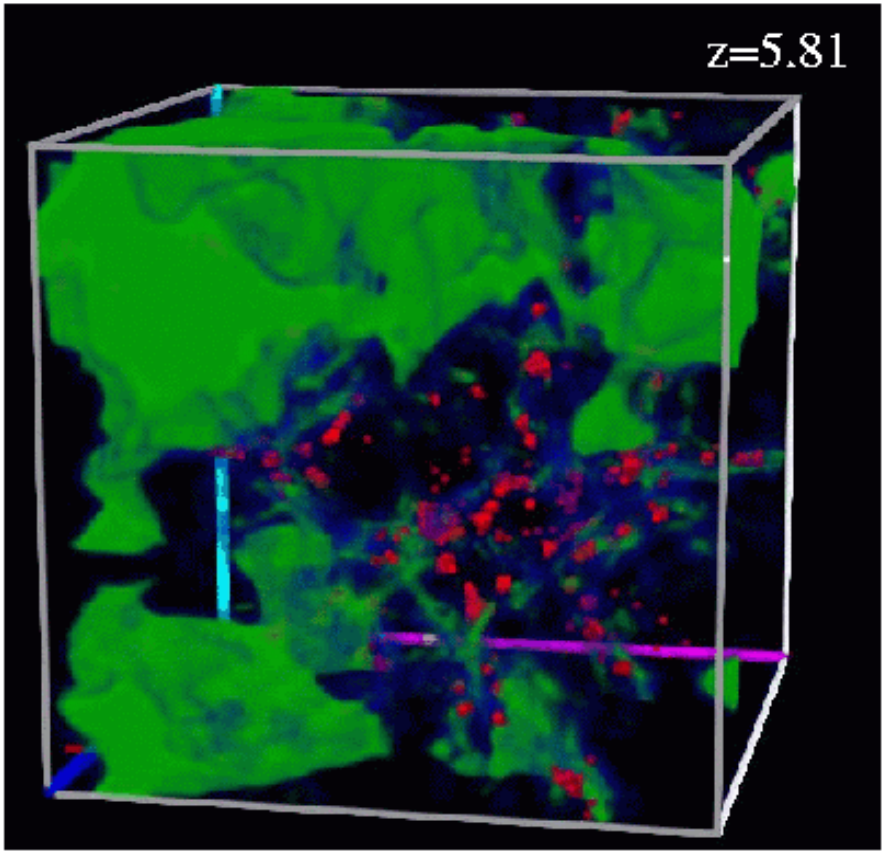
The Physics of Reionization: Clues in the Local Universe



Talk Outline

Part 1: Introduction

Motivation – The Need for Feedback

Local Analogs of High-z Galaxies

Part 2: The role of galactic winds

Wind physics & systematics

Part 3: Implications for the EOR

Indirect Indicators of escaping ionizing radiation

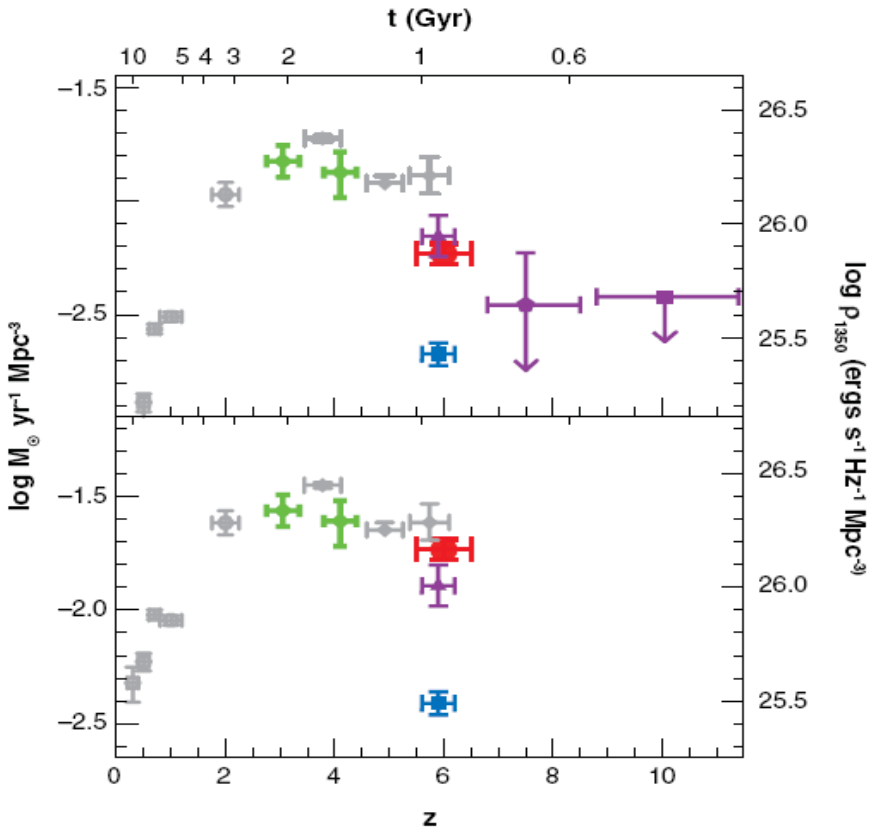
Direct confirmation

Part 4: Summary & Future Prospects

Part 5: Bonus

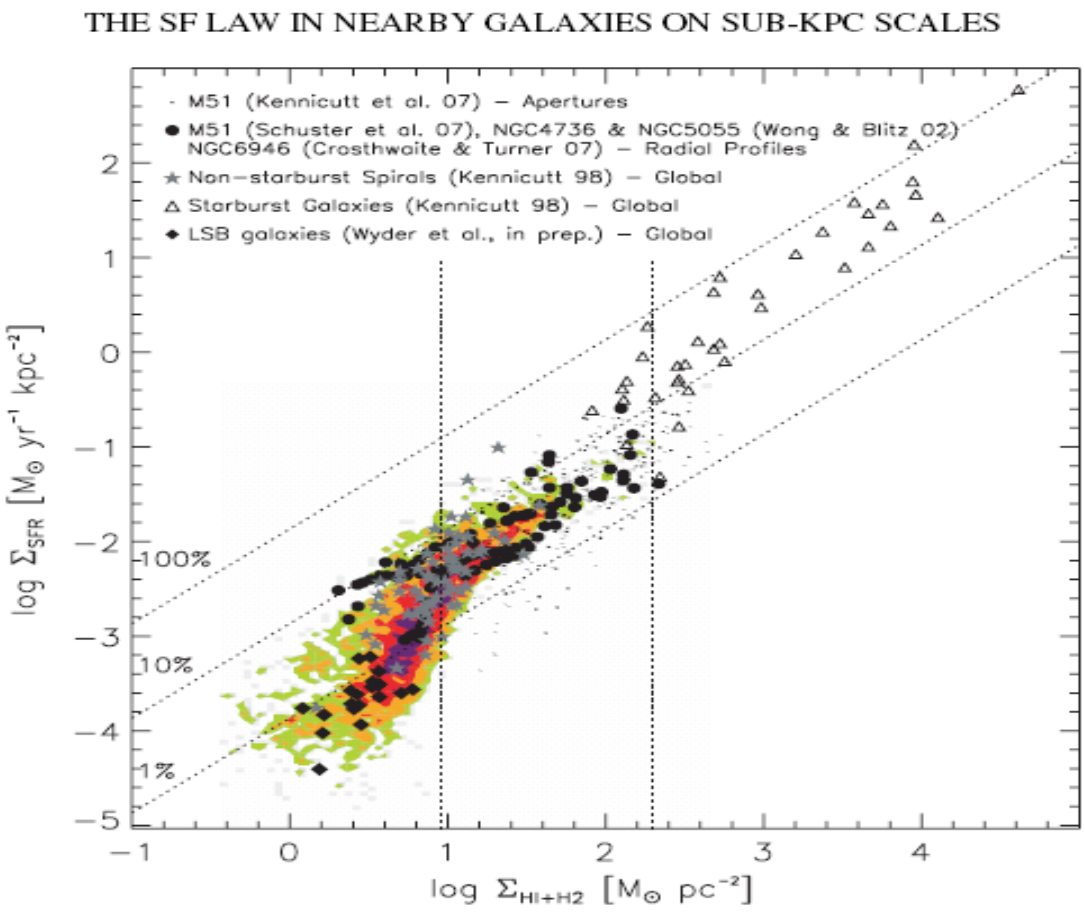
Analogs of Early Supermassive Black Holes?

Part 1: Introduction



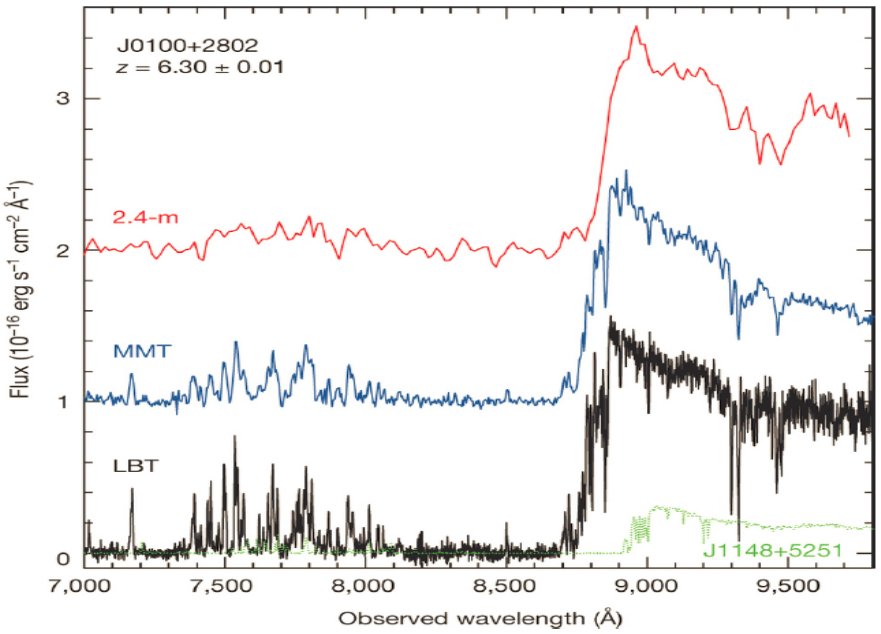
- The population of star-forming galaxies at z > 6 could be enough to reionize the universe (e.g. Bouwens et al.)
- But…what fraction of the ionizing radiation actually escapes from these galaxies?

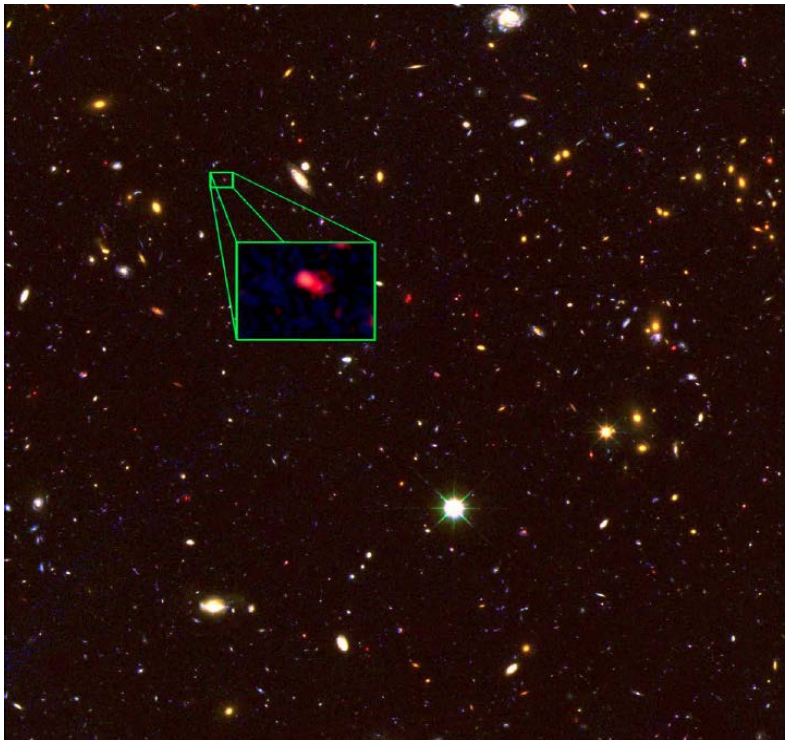
Feedback is key



- H I column of ~10^{-3} $M_\odot$ pc^{-2} at Lyman edge absorbs all ionizing radiation
- Column densities are many orders-of-magnitude larger in SF galaxies
- How are very clean escape routes created/sustained? Feedback key.

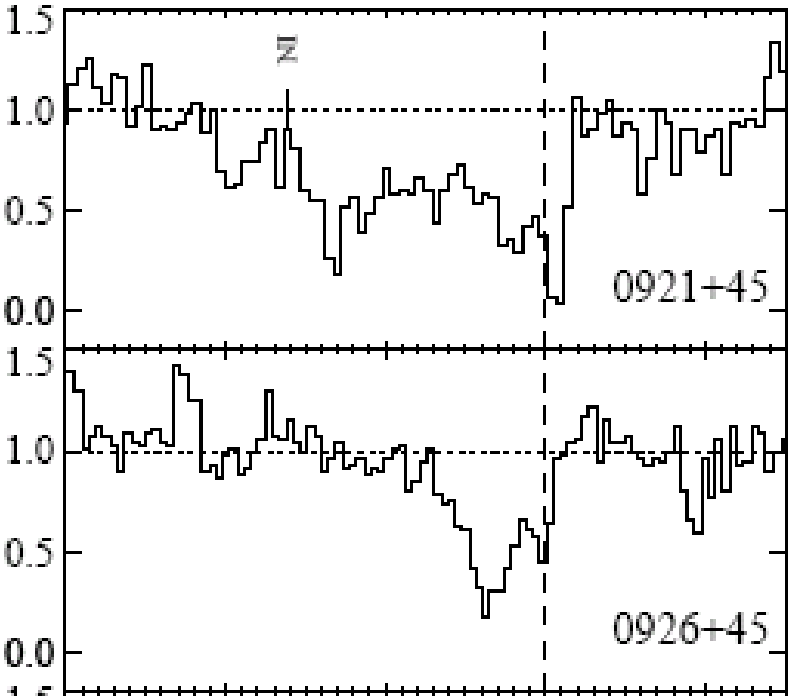
Best investigated ‘locally’

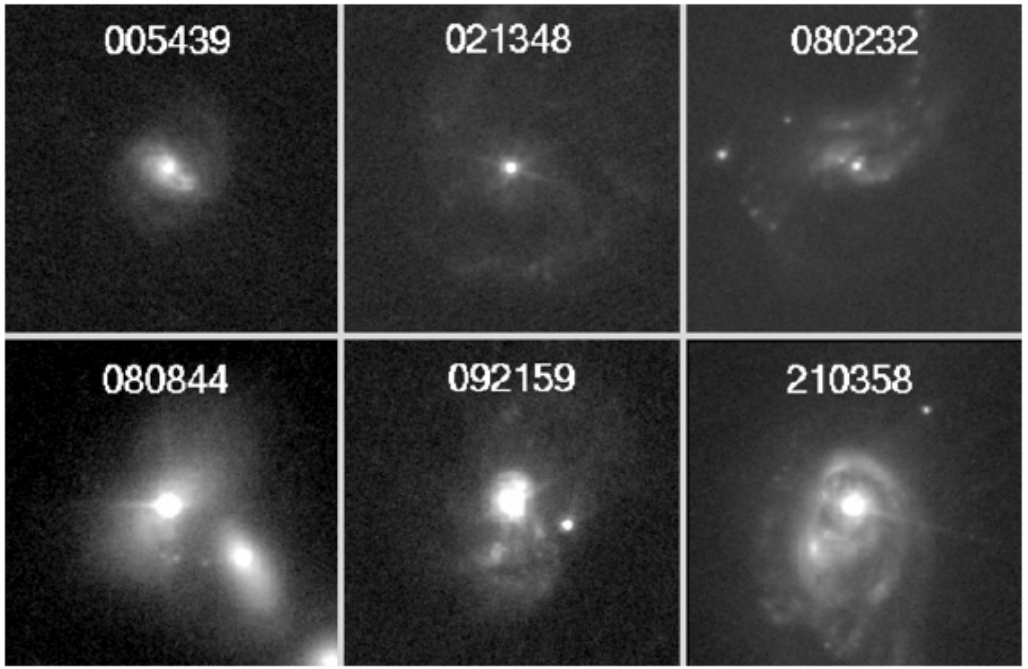




- Galaxies during the EoR cannot be observed below rest-frame Lyα
- Galaxies at these redshifts are extremely faint and difficult to study in any detail

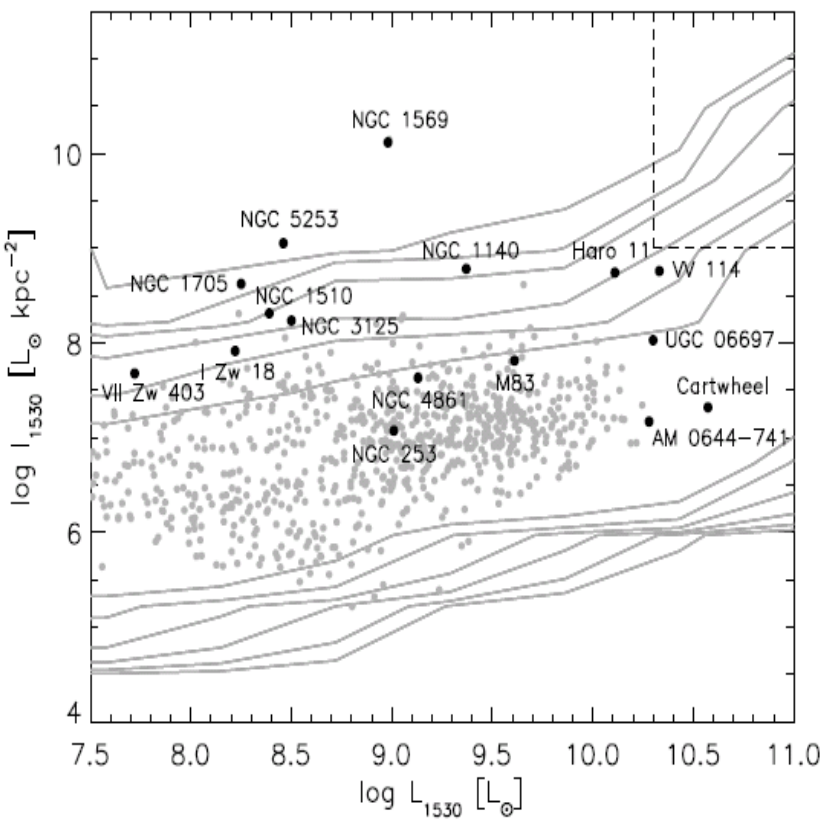
Local Analogs

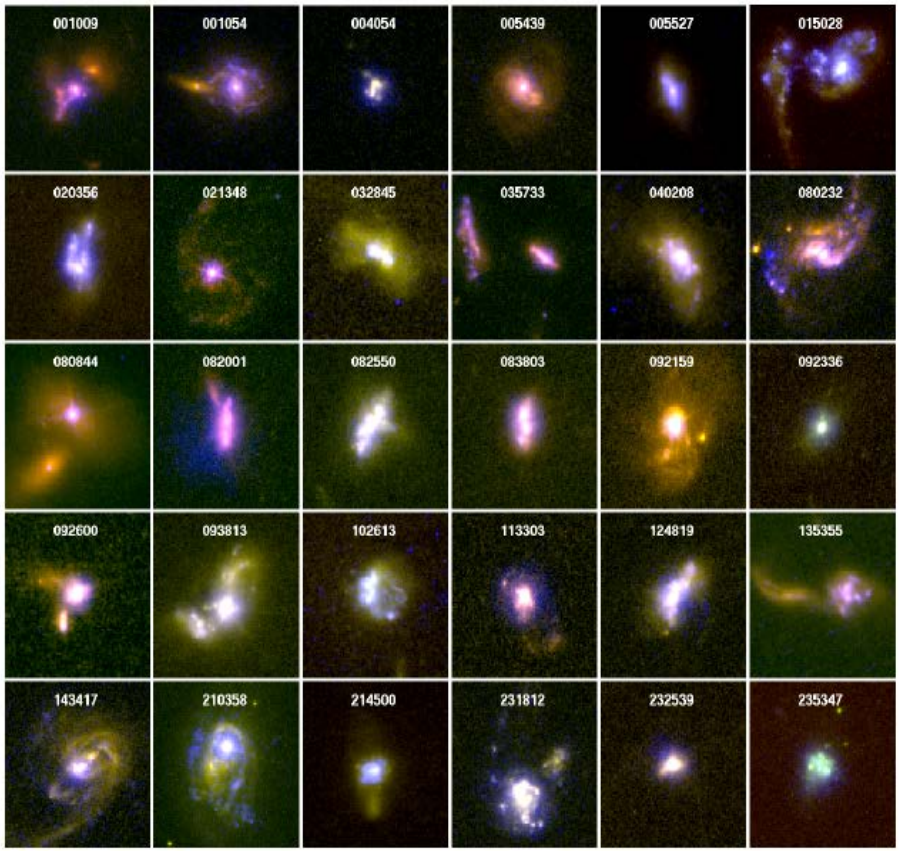




- Find relatively rare objects in the low-z universe whose properties best match high-z SF galaxies
- Will describe two such classes: ***"Lyman Break Analogs"*** and ***"Green Peas"***

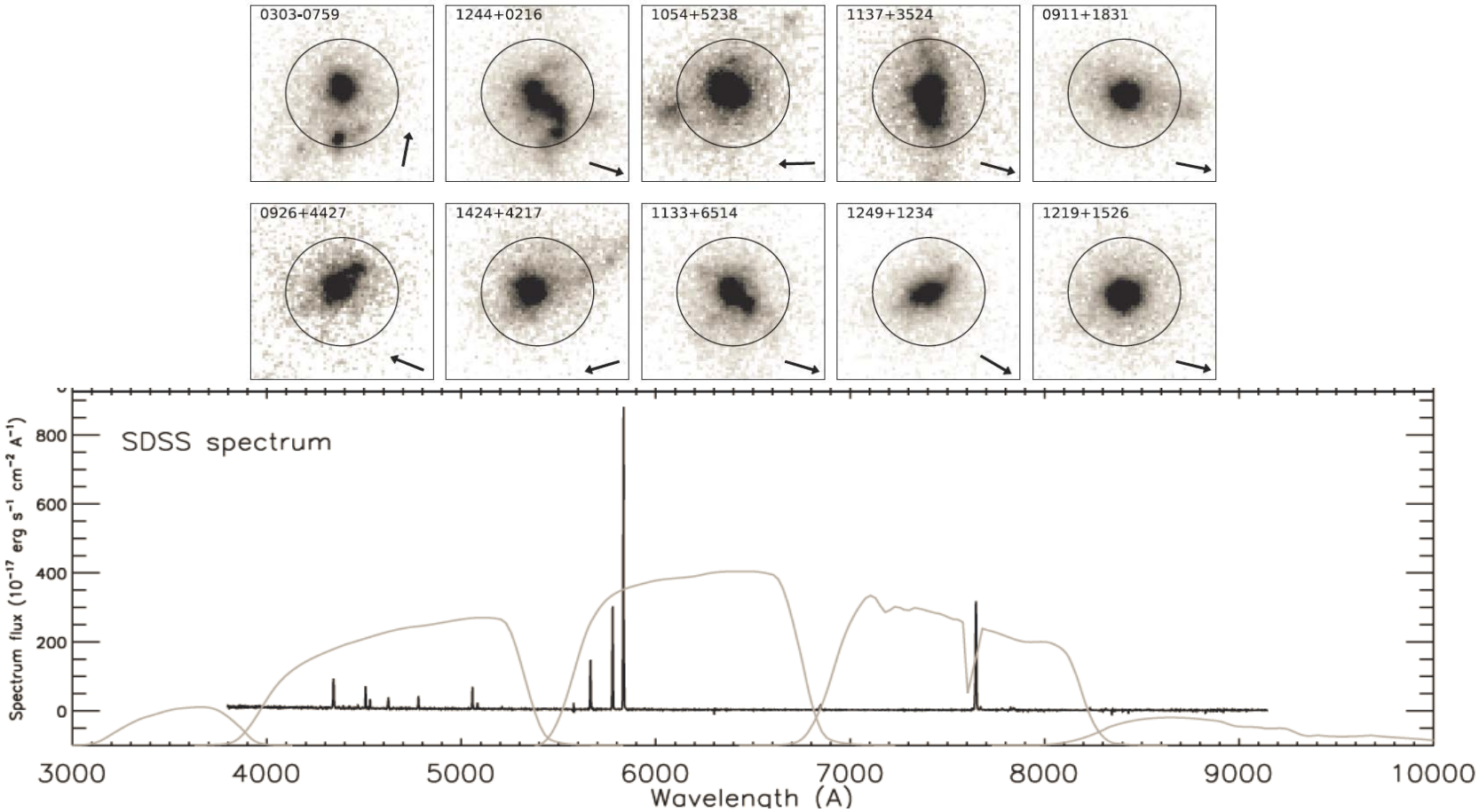
Lyman Break Analogs





- SDSS+GALEX data-mining
- Defined by FUV luminosity and surface brightness (Heckman;Hoopes;Overzier) to match LBGs

Green Peas (from Galaxy Zoo)



- Emission-line-dominated ([OIII] EQW ~ 10^3 Å!)
- Compact, low-mass, low metallicity starbursts (Cardamone+;Henry+;Jaskot & Oey;Izotov+)

Comparisons

- **O/H**: LBAs ~8.1 to 8.8 GPs ~7.9 to 8.2
- **Log M_***: LBAs ~9.0 to 10.5 GPs ~8.0 to 9.5
- **SFR** ($M_\odot$/yr): LBAs ~3 to 100 GPs ~3 to 30
- **Log sSFR** (yr^{-1}): LBAs -9 to -8 GPs -8 to -7
- **Radii** (kpc): LBAs ~0.3 to 1.5 GPs ~0.5 to1.5
- Bottom-Line: GPs are less massive and more metal poor systems than LBAs (with overlap)
- ***Reasonable matches to high-z SF galaxies***

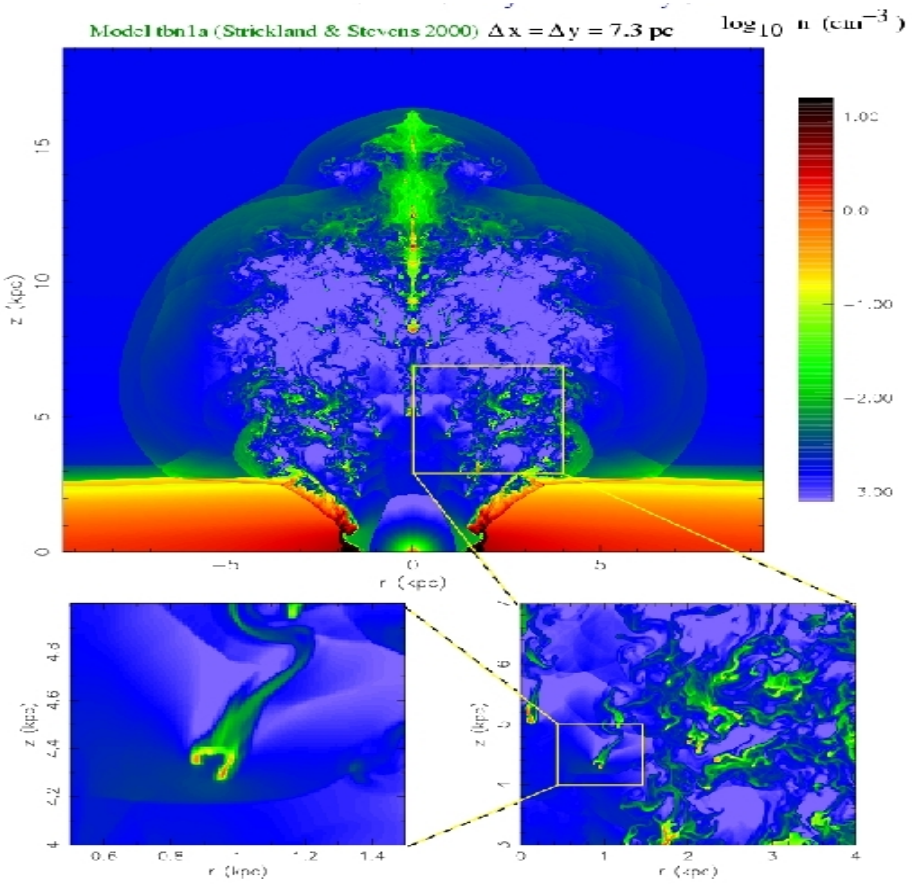
Part 2: The Role of Winds

- Can galactic winds create the clear channels for ionizing radiation to escape?

Energetics/Dynamics

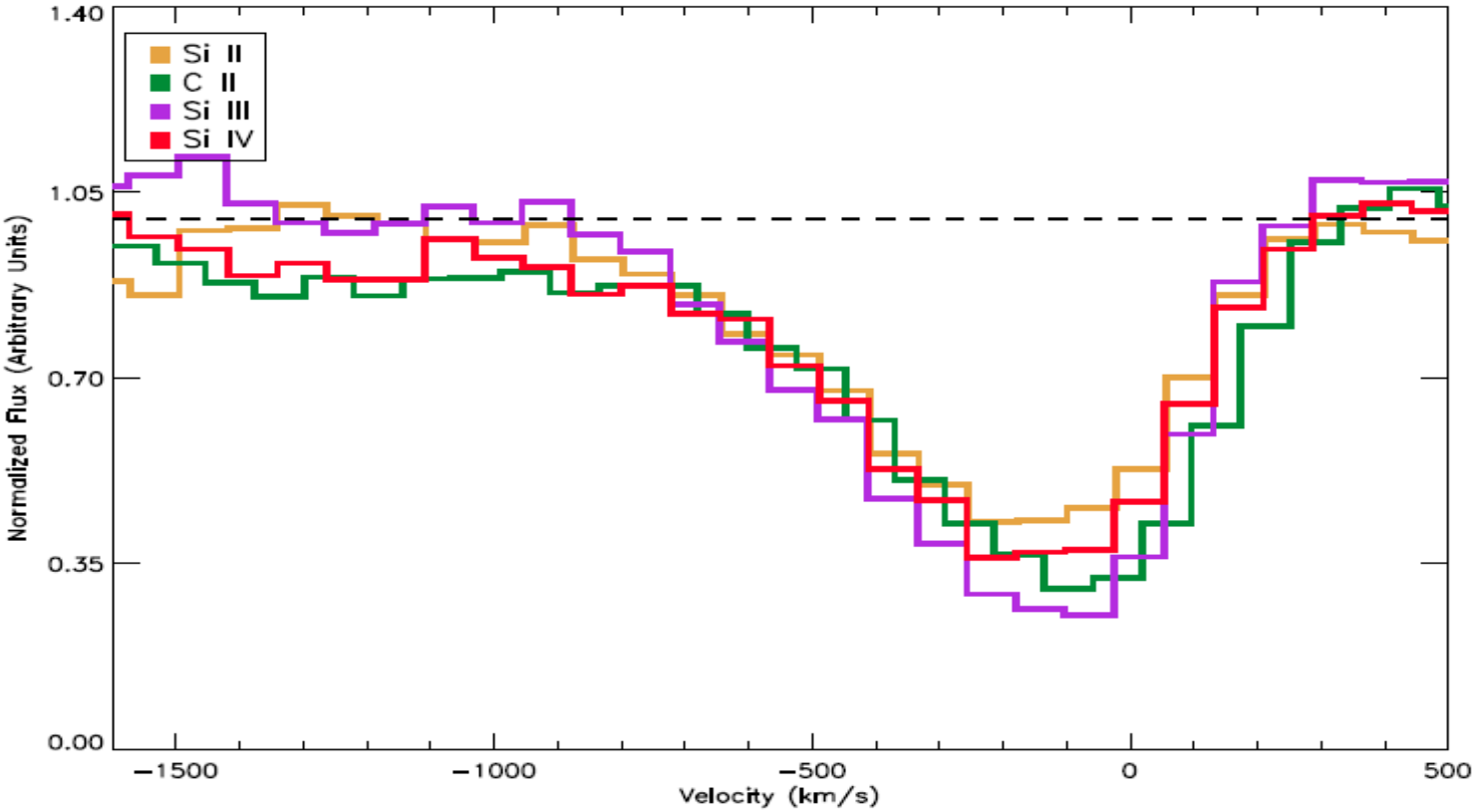
- For every 100 $M_\odot$ stars formed get 2 x 10^{51} ergs in KE (SNe ejecta and stellar winds)
- Collective effect: create gas at T ~ 10^8 K with pressure >> ambient
- Expansion along direction of steepest pressure gradient
- Blow-out into halo
- Weakly bi-polar wind with v_{max} ~ 3000 km/s
- KE flux ~ 1% L_{bol}
- Momentum flux ~ 3 L_{bol}/c

Wind Structure



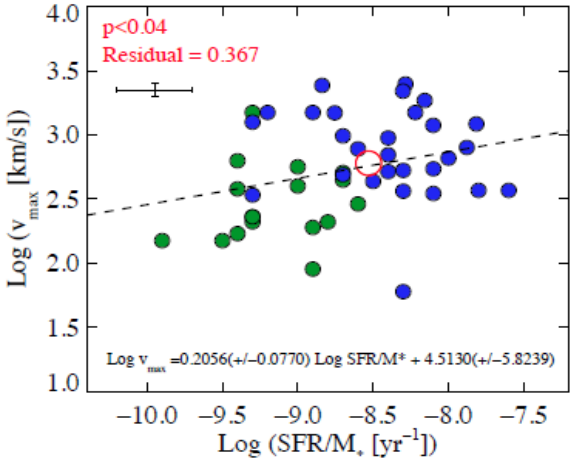
- Prime movers: energetic and tenuous "Wind Fluid" plus radiation pressure
- Most of the emission and absorption comes from denser outflowing ambient material

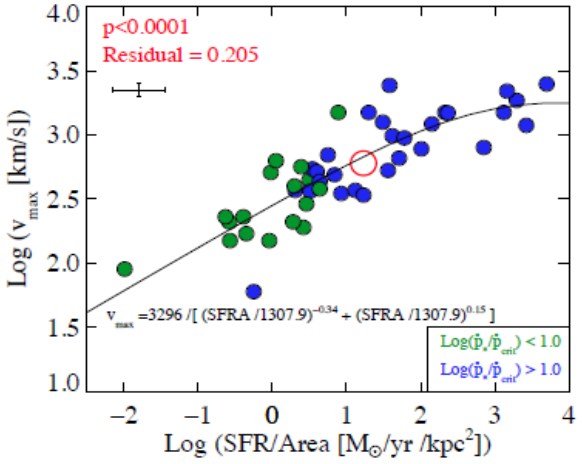
Absorption-Line Probes

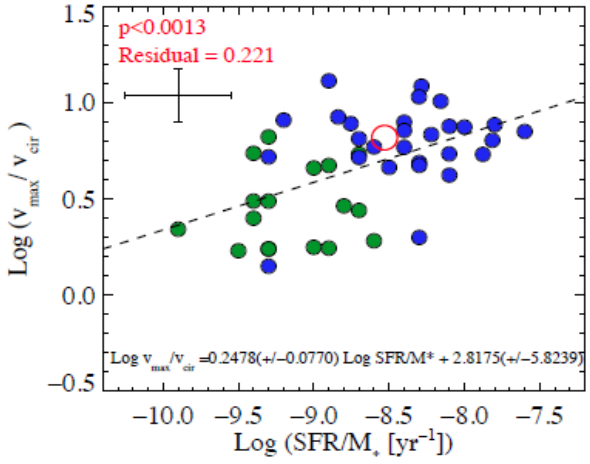


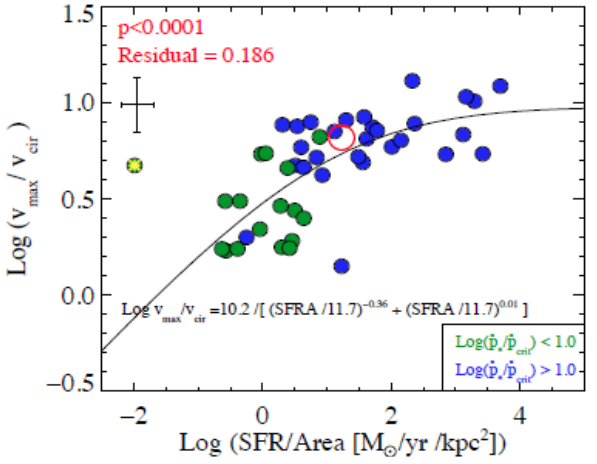
- The impact of the wind on the environment can be probed using absorption-lines tracing warm gas
- The most-available probe beyond the local universe

Systematics of outflow velocites



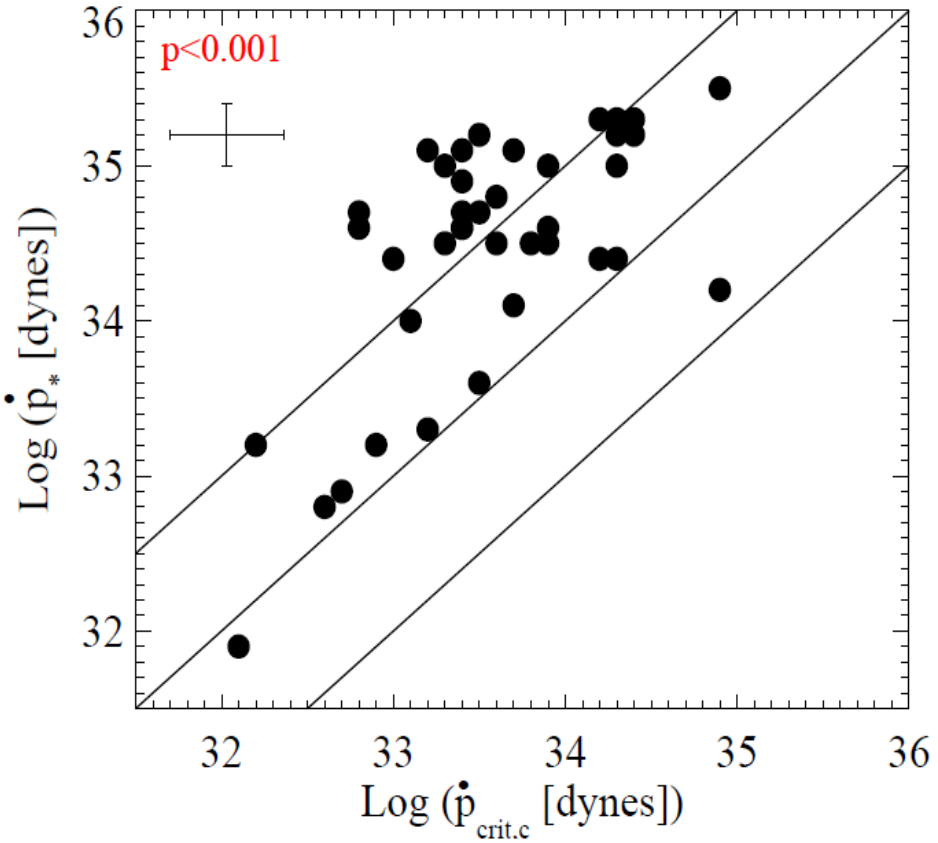






- Both v_{out} and v_{out}/v_{cir} correlate most strongly with SFR/area (Heckman & Borthakur ‘16)

What's the Physics?

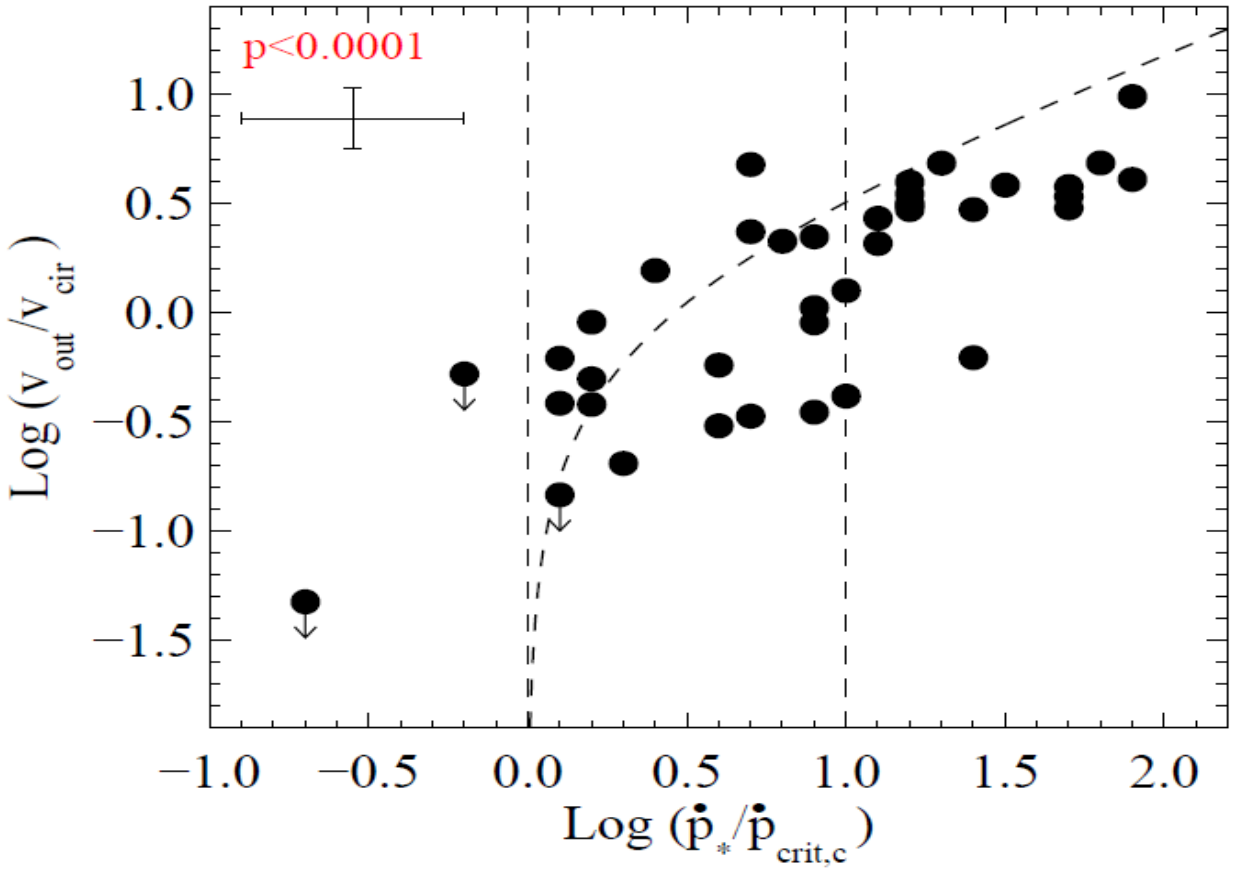


$$\dot{p}_{crit,c} = 4\pi\beta r_* N_c < m > v_{cir}^2$$

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

v_{out}/v_{cir} is then specified by the ratio of these two momentum fluxes

Outflow Velocity: Model vs. Data

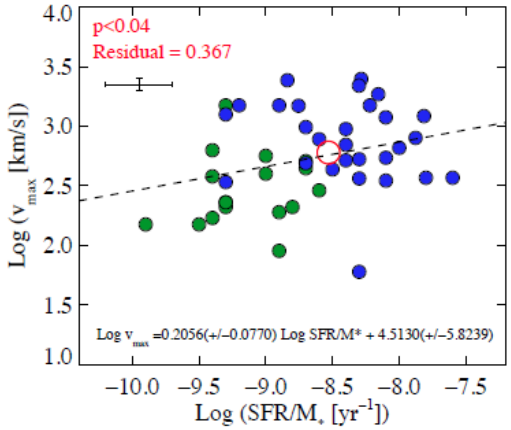


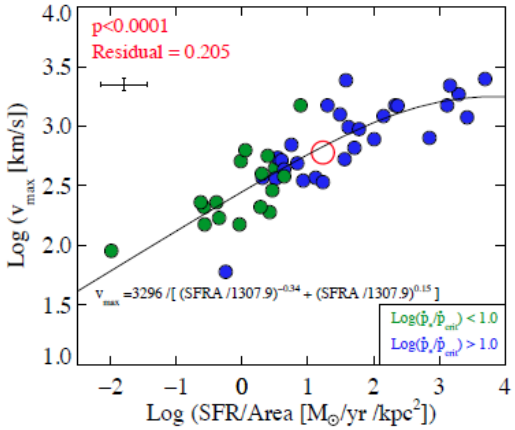
A satisfactory match for such a simple model (Heckman+15)

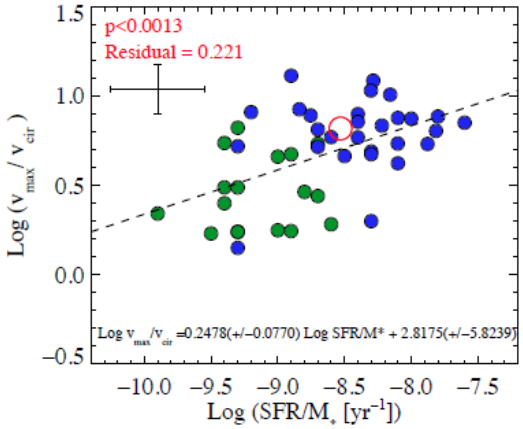
High outward pressure at launch site (high SFR/Area) produces high velocities

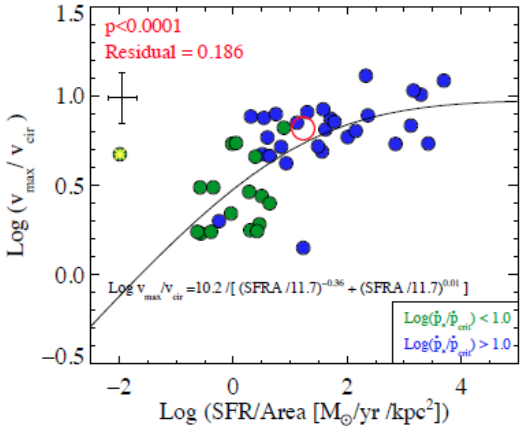
Three regimes: no-outflow, weak-outflow, strong-outflow

Clear separation of strong and weak outflows

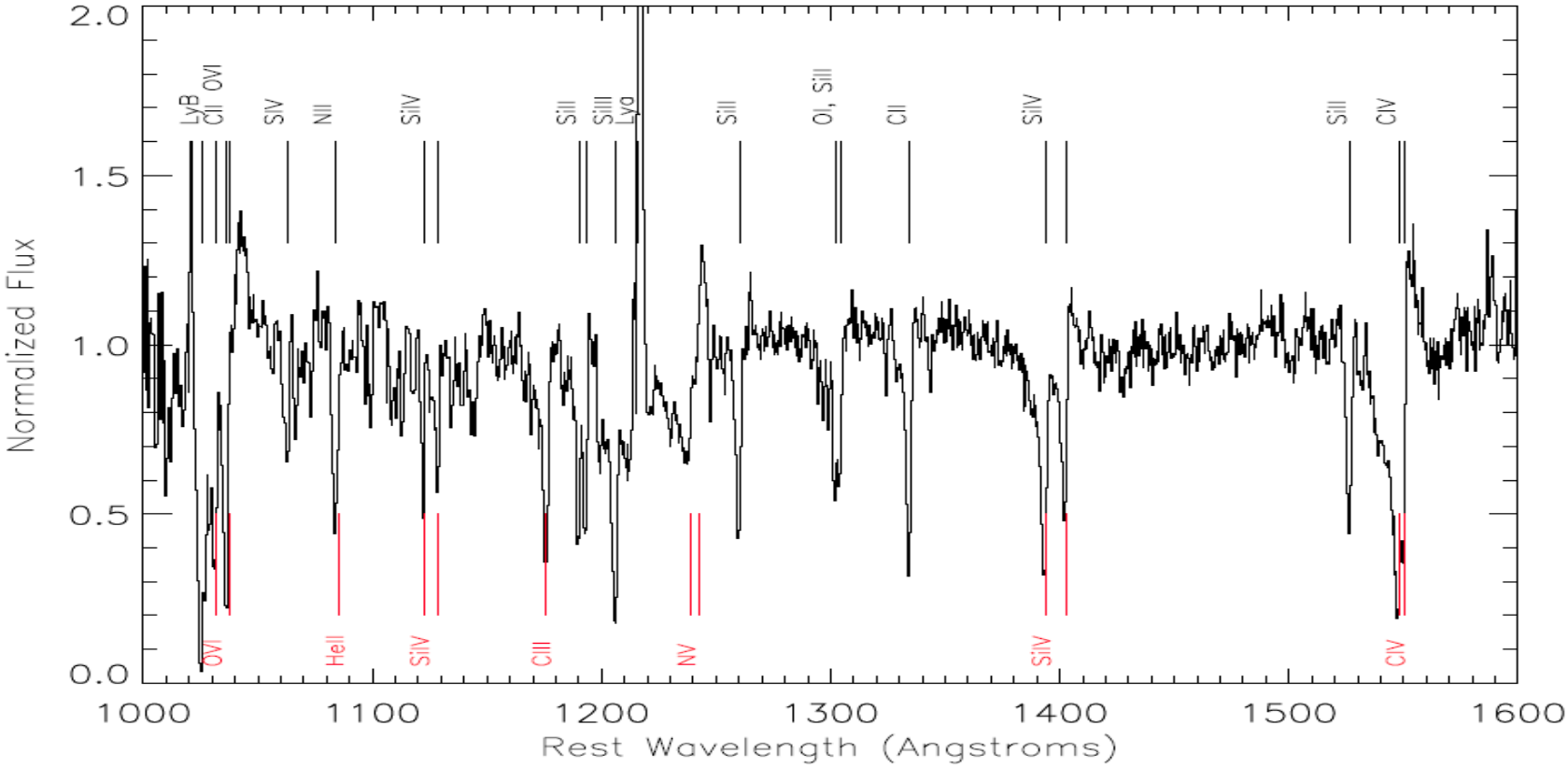






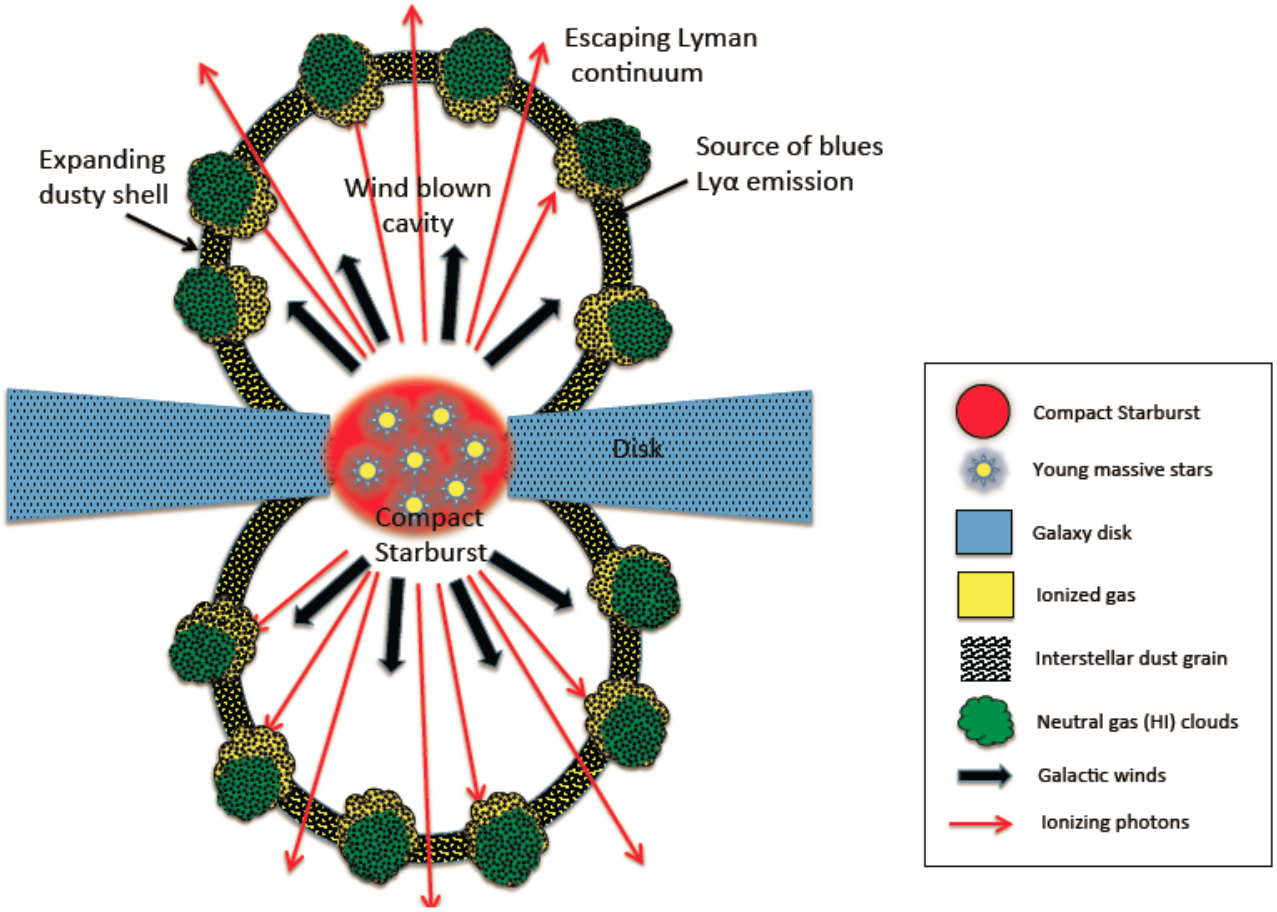


Part 3: Implications for the EOR

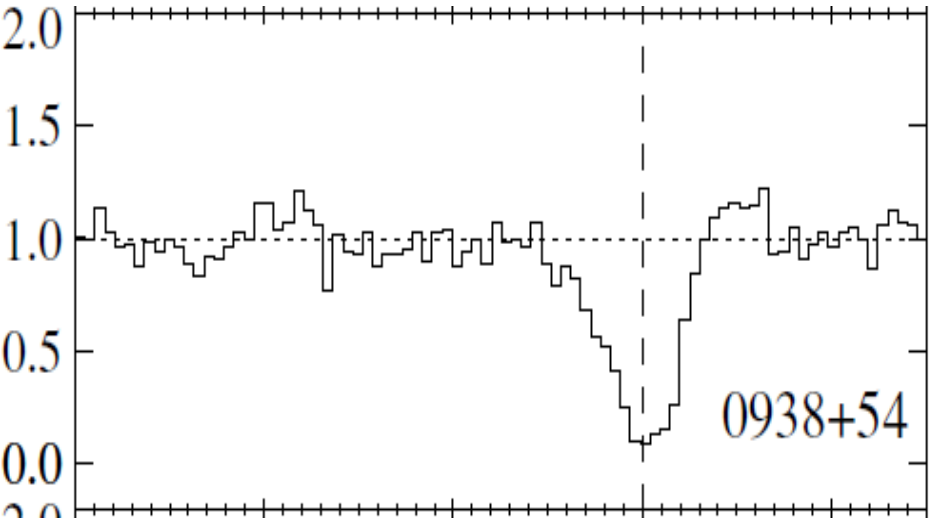


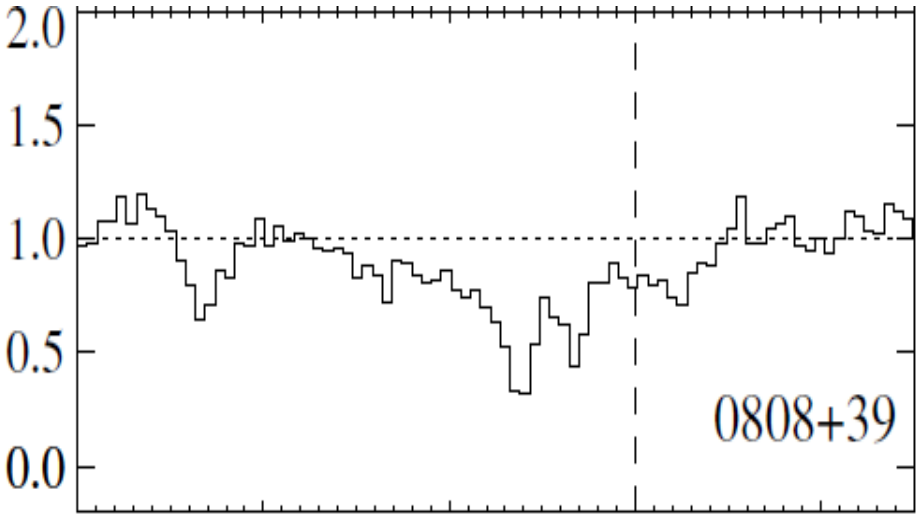
- Indirect: lack of COS sensitivity below Ly edge
- Sample of 22 LBAs (Alexandroff et al +15) and 10 GPs (Henry et al. 15)

We are looking for indirect signs of 'leakiness'



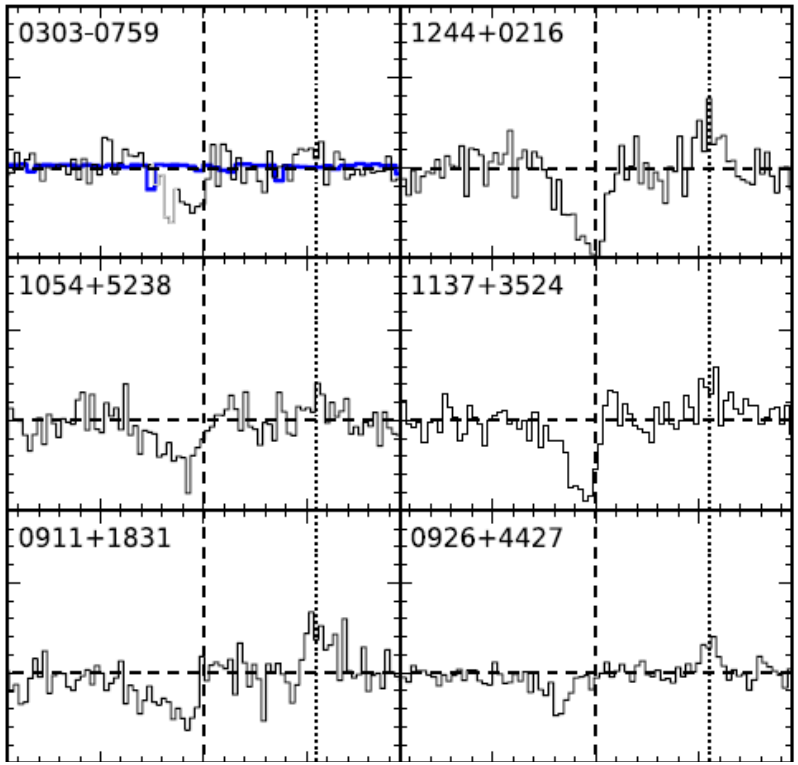
Indirect Clue #1

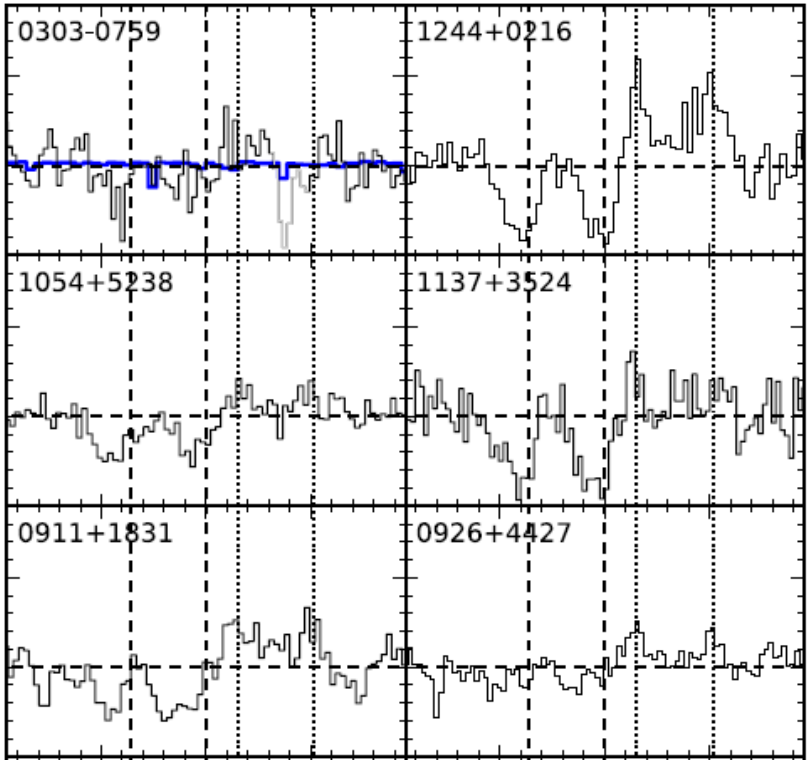




- Optically-thick lines that trace the neutral gas are usually ‘black’ in the core (Si II multplets)
- But not always. Residual Flux (RF) > 0
- Indicative of holes in the HI (‘picket fence’)

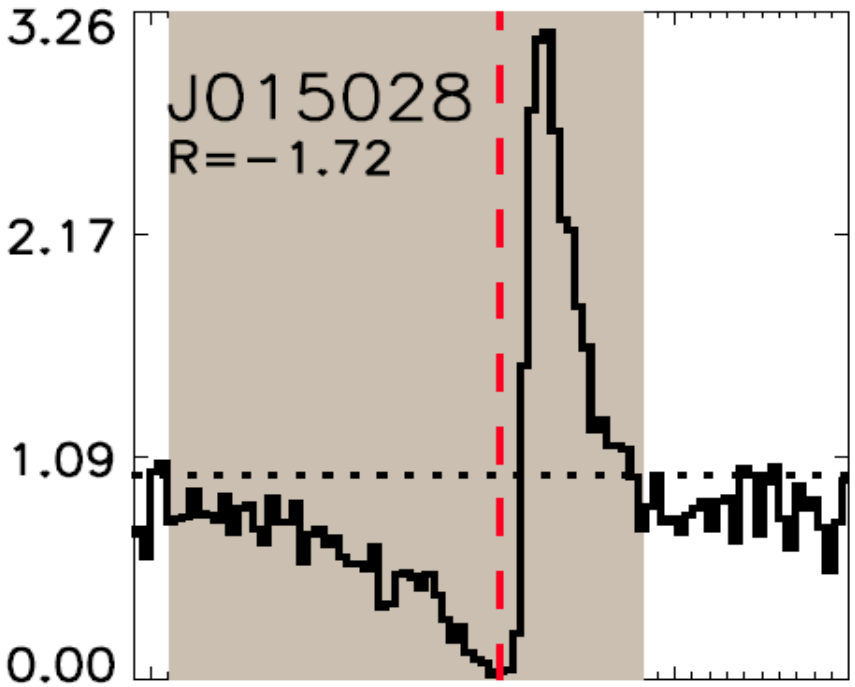
Similar Properties in Green Peas

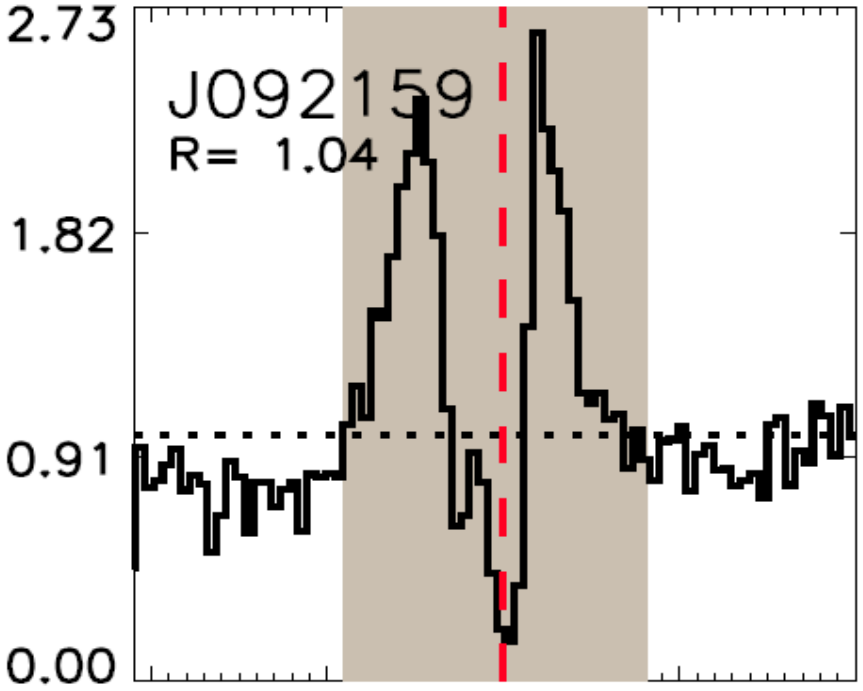




- Henry et al. (2015)

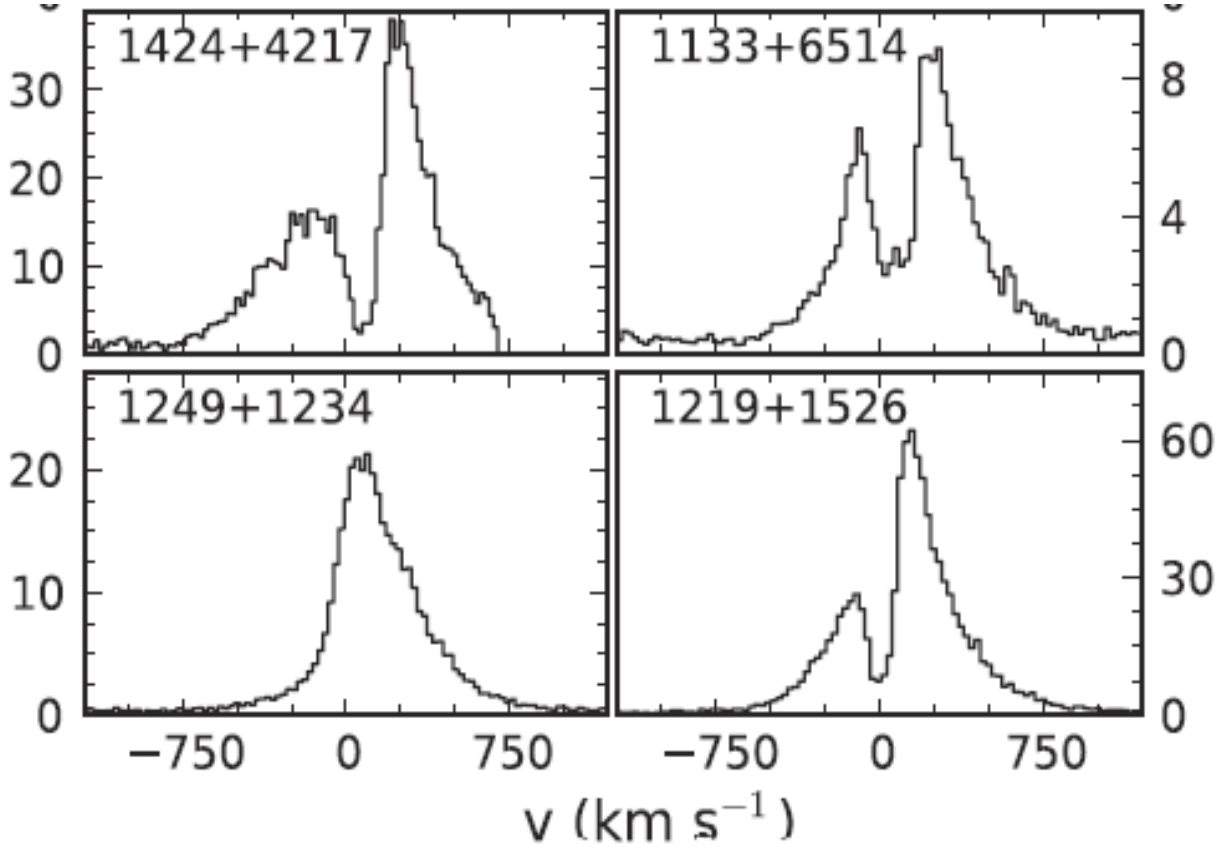
Indirect Clue #2





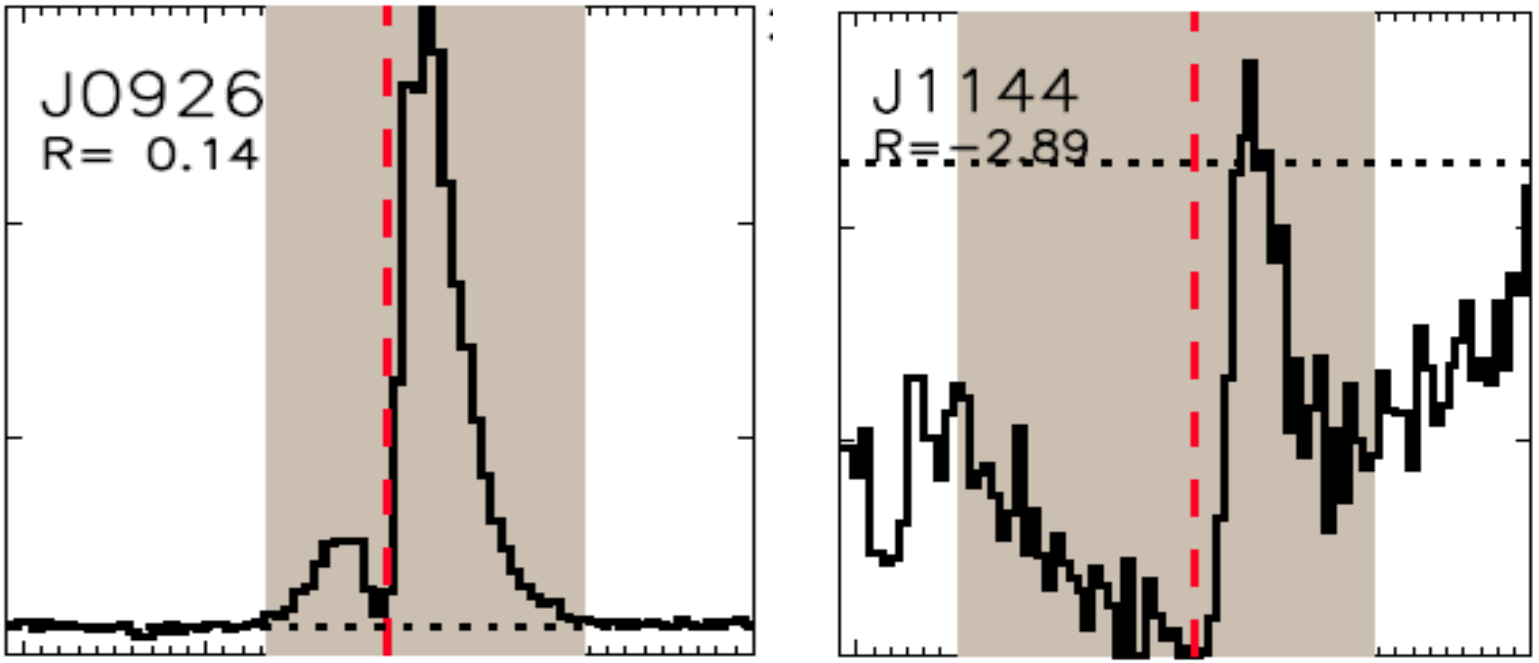
- Most Lyα emission-lines have classic P-Cygni profiles
- Some have a significant blue-shifted emission
- Holes in the HI on the front side of the outflow

Similar Profiles in Green Peas



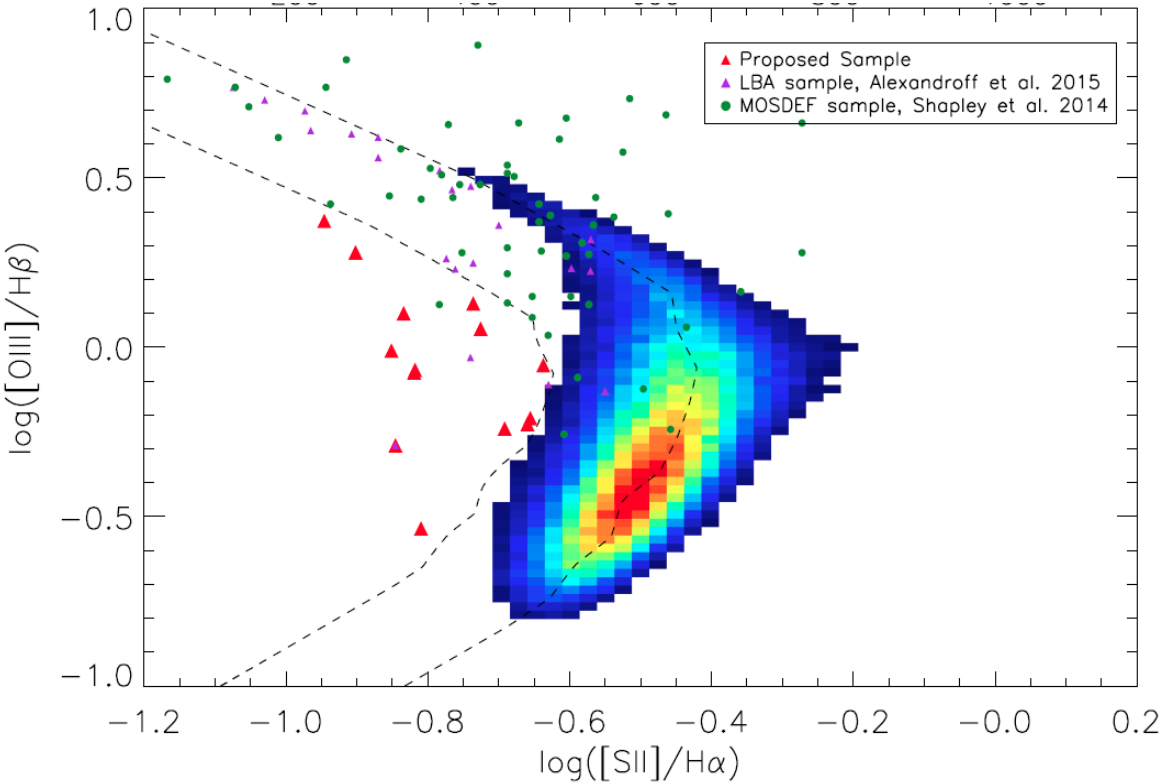
- NOTE: These profile types are associated with fast outflows (*not a static ISM*)

Indirect Clue #3



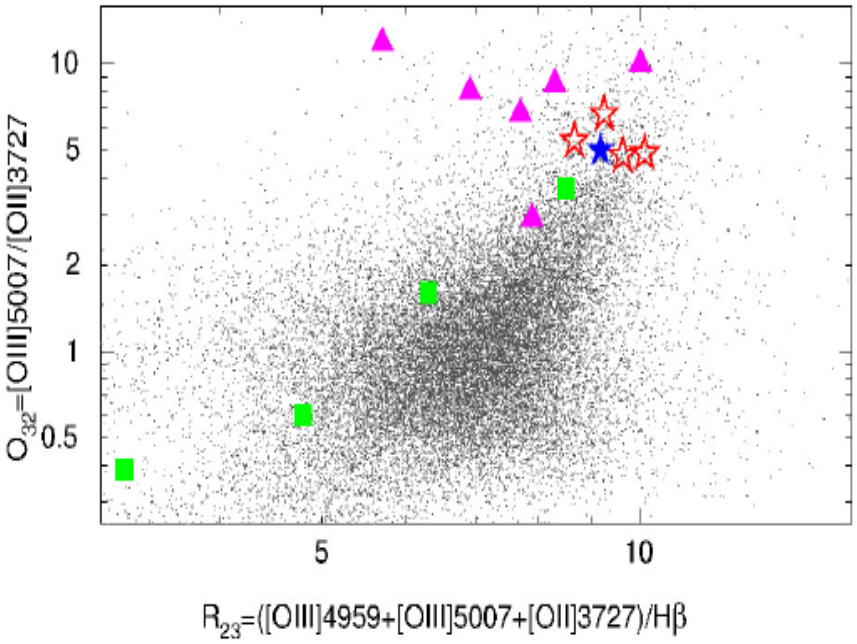
- Smaller Lyα EQW implies Lyα photons suffer more attenuation by dust than FUV continuum
- See also Verhamme +15

Indirect Clue #4



- Abnormally weak [SII] optical line emission
- [SII] arises at the outer edge of Stromgren sphere
- Weak [SII] indicative of “matter-bounded” conditions (gas that is optically-thin to Lyman continuum)

Indirect Clue #5

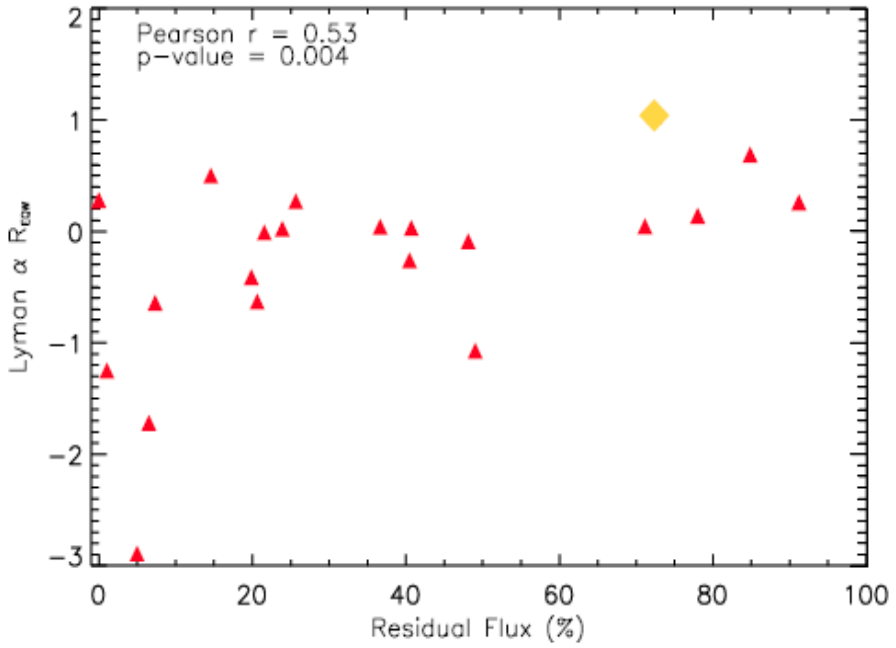


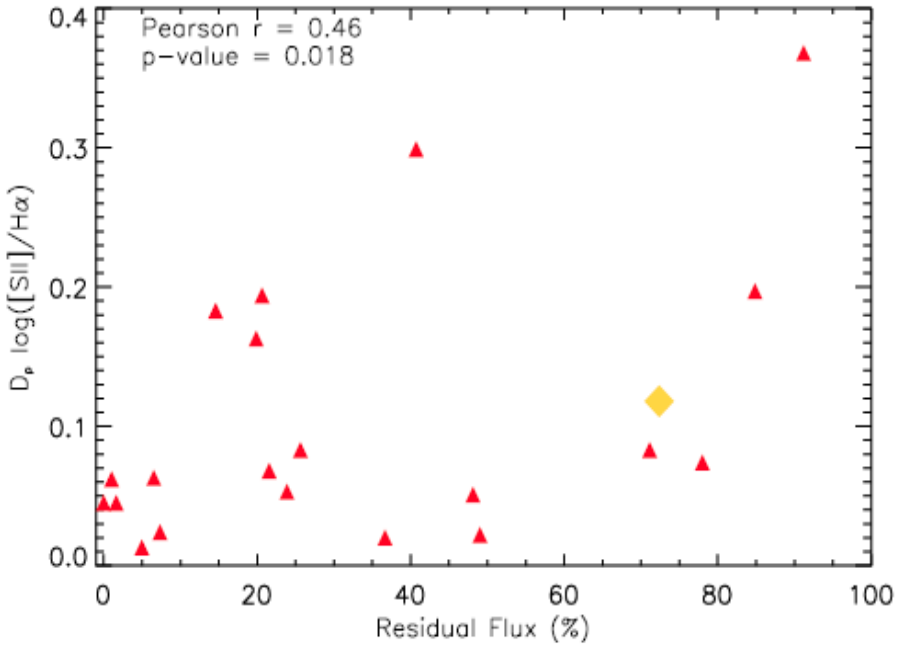
- Abnormally high ratio [OIII]5007/[OII]3727
- Implies intense ionizing flux: $U = \Phi_{rad}/(n_{gas}c)$
- High HII column for the "Stromgren Slab"

$N_{HII} \sim 10^{23}\ U\ cm^{-2}$

- Jaskot & Oey; Izotov+

Consistency

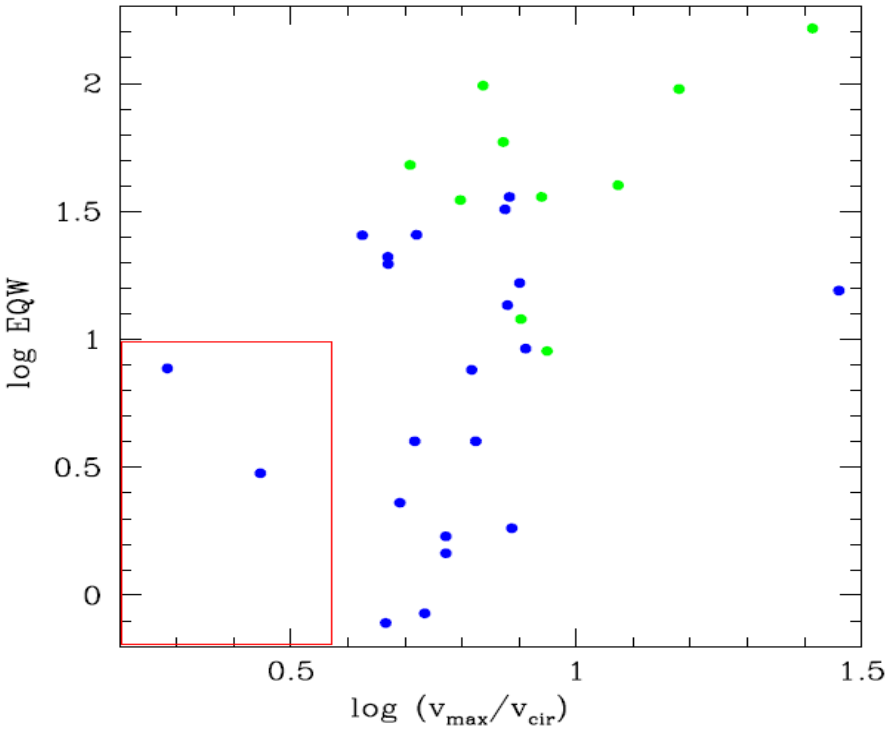


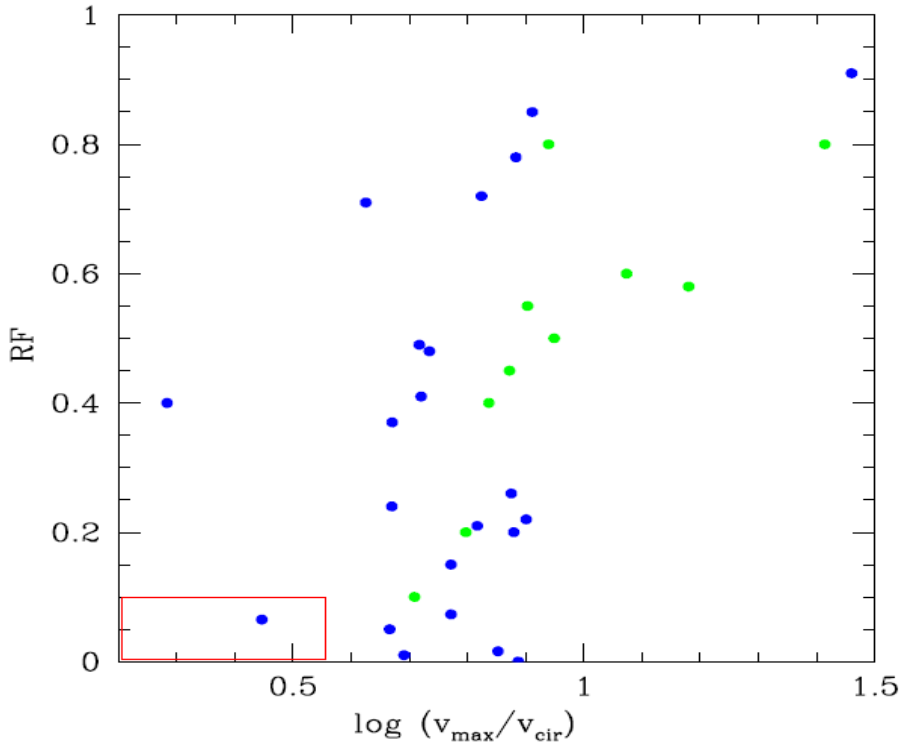


- Statistically significant correlations between indirect indicators w/ scatter
- Alexandroff+15

Why are Some Galaxies Leaky?

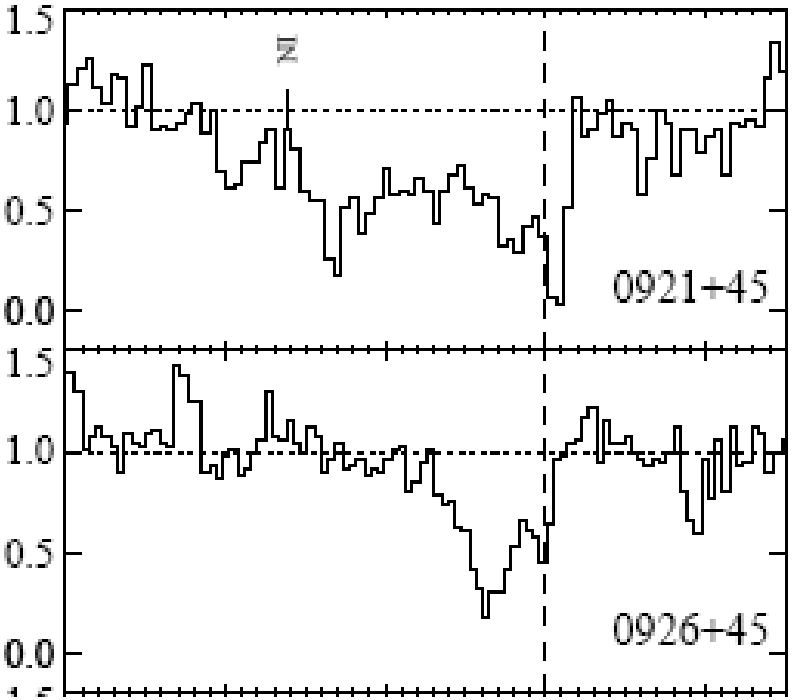
Compact Systems w/ High Velocity Outflows

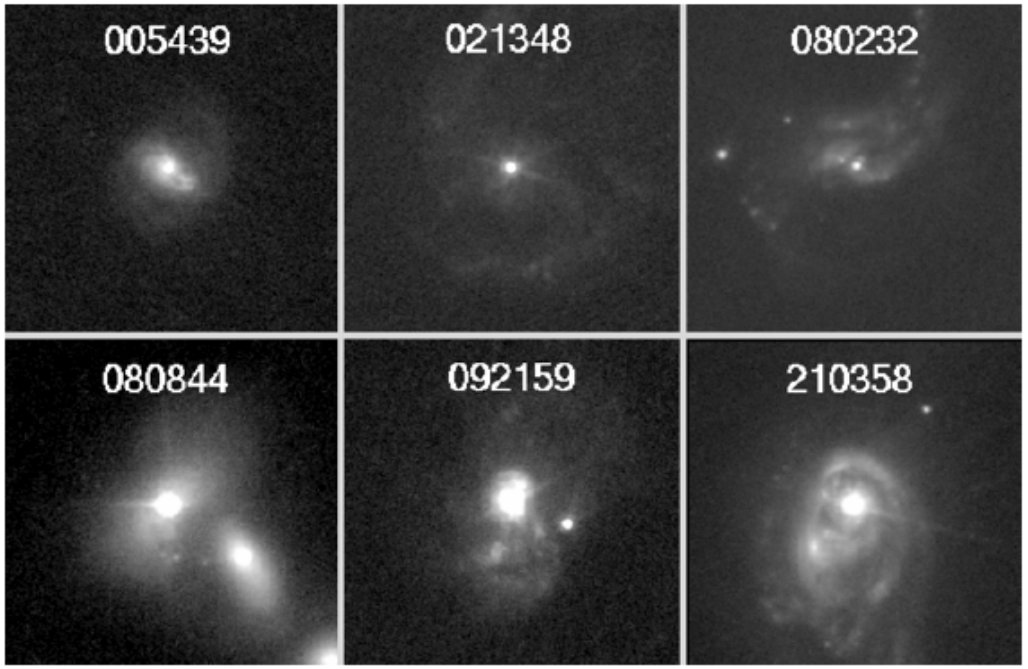




- And correspondingly large SFR/Area
- Strong Outflows: $\dot{p}_* > 10\,\dot{p}_{\rm crit}$
- Gravity unimportant & feedback dominates

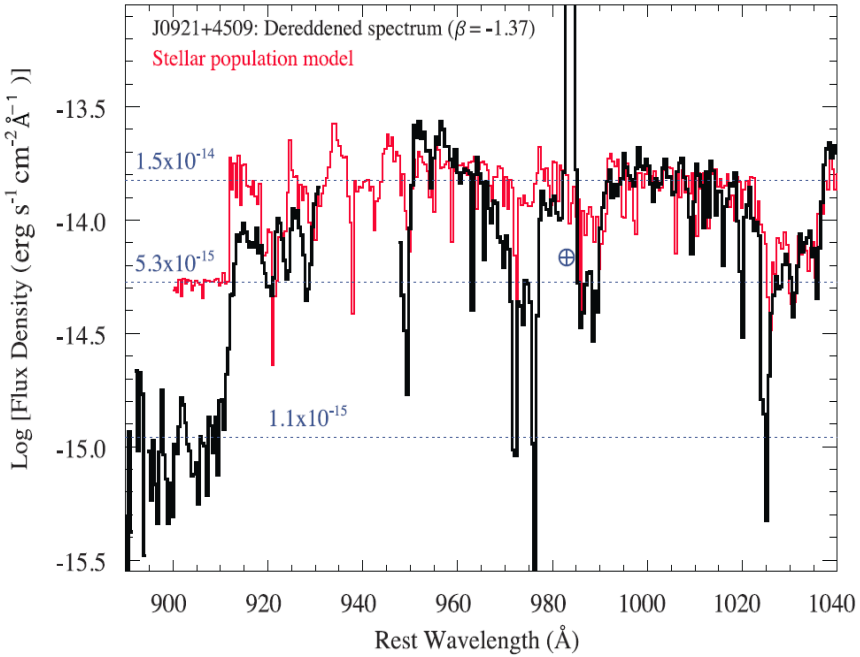
'Extreme Feedback'?

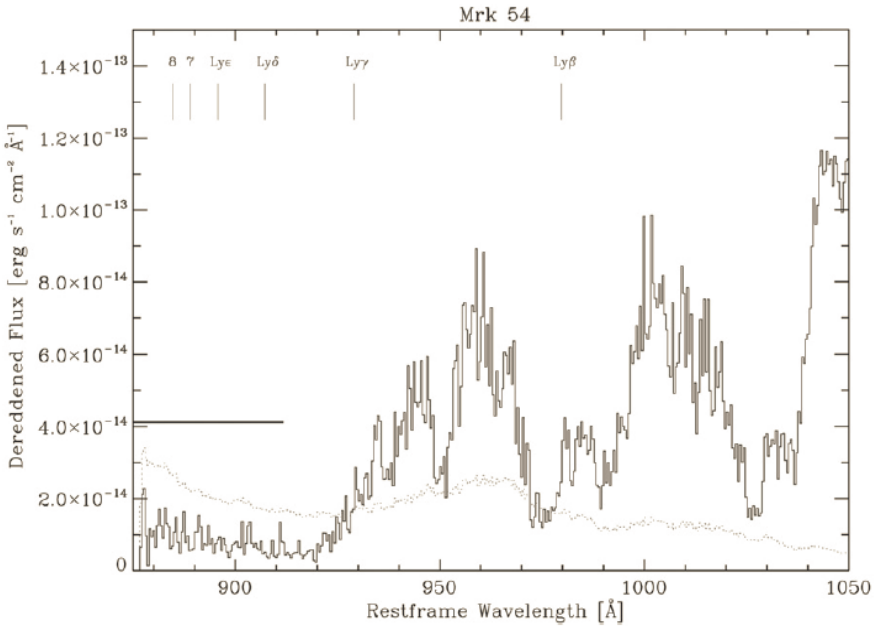




- High SFR in a small region leads to a very high intensity of ionizing radiation and very large wind ram and radiation pressures
- These conditions create holes in the dense gas that allow ionizing radiation to escape

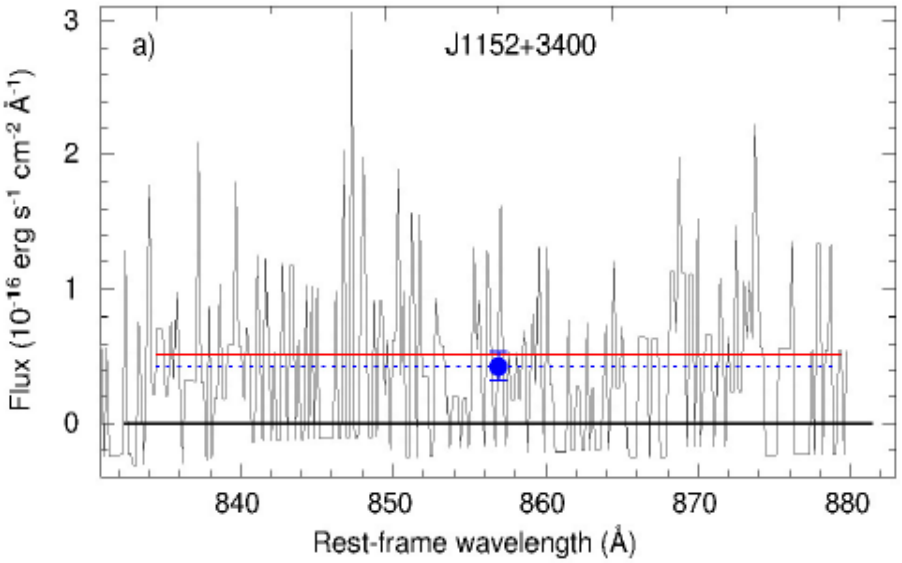
Direct Detections

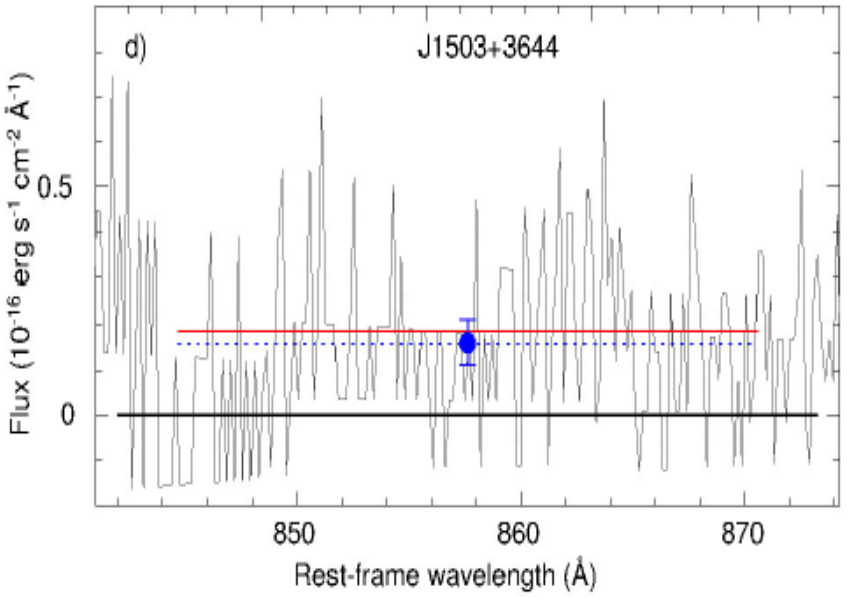




- In two LBAs, COS is sensitive enough to directly observe below the Lyman edge
- ‘Escape fractions’ ~20% (Borthakur 14;Leitherer+16)

More direct detections in low-z analogs





- 5 Green-Pea-like starbursts (Izotov+16)

Validation of Indirect Indicators?

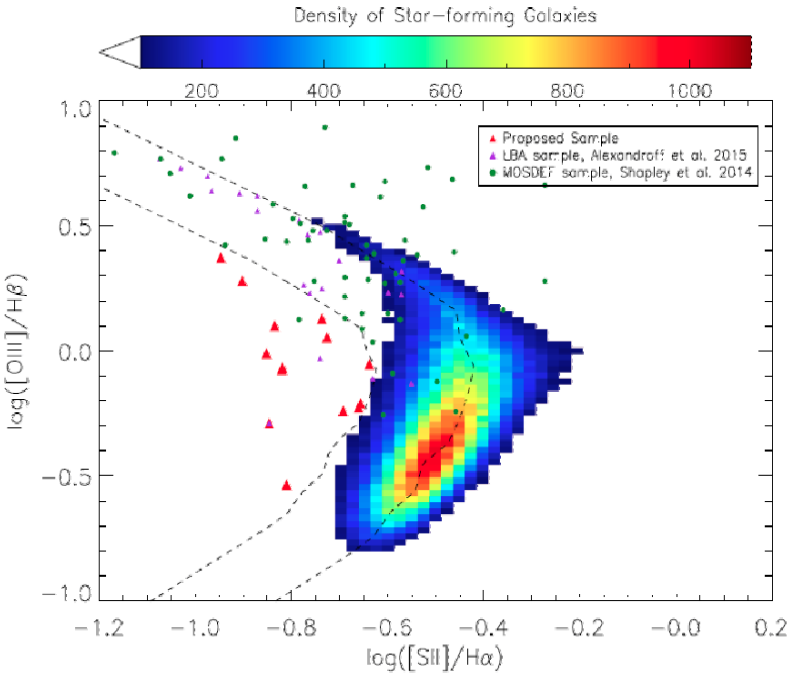
- Izotov+16 GPs: All have high [OIII]/[OII], weak [SII], large Lyα EQW, double-peaked Lyα profiles, high SFR/area. Don't know RF or v_{out}
- Borthakur et al. LBA: Large Lyα EQW, double-peaked Lyα, large RF, weak [SII], high v_{out}, high SFR/area, normal [OIII]/[OII]
- Leitherer et al. LBA: Lyα absorption, low RF, high v_{out}, high SFR/area, [OIII]/[OII],[SII] not known
- Not perfect, but we are on the right track

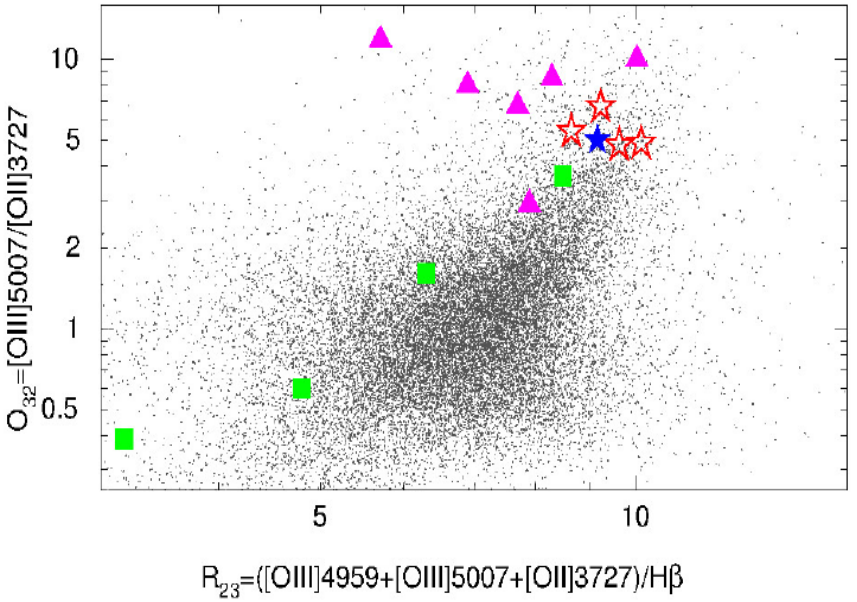
Part 4: Summary

Observations of local analogs of high-z star-forming galaxies suggest a number of indirect indicators of escaping ionizing radiation:

- Significant blue-shifted Lyα emission
- Significant residual flux in saturated low-ionization metal absorption-lines
- Large Lyα equivalent widths
- Weak [SII] and strong [OIII] emission-lines
- *Indirect indicators now verified in several cases*
- *These signposts linked to “extreme” feedback: High outflow speed,SFR/Area, wind-dominated*

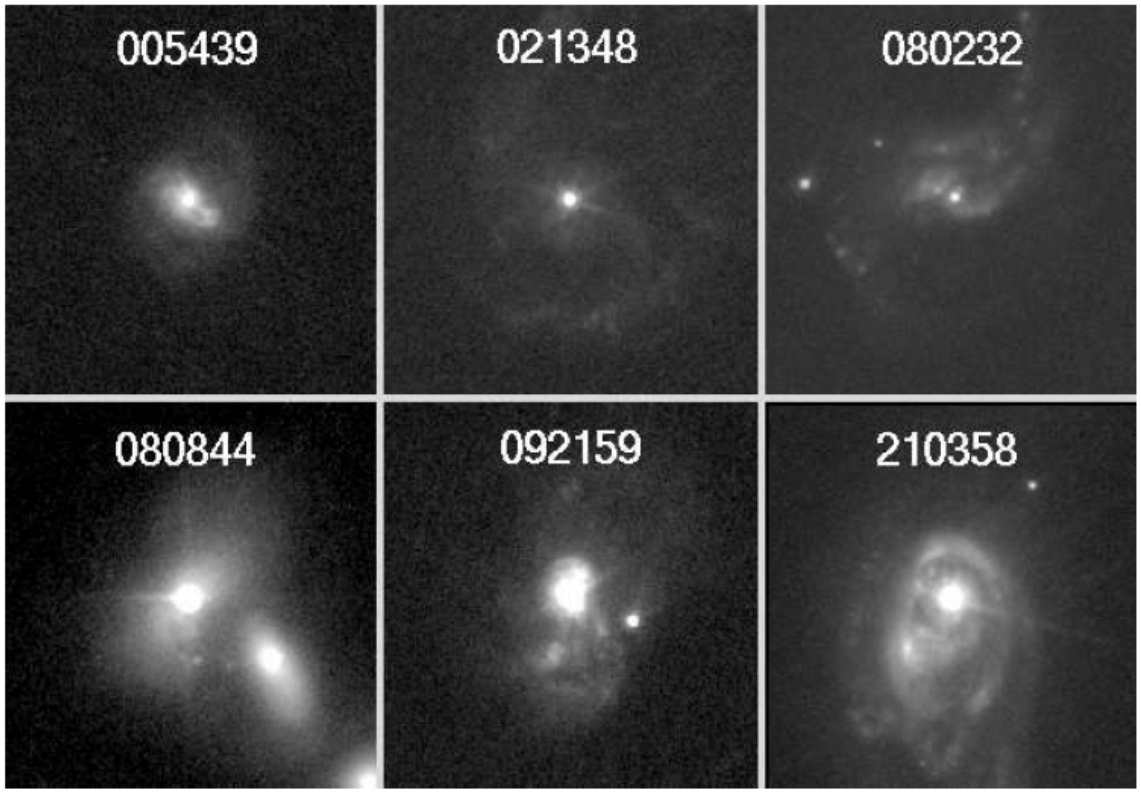
Future Prospects





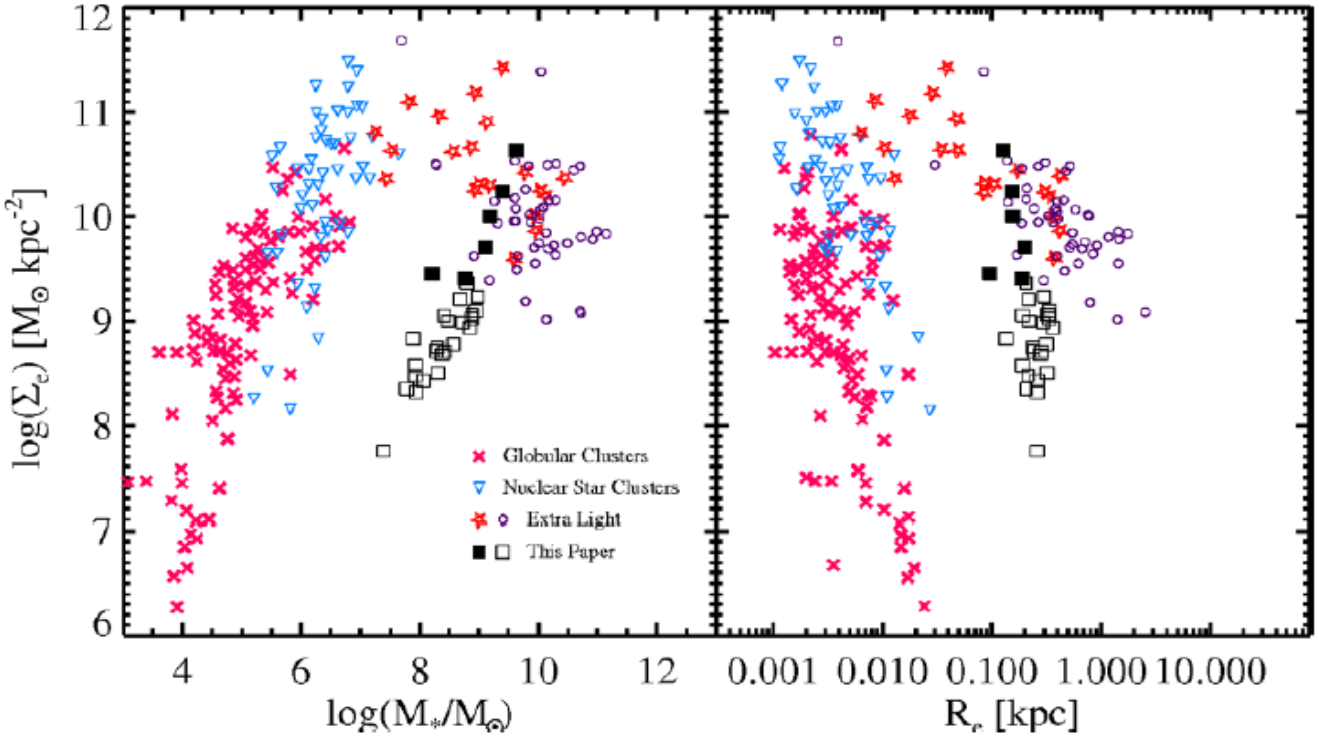
- During EOR can not readily use FUV indicators
- Validate [SII]-weakness and high [OIII]/[OII]?
- JWST NIRSpec can classify galaxies with SFR > few $M_{\odot}$/year in the EOR (z ~ 6 to 9)

Bonus: Black Holes in LBA?



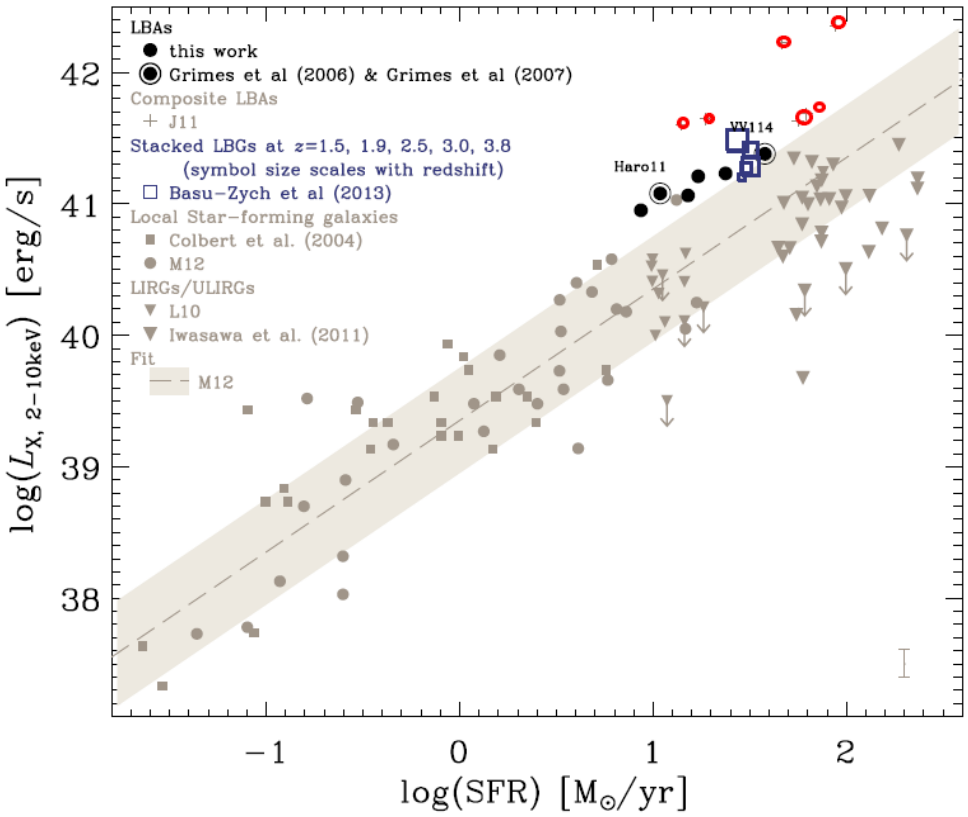
- Starbursts w/ sizes ~100 pc, masses of several billion solar masses in ~1/3 of LBAs (Overzier+)
- Should be ideal site for the formation/growth of supermassive black holes progenitor

Progenitors of Cusp-y Ellipticals?



- Masses, sizes, densities similar to “extra light” (cusps) seen in centers of L* ellipticals
- Overzier+ (Solid black squares)

Excess Hard X-Ray Emission



- These LBAs (red circles) are over-luminous in the 2-10 keV band compared to starbursts by factor ~10
- Possible signature of AGN (Jia+;Basu-Zych+)

Progenitor-Analogs?

- If these are Compton-thin AGN, the implied $L_{Bol,AGN} \sim 10^9$ to 10^{10} $L_\odot$
- This is a few % of $L_{Bol,tot}$ (consistent with starburst domination of UV/O/MIR spectra)
- For $L/L_{Edd} = 1$, the implied BH masses would be $\sim 10^5$ $M_\odot$. Similar to proto-SMBHs
- Suggestive, but not conclusive