Cleaning up the high-redshift dusty universe with JWST and Wideband ALMA

Justin Spilker
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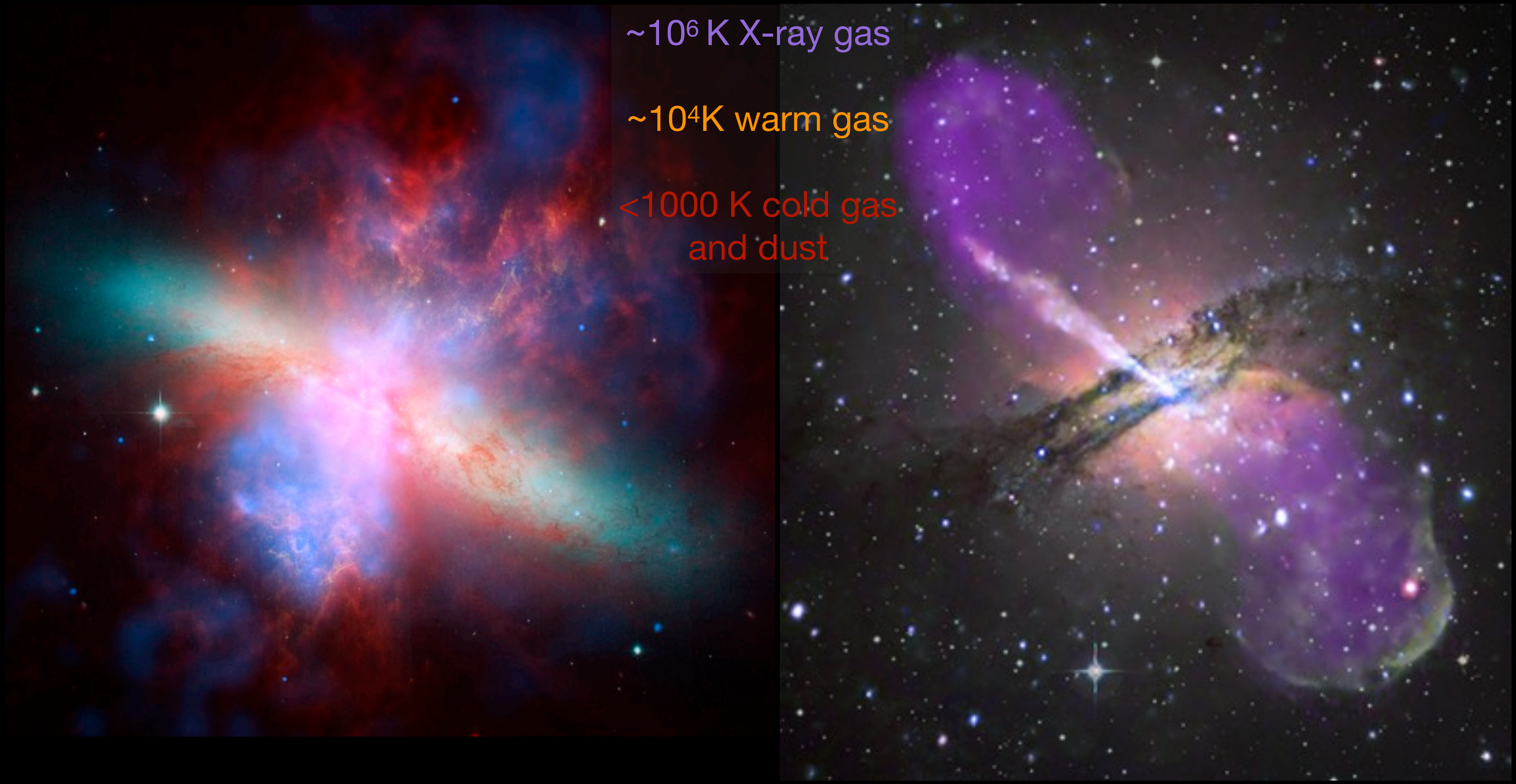
Outflows driven by star formation or black holes

M82
Supernova-driven outflow, D ~ 4Mpc

Centaurus A
AGN-driven outflow, D ~ 4Mpc



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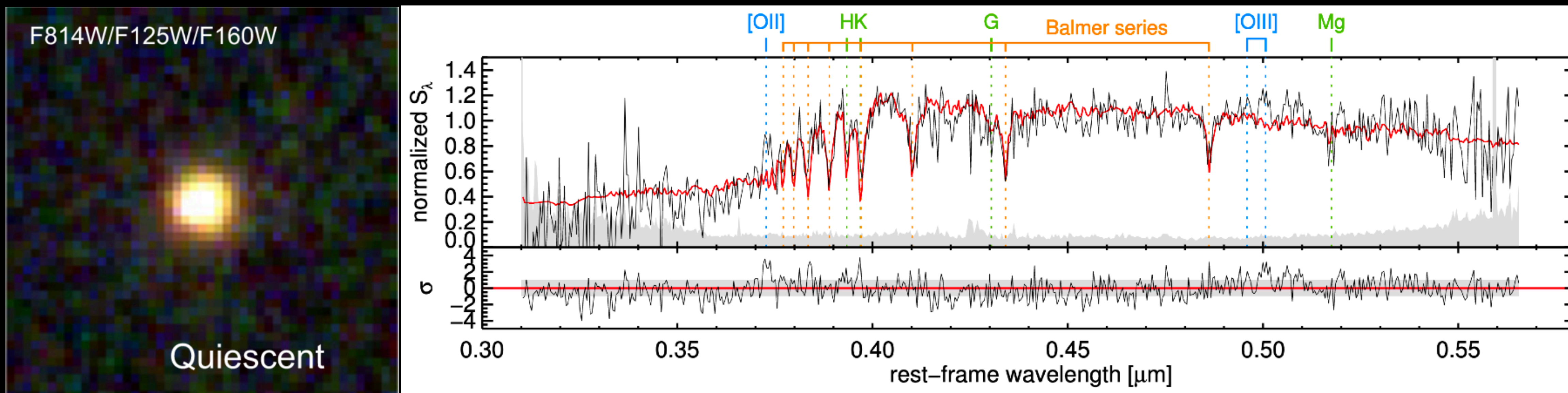
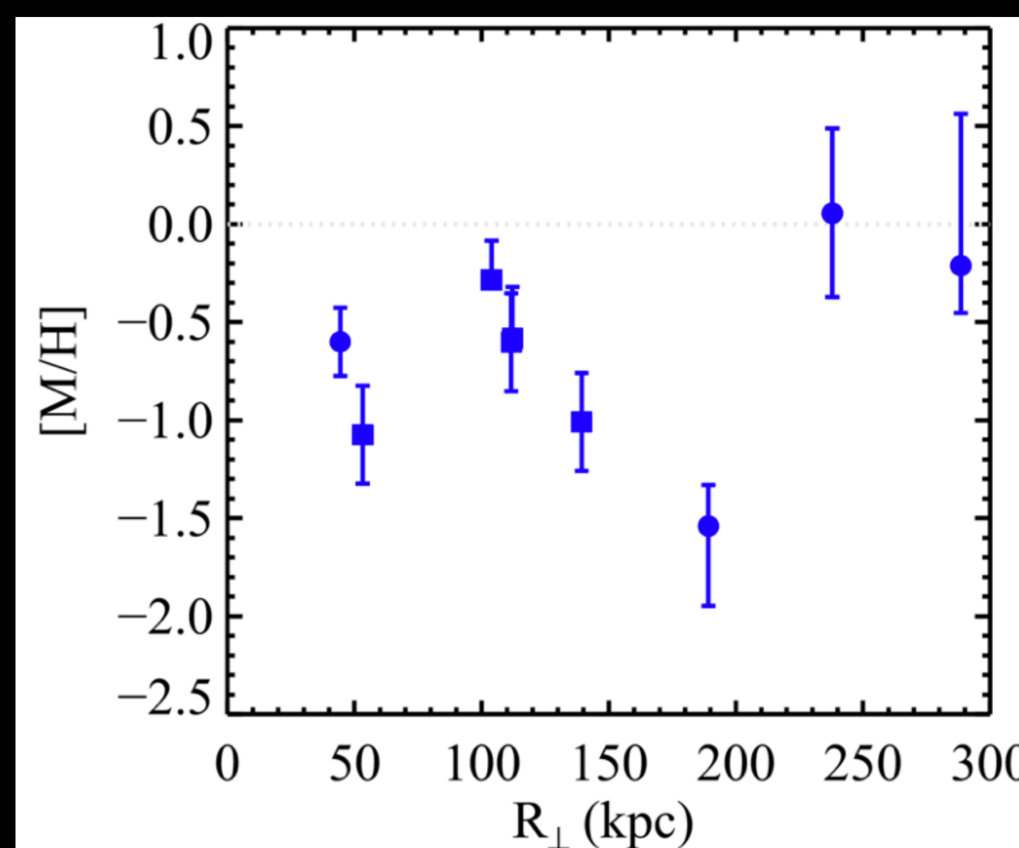
Evidence for feedback in the early universe

Massive (~10^{11} M_{sun}) quiescent galaxies discovered at z >~ 4



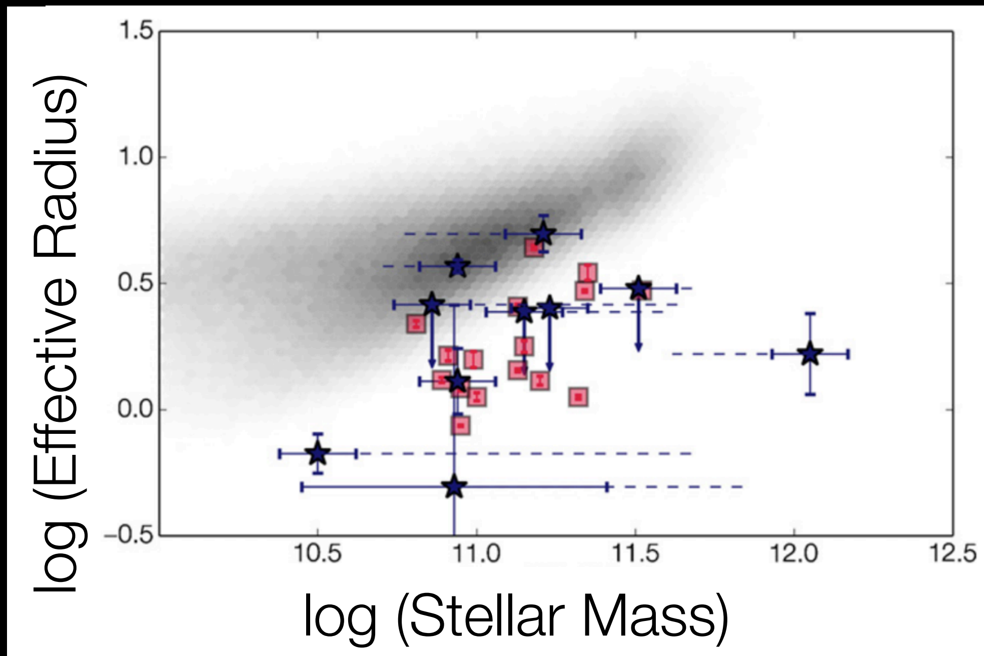
e.g. Straatman+2014, Glazebrook+2017, Schreiber+2018

Metal-enriched gas detected out to hundreds of kpc outside z ~ 3 galaxies



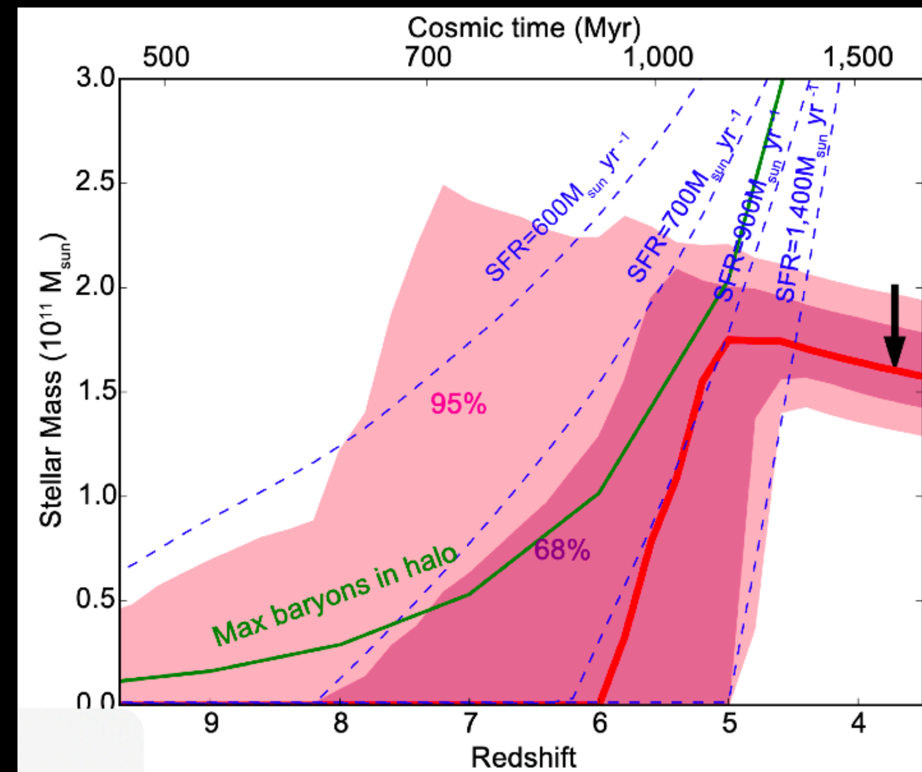
e.g. Prochaska+2014, Lau+2016

Dusty Galaxies as Plausible Quiescent Progenitors



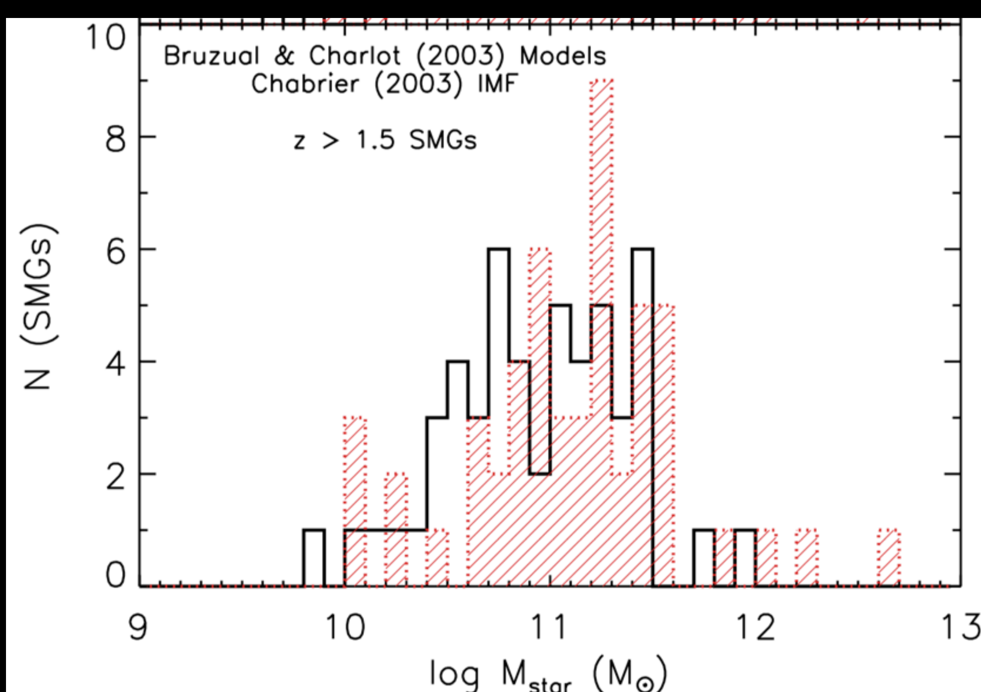
Dusty galaxies have similar structures as passive galaxies

e.g.,Toft+2014, Spilker+2016a, many others



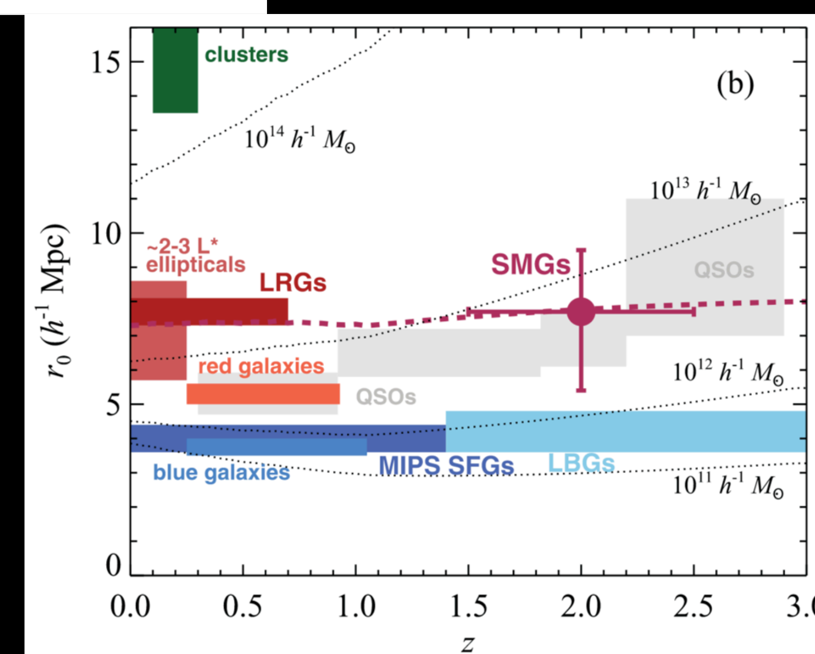
Dusty galaxy SFRs high enough to reach $10^{11}M_{sun}$ by z~4

e.g., Glazebrook+2017, Straatman+2014, Schreiber+2018, many others



Dusty galaxies have high stellar masses

e.g., Hainline+2011, Aravena+2016, many others



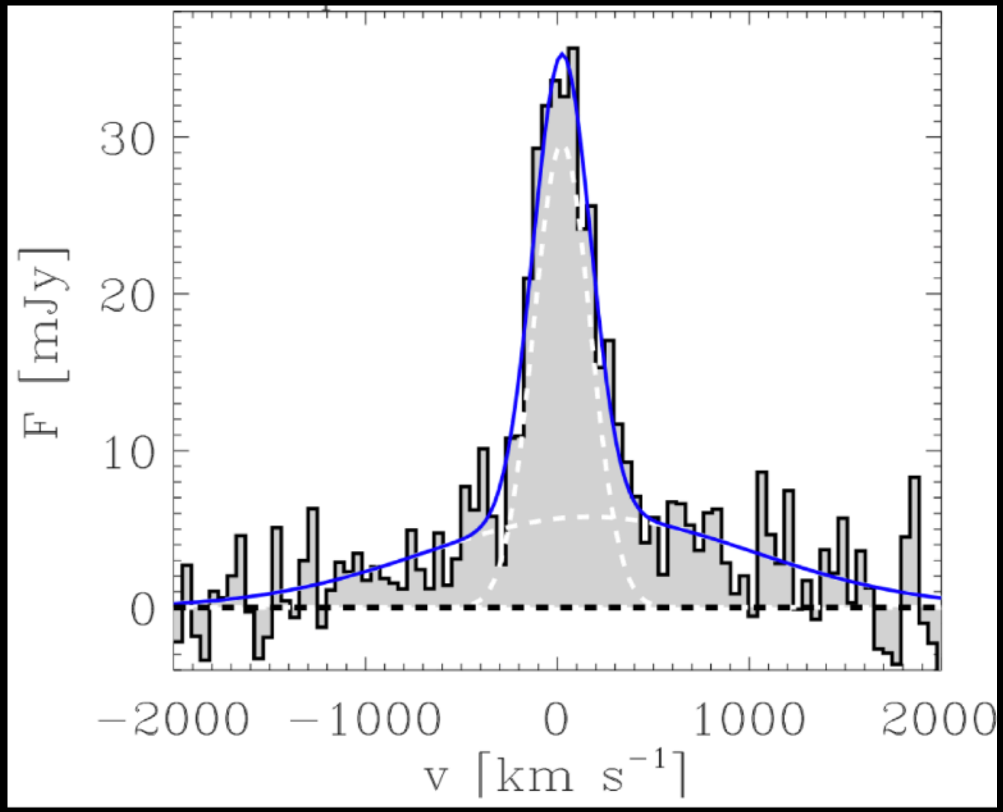
Dusty galaxies live in massive halos

e.g., Blain+2004, Weiss+2009, Hickox+2012, many others

Looking for cold outflows

- Pick a bright emission line, look for high-velocity line wings
- [CII] 158um is bright, accessible, and arises from a large portion of the cold gas

z = 6.4 Quasar SDSS J1148+5251



Maiolino+12, Cicone+15
Old PdBI data

Looking for cold outflows in all the wrong places

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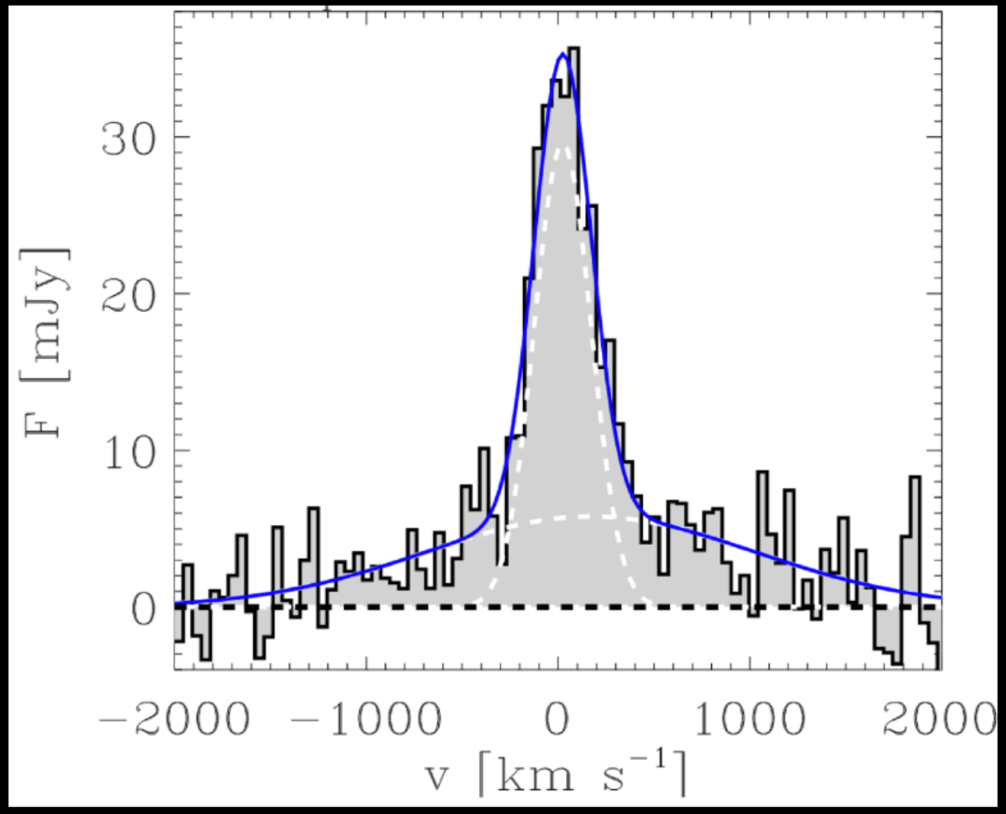
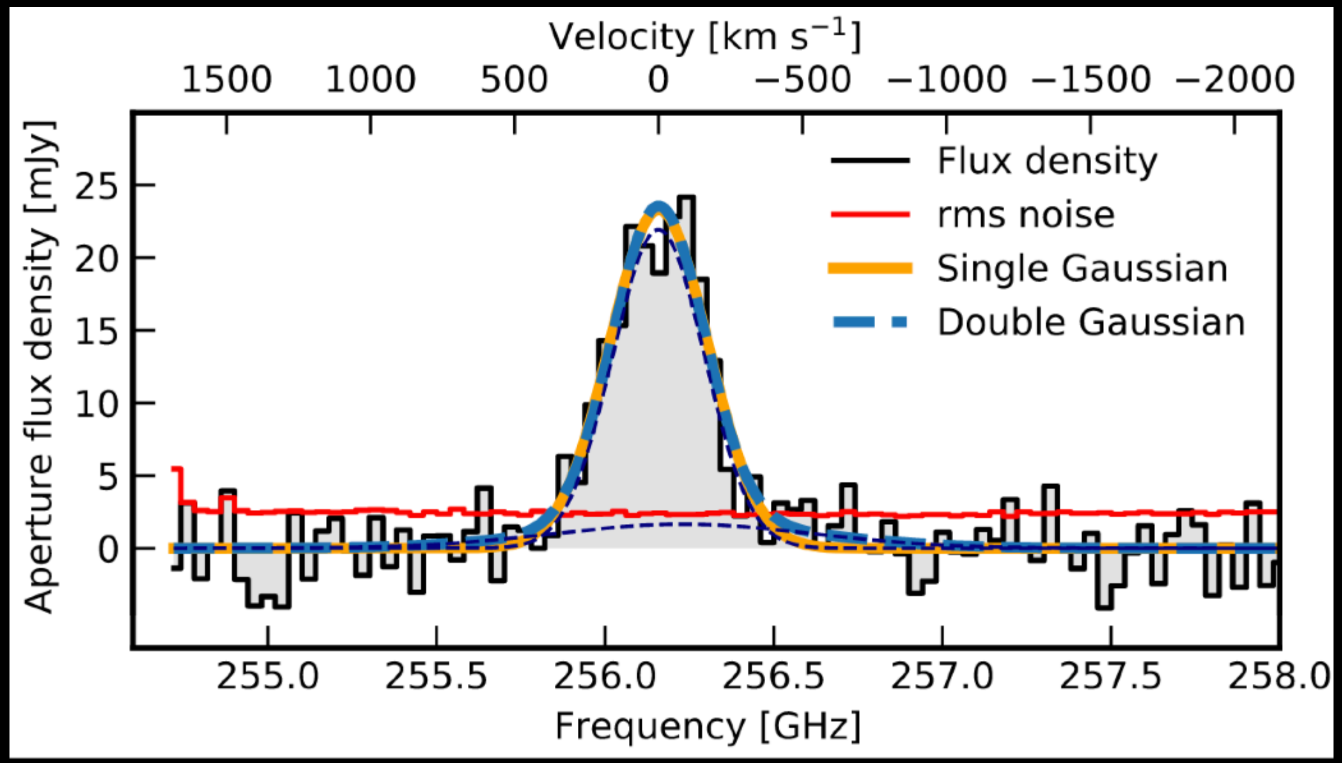


Meyer+22
Upgraded NOEMA data
Deeper, wider freq coverage



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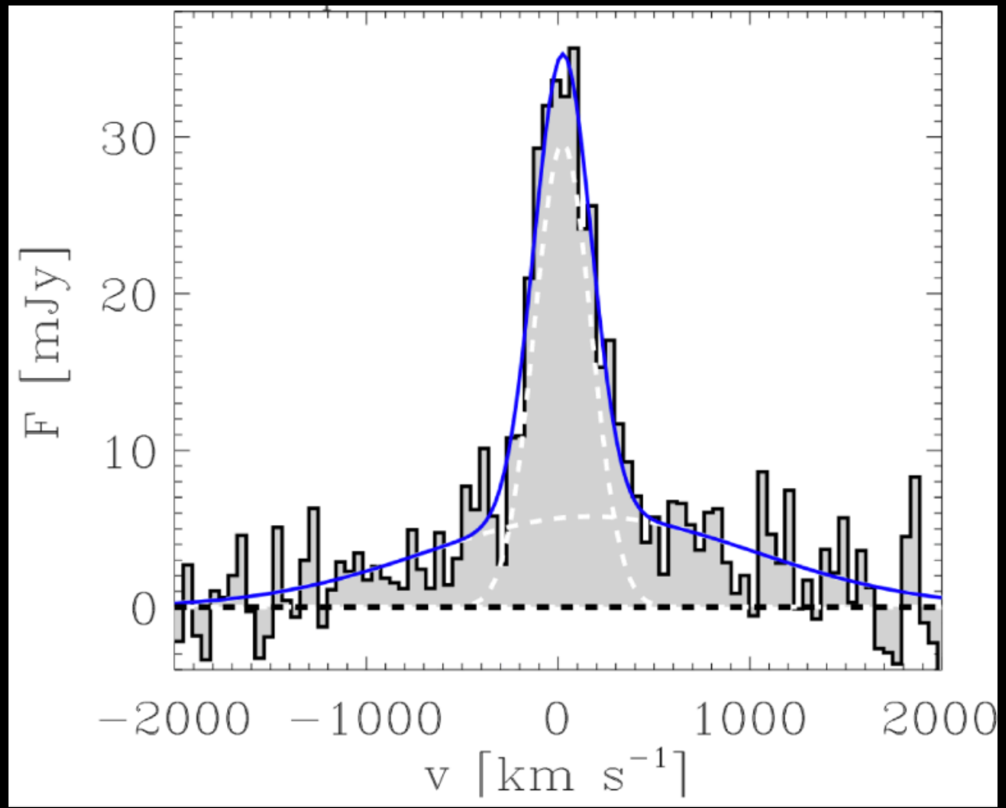

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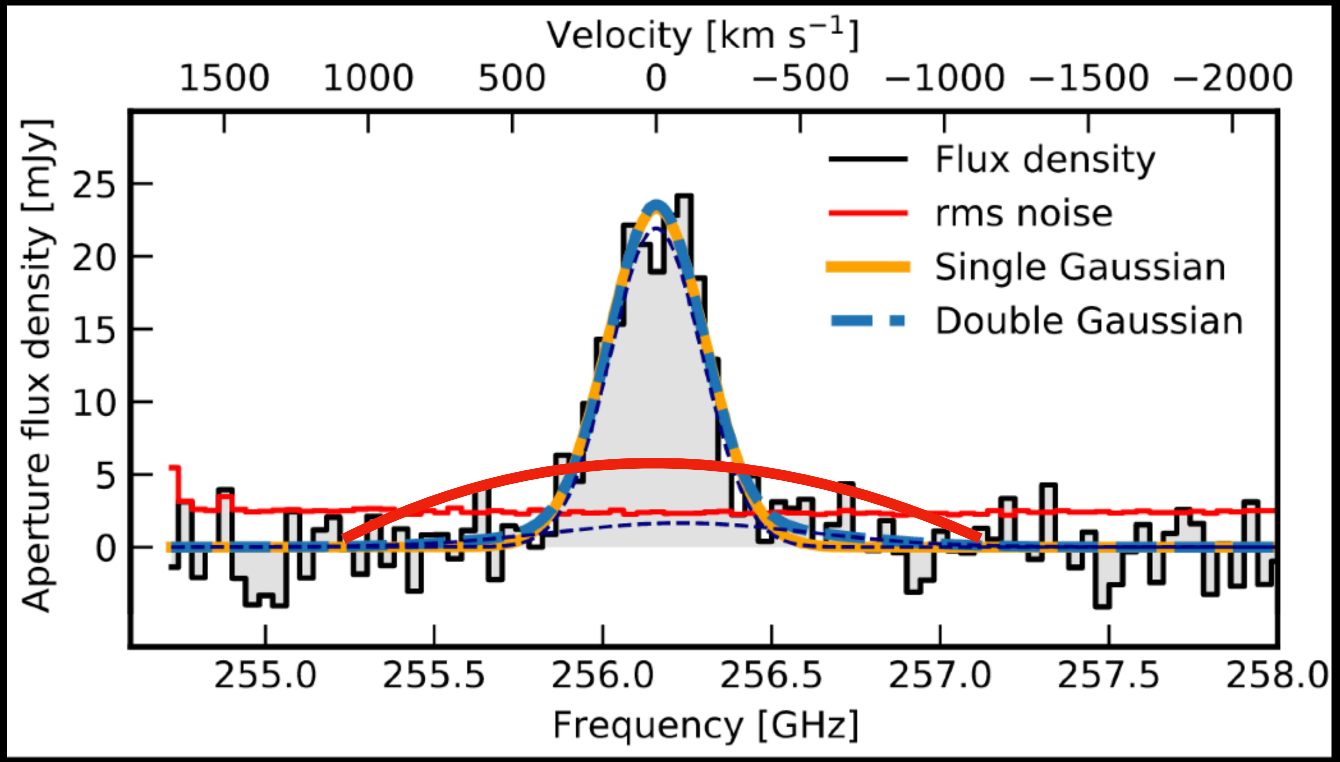

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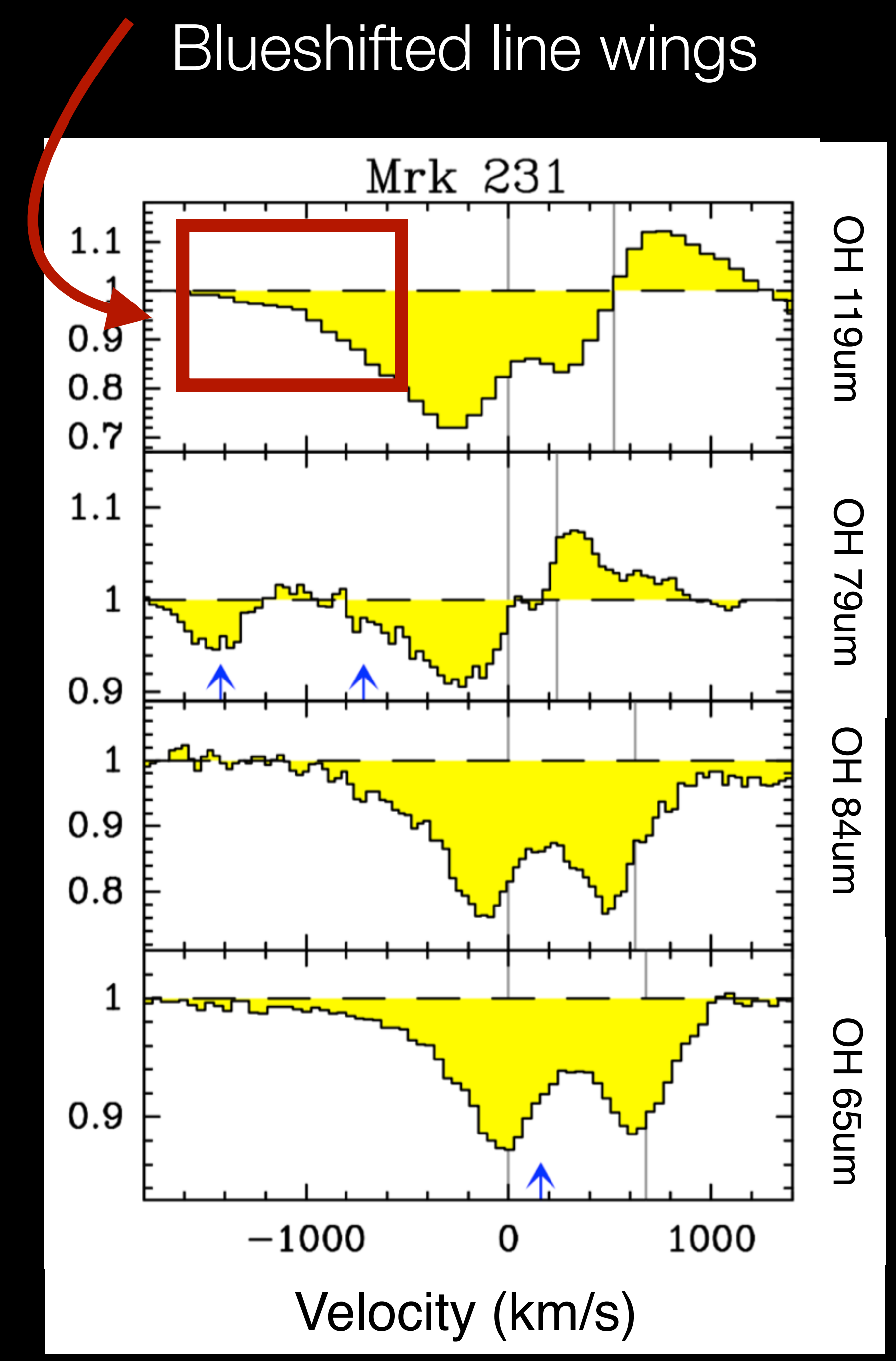
Looking for cold outflows with a better tracer (or at least a different tracer)

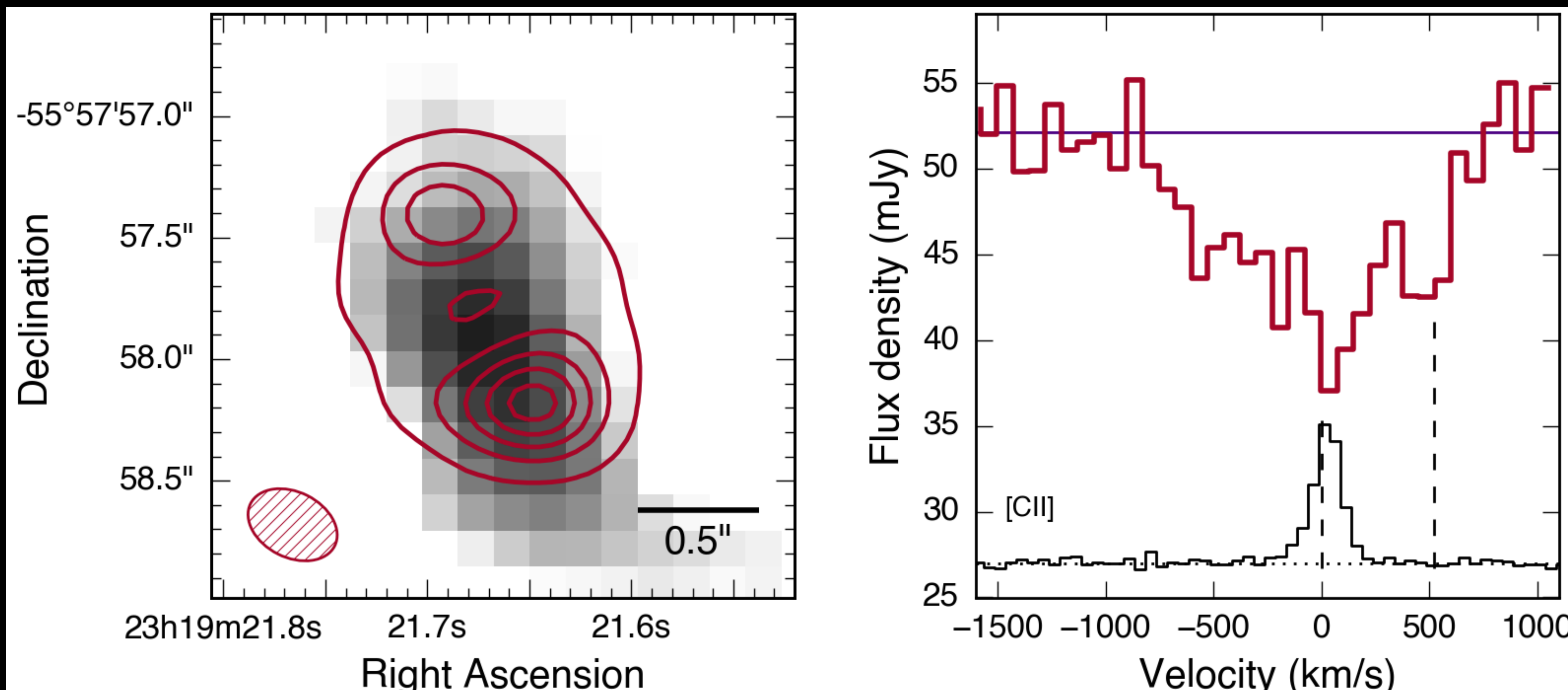
- The hydroxyl molecule (OH) is a great tracer of molecular gas flows
  - Simple, easy to form
  - Very strong transitions
  - Galaxies are bright at the wavelengths OH absorbs
  - *Herschel* observed this molecule in many nearby galaxies - natural comparison sample

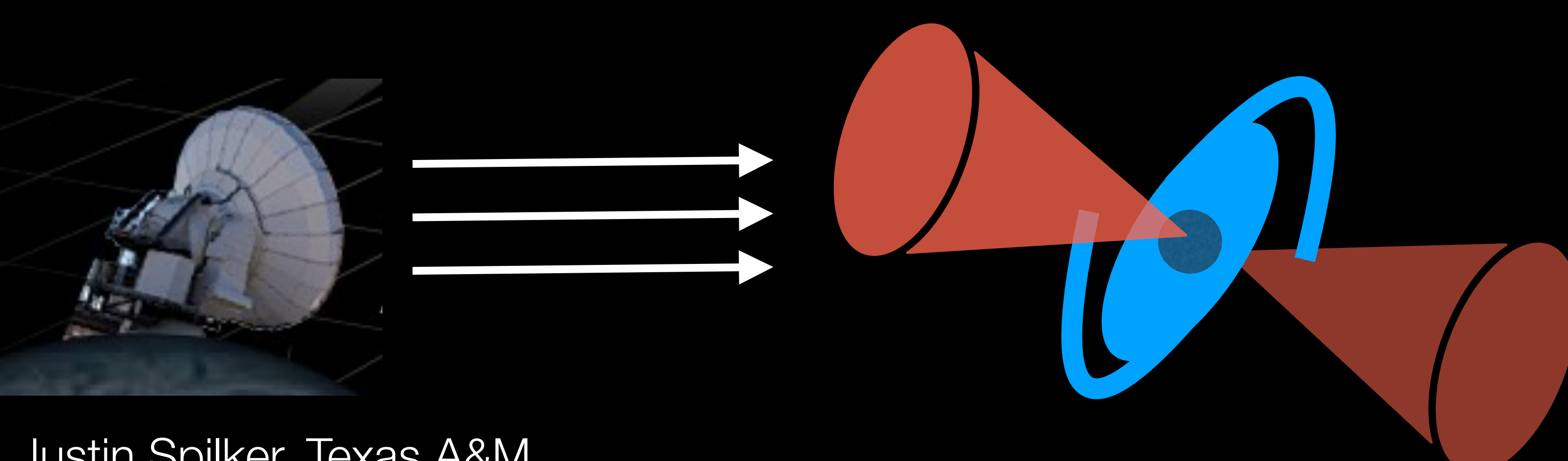
What we want to see:
Blueshifted line wings



Imaging Molecular Winds in the First Gyr

SPT2319-55, z = 5.3, SFR ~ 800 M_{sun} / yr





Spilker et al. 2018b, *Science*

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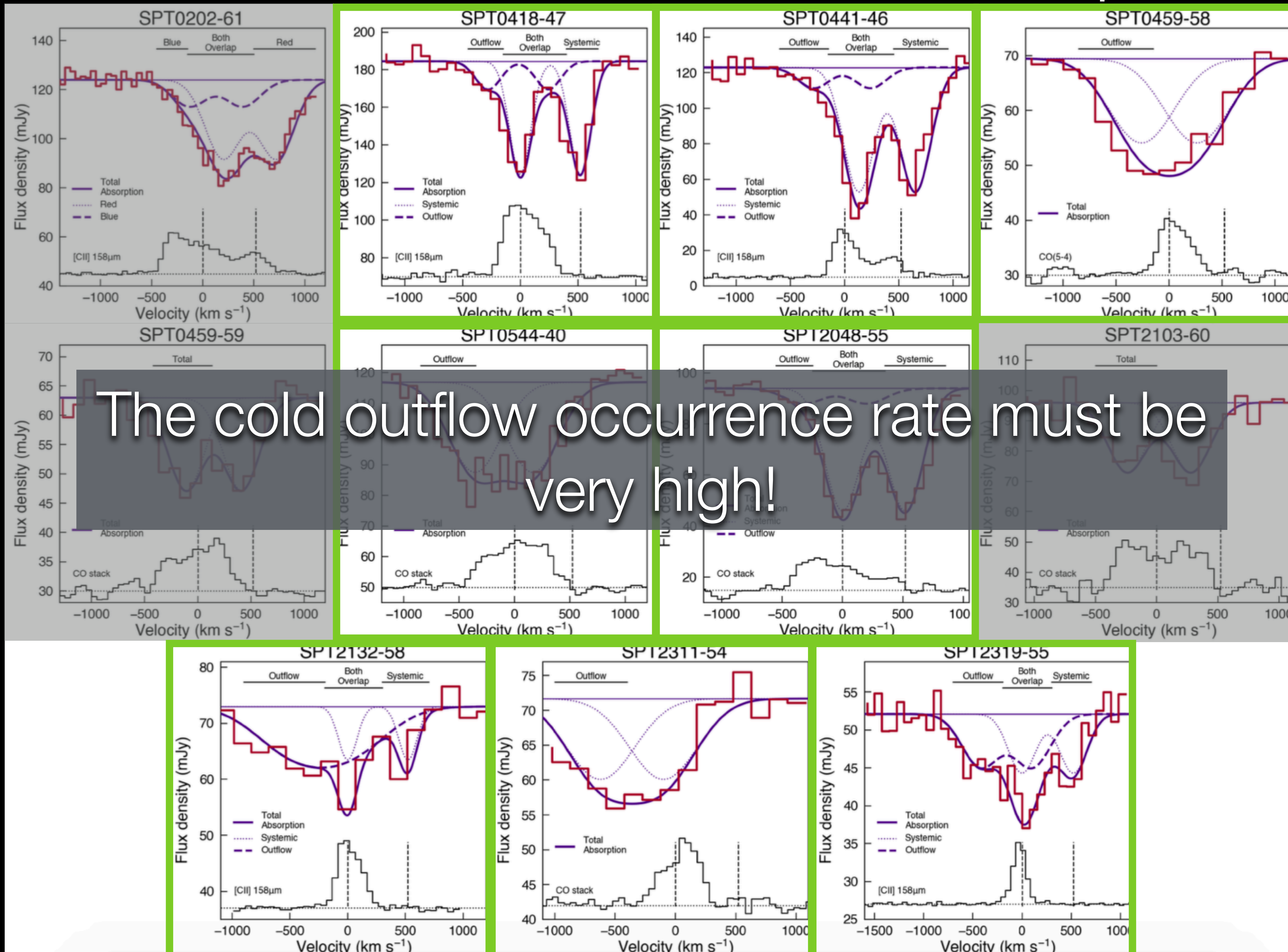
Molecular Outflows at z > 4 are Ubiquitous

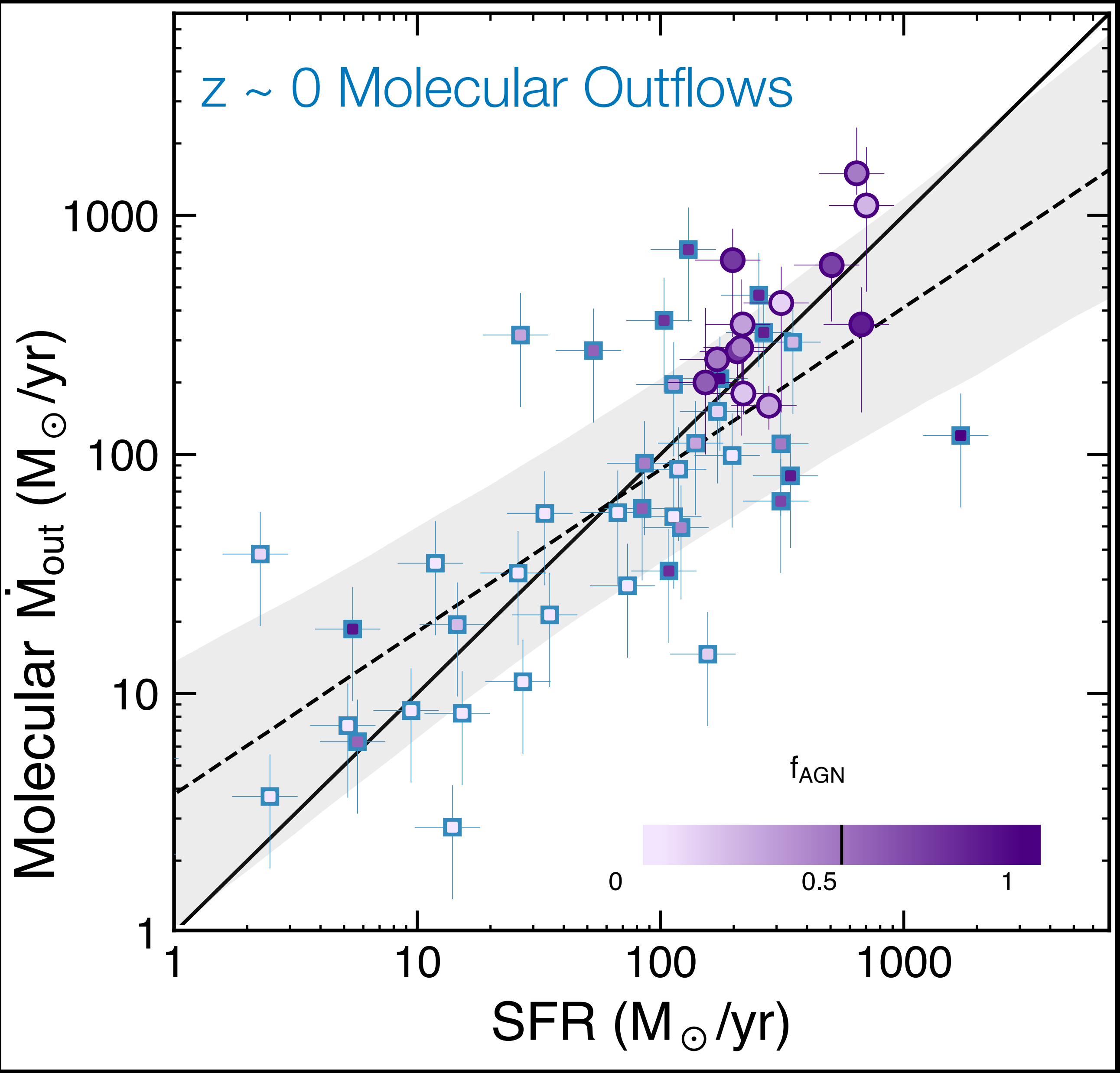


The cold outflow occurrence rate must be very high!

Spilker+2020a,b

What do we learn about feedback from high-z outflows?

At z ~ 0, molecular outflow rate is *almost* linearly proportional to the star formation rate



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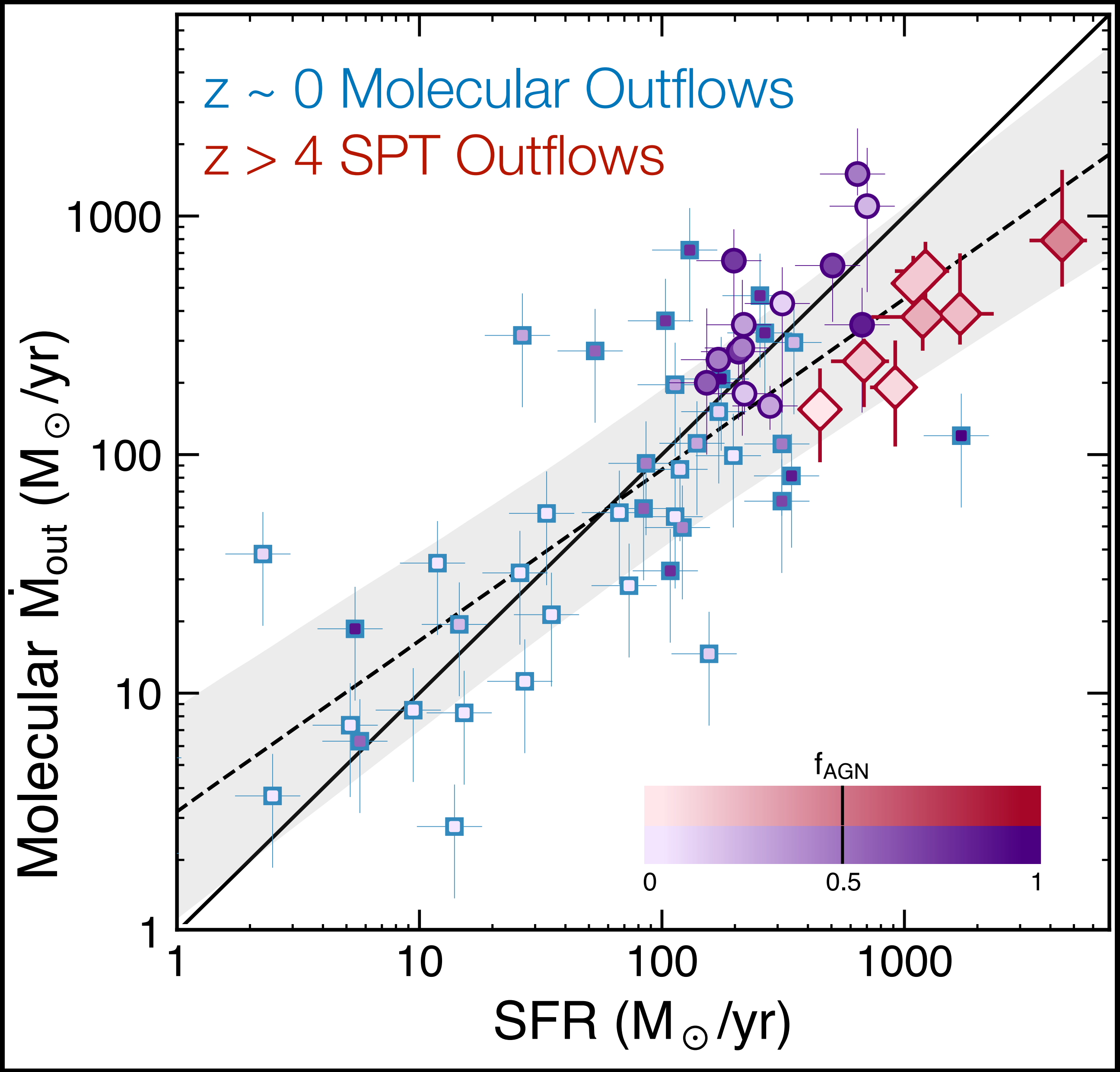
Spilker+2020a,b

What do we learn about feedback from high-z outflows?

At z ~ 0, molecular outflow rate is *almost* linearly proportional to the star formation rate

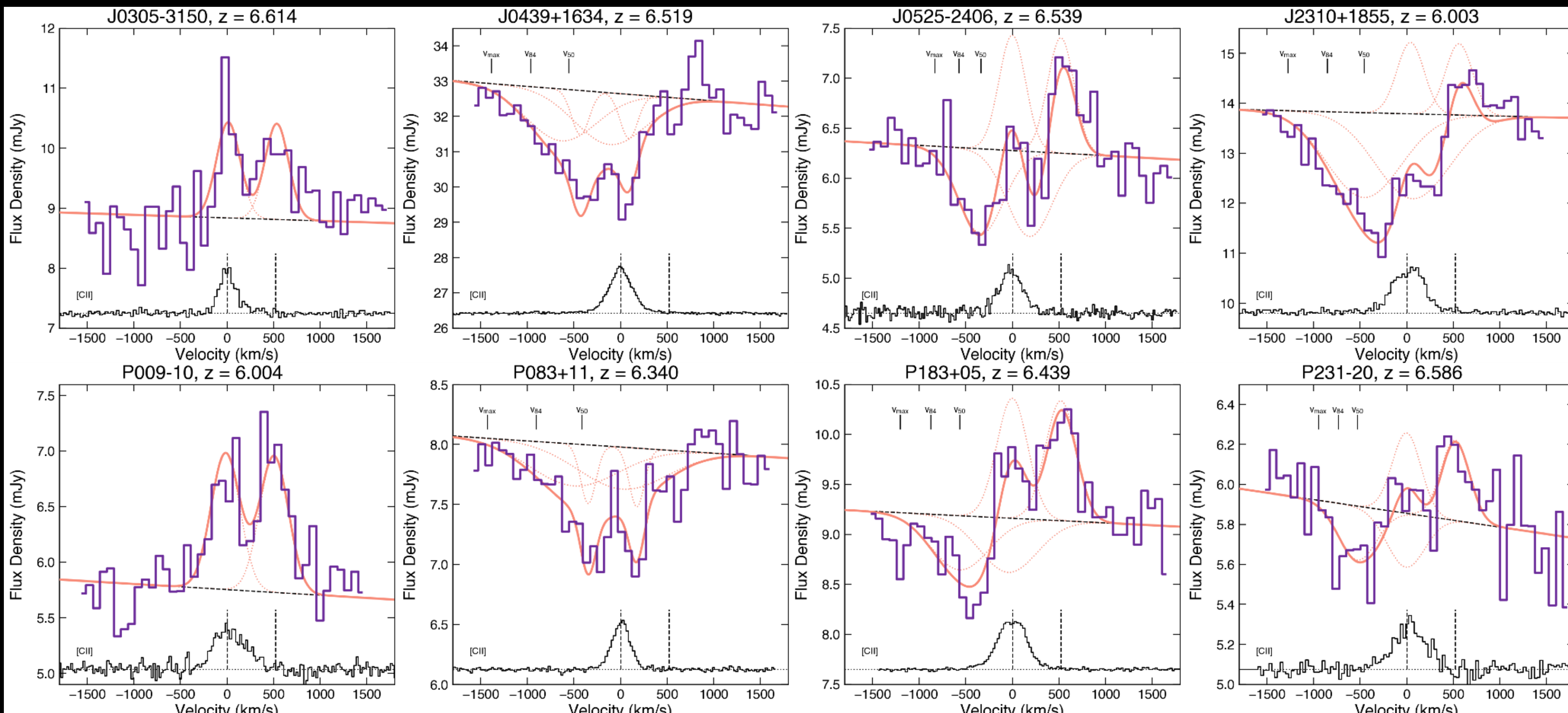
This basically continues to z ~ 5.



Spilker+2020a,b

Cold outflows in the reionization era

Many z > 6 quasars are also bright enough for quick(ish) ALMA OH observations!



Spilker+in prep. Also Herrera-Camus+20, Butler+23, Salak+23.

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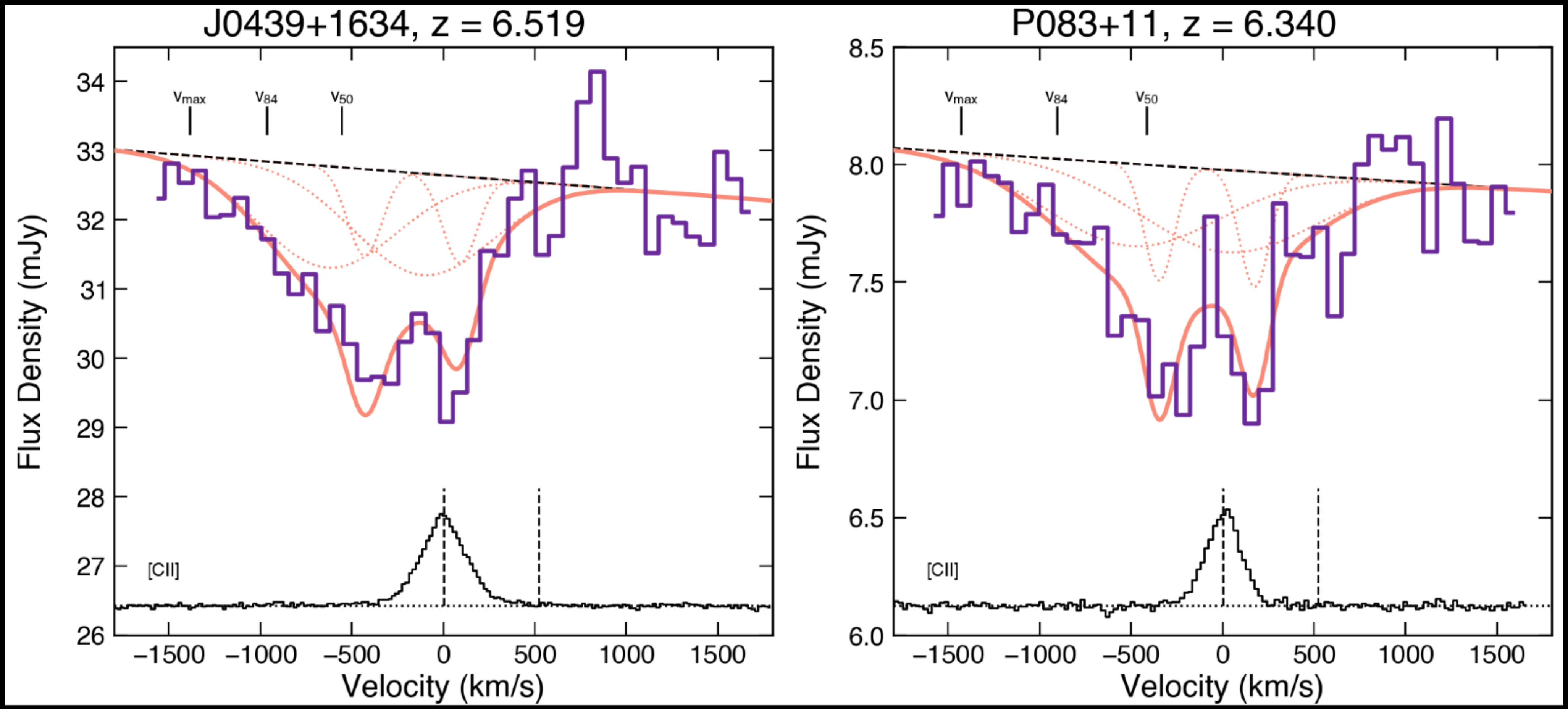
Cold outflows in the reionization era

Some of these are really fast outflows!



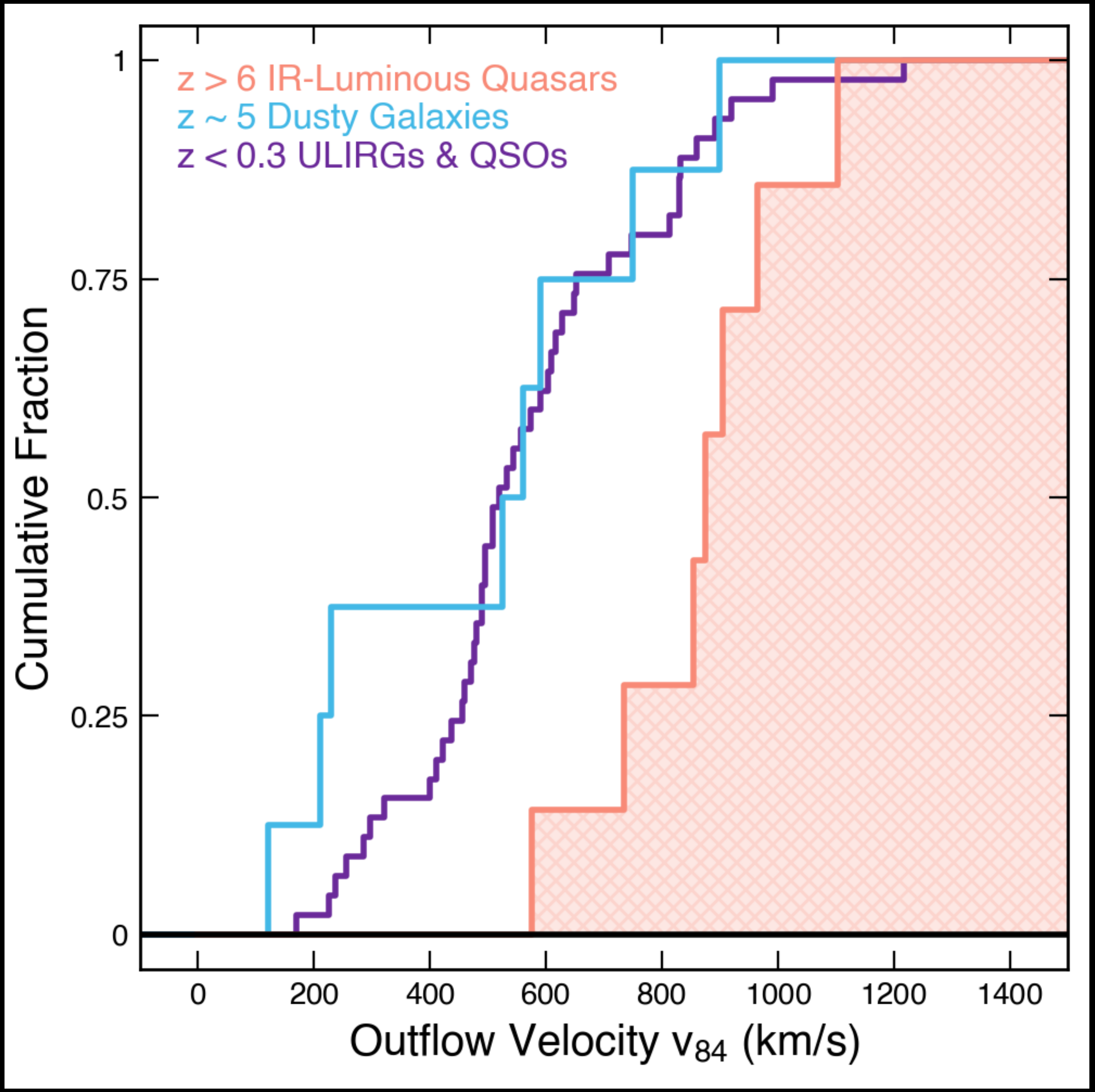
Outflow energetics scale like velocity$^{(2 \text{ to } 3)}$, so nailing down the outflow speeds helps substantially!

Spilker+in prep. Also Herrera-Camus+20, Butler+23, Salak+23.

Reionization-era quasar feedback??

Molecular outflows in z > 6 quasars are significantly faster than non-quasars…!

But these quasars are also intrinsically more luminous. Work ongoing to determine the importance of the quasars in driving these winds.

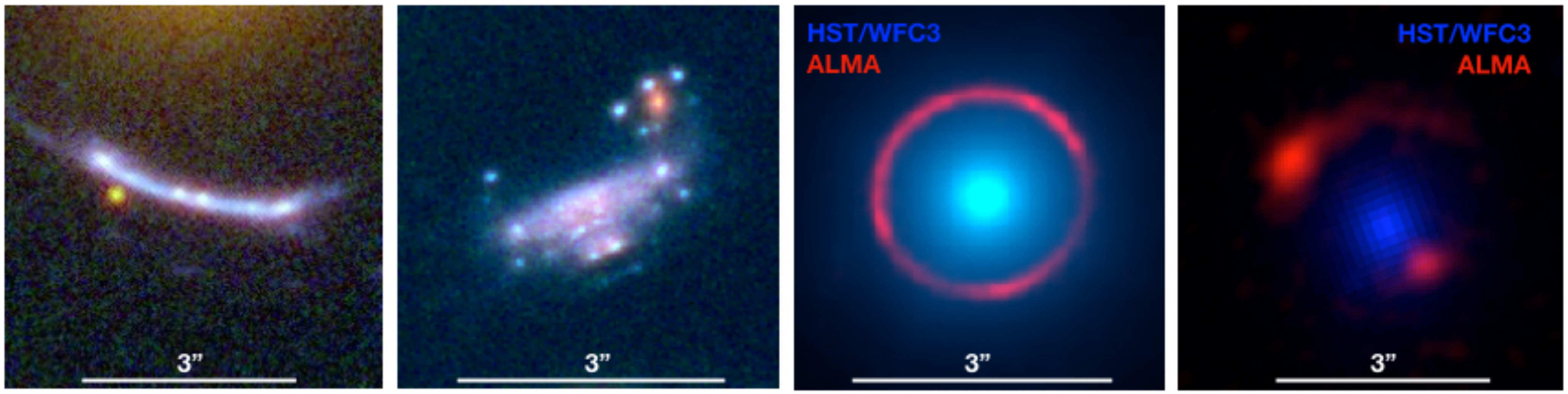


Spilker+in prep. Also Herrera-Camus+20, Butler+23, Salak+23.

Accessing Multi-phase Winds in the First Billion Years

TEMPLATES JWST Early Release Science Program

Image Plane



Source	SDSS1723+34	SDSS1226+21	SPT0418-47	SPT2147-50
redshift	1.32	2.92	4.22	3.76
magnification	20	40	32	6.6
r_E [arcsec]	4.7	9	1.2	1.2
$M_\star$ [$M_\odot$]	$<3\times10^{10}$	5×10^{9}	4.4×10^{10}	2.0×10^{10}
SFR [$M_\odot$/yr]	8	40	230	1290
sSFR [Gyr^{-1}]	>3	8	5.3	64
A_V	0.64—1.0	0.2—1	6	6

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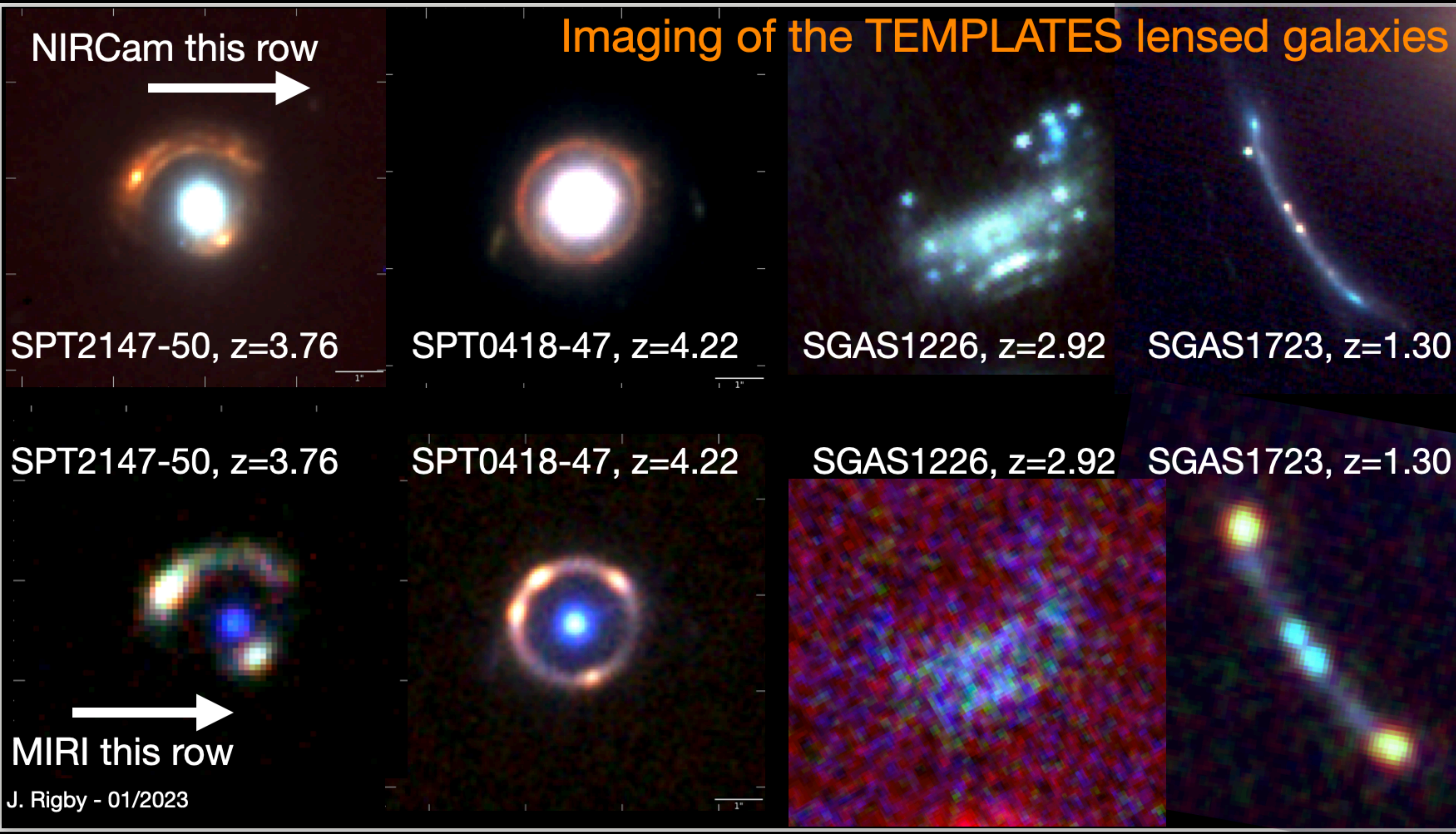
Accessing Multi-phase Winds in the First Billion Years



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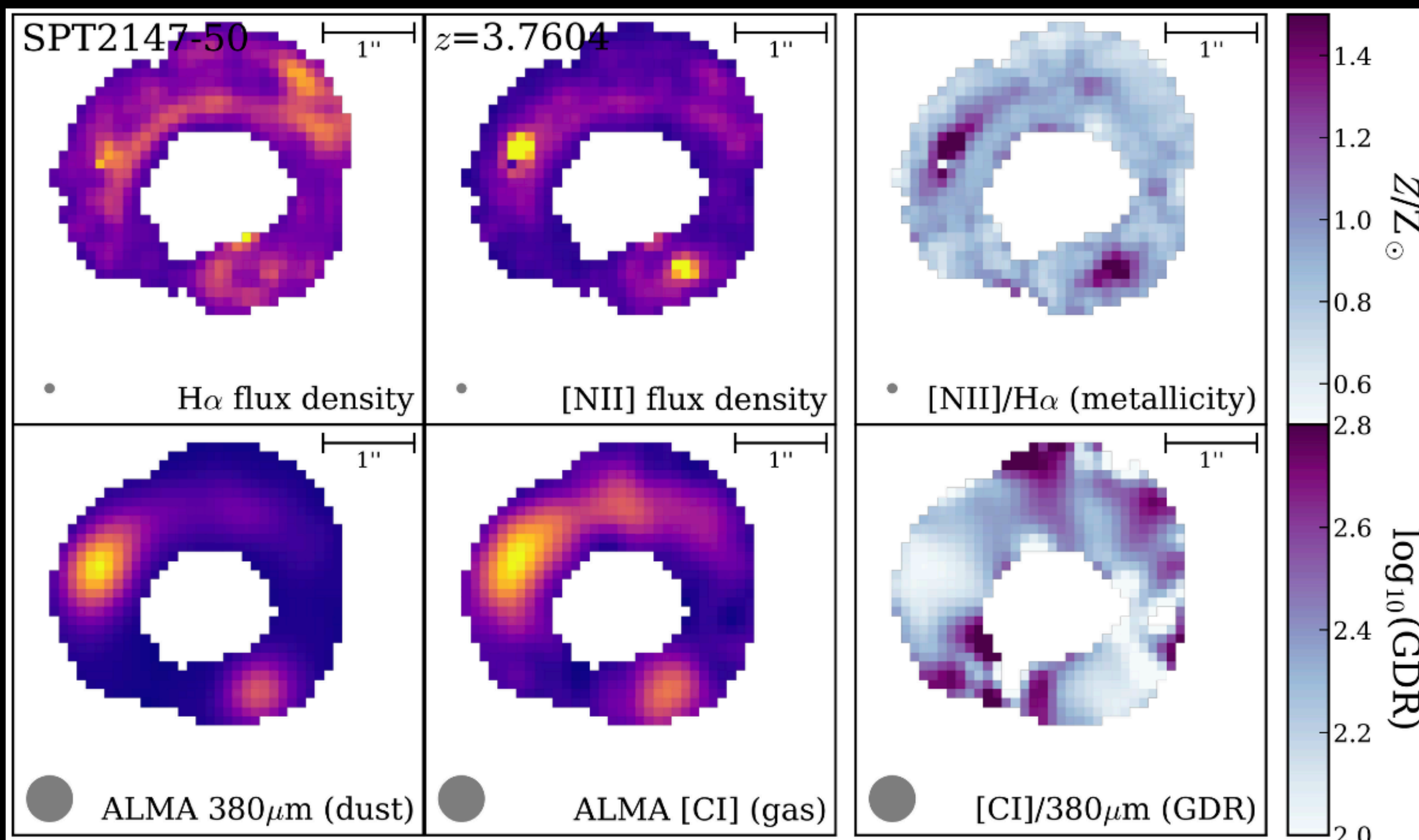
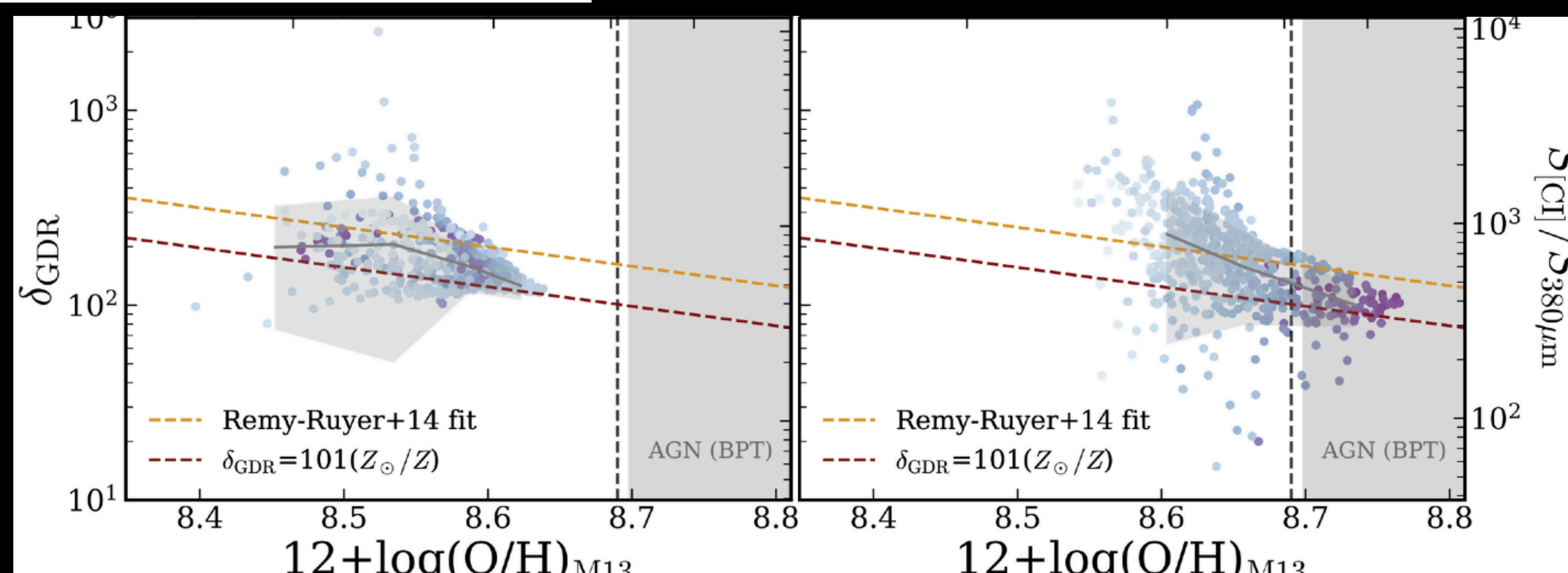
Connecting gas, dust, and metals in obscured starbursts at z ~ 4

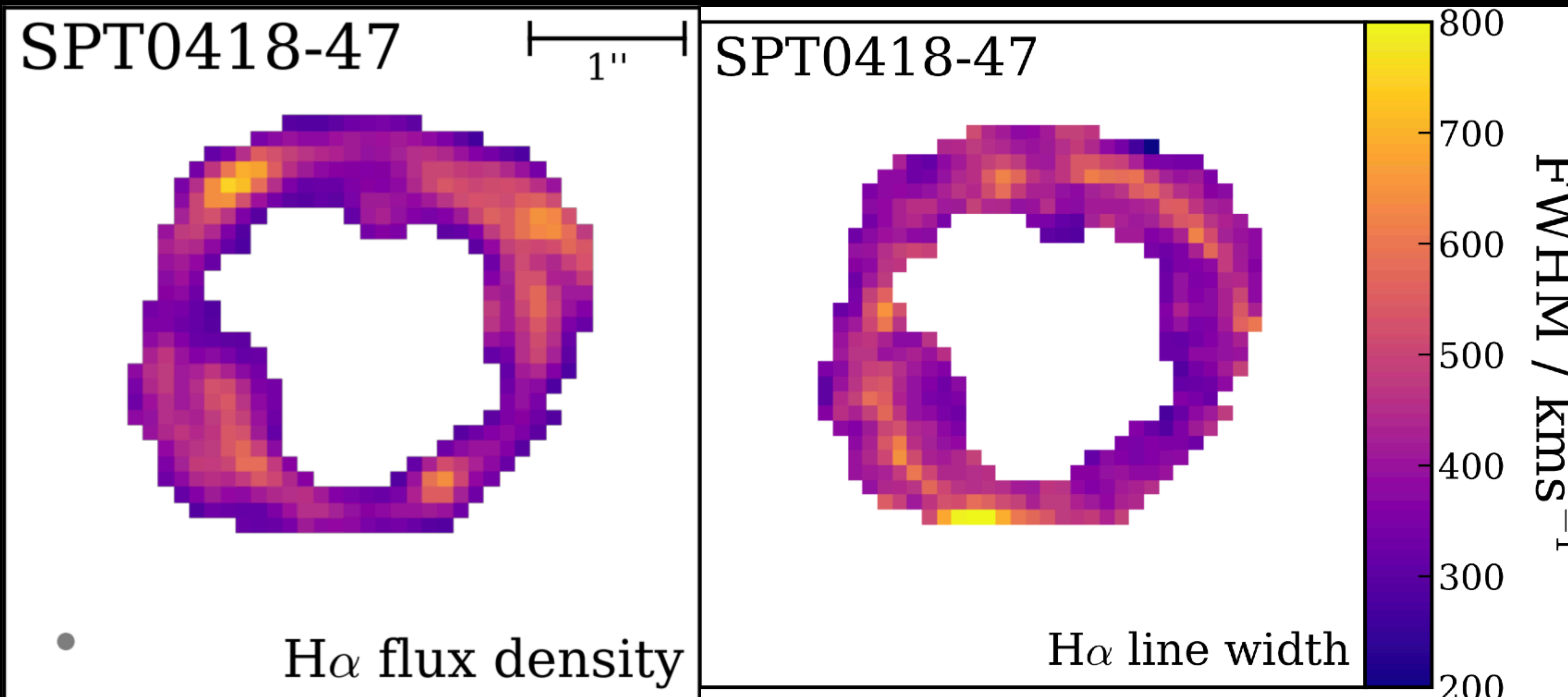


Jack Birkin (TAMU)
on arxiv ~tomorrow

Gas/dust mass ratio increases to lower metallicity on ~200pc scales, quantitatively similar to low-z!



Towards resolving multiphase outflows at z > 4



Jack Birkin (TAMU)

Broad H-alpha on highly-resolved scales,
no sign of AGN = warm ionized outflow?

Conclusions

- Cold molecular outflows are very common in early galaxies
- … but we need wide bandwidth to accurately measure their properties!
- JWST will let us access multiphase winds at high-z for the first time