Galactic Feedback and Outflows Throughout the Universe

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Results based on:
Spilker+2020a,b, ApJ, 905, 85 & 86

ngVLA Science Book Chapters:
Bolatto+, arXiv:1810.06737
Spilker & Nyland, arXiv:1810.06605

Feedback is *essential* in the evolution of galaxies

Simulations require outflows and feedback to:

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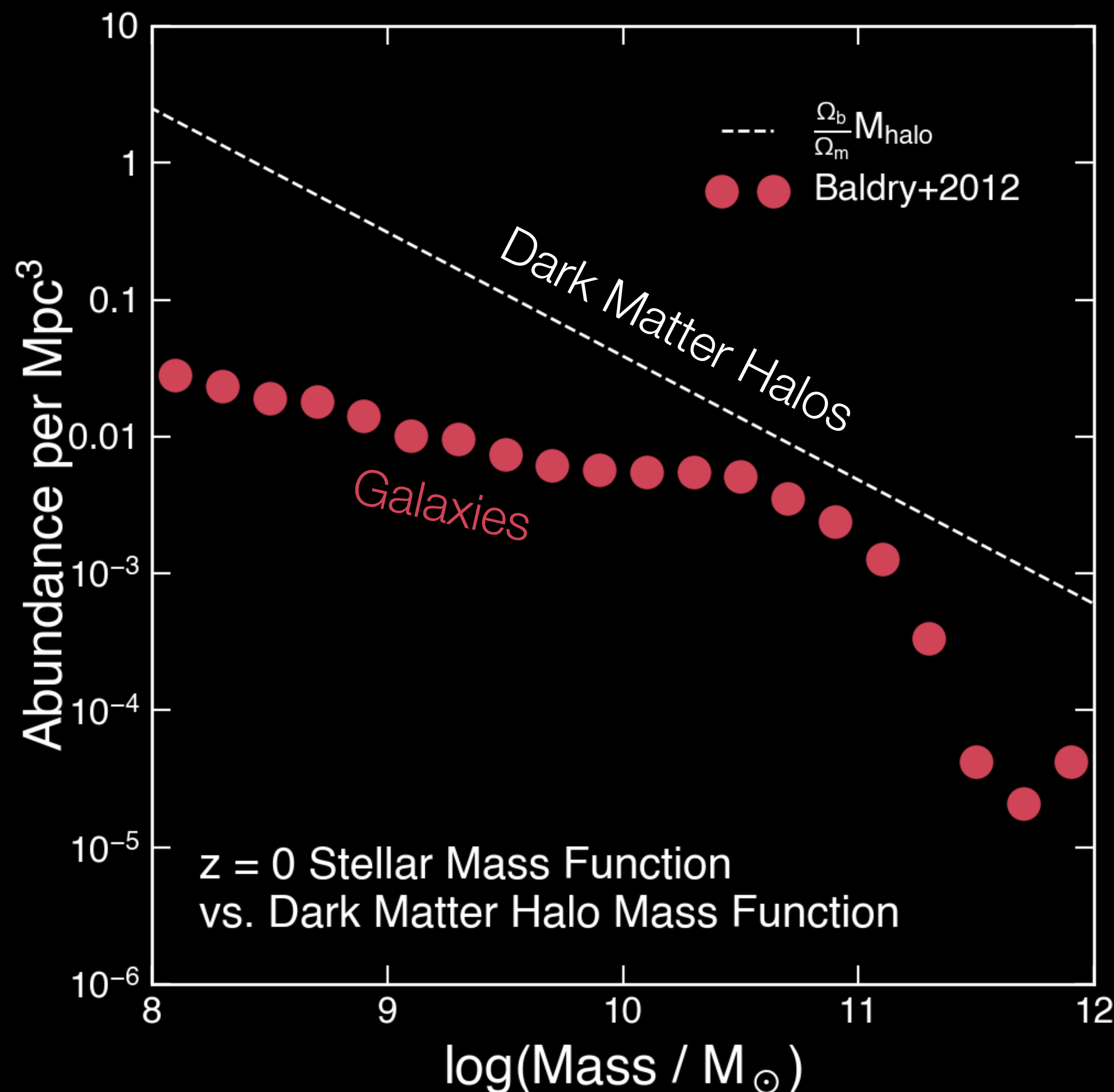
- Reproduce the stellar mass function



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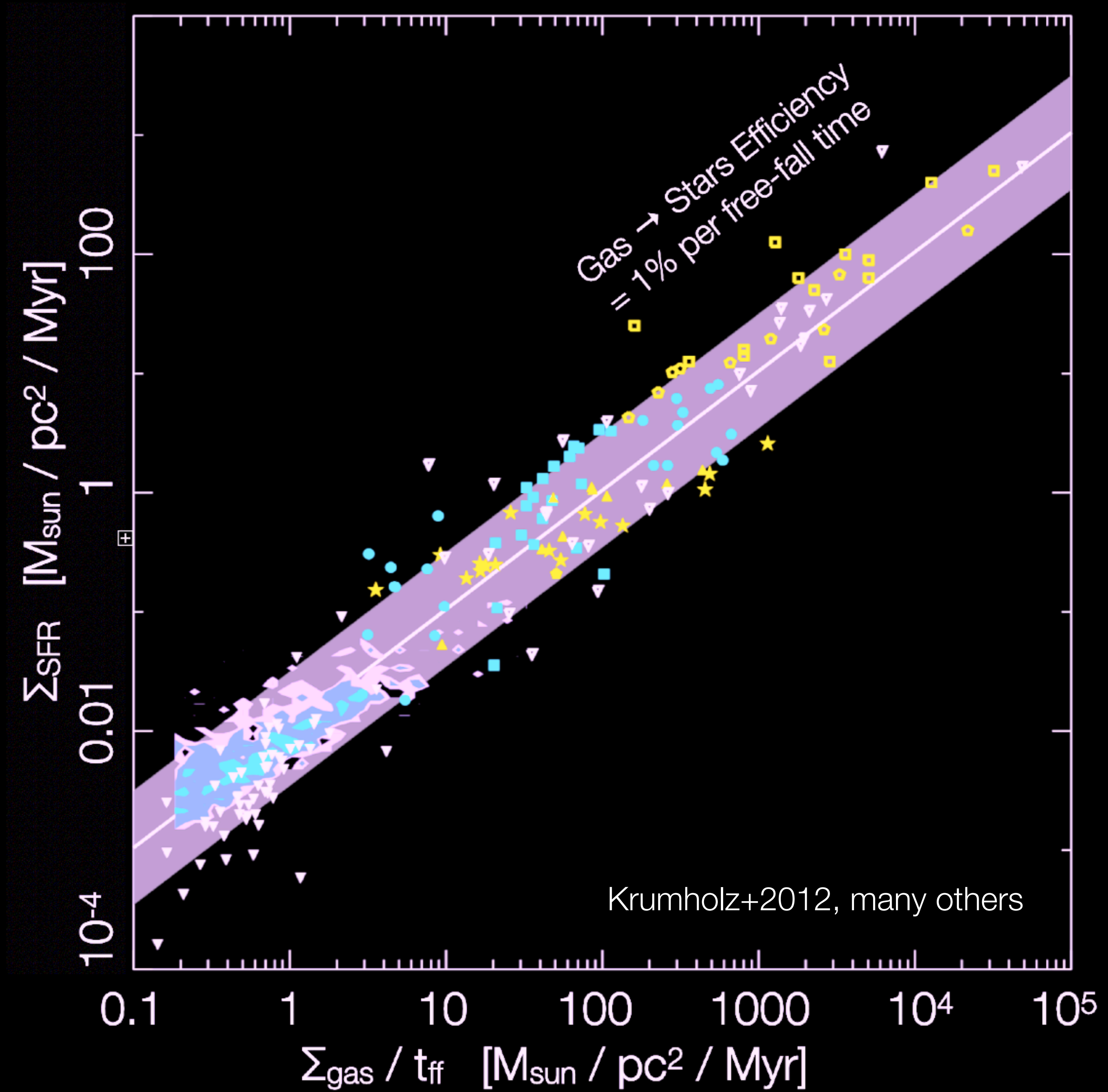
Simulations require outflows and feedback to:

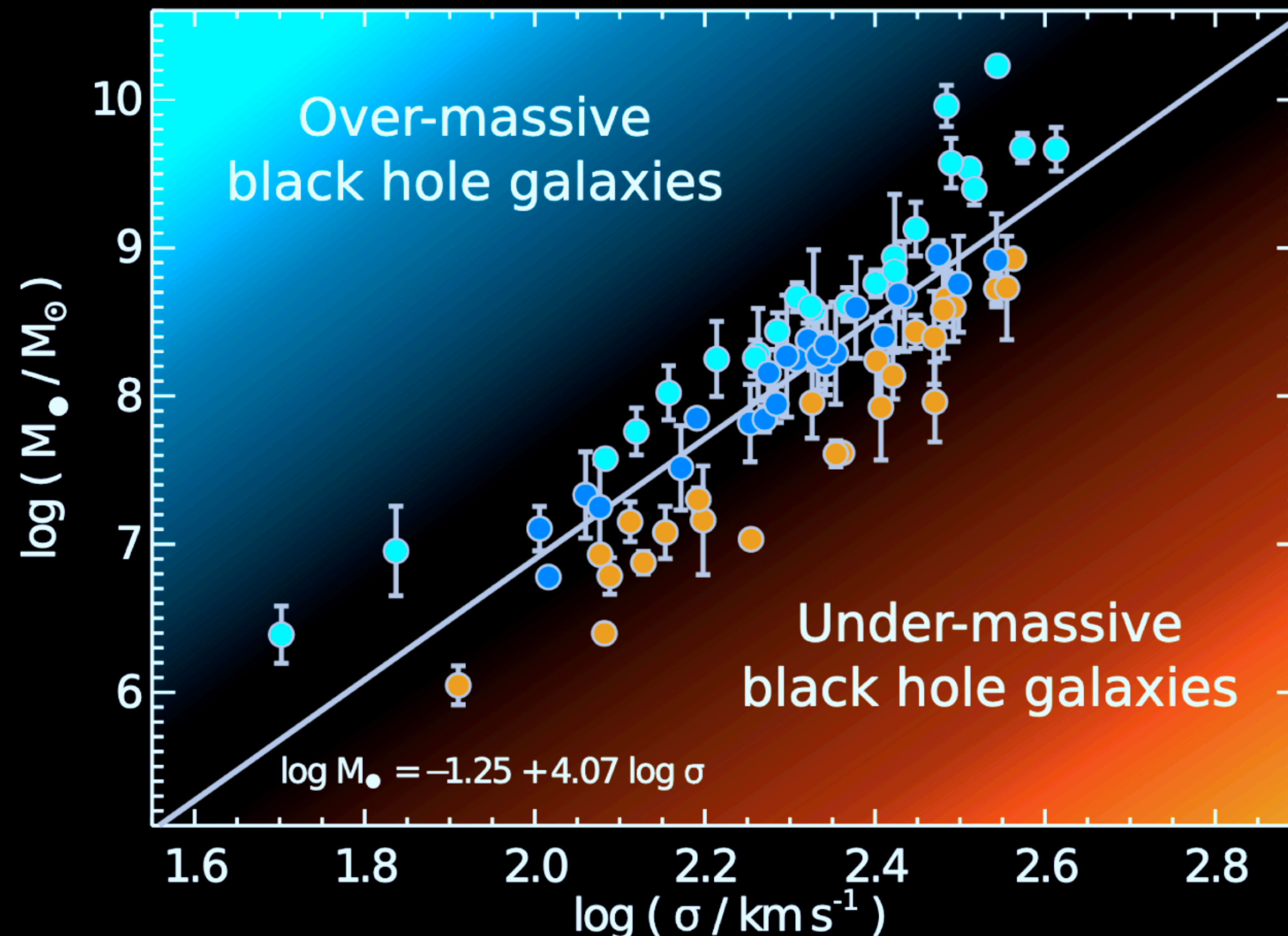
- Reproduce the stellar mass function
- Set the efficiency of star formation



Feedback is *essential* in the evolution of galaxies

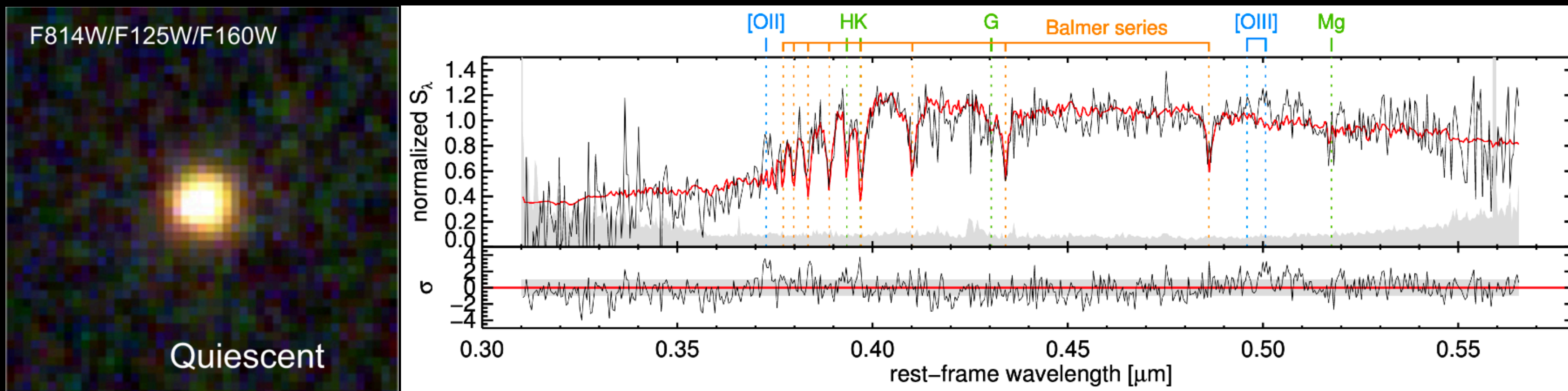
Simulations require outflows and feedback to:

- Reproduce the stellar mass function
- Set the efficiency of star formation
- Connect black holes and the galaxies they live in



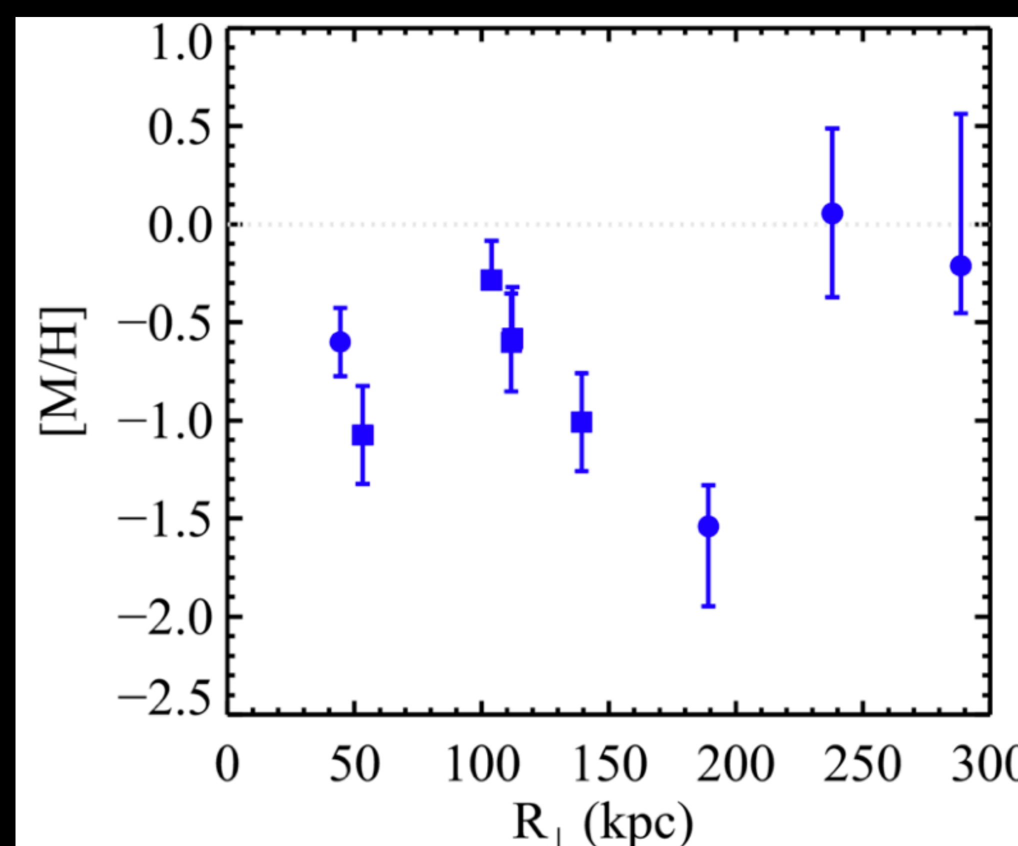
Evidence for feedback in the early universe

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 galaxies by z ~ 3



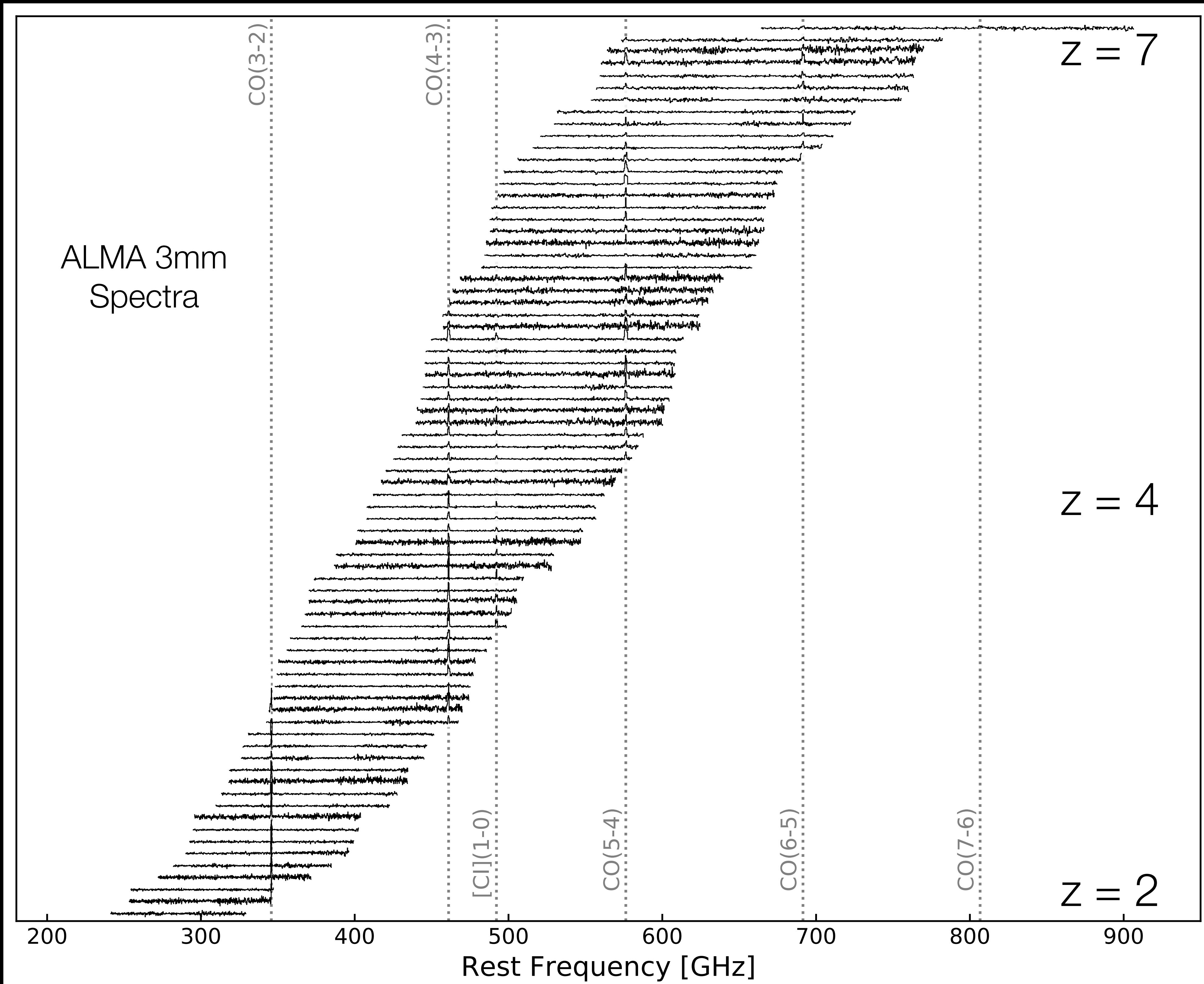
e.g. Prochaska+2014, Lau+2016

Open questions about feedback

- How do feedback and outflows evolve over time?
- What are the physical drivers of galaxy growth, feedback, and quenching?
- When do star formation, AGN, environment matter most?
- How are mass, momentum, and energy distributed in galactic outflows?
- How do the very small-scale physics of feedback connect to large galactic and intergalactic scales?

We can use high-redshift dusty galaxies as laboratories for feedback in the early universe

The Complete SPT Sample of Lensed, Dusty Galaxies



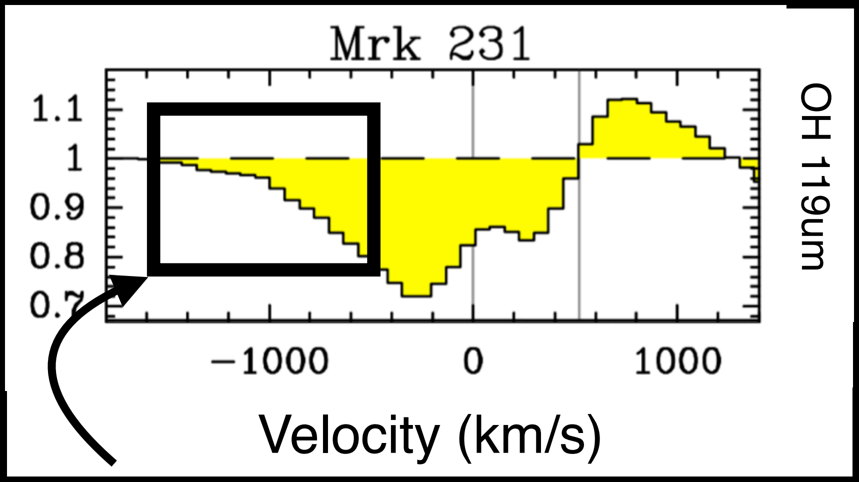
ALMA 0.03" imaging

83 confirmed redshifts, ~98% complete

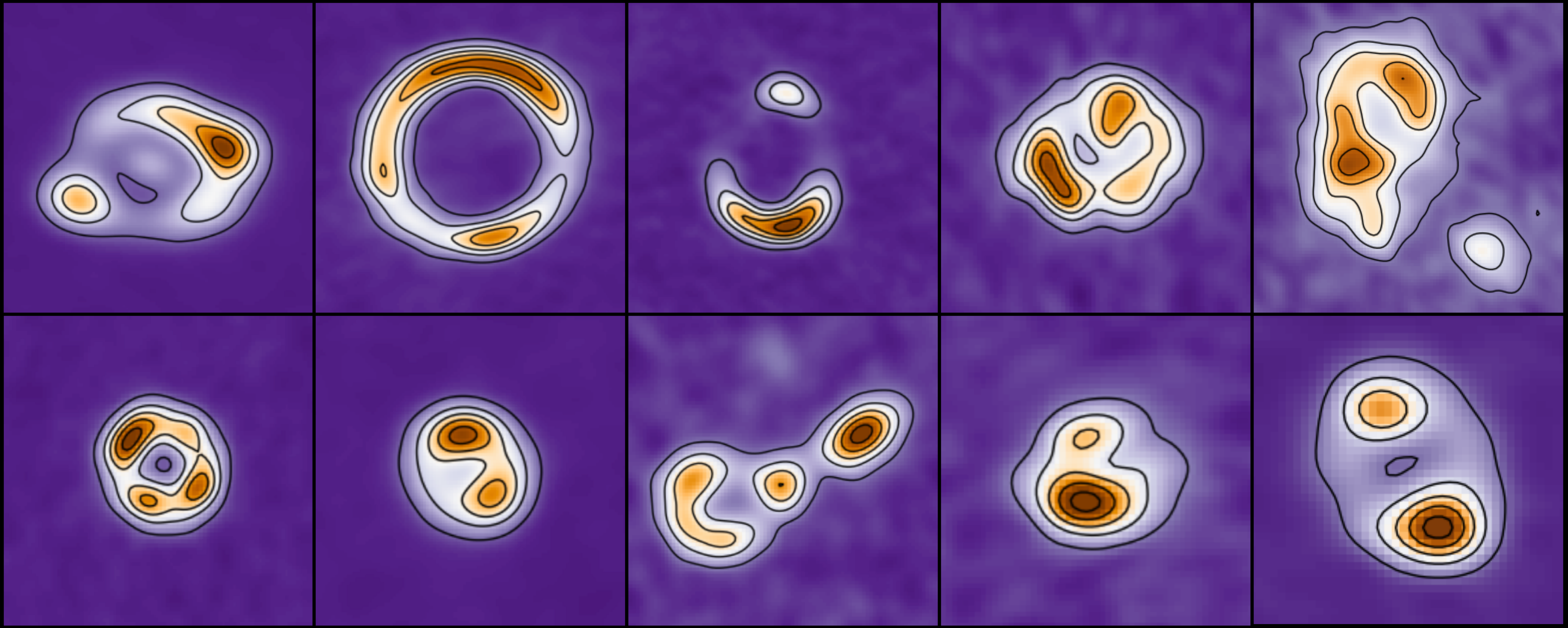
Weiss+2013, Spilker+2016, Reuter+2020

Tracing Molecular Winds in the Early Universe

With ALMA + lensing, we can quickly build up a decent-sized sample of molecular outflows at z ~ 4 — 7

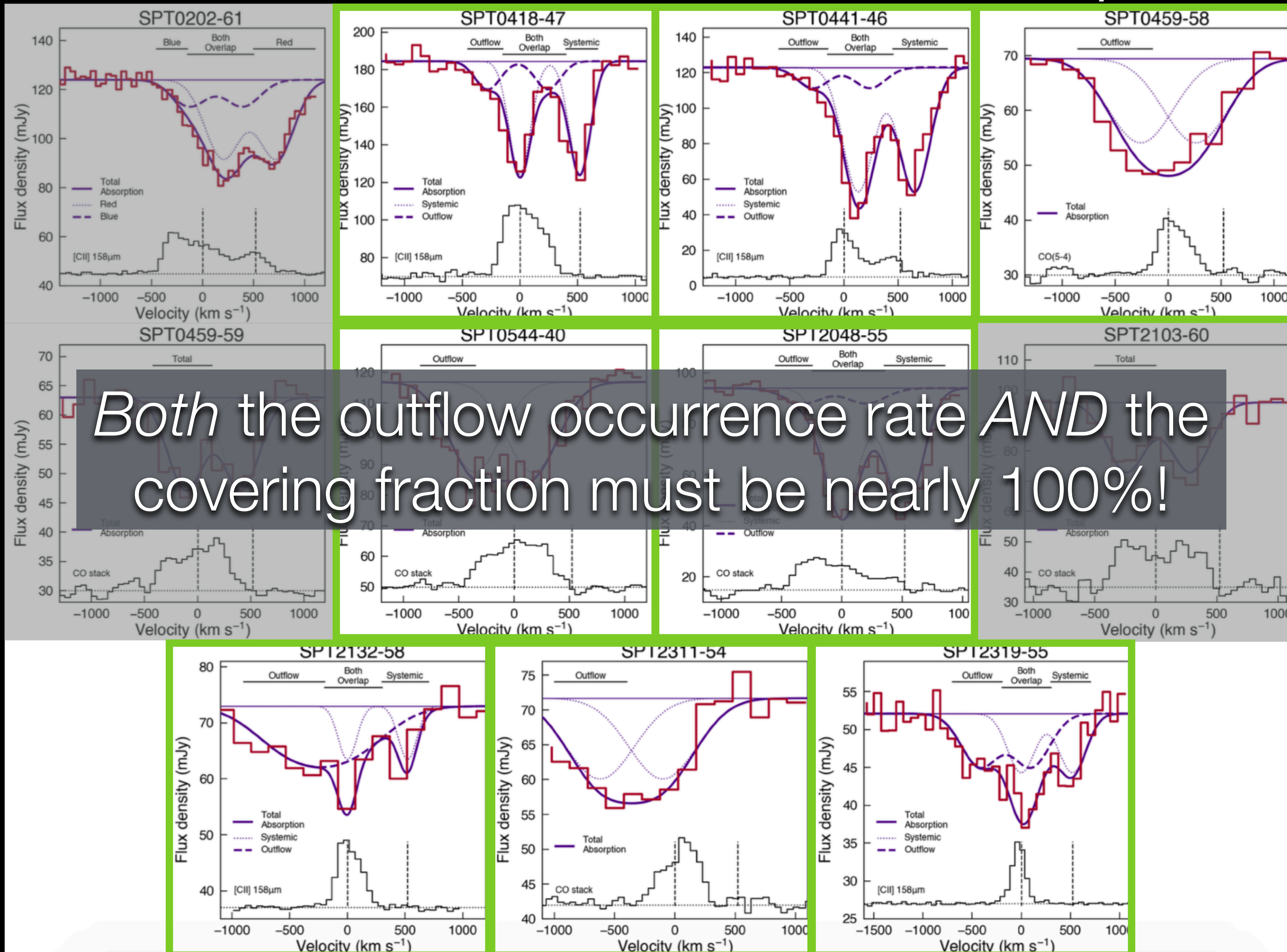


What we want to see:
Blueshifted line wings



Spilker+2020a,b

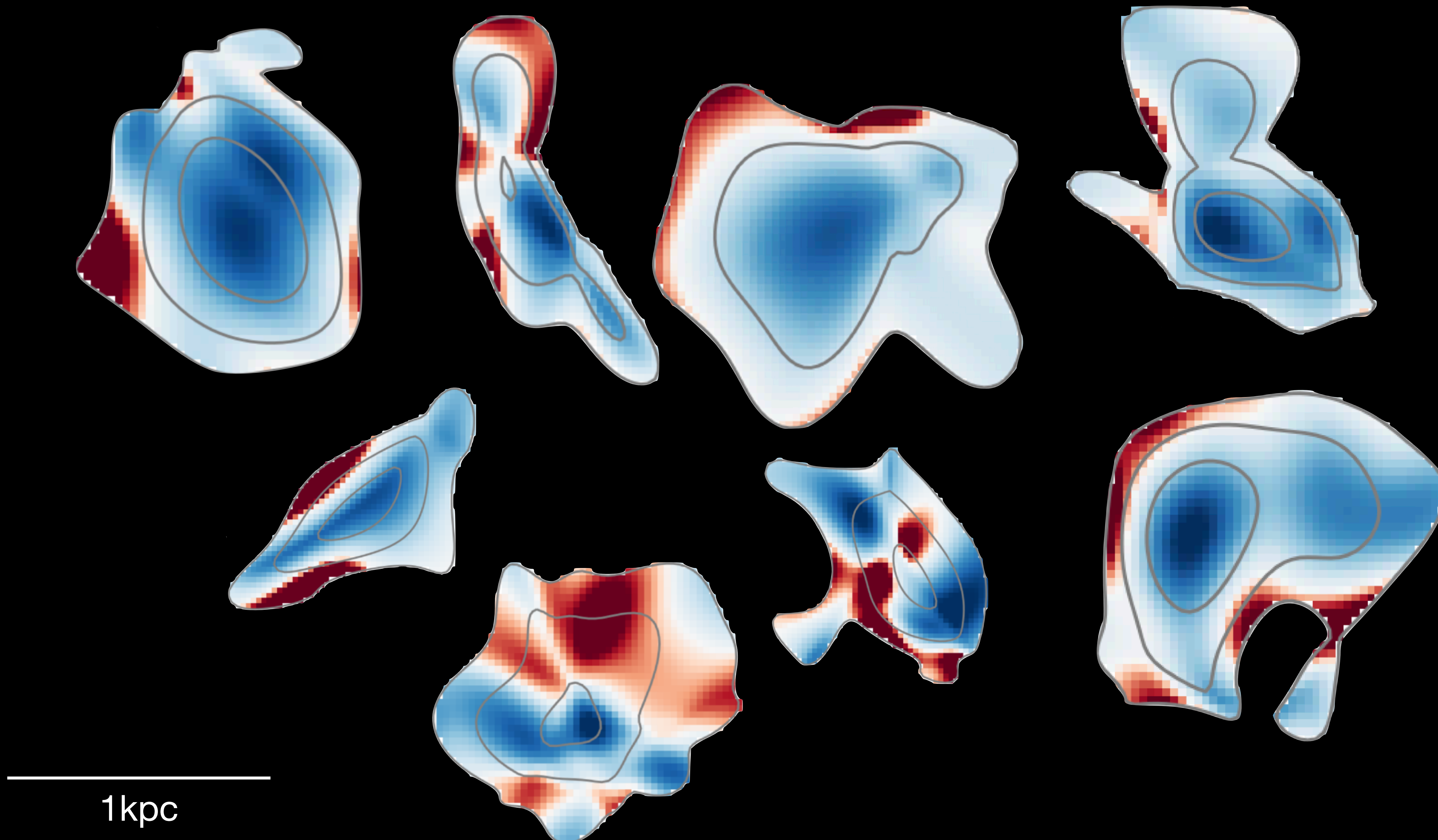
Molecular Outflows at z > 4 are Ubiquitous



Both the outflow occurrence rate *AND* the covering fraction must be nearly 100%!

Clumpy Molecular Outflows are Ubiquitous

Lensing reconstructions of outflowing gas only



Spilker+2020a,b

Molecular outflows are now accessible at z > 4!

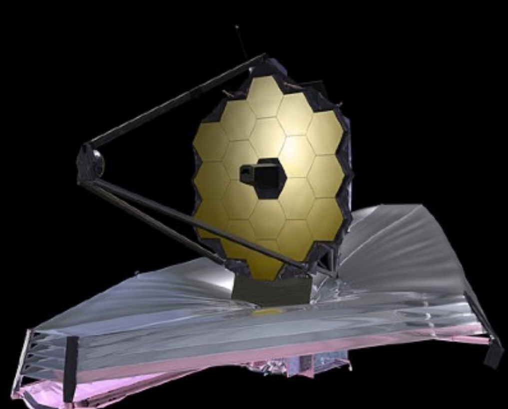
… but we need either very luminous galaxies, or lensed galaxies (or both)

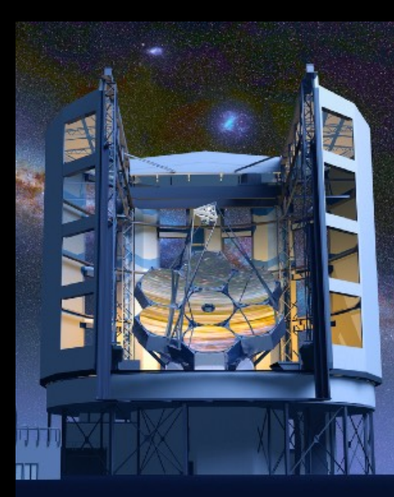
The Landscape for Feedback in the 2030s

Warm & Hot Ionized Gas

dominates kinetic energy budget

- Large samples of ‘normal’ galaxies to z > 6 (*JWST* MOS)
- Stunningly detailed maps at 50-100pc resolution (30m ELTs)
- Metallicities and energetics of hot plasma (Athena, Lynx)





Cold Molecular Gas

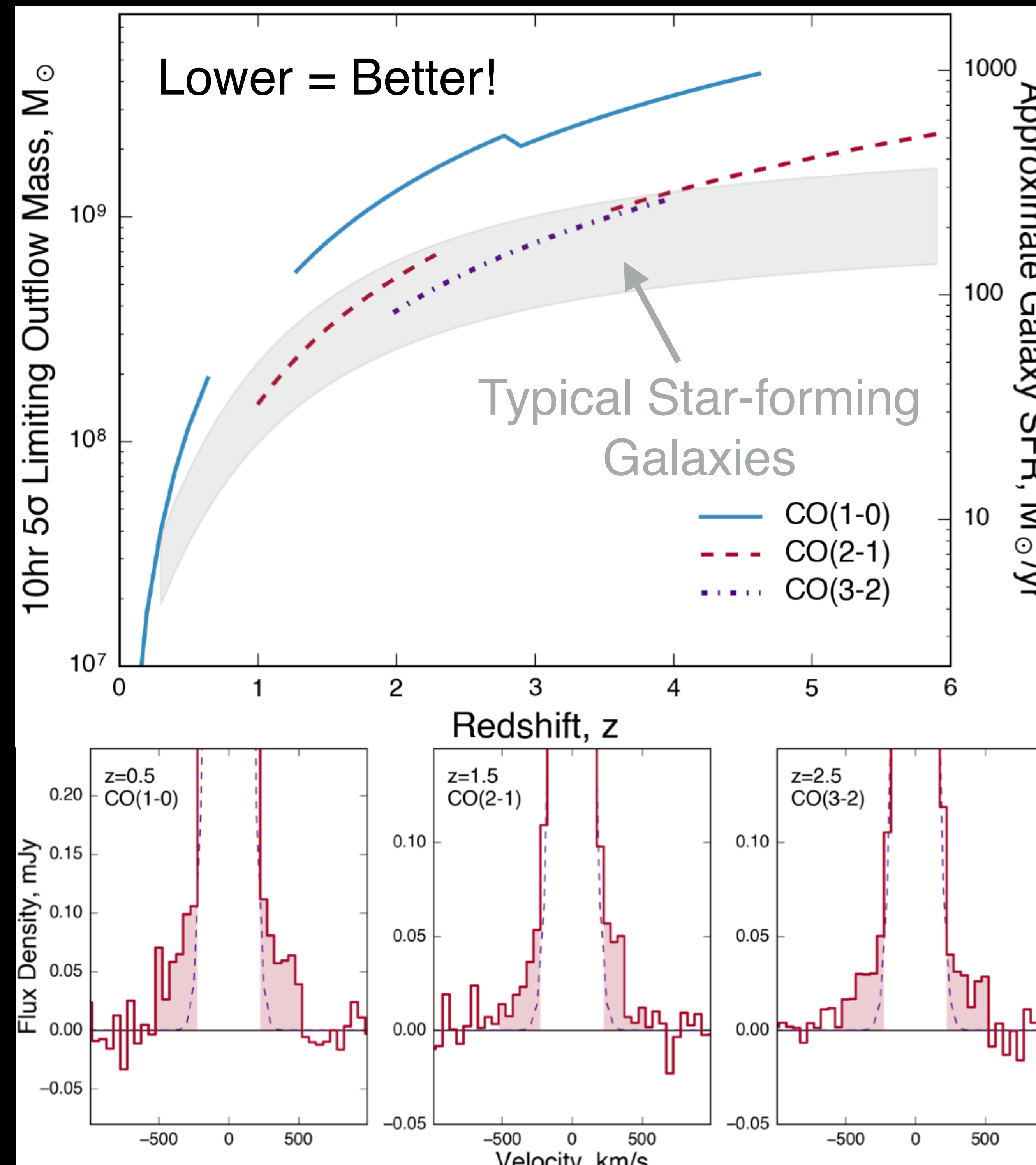
dominates mass, momentum budget

- IR-luminous AGN, high-SFR galaxies not representative of broad galaxy population (ALMA)
- (optimistically) Some ‘normal’ galaxies assuming >10hr / source time investment (ALMA)

Tracing Molecular Outflows Across Redshift

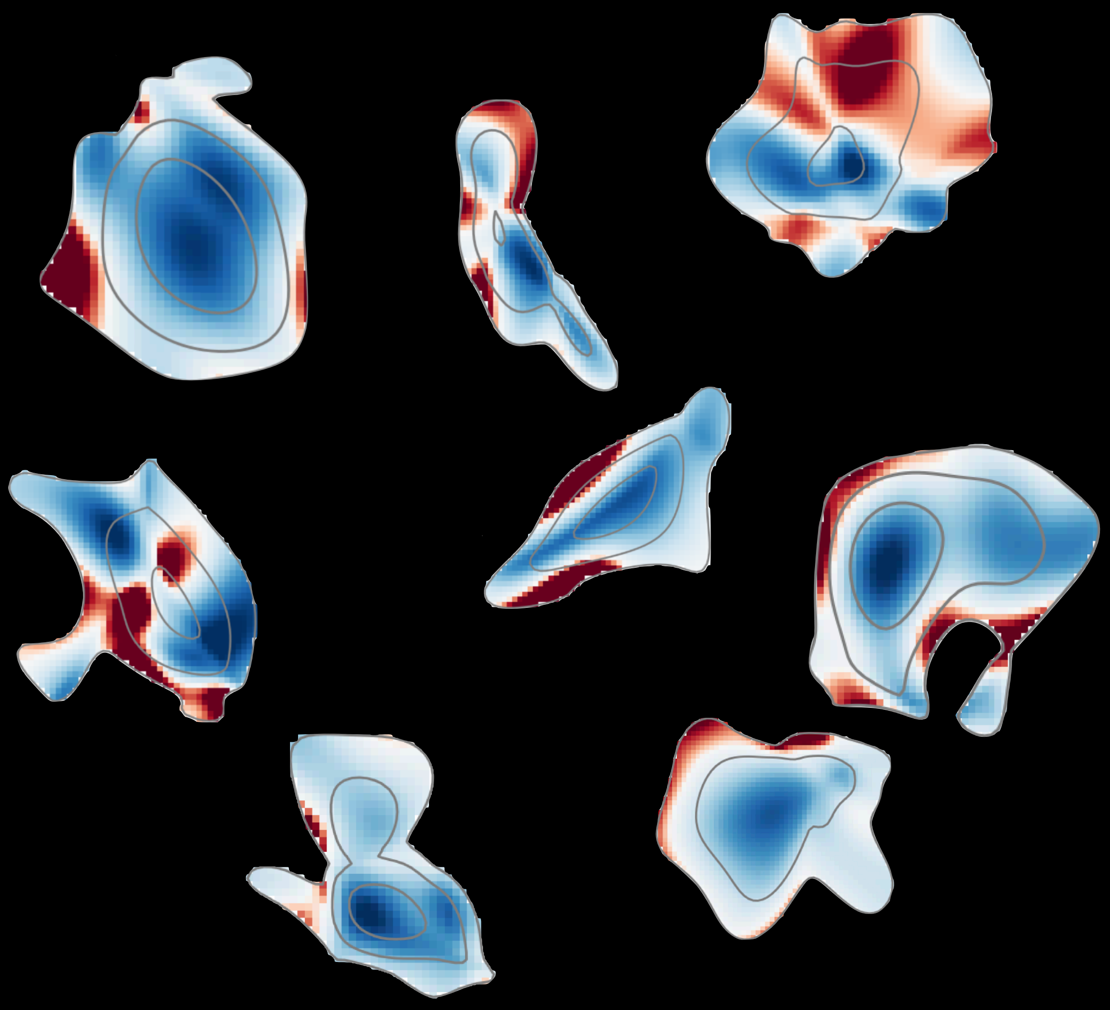
The ngVLA can detect outflows in “normal” galaxies to z~4

This comes “for free” given the time needed for deep fields, CO kinematics, etc.



Spilker & Nyland 2018
ngVLA Science Book

Conclusions



Molecular outflows are key to regulating star formation in galaxies

Outflows are now detectable at z > 4, appear to be common and clumpy on ~500pc scales

We will need a large increase in sensitivity to track molecular feedback in typical galaxies