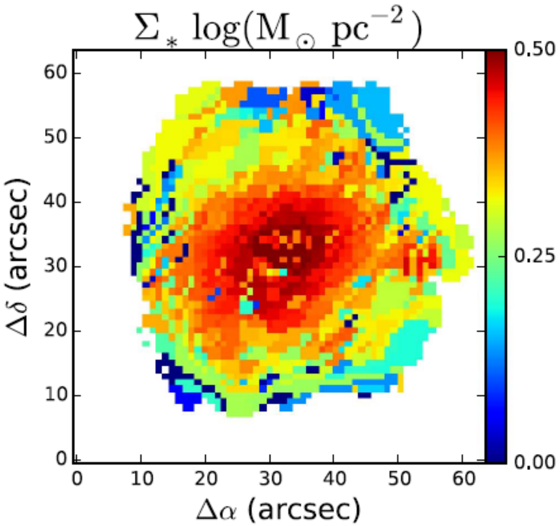
> Test with MaNGA data: SDSS IV program to get 3-D spectral maps of ~10^4 nearby galaxies

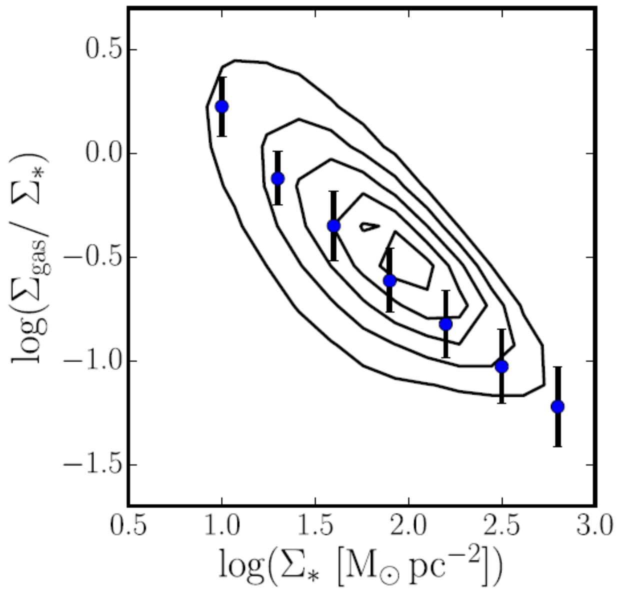
Local escape velocity from rotation curve assuming a spherical isothermal potential

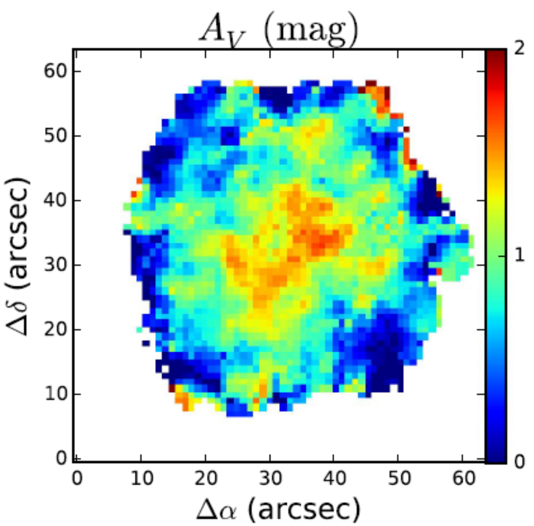


- Jorge Barrera-Ballesteros, TH + 2018

Maps of gas-mass fraction from MaNGA maps of stellar and gas surface mass densities





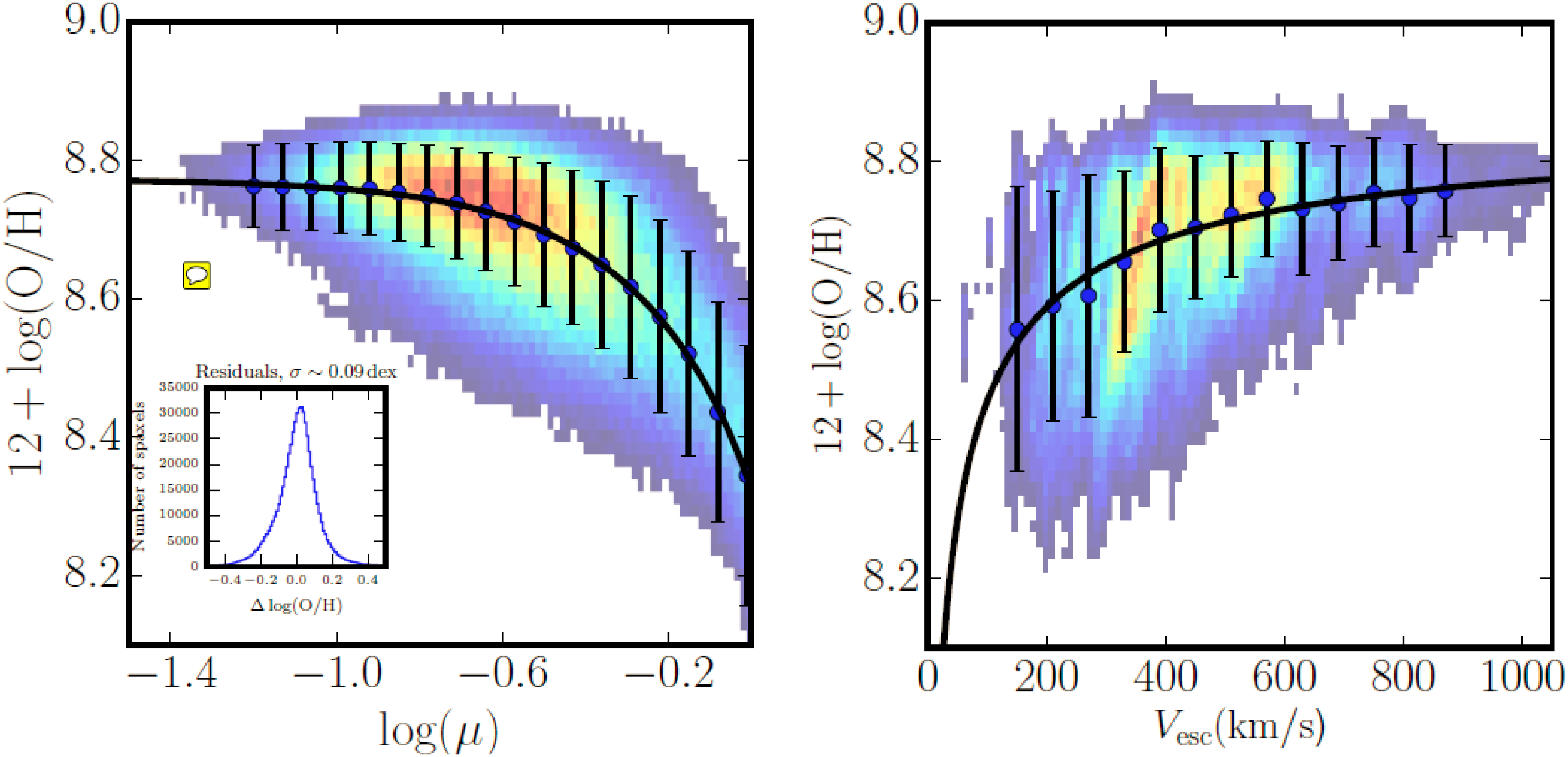


Gas column from dust extinction:

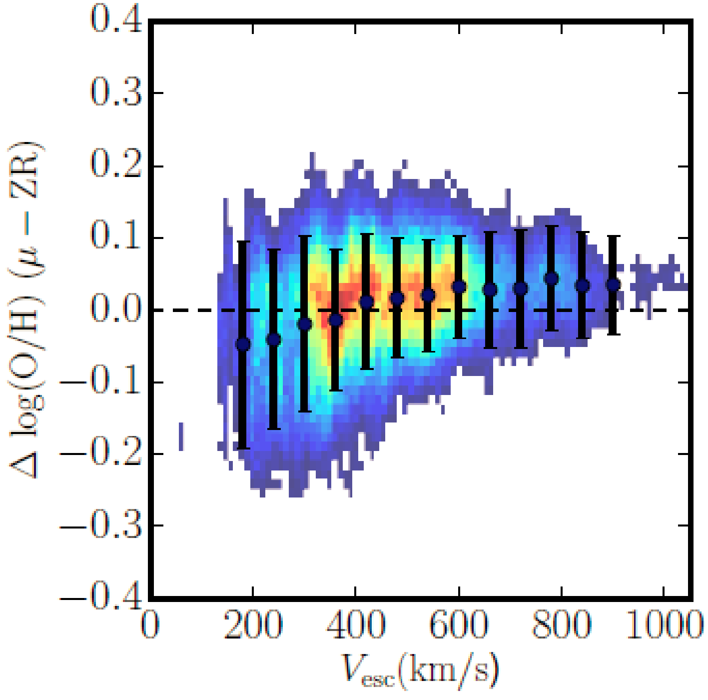
$\Sigma_{gas} = 30\, A_V\, (Z_{\odot}/Z)\; M_{\odot}\, pc^{-2}$

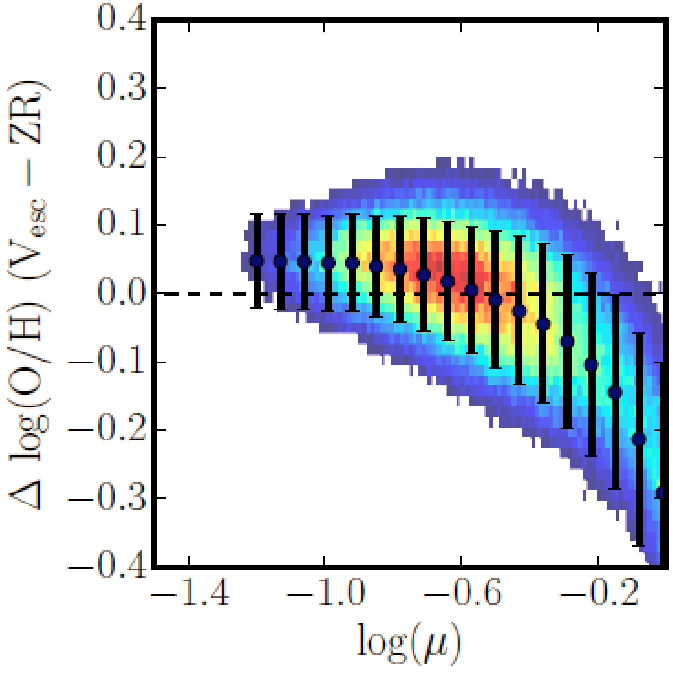
Calibrated with CO and HI maps

Local metallicity correlates with both local μ and local v_{esc}



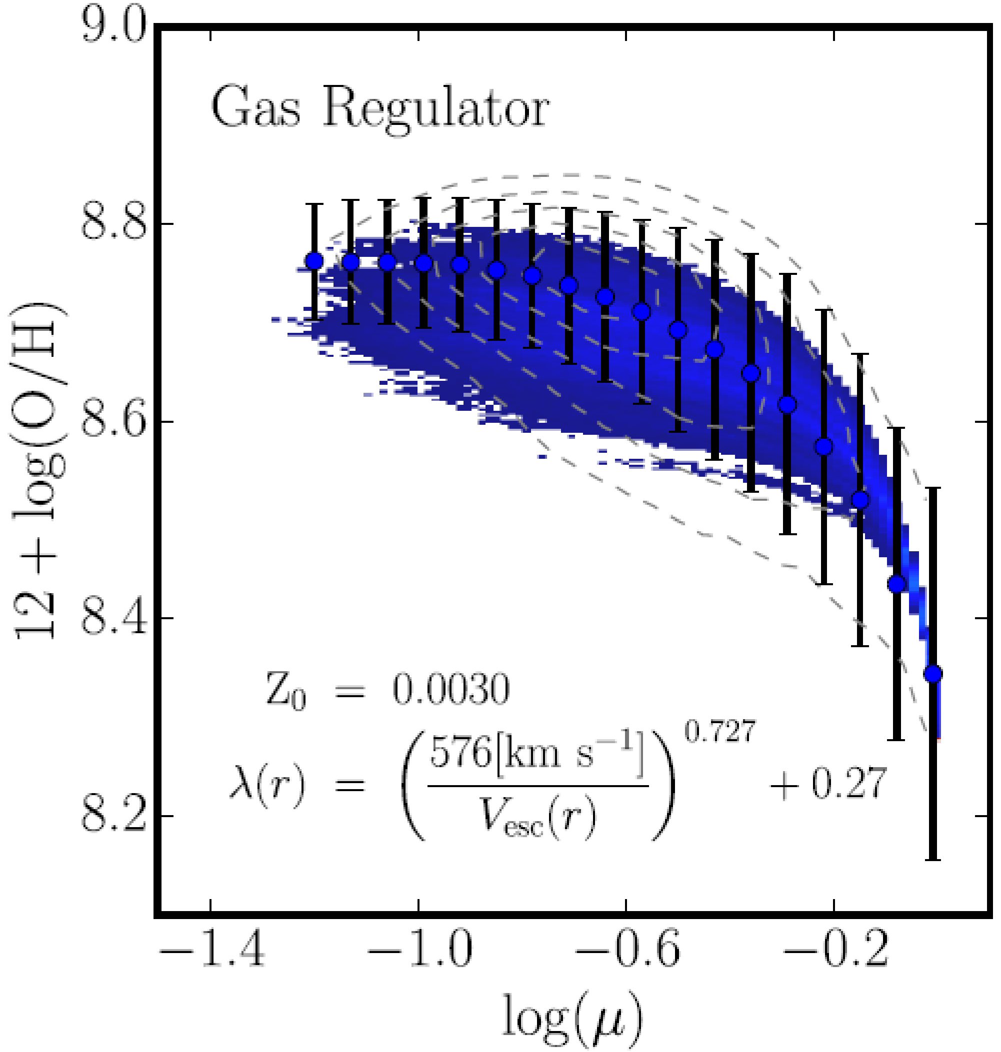
Residuals in Z vs. μ correlate with v_{esc} (and vice versa)





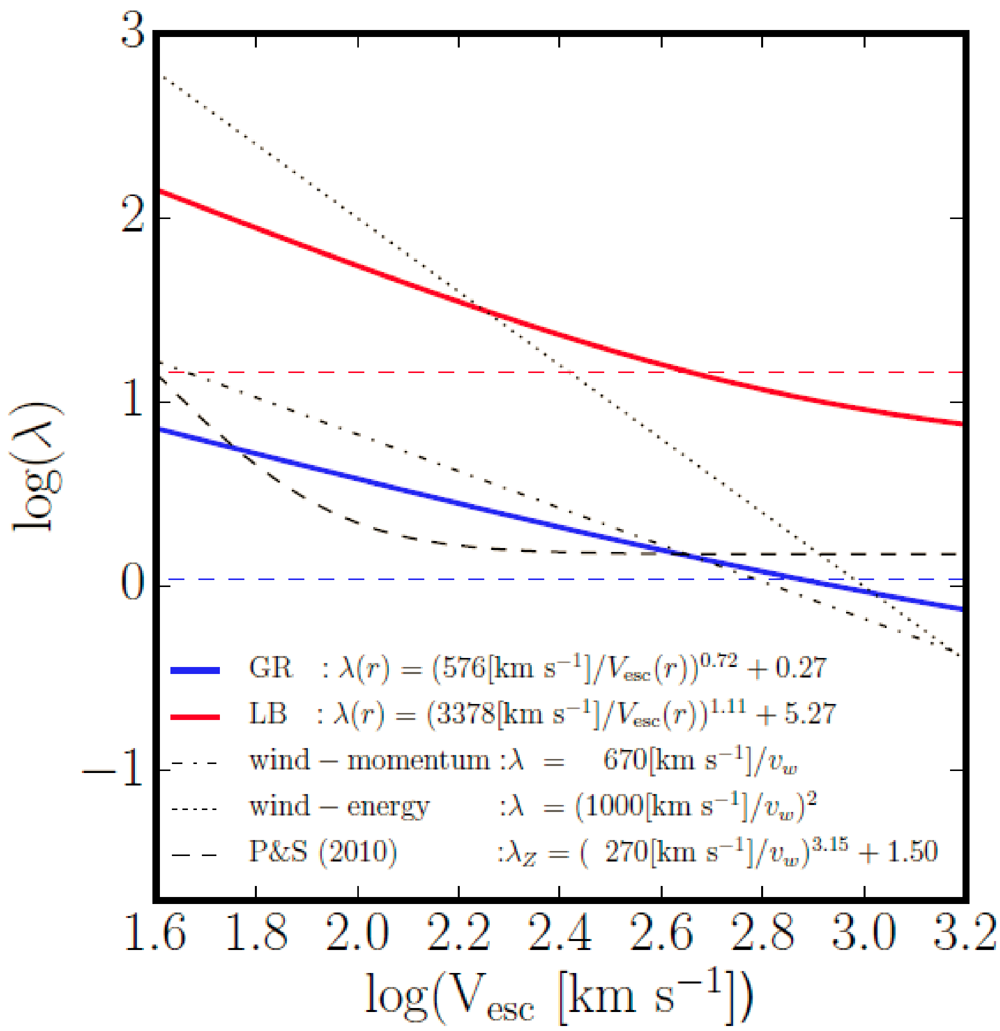
- The gas fraction is the stronger factor
- The escape velocity also matters

Good fit with "Gas Regulator" model of Lilly+: inflows, star-formation and outflows



Free parameters are the metallicity of the accreted material and the scaling of the outflow rate with the local v_{esc}

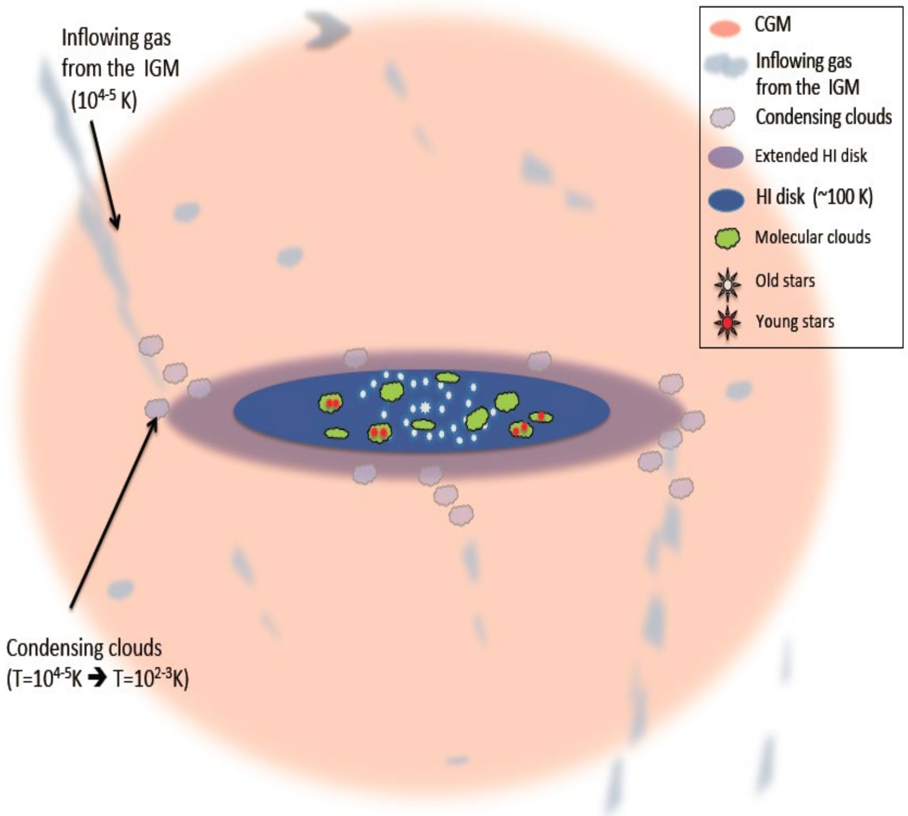
Best-fit parameters consistent with outflows driven by momentum from massive stars



Summary of Part 3

- A simple model in which the outflow of chemically-enriched gas is driven by the momentum supplied by massive stars (SNe, stellar winds, radiation pressure) fits the local dependence of metallicity on local gas-mass fraction and escape velocity
- This is the same scaling deduced from the systematic properties of winds in section 2

Part 4: Winds and the Circum-Galactic Medium

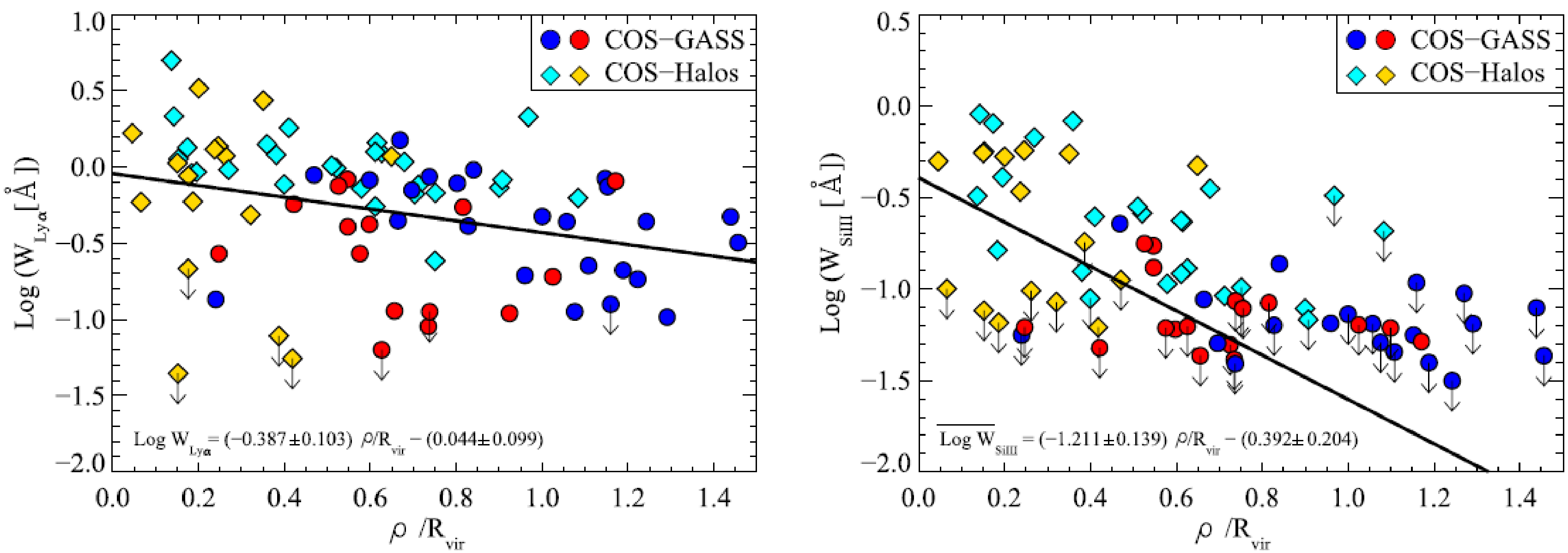


- The gaseous halo: reservoir of gas that can be accreted onto the disk and fuel star formation
- It will be affected by feedback from massive stars
- A key part of the galactic ecosystem

Probing the CGM in absorption

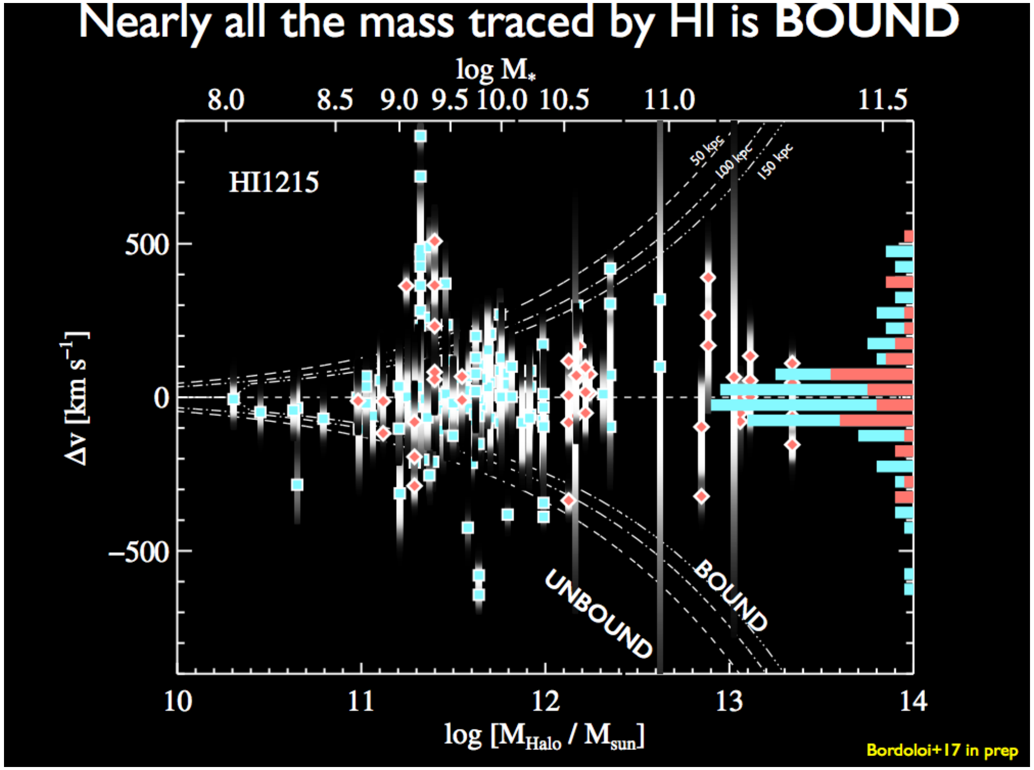
- Low densities imply low surface brightness (emission-measure α n^2 L)
- Absorption: column density α n L
- Lines almost all in FUV: a window opened by COS on HST
- Lots of progress: e.g. Stock+13;Liang & Chen 14; Bordoloi +14; Werk+14; Johnson +15; Borthakur+15,16

The Warm CGM in typical low-z galaxies



- Characteristic size of CGM in Lyα ~ virial radius
- Metals more concentrated (~ 0.5 R_{vir})
- Borthakur et al. 2016 (B16) – COS-GASS plus COS-Halos

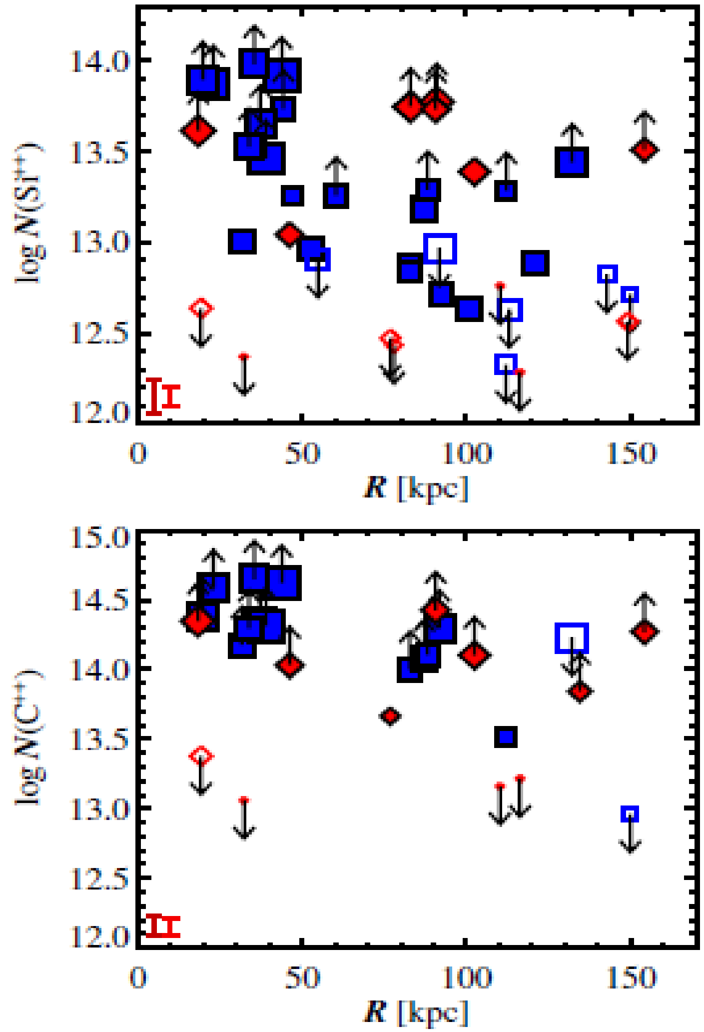
Kinematics – Warm CGM Clouds are Bound



- Bordoloi – in prep

Physical/Chemical State

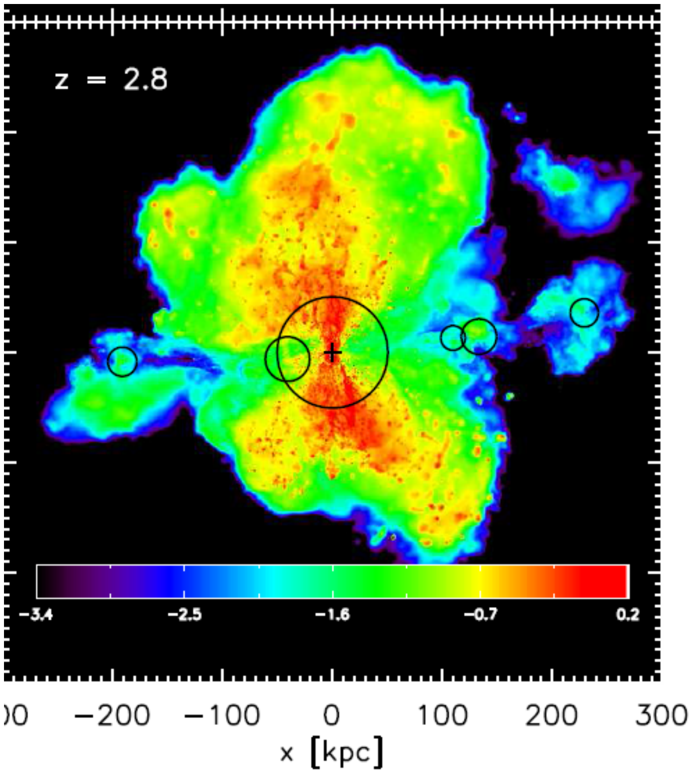
- The warm gas in the CGM is metal-enriched (~10% to 100% solar) and mostly ionized
- The metal mass of this gas is similar to that of the stellar disk
- This material is in the form of cloud/sheets/filaments
- Werk et al. 2014



What happens when a wind flows into the CGM?

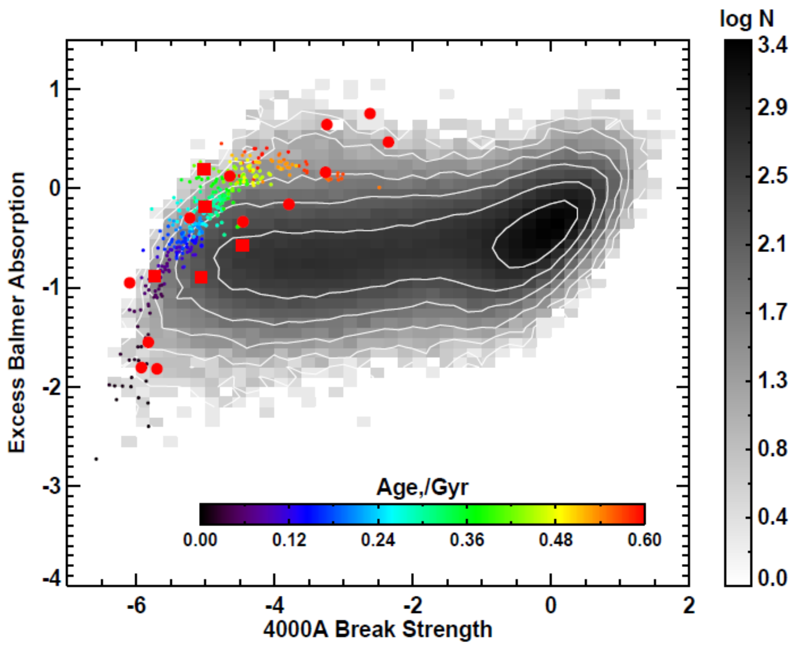
Test using QSO sightlines through the CGM of starbursts using COS

COS-Burst: Heckman, Borthakur, Wild, Schiminovich, & Bordoloi 2017



Compare to control sample of normal star-forming galaxies matched in M_* and impact parameter (ρ) observed with HST/COS

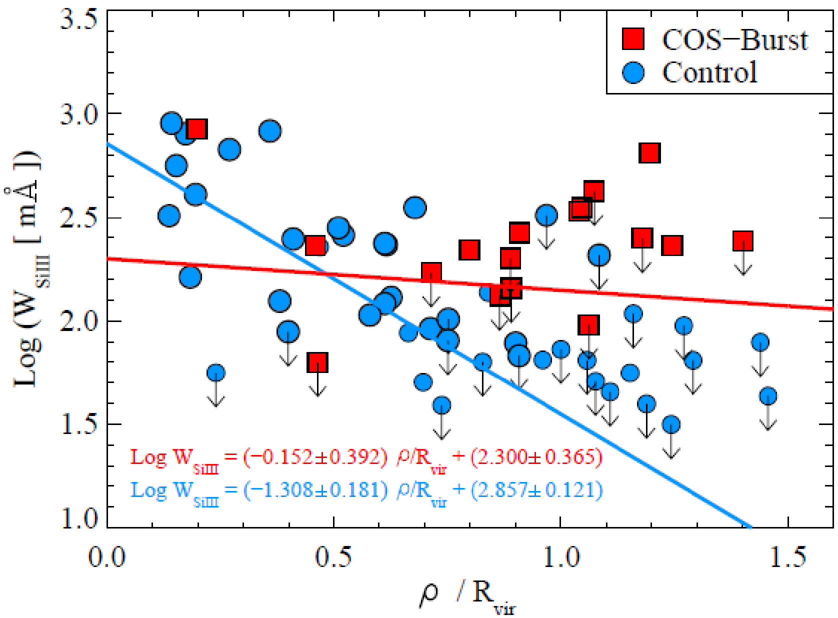
COS-Burst Sample

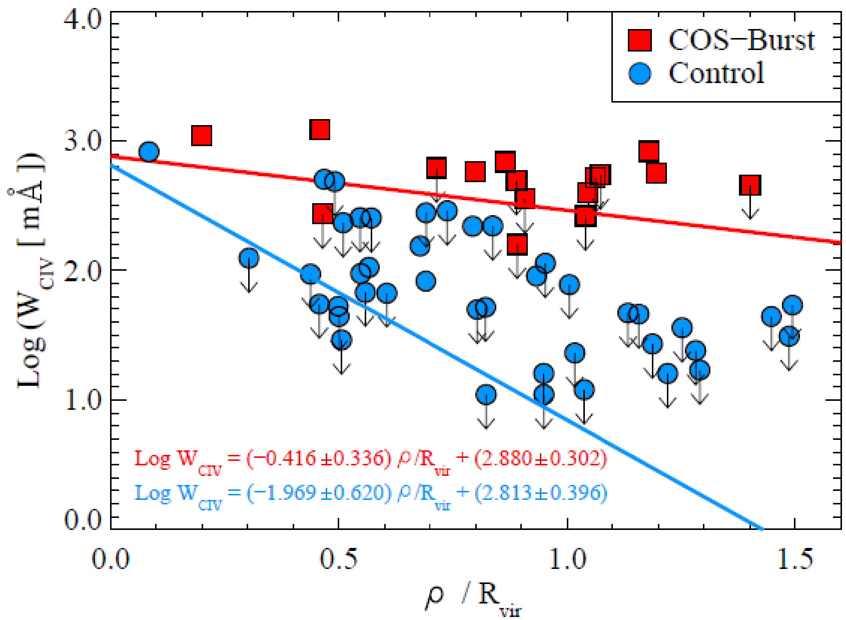


- Galaxies selected from SDSS legacy spectra based on PCA approach
- 17 cases with suitable QSO
- Burst parameters derived from PCA vs. models plus Balmer emission-lines

$\log M_*$	v_c^b	R_{50}	R_{vir}	ρ	f_{burst}	t_{burst}	logsSFR	logSFR
Log $M_\odot$	km s^{-1}	(kpc	kpc	kpc		(Myr	(Log yr^{-1})	(log $M_\odot yr^{-1}$)
10.34	129	3.2	184	179	0.17	280	-9.24	1.07

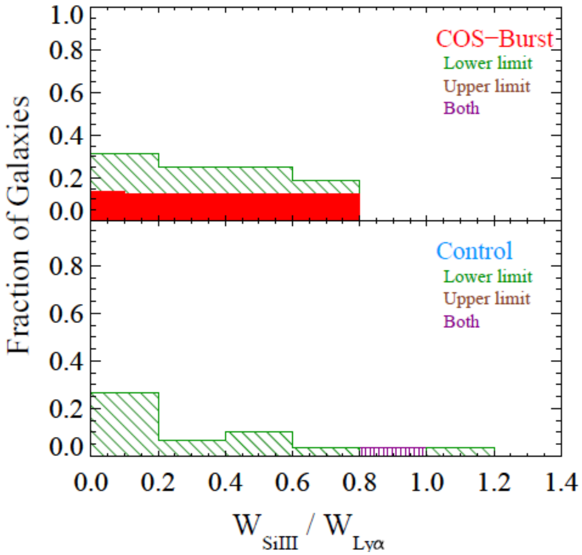
Higher column densities of metals compared to the *outer* CGM of normal star-forming galaxies

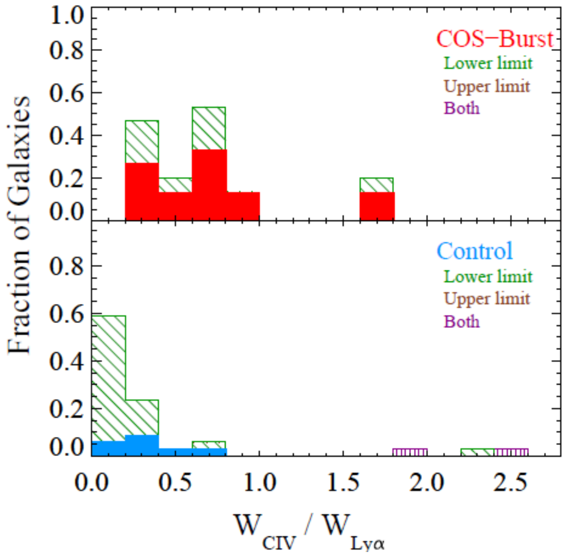




- Note that Si III and C IV lines have τ ~ 1, so that EQW traces column density
- Typical values are ~ few x 10^{13} and few x 10^{14} cm^{-2} respectively
- Covering factor ~ 50% in outer CGM

Larger ratio of Si III/Lyα and C IV/Lyα EQWs

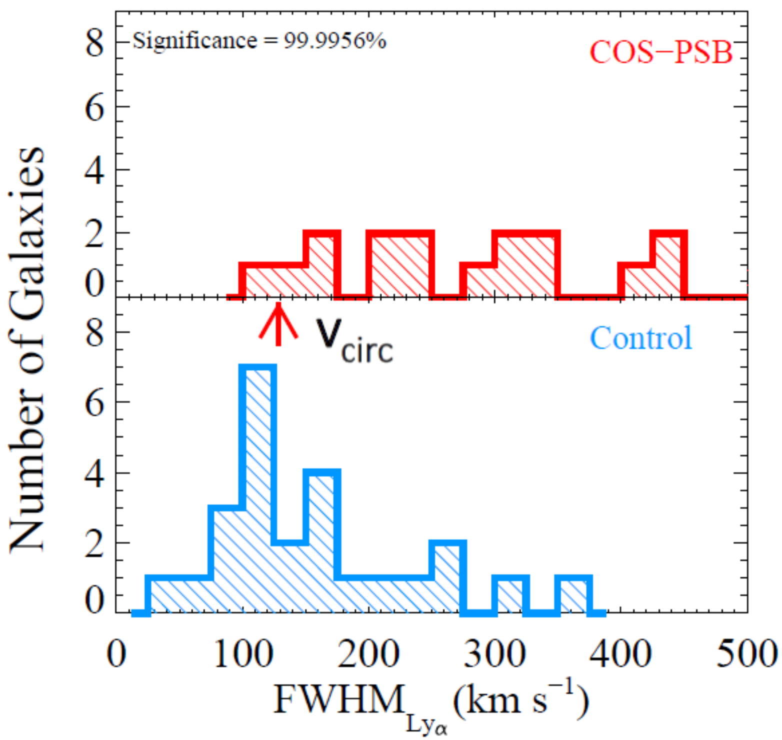


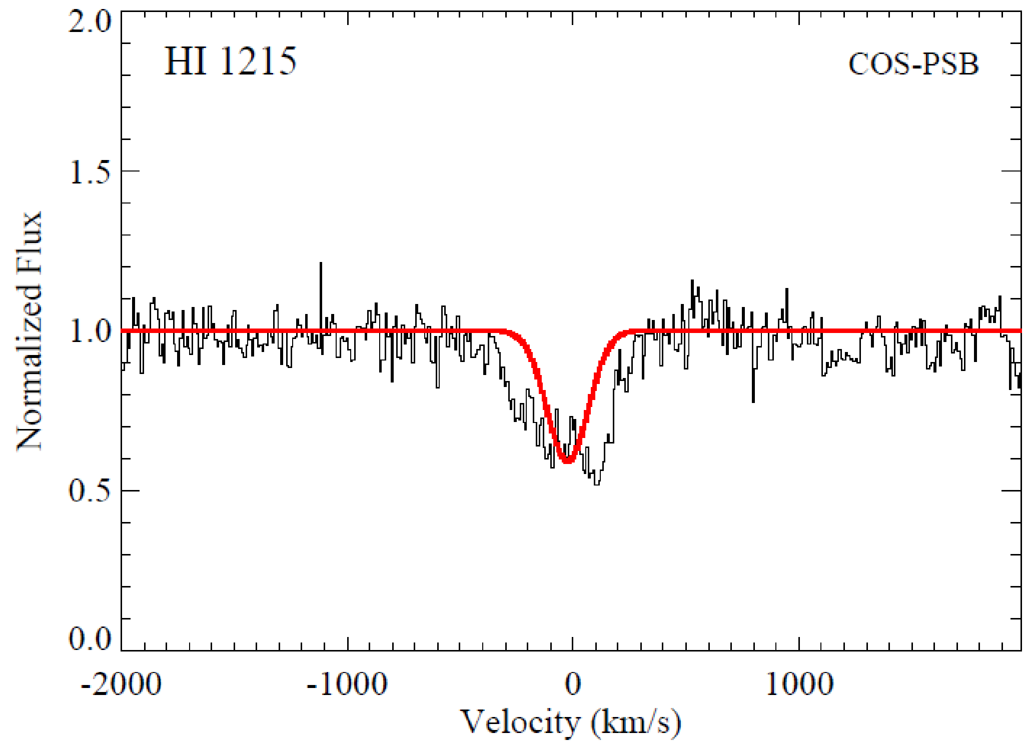


- C IV and Si III have τ ~ 1 while Lyα has τ>> 1
- Implication: higher gas column densities in CGM in COS-Burst sample enhances the ratio of EQW of optically-thin vs. saturated lines

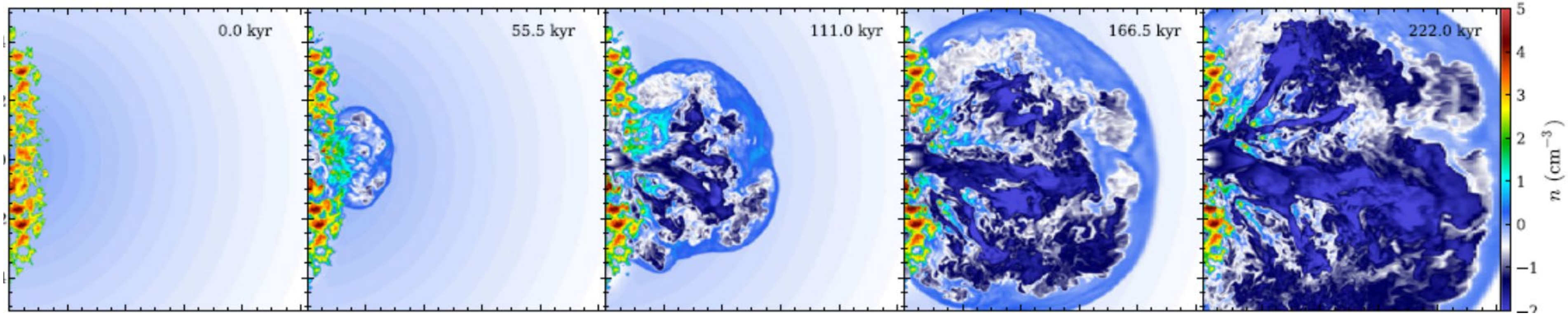
Super-virial velocities

$v_{cgm} \sim 2\ v_{vir}$ (FWHM ~ 425 km/s in stack)





Interpretation



- Starburst-driven wind-fluid drives an expanding bubble (shock) out into a pre-existing multiphase CGM (clouds and volume-filling hot phase)
- This can accelerate clouds and drive and outflow of metals

Can the wind fluid reach the outer CGM?

- Consider classic wind-blown bubble expanding into the CGM (Weaver + 1977)
- Volume-filling phase has a total mass $10^{10}\ M_{\odot}$ and $\rho \propto r^{-1}$ (cf. Miller & Bregman; Voit+)
- Similarity solutions (cf. Dyson 1989):

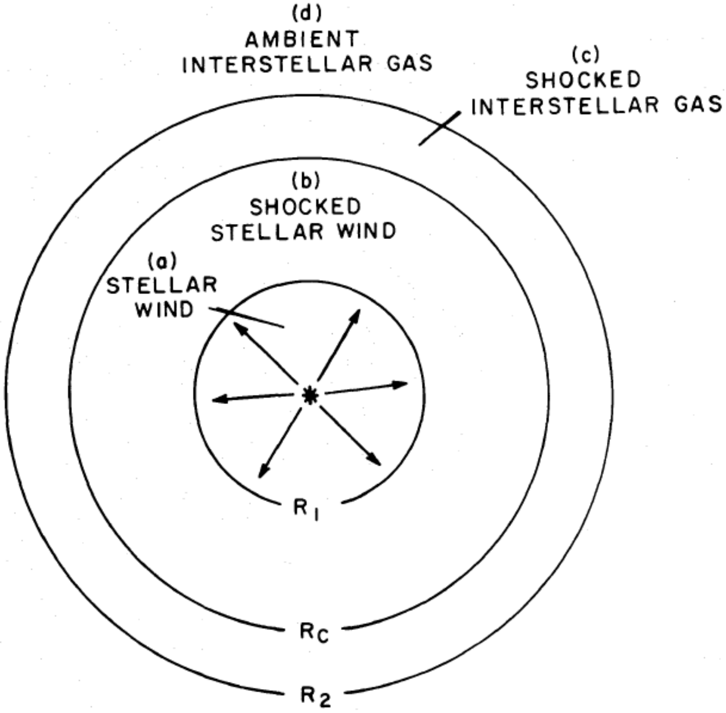
> Energy-driven case:

$R_{bubble} \sim 195\ dE/dt_{43}^{\ 1/4}\ M_{hot,10}^{\ -1/4}\ t_{300}^{\ 3/4}$ kpc

>Momentum-driven case:

$R_{bubble} \sim 170\ dp/dt_{34.7}^{\ 1/3}\ M_{hot,10}^{\ -1/3}\ t_{300}^{\ 2/3}$ kpc

- **The answer is "Yes"**



Summary of Part 4

- The circum-galactic medium is a key component of the galactic eco-system
- It is a potential source of gas for fueling the gas disk and subsequent star-formation
- Observations suggest that strong starburst-driven winds can affect the CGM
- The interplay between accretion and winds will be crucial in the evolution of galaxies

Grand Summary

- Galactic winds driven by massive stars play a key role in the evolution of galaxies and the intergalactic medium
- Observations of local starbursts provide a critical laboratory for understanding how winds *actually* work (attention: simulators)
- Winds can dramatically affect the circum-galactic medium and influence the building of galaxies via gas accretion
- Momentum-driven outflows shape the local and global chemical evolution of galaxies